KAMPALA INTERNATIONAL UNIVERSITY

KIU
Journal of Science, Engineering and Technology

KJSET

Research Article

Impacts of electrode geometry and gap length on the breakdown voltage of insulating liquids

S. H. Sulaiman[1], S. Ebenezer[2], I. Abdulwahab[3*], I. Mahmud[4], N. A. Iliyasu[5], A. J. Aliyu[6]

[1,2,3,4,5,6]Department of Electrical Engineering, Ahmadu Bello University Zaria, Nigeria
[6]Department of Electrical and Electronics Engineering, Universiti Technology PETRONAS, 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia
[1]shsulaiman@abu.edu.ng, [2]ebenezersamuel171@gmail.com, [3]iabdulwahab@abu.edu.ng, [4]imahmud@abu.edu.ng, [5]nailiyasu@abu.edu.ng, [6]ajaliyu@abu.edu.ng*

Corresponding Author: iabdulwahab@abu.edu.ng

Paper history:
Received 24 April 2025
Accepted in revised form 21 May 2025

Keywords
Breakdown Voltage;
Electrode;
Gap Length;
High Voltage Direct Current;
Insulating Oil.

Abstract

This paper investigates the impact of different electrode geometries on the dielectric strength of insulating liquids under high-voltage direct current (HVDC). The study focuses on two electrode configurations sphere-to-sphere and mushroom-to-mushroom and two insulating liquids: soybean oil and mineral oil. Experimental tests were conducted at varying electrode gaps (1.0 mm to 4.0 mm) to determine the breakdown voltages (BV) for each liquid. The BVs were analyzed to understand the effects of both electrode geometry and liquid type on dielectric performance. Although the prospect of vegetable oils as alternative insulation liquid for high voltage applications have been reported in the literature, the statistical variability under the stated electrode configurations have not been covered, to the best knowledge of the authors. Results show that electrode geometry plays a crucial role in determining breakdown strength of liquids.The BV of the liquids increases with increasing gap length under both configurations. For the sphere-sphere configuration, soybean oil broke down at 6.90kV at a gap length of 1.0mm, while that of mineral oil occurred at 3.975kV. At 4.0mm, the breakdown voltages were recorded as 14.15kV and 11.225kV for soybean and mineral oils respectively. For the mushroom-mushroom configuration, Soybean oil broke down at 4.95kV at 1.0mm, while that of mineral oil occurred at 4.225kV. At 4.0mm, the breakdown voltages were recorded as 12.5kV and 12.925kV for the vegetable oil and mineral oil respectively. Thus, soybean oil demonstrated competitive dielectric properties compared to the mineral oil. However, statistical analysis revealed a lower variability in the performance of mineral oil compared to vegetable oil in which the highest standard deviations (SDs) were both obtained at gap length of 2.0mm as 0.45kV for the former and 0.86kV for the latter. Despite the higher BV of vegetable oil, the mineral oil is more stable over a range of operation conditions which suggests a complex nature of choosing appropriate liquid dielectrics for insulation purposes in HV equipment.

Nomenclature and units

E	Electric Field (V/m)
V	Electric Potential (V)
d	Distance between electrodes (mm)
V_b	Breakdown Voltage (V)

Copyright© 2025 by authors; licensee KJSET. This publication is open access and can be freely accessed and distributed.

1.0 Introduction

One important factor in the design and operation of high-voltage (HV) equipment is the understanding of breakdown voltages (BVs) of the dielectric materials used in their insulation systems (Ushakov *et al*., 2023). The kind of electrodes used, the spacing between them, their size and form, and the surrounding environmental factors like humidity and temperature, presence of contaminants, the intrinsic properties (dielectric constant, viscosity) of the insulator all have an impact on the BV of the insulators (Uydur *et al*., 2018). Breakdown voltage is the minimum voltage at which a section of an insulator turns electrically conductive. When the electric field supplied to the liquid insulation is greater than its dielectric strength, electrical breakdown occurs (Baliga, 2018). The applied electric field induces the rate of ionization process and streamer propagation in the liquid. Eventually, these activities result in a sharp rise in current flow, which denotes a breakdown event (Ramesh et al., 2019). Although mineral oil has numeral characteristics such as reasonable dielectric strength and isolation resistance that make them a good choice for HV insulations, synthetic and natural esters are also used in power transformers due to their biodegradability and better ageing behavior compared to the mineral oils (Atalar *et al*., 2022). Generally, when subjected to sufficiently high electric fields, liquid dielectrics can easily can break down, leading to a surge of current and potential equipment damage (Guedes & Silva, 2020; Ku & Liepins, 1987). Also, the geometry of one or both electrodes can as well lead to the concentration of electric field lines, thereby increasing the probability of partial discharge (PD) occurrence. Several researches have attempted to investigate various forms of oils as alternative to the conventional mineral oil that is usually employed in most HV apparatus such as transformers that require liquid insulation. A liquid with high BV has the ability to withstand electrical stress. The deterioration of insulation quality is one of the most serious concerns in HV equipment.

For HV systems to operate safely and dependably, it is essential to understand and mitigate electrical breakdown in their insulation systems (Thiviyanathan *et al*., 2022). The performance and reliability of HVDC systems heavily depend on the dielectric strength of insulating liquids and the geometry of the electrodes. While mineral oil has been the standard insulation liquid for most power applications, there is a growing interest in biodegradable alternatives like vegetable oil (Tlhabologo *et al*., 2021). Several researches have compared the performances of mineral oil with the synthetic and natural esters. Findings in (Martin & Wang, 2008) show that for AC voltage stress, both mineral oil and ester oils are capable of being used as mineral oil due to the closeness in their breakdown voltage (BV) magnitudes. In (Wang *et al*., 2018), mineral oil was found to exhibit higher BV compared to the ester oil under pin electrode configurations, but there was no significant difference between the performances of the two oils under flat-flat electrode configurations However, the combined effect of electrode geometry and the distance of separation on the breakdown voltage under HVDC conditions is still a topic of interest. Traditionally, experimental measurements have been used to study the breakdown voltage of various insulators (Rizwan *et al*., 2024). This study focuses on testing two electrodes configurations, namely sphere – sphere and mushroom-mushroom with two insulation liquids (mineral oil and vegetable oil) in order to identify the influence of the electrode configurations as well as their spacings when fully immersed on the breakdown voltage for each liquid and also the effect of the liquid's properties (dielectric constant, viscosity) on its breakdown voltage. The aim of this work is to ascertain the prospects of using Soybean oil as an alternative to mineral oil for power applications and to also investigate the extent to which geometrical dimension of the electrodes affect the ionization and eventual breakdown of the liquid dielectrics.

1.1 Breakdown Mechanism in Liquids

When evaluating liquid insulations for use in high-voltage applications, one of the most important factors is their breakdown voltage. It is possible to design more reliable and effective insulation systems by having a better understanding of the factors that cause electrical breakdown. The main processes that lead to the disintegration of liquid insulations are thermal impacts, bubble formation, and electron avalanche (Fisher et al., 2021; Zhang et al., 2022). Some common factors that influence avalanche formation and eventual breakdown of liquid dielectrics include the liquid's dielectric strength, ionization energy and electron mobility, applied Electric Field Strength, ambient temperature, Contaminants and defects as well as Charge injection and accumulation (Emlin *et al*., 2024; Fisher et al., 2021).

Generally, the relationship between breakdown voltage, V_b, the applied electric field, E, and is the distance, d, between the high voltage (HV) and the low voltage (LV) electrodes can be expressed as:

$$V_b = E \times d \quad (1)$$

It is important to know, while these three parameters are crucial, they may not be sufficient alone to determine the breakdown behavior of a liquid insulator comprehensively. Other factors also play significant roles which include temperature, impurities, pressure, frequency of voltage applied (DC or AC) and electrode geometry.

2.0 Materials and Methods

This section describes the experimental methods used to study the behavior of different insulating liquids with varying electrode configurations. It covers the materials, equipment, experimental setup, and the processes for data collection and analysis, ensuring a structured approach to obtaining accurate results for the research. The experiment was conducted at the High Voltage Laboratory, Ahmadu Bello University, Zaria-Nigeria. Only dielectric breakdown test was carried out on the insulation samples. Other chemical tests such as viscosity, thermal strength etc., are beyond the scope of this paper.

2.1 Materials

The Materials on which the tests were carried out are Vegetable oil (Soybean oil) and Mineral oil (Mineral oil). Various electrode spacers of width 1.0mm, 1.5mm, 2.0mm, 2.5mm, 3.0mm, 3.5mm, and 4.0mm were used to provide the required gap lengths.
The properties of the oils used in this paper are summarized in Table 1.

Table 1 Properties of the Insulating Liquids

Parameter	Soybean Oil	Mineral oil
Electric permittivity	2.9	2.3
Density 20ºC at (g/cm^3)	0.918	0.85
Viscosity at 40ºC (mm^2/s)	31.83	95
Flash Point (ºC)	260	185

2.2 Electrode Configurations

Two electrode configurations were used in the determination of the withstand capabilities of the liquids. These configurations are:

(i) sphere – sphere configurations
(ii) Mushroom – mushroom configurations

Each of the liquids was subjected to HVDC stress under the two configurations and the BV was recorded at various electrode gap lengths. The gap lengths considered in this paper are from 1.0 mm to 4.0 mm in steps of 0.5 mm. Figure 1 shows the sphere – sphere electrodes configuration while Figure 2 shows the mushroom-mushroom electrodes configuration. The electrodes are made of steel in both cases.
The various electrode configuration sphere to sphere and mushroom to mushroom immersed in the insulating liquid sample during the experiment are shown in Figure 1 and Figure 2 respectively.

Figure 1 Mushroom – Mushroom Electrode Configuration

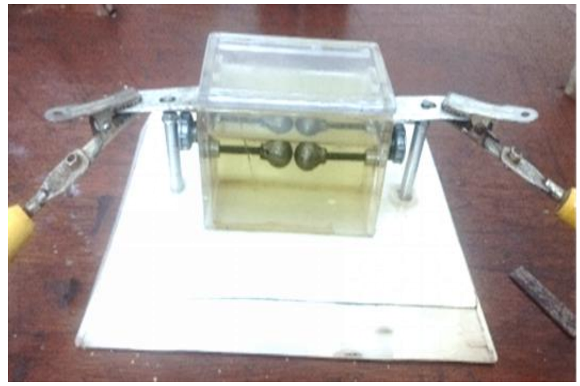

Figure 2 Sphere – Sphere Electrode Configuration

2.3 High Voltage DC (HVDC) Generator

A HVDC test set capable of producing controllable voltage up to 40 kV, it has a high-voltage voltmeter and a high-current Ammeter for measuring BV and leakage currents respectively.

Figure 3 40kV HVDC Generator Test Set

2.4 Experimental procedure

A. Liquid container preparation: the liquid containers were cleaned and rinsed with the intended liquid to be used in order to avoid contamination.
B. Electrode preparation. The electrodes were cleaned mounted in the test cell, and the required gap between them was adjusted using the electrode spacers.
C. Liquid filling: The selected liquid was poured into the container, ensuring complete immersion of the electrodes.
D. The setup above was connected to the high voltage DC generator using two high voltage cables. The generator was properly earthed
E. High voltage application: the HVDC generator was connected to the 240V AC mains and turned on. Its output voltage was gradually increased at a steady rate until the dielectric breakdown occurred. The voltage at which the breakdown occurred was observed was recorded.
F. The process was repeated for different gaps (1.0 mm to 4.0 mm) for both sphere-to-sphere and mushroom – mushroom electrode configurations.

G. For each gap and configuration, multiple readings were taken to ensure accuracy and repeatability of the results.
H. The BV for each trial was recorded for analysis.

The Schematic diagram of the BV test the experimental setup is depicted in Figure 4.

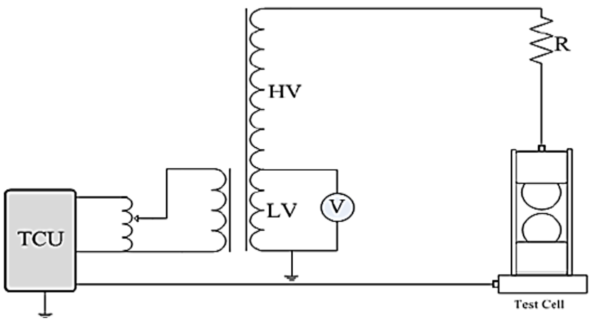

Figure 4 Circuit Diagram of the Experimental Setup

The BV for each liquid was tested using the various configurations with gaps ranging from 1.0 mm to 4.0 mm. In each case, 4 trials were conducted to obtain an average BV for each gap setting using the expression (equation 2).

$$V_{avg} = \frac{1}{4}\sum_{i=1}^{4} V_i \quad (2)$$

where V_{avg} is the breakdown voltage and V_i is the voltage at i_{th} repetition.
The standard deviations (STD) were calculated by taking the absolute values of breakdown voltages for each electrode gap using the formula (Lee *et al.*, 2015):

$$STD = \sqrt{\frac{\sum\left(V_{bi}-V_{avg}\right)^2}{N}} \quad (3)$$

where V_{bi} = is each individual breakdown voltage in *ith* reading, V_{avg} is the arithmetic mean and N is the number readings taken.
According to the ASTMD1816-84a and the ASTM D877-87 standards, a breakdown tests are considered to have been performed correctly if the ratio of the standard deviation (STD) to the breakdown voltage does not significantly exceed 0.15 (Atalar *et al*., 2022). These values signify the stability of the oils tested under various conditions.

3.0 Results and Discussion

This section presents the analysis of the experimental data obtained from investigating the impact of different electrode geometries on the dielectric strength of vegetable oil (soybean) and mineral oil (mineral oil) under HVDC conditions. Two electrode configurations sphere-to-sphere and mushroom to mushroom were used to observe the BVs at varying electrode gaps.
The oil samples used were purchased from the local market and were used without processing and filtration. The BVs for both vegetable oil and mineral oil, using sphere-to-sphere and mushroom–to–mushroom electrode configurations, were recorded at various electrode gaps ranging from 1.0 mm to 4.0 mm.

3.1 Experimental Results for Sphere-To-Sphere Electrode Configuration

The breakdown voltage for each liquid was tested using the sphere-to-sphere configurations with gaps ranging from 1.0 mm to 4.0 mm. In each case, four (4) readings were taken, and the mean BV was computed for each gap setting as depicted in Table 2 and Table 3. The repeated experiments were taken to conform with the ASTM standards for breakdown tests.

Table 2 Soybean Oil BVs for Sphere-Sphere Electrodes

Gap Length (mm)	Breakdown Voltage (kV)				
	1st Reading	2nd Reading	3rd Reading	4th Reading	Average
1.0	6.0	7.0	7.1	7.5	6.900
1.5	7.9	8.8	8.8	9.5	8.750
2.0	9.0	9.2	10.2	10.0	9.600
2.5	11.0	11.2	11.5	12.5	11.550
3.0	12.0	13.0	11.5	13.0	12.375
3.5	12.8	12.2	11.9	14.0	12.725
4.0	13.2	14.0	14.5	14.9	14.150

Table 3 Mineral Oil BVs for Sphere-Sphere Electrodes

Gap Length (mm)	Breakdown Voltage (kV)				
	1st Reading	2nd Reading	3rd Reading	4th Reading	Average
1.0	4.0	4.0	3.9	4.0	3.975
1.5	4.5	5.0	4.9	5.5	4.975
2.0	6.0	5.9	6.2	6.0	6.025
2.5	6.8	6.8	7.2	7.0	6.950
3.0	8.0	7.9	8.2	8.8	8.225
3.5	10.5	10.2	10.0	9.8	10.125
4.0	12.0	11.9	11.0	10.0	11.225

Figure 5 shows the performance of the soybean oil and the mineral oil in withstanding electrical stress at various gap lengths. As seen from the graph, vegetable oil consistently has higher breakdown voltages than mineral oil across all electrode spacings. it is observed that the breakdown voltage is increased consistently with the increasing gap distance between the electrodes. In sphere-to-sphere configuration the BV of vegetable oil (soybean oil) increased from 6.9kV at 1.0mm to 14.15kV at 4.0mm. While the breakdown voltage for mineral oil in the sphere-to-sphere configuration was significantly lower than that of vegetable oil. The BV ranged from 3.975kV at 1.0mm to 11.225kV at 4.0mm. The lower BV suggests that mineral oil has a lower dielectric strength compared to vegetable oil under the same HVDC stress. The standard deviation for each trial was small, indicating consistent results across trials. This suggests that the electric field distribution in the sphere-to-sphere configuration provided a uniform dielectric stress, which increased with the electrode gap.

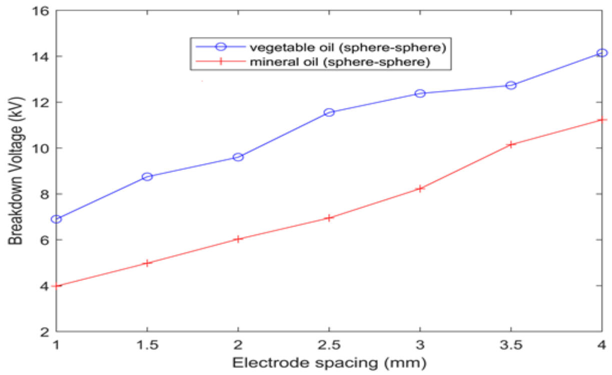

Figure 5 BV Comparison for Sphere-Sphere Configuration

The implication of these differences suggests that at lower electrode spacing the electric field is more concentrated, and vegetable oil's higher dielectric strength allows it to handle the stress much better than mineral oil. This is likely due to its molecular composition, which offers greater resistance to ionization and breakdown. At higher gap lengths, where the electric field is more spread out, difference in the breakdown voltage is observed to decrease. The narrowing gap in performance suggests that mineral oil may be more suited to applications where larger electrode spacings are common, although vegetable oil still remains superior in overall breakdown voltage.

3.2 Result for Mushroom-Mushroom Electrode Configuration

The breakdown voltage of vegetable oil (soybean oil) for the mushroom-to-mushroom configuration resulted in slightly lower breakdown voltages compared to the sphere-to-sphere configuration as depicted in Figure 6. The average breakdown voltages ranged from 4.95kV at 1.0mm to 12.50kV at 4.0mm. The increase in breakdown voltage with gap distance remained consistent, but the values were lower due to the non-uniform electric field distribution in this electrode geometry. This configuration tends to concentrate the field at the edges of the electrodes, leading to breakdown at lower voltages. For mineral oil (mineral oil) the breakdown voltages in the mushroom-to-mushroom configuration were slightly lower than those in the sphere-to-sphere setup, ranging from 4.225kV at 1.0mm to 12.925kV at 4.0mm, exhibited lower dielectric strength than vegetable oil.

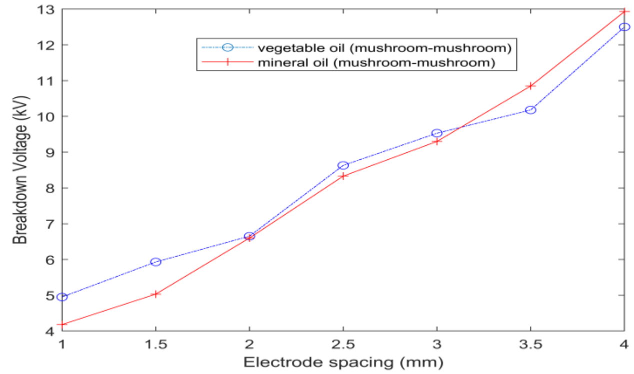

Figure 6 BV Comparison for Mushroom-Mushroom Electrode Configuration

The actual experimental data obtained as well as the arithmetic mean of the BVs for each of the electrode gap separations and configurations are presented in Table 4 and Table 5 for the soybean oil and mineral oil respectively.

Table 4 Soybean Oil BVs for Mushroom-Mushroom Electrodes

Gap Length (mm)	Breakdown Voltage (kV)				
	1st Reading	2nd Reading	3rd Reading	4th Reading	Average
1.0	4.9	5.0	5.0	4.9	4.950
1.5	6.0	6.2	5.5	6.0	5.925
2.0	5.2	7.5	7.0	6.9	6.650
2.5	8.0	8.0	8.5	10.0	8.625
3.0	9.5	9.8	9.8	9.0	9.525
3.5	9.2	10.0	10.5	11.0	10.175
4.0	12.0	12.2	12.8	13.0	12.500

Table 5 Mineral Oil BVs for Mushroom-Mushroom Electrodes

Gap Length (mm)	Breakdown Voltage (kV)				
	1st Reading	2nd Reading	3rd Reading	4th Reading	Average
1.0	4.2	4.0	4.5	4.2	4.225
1.5	5.0	5.0	4.9	5.2	5.025
2.0	7.0	6.9	6.0	6.5	6.600
2.5	8.5	8.6	8.2	8.0	8.325
3.0	9.0	9.5	9.2	9.5	9.300
3.5	11.0	10.5	10.9	11.0	10.850
4.0	12.8	13.5	12.9	12.5	12.925

3.3 Standard deviations and variability

Standard deviations are calculated by taking the absolute values of breakdown voltages for each electrode gap. Table 6 shows the standard deviations in the sphere-to-sphere electrode configuration measurements. For this configuration, the standard deviation is generally higher for vegetable oil, especially at larger gaps, indicating greater variability in the breakdown voltage values. Mineral oil has much lower variability at lower gaps but a spike in variability at 4.0mm. The high variability in the breakdown voltage magnitudes indicates less consistency and predictability in the insulating performance of the liquid. This increases uncertainty, reduces the reliability of the material in high-voltage applications.

Table 6 Standard Deviation for Sphere-Sphere Configuration

Electrode gap (mm)	Standard Deviation (kV)	
	Vegetable oil (soybean oil)	Mineral oil
1.0	0.55	0.04
1.5	0.57	0.36
2.0	0.51	0.11
2.5	0.58	0.36
3.0	0.65	0.35
3.5	0.80	0.23
4.0	1.03	0.81

For the mushroom to mushroom configuration, the standard deviation values are given in Table 7. For the soybean oil the standard deviation values range from 0.05kV to 0.86kV, indicating that there is a moderate level of variability in the breakdown voltage measurements, especially as the electrode gap increases. The highest variability occurs at the 2.0mm and 2.5mm gaps (0.86kV and 0.83kV, respectively), suggesting more fluctuation in the breakdown voltage at these larger gaps.

The standard deviation values for mineral oil range from 0.12kV to 0.45kV, showing generally lower variability compared to vegetable oil. The highest variability occurs at the 2.0mm gap (0.45kV), but overall, the breakdown voltage values for mineral oil are more consistent across the gap-length variations.

Table 7 Standard Deviation for Mushroom-Mushroom

Electrode gap (mm)	Standard Deviation (kV)	
	Soybean Oil	Mineral oil
1.0	0.05	0.12
1.5	0.29	0.12
2.0	0.86	0.45
2.5	0.83	0.25
3.0	0.33	0.25
3.5	0.65	0.25
4.0	0.50	0.36

To evaluate the stable performance of the oils and also ascertain the dependability of the experimental results, the standard deviation to breakdown voltage ratio (STD/BV) for both oils under all the gap lengths were computed and summarized in Table 8. It can be observed from the table that all the values are within the range (0.15) specified by the ASTM standards. In both the electrode configurations, mineral oil exhibits smaller STD/BV ratio which shows its more stable behavior under repeated experiments compared to the soybean oil. It can also be seen that mineral oil exhibits the smallest ratio of 0.008 at 1.0mm gap length and largest ratio of 0.065 at 4.0 mm under sphere to sphere configuration. Thus, although the Soybean oil exhibits better BV performance under various conditions, mineral oil will still have an upper hand for transformer insulation in terms of stability which is an essential factor considering the voltage level at which the transformers operate.

Table 8 Standard Deviation to Breakdown Voltage Ratio

Electrode Configuration	Gap Length (mm)	Soybean Oil	Mineral Oil
Sphere-Sphere	1.0	0.111	0.008
	1.5	0.096	0.061
	2.0	0.077	0.017
	2.5	0.067	0.042
	3.0	0.068	0.037
	3.5	0.079	0.023
	4.0	0.082	0.065
Mushroom-Mushroom	1.0	0.012	0.028
	1.5	0.058	0.024
	2.0	0.130	0.068
	2.5	0.100	0.030
	3.0	0.036	0.027
	3.5	0.060	0.023
	4.0	0.039	0.028

3.4 Effect of Electrode Configuration

Under the two electrode configurations considered in this paper, the BVs for soybean oil and mineral oil were found to increase consistently as the electrode gap increases as depicted in Figure 7. This trend reflects a relatively uniform electric field between two spherical electrodes leading to higher breakdown voltages. However, at larger gaps, mineral oil's breakdown voltage approaches that of soybean oil. This suggests that at larger electrode spacings, both oils perform more similarly under sphere-to-sphere configuration.

In the mushroom-to-mushroom configuration, soybean oil and mineral oil show a consistent increase in breakdown voltage, but the values are slightly lower compared to the sphere-to-sphere configuration. The mushroom-to-mushroom configuration results in lower breakdown voltages compared to the sphere-to-sphere configuration for both liquids. This is likely due to the more concentrated electric field around the curved surface of the semispherical electrode, leading to earlier dielectric breakdown. Figure 7 shows the impact of each electrode configuration on the breakdown voltage of the two liquids used.

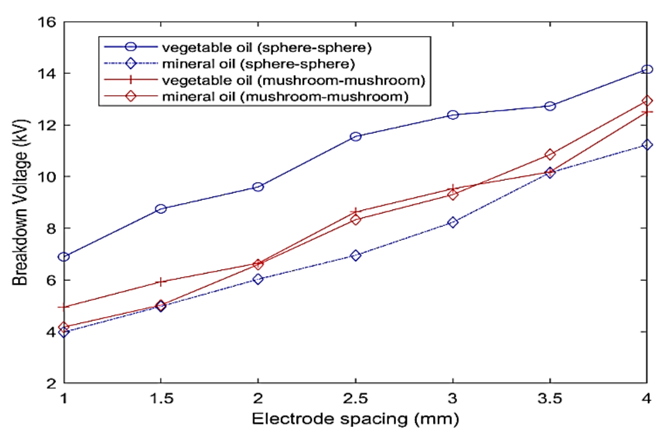

Figure 7 A Plot Comparing Breakdown Voltage of the Two Liquid for Different Electrode Configuration

4.0 Conclusion

This study investigated the impact of various electrode configurations on the breakdown voltage of different liquid insulators, specifically soybean oil and mineral oil. The experimental findings indicated that the soybean oil generally outperformed mineral oil in terms of breakdown voltage across both sphere-to-sphere and mushroom to mushroom configurations. At smaller electrode gaps, soybean oil's breakdown voltage was relatively higher than that of mineral oil, but the difference became less significant at larger gaps. Also, the sphere-to-sphere configuration consistently yielded higher breakdown voltages than the mushroom configuration, demonstrating the influence of electrode geometry on dielectric strength. However, mineral oil exhibited lower variability over repeated experiments, demonstrating its more stable behavior than the soybean oil. This paper, therefore, concludes that although vegetable oil can serve as an alternative to mineral oil in terms of breakdown voltage strength and also both mineral oil and soybean oil conform to the ASTM standards, mineral oil has a better stability over the v scenarios of gap length and electrode configuration. Hence, choice of an insulating liquid is a complicated process that will require not only the dielectric strength assessment of the liquid, but also require various considerations of the stress type, electrode configurations, as well as the stability of the liquid over long operation time in order to enhance the overall efficiency of the transformer.

Declaration of conflict of interest

The authors have collectively contributed to the conceptualization, design, drafting and execution of this article. This manuscript has not been previously submitted or reviewed by any other journal or publishing platform. Additionally, the authors do not have any affiliation with any organization that has a direct or indirect financial stake in the subject matter discussed in this manuscript.

References

Almehdhar, A. & Procházka, R. (2025). Hybrid CNN-LSTM for Classifying Multiple Partial Discharge Sources Via Time-Frequency Analysis in FEM PD Models. Available at SSRN 5168721.

Atalar, F., Ersoy, A., & Rozga, P. (2022). Investigation of Effects of Different High Voltage Types on Dielectric Strength of Insulating Liquids. Energies, 15, 8116. https://doi.org/10.3390/en15218116

Baliga, B. J. (2018). Breakdown voltage. In Fundamentals of Power Semiconductor Devices (pp. 89-170): Springer.

Emlin, R., Punanov, I., & Kulikov, V. (2024). Fast breakdown phenomena in liquid dielectrics under pulsed voltage conditions. Paper presented at the Proceedings of 9th International Congress on Energy Fluxes and Radiation Effects.

Fisher, L. E., Haries, C. D., & Lehr, J. M. (2021). Initiation and growth of the secondary electron avalanche along high-gradient insulators in vacuum. IEEE transactions on Dielectrics and Electrical Insulation, 28(3), 972-980.

Guedes, A. S., & Silva, S. M. (2020). Insulation failures prognosis in electric machines: preventive detection and time to failure forecast. IET Electric Power Applications, 14(6), 1108-1117. doi:10.1049/iet-epa.2019.0711

Ku, C. C., & Liepins, R. (1987). Electrical properties of polymers: Hanser publishers Munich.

Lee, D. K., In, J., & Lee, S. (2015). Standard deviation and standard error of the mean. Korean journal of anesthesiology 68(3), 220-223.

Madavan, R., Saroja, S., Karthick, A., Murugesan, S., Mohanavel, V., Velmurugan, P., . . . Biorefinery. (2025). Performance analysis of mixed vegetable oil as an alternative for transformer insulation oil. Biomass Conversion and Biorefinery 15(2025), 1939-1944. doi:https://doi.org/10.1007/s13399-021-02142-0

Martin, D. & Wang, Z. D. (2008), Statistical analysis of the AC breakdown voltages of ester based mineral oils. IEEE Trans. Dielectr. Electr. Insul. 2008, 15, 1044–1050.

Ramesh, M., Cui, L., & Gorur, R. S. (2019). Impact of superficial and internal defects on electric field of composite insulators. International Journal of Electrical Power Energy Systems, 106, 327-334.

Rizwan, M., Khan, S. A., Khan, M. R., & 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), 5.

Sima, W., Chen, X., Sun, P., Yuan, T., Yang, M., Pang, W., Li, N., & Tang, X. (2025). High-performance insulating materials with high breakdown strength and low permittivity for eco-friendly electrical equipment. Journal of Colloid and Interface Science, 680, 2-8.

Thiviyanathan, V. A., Ker, P. J., Leong, Y. S., Abdullah, F., Ismail, A., & Jamaludin, M. Z. (2022). Power transformer insulation system: A review on the reactions, fault detection, challenges and future prospects. Alexandria Engineering Journal, 61(10), 7697-7713.

Tlhabologo, B. A., Samikannu, R., & Mosalaosi, M. (2021). Alternative liquid dielectrics in power transformer insulation: a review. Indonesian Journal of Electrical Engineering and Computer Science, 23(3), 1761-1777.

Ushakov, V. Y., Mytnikov, A. V., & Rakhmonov, I. U. (2023). High-voltage equipment of power systems. Power systems. Springer, Cham. https://doi. org/10./978-3-031-38252-9

Uydur, C. C., Arikan, O., & Kalenderli, O. (2018). The Effect of insulation defects on electric field distribution of power cables. Paper presented at the 2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE).

Xiang, J., Liu, Q., & Wang, Z. D. (2018). Streamer characteristic and breakdown in a mineral oil and a synthetic ester liquid under DC voltage. IEEE Transaction on Dielectrics and Electrical Insulation 2018(25), 1636–1643.

Zhang, R., Zhang, Q., Guo, C., He, X., Wu, Z., & Wen, T. (2022). Bubbles in mineral oil: dynamic behavior, internal discharge, and triggered liquid breakdown. IEEE transactions on Dielectrics and Electrical Insulation 29(1), 86-94.