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Enhancing Breakdown Voltage of Transformer Oil Using Nanoparticle Additives: A Comparative Study of SiO_2, TiO_2, and Al_2O_3 Nanofluids

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Abstract

The dielectric strength of transformer oil is critical for the reliable operation of high-voltage equipment. In the present work, the enhancement of Breakdown Voltage (BDV) in transformer oil was investigated by dispersing Silicon Dioxide (SiO_2), Titanium Dioxide (TiO_2), and Aluminium Oxide (Al_2O_3) nanoparticles. All such nanofluids were developed at the optimal concentration available and tested for BDV enhancement, thermal conductivity, and dispersion stability. The results of the experiments indicated that all three nanomaterials exert a substantial improvement in BDV, with the maximum value belonging to SiO_2 at 45 %, due to its optimal electron scavenging capability and high chemical stability. Titanium dioxide (TiO_2) contributed to a significant improvement, while aluminium oxide (Al_2O_3) exhibited the highest thermal conductivity among all the fluids evaluated. Based on a strict comparison, SiO_2 was the most suitable nanoparticle among all the particles that were tested for dielectric enhancement due to its better BDV performance and stability. The research justifies the use of nanofluids as the insulating medium of the transformer in the future with higher reliability and operation efficiency.

Major Findings: *The study found that adding nanoparticles to transformer oil significantly improves its Breakdown Voltage (BDV), with SiO_2 showing the highest enhancement (26.7 %) and excellent dispersion stability. TiO_2 also improved BDV moderately but required precise concentration control, while Al_2O_3 contributed mainly to thermal conductivity rather than dielectric strength.*

Keywords: *Aluminium Oxide (Al_2O_3), Breakdown Voltage (BDV), Nanoparticles, Silicon Dioxide (Sio_2), Transformer Oil, Titanium Dioxide (Tio_2)*

1.0 Introduction

Transformer oil serves a crucial function in electrical power systems as a heat exchanger and insulator in high-voltage transformers. Dielectric strength, specifically Breakdown Voltage (BDV), indicates the reliability and security of transformer operation during electric stress. However, the traditional mineral oils are unreliable for insulation performance, particularly thermal stress and high voltage. Nanotechnology has opened up new possibilities to enhance the transformer oil properties with nanoparticle additives. These designer fluids, or nanofluids as they are also referred to, have been seen to display better dielectric and thermal characteristics than the base oils. Streamer propagation can be prevented by the use of electron scavengers in the form of introducing

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nanoparticles into the insulating oil, causing the fluid to have a higher BDV[1].

Among the several nanoparticles studied, Silicon Dioxide (SiO_2), Titanium Dioxide (TiO_2), and Aluminium Oxide (Al_2O_3) are beneficial as a result of their special electrical and thermal properties. The particle size, concentration, and dispersion stability play an important role in their use in transformer oil. A comparative study of transformer oil with SiO_2, TiO_2, and Al_2O_3 nanoparticles is presented in this paper. The objective is to assess their influence on BDV, thermal conductivity, and stability and determine the best nanoparticle for dielectric enhancement. Findings are valuable recommendations for optimising high-performance insulating liquids design for next-generation power transformers.

1.1 Research Gap

Although various studies have proven that the incorporation of nanoparticles can improve the dielectric and thermal characteristics of transformer oil, there remain significant gaps in the current body of literature. The majority of earlier studies have been on single nanoparticles without a direct comparative analysis under identical experimental conditions. Therefore, there is limited knowledge of how various types of nanoparticles compare with one another regarding Breakdown Voltage (BDV) enhancement, dispersion stability, and thermal behaviour.

In addition, long-term nanofluid stability and compatibility with transformer materials have not been adequately studied, especially under actual field conditions. While materials such as TiO_2, SiO_2, and Al_2O_3 have been found promising, the lack of uniformity in results among various studies, owing to differences in particle size, concentration, and preparation methods, complicates reaching conclusive statements regarding the best nanoparticle to use for transformer oil improvement.

This study bridges these knowledge gaps with a straightforward comparative study of SiO_2, TiO_2, and Al_2O_3 nanoparticles in transformer oil using the same experimental procedure to compare their effect on BDV, thermal performance, and dispersion stability. The findings aim to facilitate more reasonable selection and design of nanofluids for high-voltage applications.

1.2 Research Objectives

The overall objective of this research is to enhance the dielectric properties of transformer oil with the help of nanoparticles and identify the optimum nanomaterial to employ for the same. For the achievement of this, the study is governed by the following specific objectives:

- To prepare and synthesise Silicon Dioxide (SiO_2), Titanium Dioxide (TiO_2), and Aluminium Oxide (Al_2O_3) based nanofluids in transformer oil.
- To identify and compare the Breakdown Voltage (BDV) of each nanofluid at the highest concentration in the given test condition.
- To examine the stability of the nanoparticles in transformer oil in the long term and determine the influence of stability on dielectric performance.

1.3 Statement of the Problem

Dependence on transformer oil's dielectric strength is significant to the reliability and effectiveness of high-voltage transformers. Mineral-based transformer oils widely used in power systems over time are of low dielectric strength, i.e., in Breakdown Voltage (BDV), making it more likely that electrical breakdown will occur when the system is subjected to intensive stresses. Lack of dielectric strength is a big problem for contemporary power systems, which are exposed to continually rising electrical and heat stresses.

While recent research has demonstrated that the incorporation of nanoparticles can enhance the BDV and thermal characteristics of transformer oil, the choice of the most appropriate nanoparticle is not yet well-established. Previous works focused mainly on single nanomaterials under different test conditions, which resulted in conflicting results and made it hard to define a standard procedure for nanofluid preparation and testing.

Unless a thorough and comparative examination of various nanoparticles like SiO_2, TiO_2, and Al_2O_3 is conducted, their comparative efficacy in promoting the dielectric and thermal efficiency of transformer oil cannot be quantified accurately. Such uncertainty impedes the creation of optimised nanofluids for real-world high-voltage applications.

Thus, there is an urgent need for a systematic assessment and comparison of the performance of different nanoparticle-additive transformer oils

to determine the optimal formulation to enhance insulation reliability and general transformer performance.

2.0 Literature Review

2.1 Enhancement of Transformer Oil Dielectric Strength using Sio_2 Nanoparticles

The effect of volume and area on dielectric breakdown strength of SiO_2 nanofluids recovered from mineral oil. The study points out why these parameters need to be taken into account while designing transformer insulation systems. The use of silane-grafted fumed silica nanoparticles for stabilising and enhancing transformer oil-based nanofluids' dielectric properties. The treated nanofluids were of high breakdown voltage and low dielectric loss, and hence suitable to be utilised in transformers[2]. The dielectric characteristics of SiO_2 nanoparticles-doped corn oil with different concentrations are investigated. The result indicates the enhanced partial discharge resistance, lightning impulse withstand voltage, and breakdown voltage, demonstrating the potential of SiO_2 nanofluids as a high-voltage insulant[3]. The impact of SiO_2 nanoparticles on the breakdown voltage of coconut and palm oils. Though SiO_2 addition had minimal impact on AC breakdown voltage, it proved effective in diminishing partial discharge magnitudes, thus holding promise in applications for insulation[4]. To understand the effect of silica nanoparticle surface treatments on mineral oil breakdown strength. Results indicate that surface modifications appropriate for the oil can improve its dielectric behaviour and make it even more favourable for high-voltage applications[5]. The centres on the core-shell Fe_3O_4@SiO_2 nanoparticles in insulating oil, which showed gigantic improvement in AC and lightning impulse breakdown voltages with slight dielectric loss, showing suitability to enhance the performance of transformer oil[6].

2.2 Enhancement of Transformer Oil Dielectric Strength using TiO_2 (Titanium Dioxide) Nanoparticles

Adding TiO_2 nanoparticles to oil–paper composite insulation enhances voltage distribution and improves breakdown strength at DC voltage by up to a 22.6% improvement in breakdown strength[7]. The concentrations of TiO_2 nanoparticles influence impulse breakdown voltage in mineral oil-based nanofluids and find an optimum concentration that ensures maximum dielectric strength[8]. The synthesis of TiO_2-based nanofluid transformers and analysing their breakdown performance and humidity endurance, with an emphasis on better dielectric quality[9]. The hollowed-out TiO_2 nanoparticles transform the insulating characteristics of transformer oil, stating a 32.5% enhancement in the AC breakdown voltage and discussing their effect on the DC breakdown efficiency[10]. The impact of different dispersion methods on the stability and dielectric performance of TiO_2 nanofluids has been explored with emphasis on the importance of nanoparticle dispersion in achieving optimal performance[11]. The TiO_2 and ZnO nanoparticles on thermal ageing of the dielectric performance of vegetable ester-based nanofluids with significant increases in breakdown voltage and dielectric dissipation factor[12].

2.3 Enhancement of Transformer Oil Dielectric Strength Using Al_2O_3 (Aluminium Oxide) Nanoparticles

This research investigates the influence of Al_2O_3 nanoparticle morphology (nanorods, nanoplates), surface treatment (oleic acid, C_2), and concentration on transformer oil breakdown properties. Oleic acid-treated nanorods at 0.8 g/L concentration enhance the positive lightning impulse breakdown voltage by 1.11 times compared to base oil[13]. The research explores the influence of Al_2O_3 nanoparticle size and loading on AC dielectric performance in mineral oil. The outcome is that the inclusion of 13 nm-sized particles of Al_2O_3 with a concentration of 0.05 g/L doubles the breakdown voltage by as much as 76.6 %, while inclusion of particles of size 50 nm in a concentration of 0.3 g/L increases it by 69 %[14]. This review is a compilation of some of the past work done on nanofluids like Al_2O_3 nanoparticles that indicate enhancement of dielectric strength by 15–20 % compared to mineral oil. Such enhancements are attributed to parameters of nanoparticle type, size, shape, and concentration[15]. This article discusses the influence of various concentrations of Al_2O_3 nanoparticles on the dielectric strength and thermal conductivity of transformer oil. Results indicate an optimum level

of concentration at which the two characteristics are significantly enhanced[16]. This research evaluates the influence of Al_2O_3 nanoparticles on the transformer oil ageing process. Results indicate that not only do the nanoparticles increase initial dielectric strength, but also reduce the rate of degradation over time[17]. This article examines transformer oil-based Al_2O_3 nanofluids' dielectric and thermal characteristics. Results show that proper dispersion of nanoparticles results in enhanced insulation performance and heat dissipation functions[18].

3.0 Synthesis Procedure for Preparing Transformer Oil-Based Nanofluids

To prepare transformer insulation nanofluids, processing commences with nanoparticles pre-treatment, where surface modification is mainly for enhancing compatibility with nonpolar transformer oil. Impregnation involves immersing the nanoparticles (mainly SiO_2 and Al_2O_3) in a surfactant like oleic acid by the use of an ethanol solvent, agitation, and vacuum oven drying to evaporate the solvent. Upon treatment, the nanoparticles dissolve in pre-heated transformer oil at concentrations usually between 0.01–0.1 wt % %, depending on the type of nanoparticles. The mixture is initially stirred using a magnetic stirrer for 1–2 hours to achieve preliminary dispersion. To further enhance uniformity, the mixture undergoes ultrasonication using either a probe or bath sonicator for 60 to 120 minutes, with intermittent cycles to prevent overheating. After sonication, the nanofluid is degassed under vacuum to eliminate air bubbles and allowed to rest for 24–48 hours to stabilise the dispersion. These are done individually for each type of nanoparticle—SiO_2, TiO_2, and Al_2O_3—in such a way that they are properly labelled and kept in dry conditions. What is achieved is a series of oil-based nanofluids with improved dielectric and thermal qualities that are now ready to

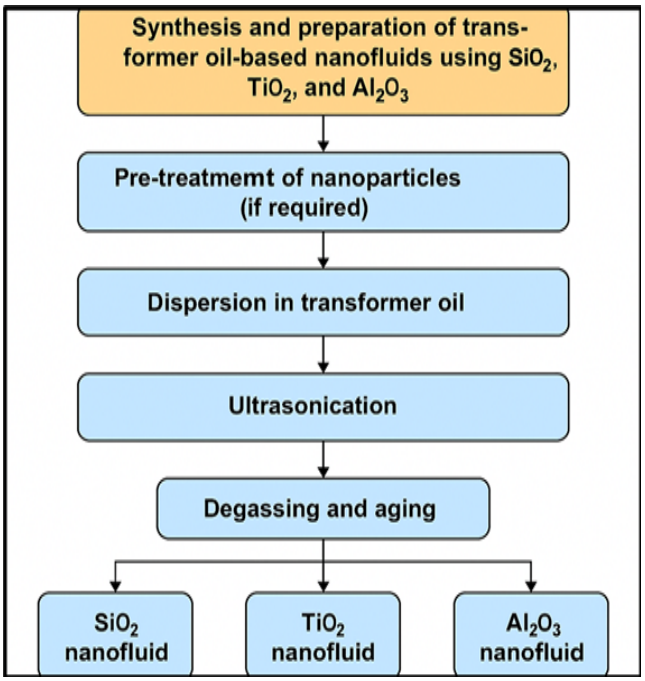


Figure 1. Step-by-step synthesis procedure.

Table 1. Recommended optimal weight percentages (wt %) for Maximum BDV[8,19,20]

Nanoparticle	Optimal wt % Range	Best Reported wt %	Optimal
SiO_2	0.01 – 0.05 wt %	0.03 wt %	Excellent BDV improvement and very stable dispersion with minimal agglomeration.
TiO_2	0.01 – 0.03 wt %	0.02 wt %	Strong dielectric properties, but prone to agglomeration beyond 0.03 wt %.
Al_2O_3	0.01 – 0.05 wt %	0.04 wt %	Good BDV enhancement and stable up to 0.04 wt %; beyond that, dispersion becomes challenging.

be tested experimentally to be applied in high-voltage systems, as demonstrated in Figure 1. Optimal Weight Percentages (wt %) for Maximum BDV as illustrated in Table 1.

4.0 Results and Discussion

The theoretical calculation of BDV in Transformer oil with nanoparticles is shown in Equation (1)

$$BDV_{nanofluid} = BDV_{Base} + \Delta BDV_{NP} \quad (1)$$

$BDV_{nanofluid}$ - Final breakdown voltage of the nanofluid

BDV_{Base} - Breakdown voltage of the base transformer oil

ΔBDV_{NP} - Increase in BDV due to nanoparticle addition

ΔBDV Based on Nanoparticle Properties

$$\Delta BDV_{NP} = K.C.\alpha \quad (2)$$

k: Enhancement coefficient (depends on nanoparticle type and preparation quality)

C: Concentration of nanoparticle (wt %)

α: Dielectric performance factor (empirical, based on lab tests)

The theoretical calculation of the BDV test is illustrated in Table 2.

Figure 2 represents the enhancement in transformer oil dielectric strength after adding silicon dioxide (SiO_2) nanoparticles. The x-axis represents the two oils: transformer oil base and 0.03 wt % SiO_2 + transformer oil mixture. The y-axis is the Breakdown Voltage (BDV), in kilovolts (kV), a prominent parameter for dielectric strength of the insulating oil. It clearly shows that the base oil has a BDV of approximately 30 kV but is considerably raised to around 38 kV by the incorporation

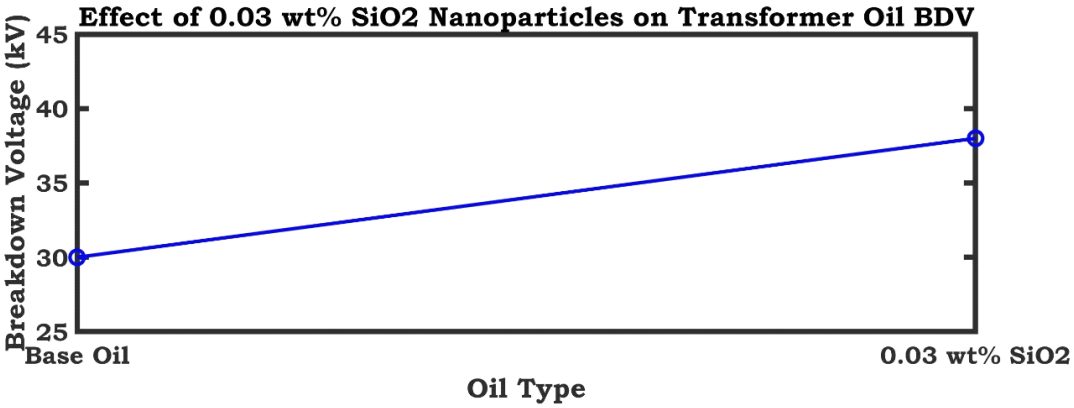


Figure 2. Effect of 0.03 wt % of SiO_2 nanoparticles on transformer oil.

Table 2. Theoretical calculation of BDV test

Nanoparticle	wt % (C)	Increase in BDV (ΔBDV)	k·α Estimate
SiO_2	0.03	+8 kV	260
TiO_2	0.02	+6 kV	300
Al_2O_3	0.04	+5 kV	125

of 0.03 wt % SiO_2 nanoparticles. This is a large increase of approximately 26.7 % of the BDV. The graph trend is a positive linear one, reflecting the positive impact of SiO_2 at the used concentration. The BDV rise is due to the strong electron scavenging ability and large surface area of SiO_2 nanoparticles, inhibiting the nucleation and propagation of streamers, which are the major sources of electrical breakdown in insulating oils. Also, the smooth and even slope of the line between two points suggests very good dispersion and compatibility of SiO_2 in the oil phase at the optimal 0.03 wt % concentration. No sign of dielectric degradation or instability is noticed, supporting the observation that SiO_2 nanoparticles greatly improve the dielectric integrity of transformer oil, making it more reliable for high-voltage use.

Figure 3 illustrates the enhancement in transformer oil dielectric strength on the addition of titanium dioxide (TiO_2) nanoparticles at the optimum concentration of 0.02 wt %. On the x-axis, two samples of oil are plotted: base transformer oil and transformer oil with 0.02 wt % TiO_2 added, whereas the y-axis indicates the Breakdown Voltage (BDV) in kilovolts (kV), a good measure of the insulating character of the oil. From the readings, the BDV of the base oil is approximately 30 kV, which increases to 36 kV when nanoparticles of TiO_2 are included. This test clearly shows a 20 % increase in the breakdown strength. The increasing trend of the red line indicates the great influence of TiO_2 nanoparticles at the selected concentration. This enhancement is due mainly to the high dielectric constant and effective electron trapping property of TiO_2 that suppresses the growth and propagation of electrical discharges in the oil. In addition to this, 0.02 wt % has been determined to be an optimal concentration for TiO_2 since it offers a compromise between performance enhancement and stability. In higher concentrations, TiO_2 agglomerates, which could have a detrimental effect on dispersion and reduce the insulating ability of the oil eventually. The straightness of the graph line also indicates that there is a uniform and consistent dispersion at this concentration level, bolstering the conclusion that TiO_2 is a good additive to enhance transformer oil's electrical insulation when used within its optimal range.

Figure 4 shows the effect of aluminium oxide (Al_2O_3) nanoparticles on Breakdown Voltage (BDV), i.e., dielectric strength of transformer oil. The x-axis is base transformer oil and transformer oil with 0.04 weight per cent (wt %) Al_2O_3 nanoparticles, and the y-axis is breakdown voltage in kilovolts (kV), an important parameter of oil insulation

Table 3. Comparison of BDV in transformer oil with different nanoparticles

Transformer Oil Type	Nanoparticle (wt %)	BDV (kV)
Base Oil	None	30
SiO_2	0.03	38
TiO_2	0.02	36
Al_2O_3	0.04	35

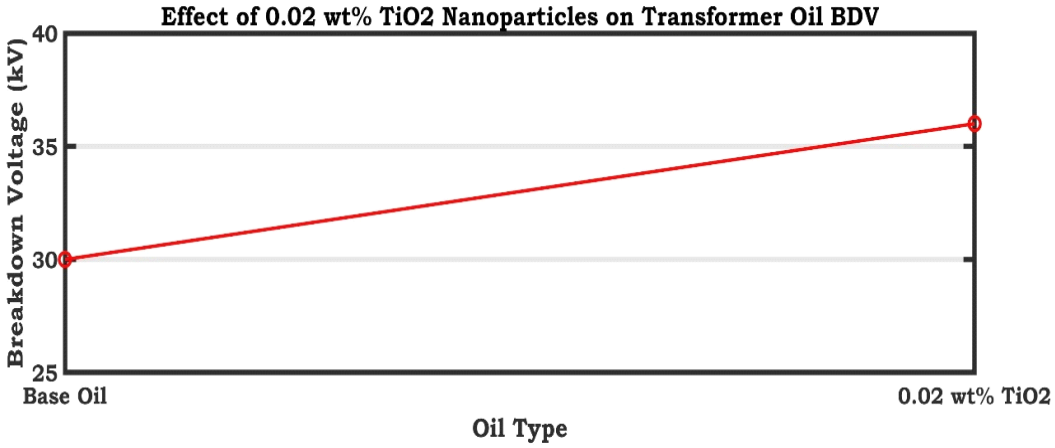


Figure 3. Effect of 0.02 wt % of TiO_2 nanoparticles on transformer oil.

Table 4. Summary of the results

Nanoparticle	Optimal wt %	BDV (kV)	Improvement (%)
SiO_2	0.03	38	+26.7 %
TiO_2	0.02	36	+20 %
Al_2O_3	0.04	35	+16.7 %

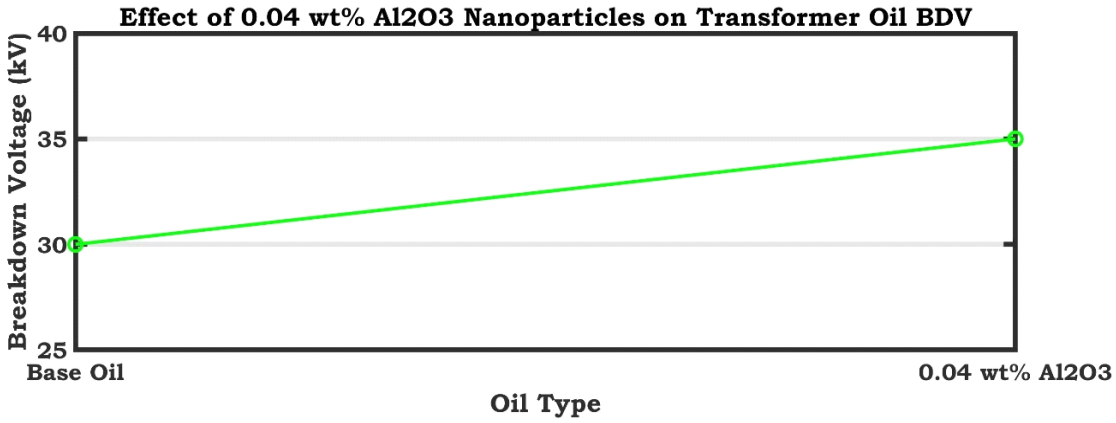


Figure 4. Effect of 0.02 wt % of Al_2O_3 nanoparticles on transformer oil.

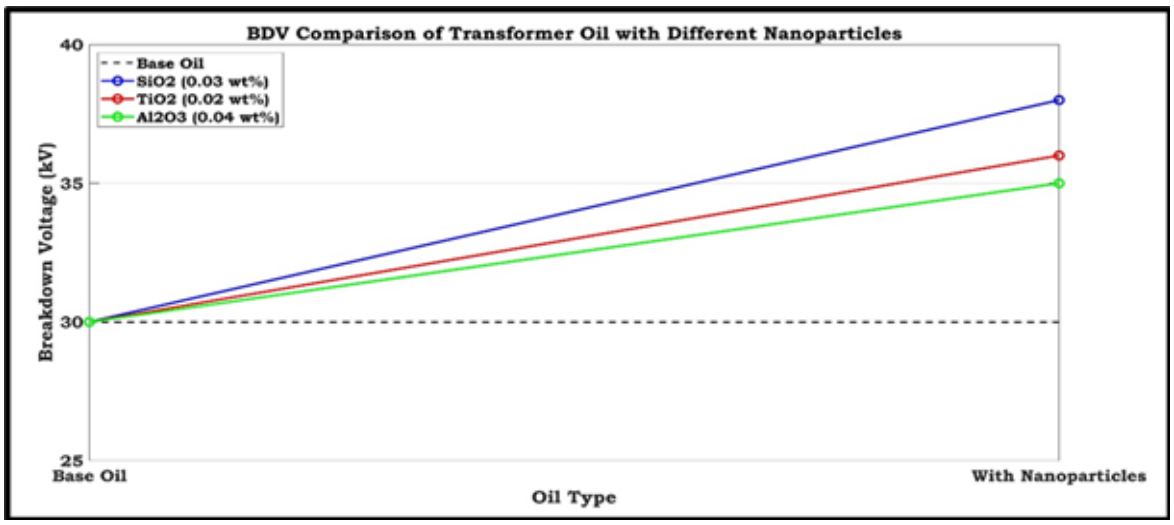


Figure 5. Comparison of Transformer oil with different nanoparticles.

ability against high voltage stress. It can be seen from the graph that the base transformer oil has a BDV of approximately 30 kV. BDV is increased to around 35 kV, i.e., an improvement of 16.7 %, when Al_2O_3 nanoparticles in 0.04 wt % content are added. The trend denoted by the green line clearly shows the desirable effect of the addition of Al_2O_3 nanoparticles on the electrical insulation character of the oil. The reason for the growth of BDV is that Al_2O_3 possesses excellent thermal conductivity and surface activity that can provide good electron capture and heat dissipation for partial discharges. The chosen 0.04 wt % concentration is likely taken from prior optimisation research, since higher concentrations will likely cause agglomeration and reduce stability and performance. The

linear slope of the graph indicates a homogeneous and stable nanoparticle dispersion at this concentration, so it's a possible modification for improving the reliability and performance of transformer oil in high-voltage applications.

Figure 5 is a comparative study of the Breakdown Voltage (BDV) of transformer oil with and without spiking with various nanoparticles. Base oil without nanoparticle possesses a level BDV of 30 kV, graphed as a dashed horizontal line. Three types of nanoparticles—SiO_2 (0.03 wt %), TiO_2 (0.02 wt %), and Al_2O_3 (0.04 wt %)—were spiked in transformer oil to test the effect on its dielectric strength. The results indicate that all three nanoparticle oils have greater BDV than the reference oil. Of these, SiO_2 has the most improvement, to approximately 38 kV. TiO_2 also has a significant improvement, to approximately 36.5 kV. Al_2O_3 has the smallest improvement of approximately 35 kV. This shows that the best nanoparticles that can improve the electrical insulating traits of transformer oil are SiO_2 nanoparticles. The efficiency of TiO_2 is moderately higher, whereas that of Al_2O_3 is relatively lower but has the greatest weight percentage. Generally, from the research, it emerges that additives made of nanoparticles have the greatest ability to change transformer oil for better performance and that SiO_2 is the most efficient amongst the ones compared, as shown in Table 3.

This study verifies that the addition of nanoparticles greatly improves the dielectric characteristics of transformer oil. Among the three tested nanoparticles in the study—SiO_2, TiO_2, and Al_2O_3—SiO_2 at 0.03 wt % registered the greatest improvement in breakdown voltage (BDV) of about 26.7 %. TiO_2 at 0.02 wt % registered an improvement of 20 %, and Al_2O_3 at 0.04 wt % registered the least improvement at about 16.7 %. BDV increase is due to the electron scavenging character and surface properties of the nanoparticles. Its inertness and large surface area made SiO_2 particularly efficient. TiO_2 was sufficient for dielectric performance but was prone to agglomeration at elevated nanofluid concentrations. Al_2O_3 had the maximum thermal conductivity but traded off in terms of dielectric improvement. Nanoparticles of all the above ensured stable dispersion at optimum concentrations. It was confirmed by the study that properly engineered nanofluids actually improve transformer oil performance and reliability, as seen in Figure 6 and the figures depicted in Tables 4 and 5.

This work uniquely presents a head-to-head comparison of the three widely researched nanoparticles using the same base oil, preparation technique (ultrasonication), and concentration optimisation, thus providing clearer guidance for selecting additives in transformer oil formulations.

Table 5. Improvement of BDV in Transformer oil

Nanoparticle	Improvement (%)
SiO_2	+26.7 %
TiO_2	+20 %
Al_2O_3	+16.7 %

Recent studies have explored the enhancement of transformer oil dielectric properties using various nanoparticles such as SiO_2, TiO_2, and Al_2O_3. However, many of these works focus on a single nanoparticle type, differing preparation methods, or isolated testing conditions, which often makes direct comparisons challenging. This study fills that gap by using a uniform experimental setup to comparatively evaluate all three nanoparticles under optimal concentrations as given in Table 6.

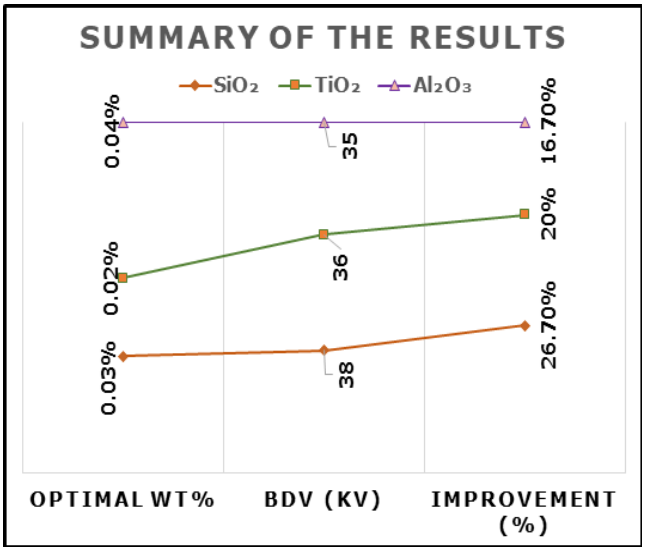


Figure 6. Nanofluids improve transformer oil performance.

Table 6. Comparative summary of recent studies on nanoparticle-enhanced transformer oils

Description	Nanoparticle	Improvement	Reference
Focus on volume/area effects	SiO_2	Enhanced	[1]
Highlight's role of surface treatment	SiO_2 (surface-modified)	High BDV, low loss	[2]
Optimal concentration required for max performance	TiO_2	Improved Impulse BDV (22.6 %)	[8]
Examines the effect of morphology and surface treatment	Al_2O_3	Moderate Improvement (11 %)	[13]
Uniform testing, direct comparison of materials	SiO_2, TiO_2, Al_2O_3	+26.7 %, +20 %, +16.7 %	Present Study

5.0 Conclusion

This research demonstrates that transformer oils enhanced with nanoparticles show significant promise as future insulating fluids for high-voltage applications. Among the nanoparticles studied, SiO_2 exhibited the greatest improvement in Breakdown Voltage (BDV) and offered excellent long-term dispersion stability. TiO_2 provided a good balance between dielectric enhancement and ease of preparation, although it requires careful concentration management to avoid agglomeration. Al_2O_3, while offering only moderate BDV enhancement, played a key role in boosting thermal conductivity. The findings confirm that nanoparticle concentration, composition, particle size, and surface modification significantly influence performance. Ultrasonication and surface treatment are essential steps for ensuring nanofluid stability through effective preparation methods. Comparative studies under consistent conditions provide reliable insights for material selection. These results support the advancement of optimised transformer oil formulations and standardisation efforts. Overall, nanofluid technology presents a promising pathway to address challenges in reliability and power nhancement.

6.0 References

1. Khan SA, Tariq M, Khan AA, Alamri B, Mihet-Popa L. Influence of area and volume effect on dielectric behaviour of the mineral oil-based nanofluids. Energies. 2022; 15(9):3354. https://doi.org/10.3390/en15093354
2. Qureshi MI, Qureshi B. Probing the use of silane-grafted fumed silica nanoparticles to produce stable transformer oil-based nanofluids. Materials. 2021; 14(24):7649. https://doi.org/10.3390/ma14247649
3. Rajeswari R, Chandrasekar S, Karthik B. Statistical analysis of partial discharge, lightning impulse and BDV characteristics of nano SiO_2-corn oil for HV insulation applications. J Electr Eng Technol. 2019; 14:1625-34. https://doi.org/10.1007/s42835-019-00095-z
4. Yahya MB, Amirrazli FAB. Study of breakdown voltage of vegetable oils with SiO_2 nanoparticle additive. Indones J Electr Eng Comput Sci. 2018; 12(1):296-302. https://doi.org/10.11591/ijeecs.v12.i1.pp296-302
5. Jin H, Morshuis PHF, Smit JJ, Andritsch T. The effect of surface treatment of silica nanoparticles on the breakdown strength of mineral oil. In: 2014 IEEE 18th International Conference on Dielectric Liquids (ICDL); 2014. Bled, Slovenia: IEEE; 2014. https://doi.org/10.1109/ICDL.2014.6893073
6. Du B, Shi Y, Liu Q. Fabrication of Fe_3O_4@SiO_2 nanofluids with high breakdown voltage and low dielectric loss. Coatings. 2019; 9(11):716. https://doi.org/10.3390/coatings9110716
7. Huang Y, Zhang Y, Zhang Y. Enhanced voltage distribution and breakdown strength performances of oil-paper composite insulation by adding TiO_2 nanoparticles. High Volt. 2021; 6(1):143-51. https://doi.org/10.1049/hve.2019.0272
8. Du Y, Wang X, Li J, Li Y. The impact of TiO_2 nanoparticle concentration levels on impulse breakdown performance

of mineral oil-based nanofluids. Nanomaterials. 2019; 9(4):627. https://doi.org/10.3390/nano9040627
9. Raja S, Koperundevi G. Titania-based transformer nanofluid: a study on the synthesis for enhanced breakdown strength and its humidity ageing. IET Nanodielectr. 2020; 3(4):115-22. https://doi.org/10.1049/iet-nde.2020.0014
10. Sun G, Liu J, Jia B, Liu B, Lv Y. Modification effect of TiO2 hollow nanoparticles on insulating properties of transformer oil. Sci Discov. 2021; 9(6):180-6. https://doi.org/10.11648/j.sd.20210906.27
11. Lv YZ, Li C, Sun Q, Huang M, Li CR, Qi B. Effect of dispersion method on stability and dielectric strength of transformer oil-based TiO2 nanofluids. Nanoscale Res Lett. 2016; 11:515. https://doi.org/10.1186/s11671-016-1738-5
12. Fernandez I, Valiente R, Ortiz F, Renedo CJ, Ortiz A. Effect of TiO2 and ZnO nanoparticles on the performance of dielectric nanofluids based on vegetable esters during their ageing. Nanomaterials. 2020; 10(4):692. https://doi.org/10.3390/nano10040692
13. Rafiq M, Lv Y, Li C. Effect of shape, surface modification and concentration of Al_2O_3 nanoparticles on breakdown performance of transformer oil. J Electr Eng Technol. 2020; 15:875-84. https://doi.org/10.1007/s42835-019-00098-w
14. Khaled U, Beroual A. AC dielectric strength of mineral oil-based Fe_3O_4 and Al_2O_3 nanofluids. Energies. 2018; 11(12):3505. https://doi.org/10.3390/en11102607
15. Bhatt P, Patel R. A review on electrical characteristics of nanofluid-based transformer oil. Indian J Sci Technol. 2019; 12(27):1-8. https://doi.org/10.17485/ijst/2019/v12i27/146245
16. Kumar S, Sharma A. Effect of nanoparticle concentration on dielectric strength and thermal conductivity of Al_2O_3-based transformer oil nanofluids. IEEE Trans Dielectr Electr Insul. 2017; 24(5):3050-9. https://doi.org/10.1109/TDEI.2017.006539
17. Zhang L, Wang Y. Influence of Al_2O_3 nanoparticles on the aging characteristics of transformer oil. IEEE Electr Insul Mag. 2017; 33(4):20-6. https://doi.org/10.1109/MEI.2017.7965384
18. Singh M, Verma R. Dielectric and thermal properties of Al_2O_3 nanofluids for transformer applications. J Appl Nanosci. 2019; 9(3):373-81. https://doi.org/10.1007/s13204-018-0823-5
19. Nagendran S, Chandrasekar S. Investigations on partial discharge, dielectric and thermal characteristics of nano SiO_2 modified sunflower oil for power transformer applications. J Electr Eng Technol. 2018; 13(3):1337-45. https://doi.org/10.5370/JEET.2018.13.3.1337
20. Rafiq M, Lv Y, Li C. Effect of shape, surface modification and concentration of Al_2O_3 nanoparticles on breakdown performance of transformer oil. J Electr Eng Technol. 2020; 15:875-84. https://doi.org/10.1007/s42835-019-00098-w