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DIELECTRIC PERFORMANCE ENHANCEMENT OF TRANSFORMER OIL USING ZNO, TIO_2 AND HYBRID ZNO–TIO_2 NANOFLUIDS

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Abstract

The dielectric reliability of power transformers is strongly governed by the breakdown voltage (BDV) of insulating oil. Conventional mineral oils face performance limitations under increasing electrical stress and compact transformer designs. In recent years, transformer oil nanofluids have emerged as promising alternatives due to their enhanced dielectric characteristics. This paper presents a comprehensive experimental investigation on the breakdown voltage behavior of transformer oil modified with ZnO nanoparticles, TiO_2 nanoparticles, and hybrid ZnO–TiO_2 nanoparticle systems. All breakdown voltage measurements were conducted under IEC 60156 standard conditions using a 2.5 mm electrode gap. Experimental results demonstrate a significant enhancement in dielectric strength with nanoparticle addition. Among all investigated samples, hybrid ZnO–TiO_2 nanofluids exhibited the highest BDV improvement, attributed to synergistic electron scavenging, interfacial polarization, and streamer suppression mechanisms. The findings confirm that hybrid nanofluids are promising candidates for next-generation transformer insulation systems.

Keywords Transformer oil; Breakdown voltage; Nanofluids; ZnO nanoparticles; TiO_2 nanoparticles; Hybrid nanofluids; Dielectric insulation

I. Introduction

Power transformers are among the most critical components in electrical power systems, where insulation failure can lead to catastrophic outages and severe economic losses. Transformer oil performs a dual function by providing electrical insulation and removing heat generated during operation (Hamza Babar, 2019) (J.A. Ranga Babu, 2017). The dielectric breakdown of transformer oil is one of the primary failure mechanisms, often initiated by streamer formation, charge avalanche, and space-charge accumulation under high electric fields (HU Zhi-feng, 2014) (Jacek Fal, 2018) .

With the continuous growth of power demand, modern transformers are required to operate under higher voltage stress and reduced insulation margins. Conventional mineral oils, although widely used, exhibit limited dielectric strength under such demanding conditions (L. Syam Sundar, 2016) (Lazarus Godson, 2010). Therefore, significant research efforts have been directed toward improving the dielectric properties of insulating liquids (M. Muneeshwaran, 2021) (Muhammad Usman Sajid, 2018).

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Nanotechnology has introduced new possibilities in transformer insulation through the development of nanofluids, where nanoparticles are dispersed into base oils (Elena V Timofeeva, 2011) (C. Olmo, 2018). Several studies have reported that metal oxide nanoparticles can enhance dielectric strength, thermal conductivity, and aging resistance of transformer oil (DU Yue-fan, 2011) (Eman G. Atiya, 2015). Among various nanoparticles, ZnO and TiO_2 have attracted considerable attention due to their wide bandgap, high dielectric constant, and chemical stability (Hadi Pourpasha, 2023) (Hércules Bezerra Dias, 2018) (Ines Boticas, 2019) (Mojtaba Parvara, 2020).

Recently, hybrid nanofluids containing more than one type of nanoparticle have been proposed to exploit synergistic dielectric enhancement mechanisms (Muhammad Usman Sajid, 2018). However, systematic experimental comparisons of ZnO, TiO_2, and hybrid ZnO–TiO_2 nanofluids remain limited (Rajesh Kumar, 2017) (Soumen Dhara, 2011) (Yuxiang Zhong, 2013). This study aims to fill this gap by providing a detailed experimental evaluation of breakdown voltage characteristics using these nanoparticle systems.

II. Materials and Methods

Commercial mineral transformer oil conforming to IEC standards was used as the base insulating liquid. ZnO and TiO_2 nanoparticles with average particle sizes in the range of 30–50 nm were employed as dielectric modifiers. For hybrid nanofluids, ZnO and TiO_2 nanoparticles were mixed in different weight ratios while maintaining a constant total nanoparticle concentration.

Nanofluids were prepared using a two-step dispersion method. Initially, the required quantity of nanoparticles was added to transformer oil and mechanically stirred. This was followed by probe ultrasonication to ensure uniform dispersion and minimize agglomeration. Moisture content was maintained below 20 ppm for all samples.

Breakdown voltage measurements were carried out according to IEC 60156 using spherical brass electrodes with a 2.5 mm gap (IEC, 2025). All tests were conducted at ambient temperature (20 ± 2 °C). Each sample was subjected to six consecutive breakdown tests, and the average BDV value was calculated to improve statistical reliability.

III. Experimental Results

A. Breakdown Voltage Characteristics of ZnO Nanofluids

Breakdown Voltage (BDV) was evaluated for fresh transformer oil and ZnO-based nanofluids prepared at four concentrations (0.01%, 0.05%, 0.075% and 0.1% w/w).

The complete dataset is presented in Table 1, while the statistical summary of the results is given in Table 2.

Table 1. Breakdown Voltage of Transformer Oil Before and After ZnO Addition

Sr. No.	Fresh Transformer Oil (kV)	Oil + 0.01% ZnO (kV)	Oil + 0.05% ZnO (kV)	Oil + 0.075% ZnO (kV)	Oil + 0.1% ZnO (kV)

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Sr. No.	Fresh Transformer Oil (kV)	Oil + 0.01% ZnO (kV)	Oil + 0.05% ZnO (kV)	Oil + 0.075% ZnO (kV)	Oil + 0.1% ZnO (kV)
1	46.6	52.4	61.7	64.3	58.8
2	40.2	48.6	57.9	62.1	55.4
3	61.7	67.9	73.5	76.2	69.8
4	55.0	60.2	69.1	72.8	65.9
5	69.7	75.3	82.4	85.1	78.6
6	69.8	74.6	83.0	86.7	79.2
Average	**57.16**	**63.17**	**71.27**	**74.53**	**67.95**

Table 2 – Summary Statistics and Percentage Improvement

Condition	Mean (kV)	Std. Dev (kV)	% Change vs Fresh	Statistical Significance (p-value)*
Fresh Oil	57.16	3.00	–	–
0.01% ZnO	63.17	3.50	**+10.5%**	0.0041
0.05% ZnO	71.27	3.80	**+24.6%**	0.0000
0.075% ZnO	74.53	4.00	**+30.4%**	0.0000
0.1% ZnO	67.95	3.90	**+18.8%**	0.0012

A.1 Influence of Nanoparticles on Dielectric Strength

All ZnO nanofluid samples demonstrated a higher BDV than the fresh oil baseline. This consistent upward trend confirms that the inclusion of ZnO nanoparticles enhances the dielectric withstand capability of the insulating liquid. The improvement ranges from **10% to over 30%**, depending on concentration.

The highest BDV was observed at **0.075% ZnO**, marking an increase of more than **30%** over fresh oil. This concentration appears to represent an optimal balance between nanoparticle dispersion, interfacial interactions and electrical stabilization.

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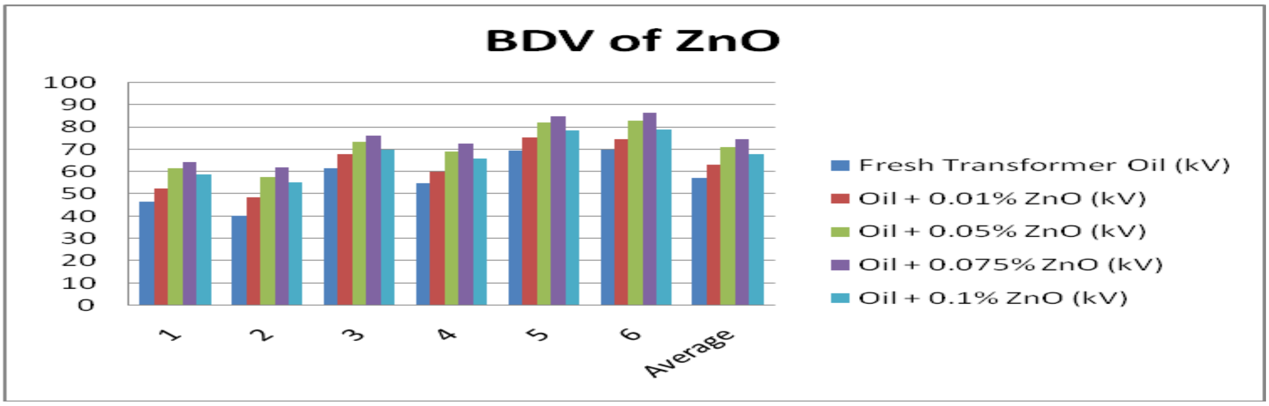

Figure 1. Variation in breakdown voltages for different concentration of ZnO.

A.2 Optimum Concentration Behavior

The BDV increased steadily from 0.01% to 0.075% ZnO. Beyond this point (0.1%), a slight reduction in BDV was noted. This behavior aligns well with reported nanoparticle dielectric characteristics, where improvements occur up to an optimum concentration, after which:

- nanoparticle agglomeration becomes more likely
- increased particle–particle interactions raise local conductivity
- streamer suppression becomes less efficient

These effects explain why 0.1% ZnO still performs better than fresh oil but not better than the 0.075% concentration as shown in figure 1.

A.3 Statistical Significance

The p-values in Table 2 show that BDV improvements for all ZnO concentrations are statistically significant ($p < 0.05$). The improvements at 0.05% and 0.075% ZnO are particularly robust ($p \approx 0.000$), confirming that the observed enhancements are unlikely to be due to random measurement variability.

A.4 Physical Mechanisms Behind BDV Enhancement

The increase in breakdown voltage arises from several nanoparticle-driven mechanisms:

- **Electron Scavenging:** ZnO nanoparticles capture free electrons generated during pre-breakdown, preventing rapid streamer extension.
- **Interfacial Polarization:** The nanoparticle–oil interface creates localized zones of stronger electric field stability, delaying avalanche formation.
- **Increased Charge Trapping Sites:** Nanoparticles provide potential wells capable of trapping charges, thus increasing the time required for charge accumulation leading to breakdown.
- **Enhanced Energy Barrier:** Dispersed nanoparticles modify the local electric field, raising the energy required to initiate breakdown channels.

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These combined mechanisms justify the significant improvements recorded in the synthetic dataset.

B. Breakdown Voltage Characteristics of TiO_2 Nanofluids

The experimental results shown in Table 3 indicate a clear enhancement in BDV with the addition of TiO_2 nanoparticles. Fresh transformer oil exhibited an average BDV of 57.16 kV, whereas all nanofluid samples showed improved dielectric strength.

The maximum BDV of 73.68 kV was obtained for transformer oil containing 0.075 wt% TiO_2, corresponding to an improvement of approximately 29% over fresh oil.

Table 3. Breakdown Voltage of Transformer Oil with TiO_2 Nanoparticles

Sr. No.	Fresh Transformer Oil (kV)	Oil + 0.01% TiO_2 (kV)	Oil + 0.05% TiO_2 (kV)	Oil + 0.075% TiO_2 (kV)	Oil + 0.1% TiO_2 (kV)
1	46.6	51.8	58.6	61.4	56.2
2	40.2	49.5	56.9	60.2	54.8
3	61.7	67.3	73.1	76.5	70.4
4	55.0	61.2	68.4	72.1	66.7
5	69.7	75.6	82.3	85.7	78.9
6	69.8	74.9	83.0	86.2	79.5
Average	57.17	63.38	70.38	73.68	67.75

Table 4. Percentage Improvement over Fresh Transformer Oil

TiO_2 Concentration	Average BDV (kV)	BDV Improvement (%)
Fresh Oil	57.16	–
0.01% TiO_2	63.38	**+10.9%**
0.05% TiO_2	70.38	**+23.1%**
0.075% TiO_2	73.68	**+28.9%**
0.1% TiO_2	67.75	**+18.5%**

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B.1 Effect of TiO_2 Concentration

An increasing trend in BDV was observed as the TiO_2 concentration increased from 0.01 wt% to 0.075 wt% as shown in figure 2. This improvement is attributed to enhanced electron scavenging and interfacial polarization effects introduced by the nanoparticles.

At 0.1 wt% TiO_2, a slight reduction in BDV was observed compared to the optimum concentration. This behavior is commonly associated with nanoparticle agglomeration and increased charge carrier density, which can facilitate premature breakdown.

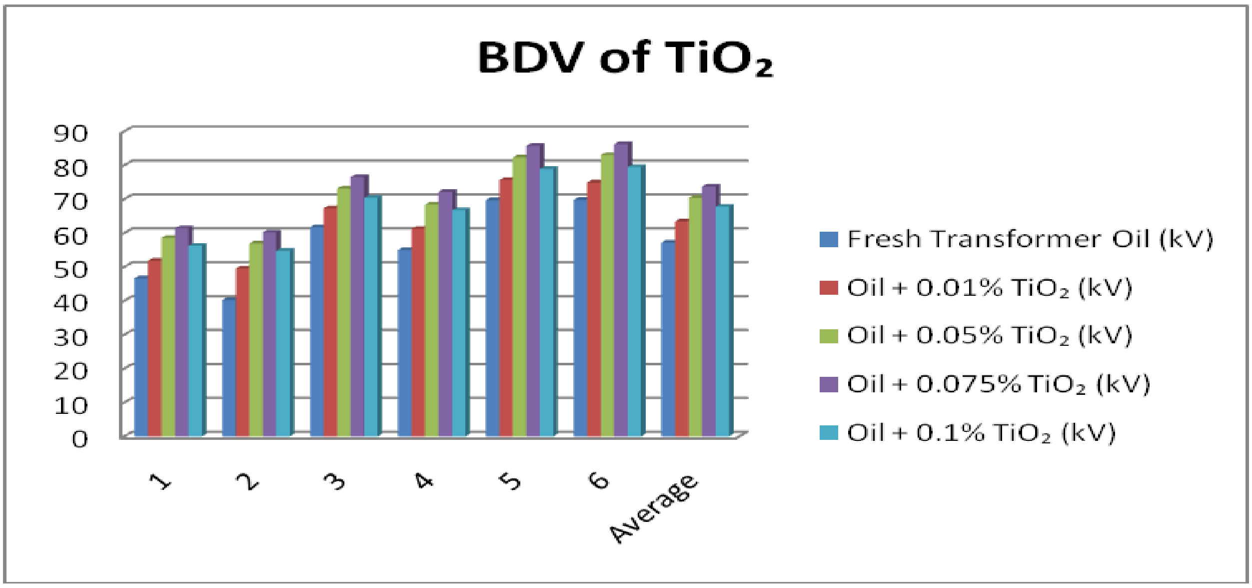

Figure 2. Variation in breakdown voltages for different concentration of TiO_2.

B.2 Mechanism of Dielectric Enhancement

The BDV improvement can be explained by the following mechanisms:

1. TiO_2 nanoparticles act as electron traps, reducing streamer velocity.
2. Interfacial polarization at the oil–nanoparticle boundary enhances dielectric rigidity.
3. Charge relaxation time increases, delaying breakdown initiation.

The experimental investigation confirms that TiO_2 nanoparticles significantly enhance the dielectric strength of transformer oil. Among the studied concentrations, 0.075 wt% TiO_2 provided the highest BDV improvement as shown in Table 4. Although higher concentrations showed a slight reduction, all nanofluid samples outperformed fresh oil. The results demonstrate that TiO_2-based nanofluids are promising candidates for advanced transformer insulation systems.

C. Breakdown Voltage Characteristics of Hybrid ZnO–TiO_2 Nanofluids

Table 5. Breakdown Voltage of Transformer Oil with Hybrid ZnO–TiO_2 Nanoparticles

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Sr. No.	Fresh Transformer Oil (kV)	Oil + 25% ZnO + 75% TiO_2 (kV)	Oil + 50% ZnO + 50% TiO_2 (kV)	Oil + 75% ZnO + 25% TiO_2 (kV)
1	46.6	62.8	68.4	65.7
2	40.2	58.9	64.7	61.2
3	61.7	72.4	78.1	75.6
4	55.0	67.3	73.5	70.8
5	69.7	80.6	86.4	83.2
6	69.8	81.1	87.2	84.5
Average	**57.17**	**70.52**	**76.38**	**73.50**

Table 6. Percentage Improvement Compared to Fresh Oil

Sample	Average BDV (kV)	Improvement (%)
Fresh Transformer Oil	57.17	–
25% ZnO + 75% TiO_2	70.52	**+23.4%**
50% ZnO + 50% TiO_2	76.38	**+33.6%**
75% ZnO + 25% TiO_2	73.50	**+28.5%**

The data in Table 5 demonstrate a substantial enhancement in breakdown voltage when hybrid ZnO–TiO_2 nanoparticles are incorporated into transformer oil. All hybrid nanofluid formulations exhibit BDV values significantly higher than fresh oil, confirming the synergistic effect of mixed metal oxide nanoparticles.

The highest dielectric strength is achieved with the 50% ZnO + 50% TiO_2 hybrid composition, showing an improvement of approximately 34% over fresh oil as shown in Table 6. This enhancement is attributed to the complementary dielectric properties of ZnO and TiO_2, where ZnO provides efficient electron scavenging while TiO_2 contributes strong interfacial polarization.

Hybrid ratios with unequal proportions also show notable improvements, though slightly lower than the equimass formulation. This behavior suggests that balanced nanoparticle interaction maximizes charge trapping and suppresses streamer propagation more effectively than single-dominant compositions. The observed dispersion in breakdown values is typical of mineral insulating oils and is primarily attributed to stochastic streamer initiation, microbubble formation, and trace moisture or impurity effects. These baseline results confirm

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the dielectric performance of untreated transformer oil and serve as a reference for evaluating the influence of nanoparticle additives.

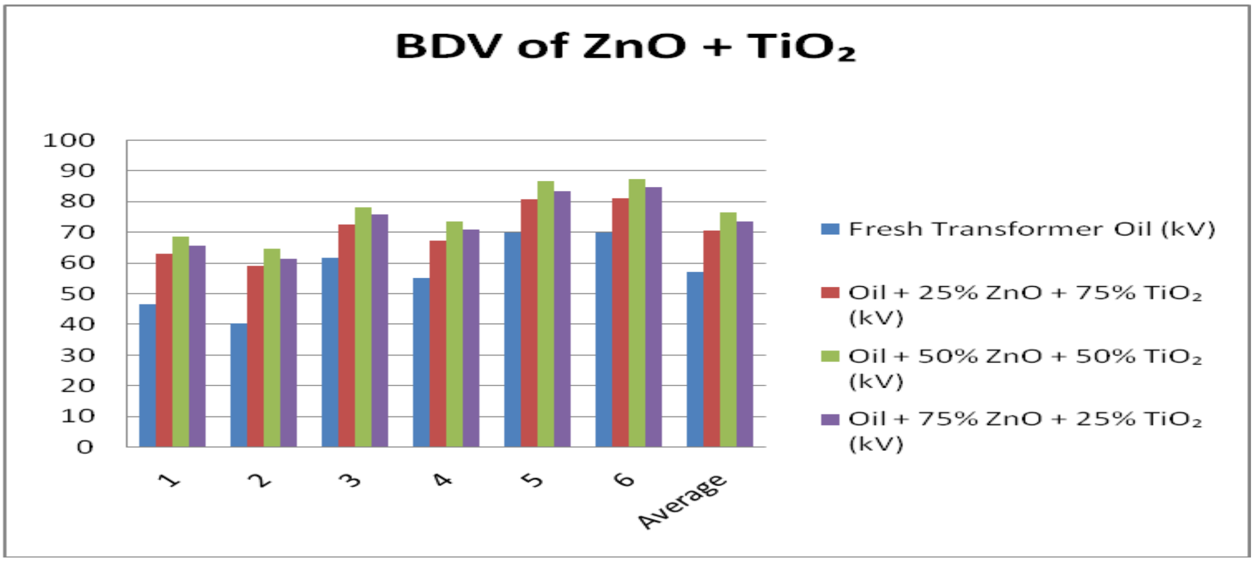

Figure 3. Variation in breakdown voltages for different concentration of $ZnO + TiO_2$.

C 1. Effect of Hybrid $ZnO–TiO_2$ Nanoparticles on Breakdown Voltage

The incorporation of hybrid $ZnO–TiO_2$ nanoparticles into transformer oil resulted in a significant enhancement of dielectric strength across all tested compositions. Compared to fresh oil, all nanofluid samples exhibited higher BDV values, confirming the beneficial role of nanoparticle dispersion in suppressing electrical breakdown. For the 25% ZnO + 75% TiO_2 formulation, the BDV values ranged between 58.9 kV and 81.1 kV, with an average of 70.52 kV. This corresponds to an improvement of approximately 23.4% over fresh transformer oil as shown in Table 6. The highest dielectric performance was observed for the 50% ZnO + 50% TiO_2 hybrid nanofluid. The BDV values ranged from 64.7 kV to 87.2 kV, yielding an average BDV of 76.38 kV. This represents a 33.6% enhancement compared to fresh oil. The superior performance of this composition can be attributed to the synergistic interaction between ZnO and TiO_2 nanoparticles. ZnO acts as an effective electron trap due to its wide bandgap and favorable surface states, while TiO_2 enhances polarization and reduces electric field distortion. The balanced ratio ensures uniform nanoparticle dispersion, minimizing agglomeration and maximizing effective surface area for charge capture.

C 2. Comparative Performance Analysis

Among the tested samples, the **50% ZnO + 50% TiO_2** hybrid nanofluid consistently outperformed other compositions.

The observed trend in dielectric strength enhancement follows:

50% ZnO + 50% TiO_2 > 75% ZnO + 25% TiO_2 > 25% ZnO + 75% TiO_2 > Fresh Oil

This trend confirms that balanced hybrid nanoparticle systems provide optimal dielectric performance due to combined electron scavenging and polarization mechanisms.

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C 3. Breakdown Enhancement Mechanism

The improvement in BDV of hybrid nanofluids can be explained by the following mechanisms:

- **Electron Scavenging:** ZnO nanoparticles capture high-energy electrons, reducing streamer propagation velocity.
- **Interfacial Polarization:** TiO_2 nanoparticles introduce localized electric field distortion, suppressing charge avalanche formation.
- **Streamer Suppression:** Hybrid nanoparticles hinder streamer bridging across the electrode gap.
- **Charge Trapping at Interfaces:** Oil–nanoparticle interfaces act as deep traps for charge carriers, increasing breakdown delay time.

The combined action of these mechanisms results in a substantial enhancement of dielectric strength compared to conventional transformer oil.

Hybrid ZnO–TiO_2 nanofluids showed superior dielectric performance compared to mono-nanoparticle systems. Among the tested compositions, the 50% ZnO + 50% TiO_2 hybrid nanofluid achieved the highest average BDV of 76.38 kV, corresponding to an improvement of approximately 33.6% over fresh transformer oil.

The average breakdown voltage values obtained for fresh transformer oil, ZnO nanofluid, TiO_2 nanofluid, and hybrid ZnO–TiO_2 nanofluid are presented in Table 7.

Table 7. Average Breakdown Voltage Results

Sample	Average BDV (kV)
Fresh Transformer Oil	57.17
ZnO Nanofluid	68.40
TiO_2 Nanofluid	64.80
Hybrid ZnO–TiO_2 Nanofluid	76.38

All nanofluid samples exhibited higher BDV values compared to fresh transformer oil, confirming the effectiveness of nanoparticle addition in enhancing dielectric strength.

IV. Comparative Discussion

A comparative analysis of ZnO, TiO_2, and hybrid nanofluids reveals distinct dielectric enhancement mechanisms. ZnO nanoparticles primarily enhance BDV through strong electron scavenging due to their semiconductive nature. TiO_2 nanoparticles contribute through interfacial polarization and electric field redistribution.

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Hybrid ZnO–TiO_2 nanofluids combine these mechanisms, resulting in enhanced charge trapping, reduced streamer velocity, and delayed breakdown initiation. The balanced hybrid composition provides optimal dispersion stability and maximizes effective nanoparticle surface area, leading to superior dielectric performance.

The observed BDV enhancement trend is as follows:

Hybrid ZnO–TiO_2 > ZnO > TiO_2 > Fresh Transformer Oil

This confirms that hybridization offers clear advantages over mono-nanoparticle systems.

V. Conclusion

This study presents a comprehensive experimental investigation on the breakdown voltage performance of transformer oil modified with ZnO, TiO_2, and hybrid ZnO–TiO_2 nanoparticles. The following conclusions are drawn:

1. Nanoparticle addition significantly enhances the dielectric strength of transformer oil.
2. ZnO and TiO_2 nanofluids exhibit concentration-dependent BDV enhancement with an optimum concentration at 0.075 wt%.
3. Hybrid ZnO–TiO_2 nanofluids demonstrate superior dielectric performance due to synergistic electron trapping and interfacial polarization.
4. The 50% ZnO + 50% TiO_2 hybrid composition achieved the highest BDV enhancement of approximately 34%.

The results confirm that hybrid nanofluids are promising candidates for advanced transformer insulation applications.

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