



Statistical Analysis of the Effect of Aging in Distribution Transformer Insulating Oil on Dielectric Characteristics

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Abstrak

Minyak transformator memiliki peran penting sebagai isolator listrik sekaligus pendingin pada sistem distribusi tenaga listrik. Namun, seiring waktu, minyak ini mengalami degradasi akibat tekanan panas, oksidasi, dan kontaminasi, yang menyebabkan penurunan sifat dielektriknya. Penelitian ini bertujuan untuk menganalisis pengaruh penuaan terhadap kemampuan isolasi minyak transformator serta mengevaluasi efektivitas proses pemurnian dalam memulihkan kualitasnya. Pengujian dilakukan pada tiga merek minyak transformator Shell Diala S4, PSP, dan Pri Apar dalam kondisi baru, bekas pakai (in-service), dan setelah pemurnian. Metode pengujian meliputi uji tegangan tembus (breakdown voltage) serta analisis distribusi Weibull untuk menilai probabilitas kegagalan dielektrik. Hasil penelitian menunjukkan bahwa minyak yang telah mengalami penuaan mengalami penurunan signifikan pada tegangan tembus, yang mengindikasikan risiko kegagalan isolasi yang lebih tinggi. Proses pemurnian terbukti efektif meningkatkan kembali tegangan tembus minyak yang telah menua, memulihkan kekuatan dielektriknya mendekati bahkan melebihi nilai pada kondisi minyak baru. Secara khusus, minyak Shell Diala S4 yang telah dipurifikasi menunjukkan peningkatan tegangan tembus sebesar 70%, minyak PSP meningkat 50%, dan minyak Pri Apar 47%. Di antara ketiga merek yang diuji, Shell Diala S4 menunjukkan performa dielektrik terbaik dan paling stabil baik sebelum maupun sesudah pemurnian. Analisis Weibull mengonfirmasi bahwa minyak yang menua memiliki probabilitas kegagalan dielektrik yang lebih tinggi seiring waktu, menekankan pentingnya perawatan berkala. Studi ini merekomendasikan pemurnian rutin untuk mempertahankan performa isolasi minyak transformator dan menyoroti pentingnya pemilihan minyak berkualitas tinggi demi menjamin keandalan sistem kelistrikan jangka panjang. Shell Diala S4 direkomendasikan untuk aplikasi sistem distribusi yang kritis dan penggunaan jangka panjang karena kinerja isolasinya yang unggul dan ketahanannya terhadap degradasi. Sebaliknya, minyak PSP dan Pri Apar, meskipun layak digunakan untuk aplikasi dengan tuntutan lebih rendah, sebaiknya dipantau lebih sering dan rutin dilakukan pemurnian untuk mengurangi risiko kegagalan isolasi.

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Abstract

Transformer oil plays a crucial role as both an electrical insulator and coolant in power distribution systems. Over time, however, it undergoes degradation due to thermal stress, oxidation, and contamination, resulting in a decline in its dielectric properties. This study aims to analyze the impact of aging on the insulating capability of transformer oil and evaluate the effectiveness of purification in restoring its quality. Experiments were conducted on three brands of transformer oil Shell Diala S4, PSP, and Pri Apar in new, aged (in-service), and purified conditions. Breakdown voltage testing was employed alongside Weibull distribution analysis to assess dielectric failure probabilities. The results demonstrate that aged oil exhibits a significant reduction in breakdown voltage, indicating a higher risk of insulation failure. Purification was found to be effective in improving the breakdown voltage of aged oils, restoring their dielectric strength close to or even exceeding that of new oil. Specifically, purified aged Shell Diala S4 oil showed a 70% increase in breakdown voltage, PSP oil improved by 50%, and Pri Apar oil by 47%. Among the tested brands, Shell Diala S4 exhibited the best and most stable dielectric performance both before and after purification. The Weibull analysis confirmed that aged oils have a higher probability of dielectric failure over time, underscoring the importance of regular maintenance. This study recommends periodic purification to maintain the insulating performance of transformer oils and highlights the importance of selecting high-quality oils to ensure long-term system reliability. Shell Diala S4 is recommended for critical and long-term distribution system applications due to its superior insulating performance and greater resistance to degradation. In contrast, PSP and Pri Apar oils, while viable for less demanding applications, should be subject to more frequent monitoring and purification to mitigate the risk of insulation failure.

Introduction

Transformer oil functions both as an insulating and cooling medium for traction transformers (Widagdo et al., 2024). It plays a critical role in transporting heat to the ambient environment, a process strongly influenced by its thermal conductivity, specific heat capacity, volumetric thermal expansion, and density (Widagdo et al., 2023). In oil-immersed traction transformers, cellulose-based insulation and naphthenic mineral oil are commonly preferred for high-voltage applications due to their well-established insulating characteristics.

However, under high-voltage operating conditions, transformer oil is continuously exposed to thermal, electrical, physical, and environmental stresses that accelerate its degradation (Akbar et al., 2025). Despite the availability of various monitoring systems, failure rates of high-voltage, oil-immersed equipment remain significant. These failures are often associated with oil degradation, overheating, and mechanical damage to windings (Widagdo et al., 2025).

Prior studies have shown that thermal and electrical stresses are the dominant contributors to early aging of transformer oil, making insulation aging one of the leading causes of transformer breakdowns (Mubarok et al., 2024).

Moisture contamination is a well-known issue affecting transformer reliability. Karl-Fischer titration is widely used to quantify water content in oil, and many studies have examined how water and oxygen accelerate oil aging. Moisture reduces the mechanical strength of cellulose insulation (Muhammad et al., 2023), degrades dielectric properties, and promotes oxidation that leads to sludge and acid formation. Over time, these mechanisms reduce breakdown voltage (BDV). Water in transformer oil may exist in free, dissolved, or emulsified form (Subekti et al., 2023). Although breathers and moisture-control systems are commonly installed, dissolved moisture and water released from cellulose decomposition remain difficult to eliminate, especially in aged traction transformers.

To maintain oil quality, the rail industry routinely performs purification processes such as thermal heating, vacuum dehydration, filtration, and oil regeneration particularly when BDV values fall below acceptable thresholds. Previous studies, including Safiddine et al. (2019) and Ridzuan et al. (2018), have demonstrated that purification helps restore dielectric strength in aged oils. In addition to BDV, thermal conductivity represents another essential property linked to cooling performance and transformer reliability. Prior research by Lopatkiewicz et al. (2012) has shown a strong relationship between thermal conductivity and water content. Moreover, several studies have proposed replacing mineral oils with synthetic or natural esters to enhance thermal performance (Ali et al., 2021). Although the aging process driven by thermal and electrical stresses has been widely discussed (Elele et al., 2022), the specific effect of purification on the thermal conductivity of aged transformer oil remains insufficiently explored. Furthermore, existing literature has yet to establish a clear understanding of the combined relationship among purification treatment, moisture reduction, thermal conductivity behavior, and breakdown voltage recovery.

This gap highlights the need for a study that not only measures how aging affects the dielectric characteristics of distribution transformer insulating oil, but also statistically explains the extent to which aging alters key dielectric parameters an aspect that directly influences insulation reliability and, ultimately, transformer service life. In addition, there is still limited research evaluating how purification processes may restore certain properties degraded by aging, particularly in terms of reducing moisture content, recovering breakdown voltage, and improving other dielectric qualities. The novelty of this study lies in conducting a

comprehensive statistical analysis of dielectric characteristics under various aging conditions while also assessing the influence of purification as a recovery effort for aged insulating oil. This approach provides an integrated evaluation of the relationships among aging level, changes in dielectric properties, and the potential improvements achieved through purification in distribution transformer oil.

By establishing statistical relationships among these parameters, this work offers new insights that have not been presented in previous studies and contributes to a deeper understanding of aging mechanisms and the effectiveness of purification in mitigating or reducing their impact on insulating oil degradation. This study aims to evaluate and quantify the effects of aging and purification on the dielectric characteristics of distribution transformer oil through a structured statistical analysis. A more comprehensive understanding of aging behavior, recovery potential through purification, and their impacts on dielectric integrity is essential for improving condition assessment, predicting insulation performance, and optimizing maintenance strategies in distribution-level power systems.

Method

1. Breakdown Voltage Test

The Breakdown Voltage (BDV) test in this study was conducted in accordance with IEC 60156 to evaluate the dielectric strength and contamination level of transformer insulating oil, with ASTM D1816 and ASTM D877 used as supplementary references. Oil samples were collected using a closed sampling method to prevent exposure to air, followed by purification through filtration (1–2 μm), heating to 60–65°C, vacuum degassing, and removal of solid particles as recommended by IEC 60422; this purification process was intended to reduce dissolved moisture, eliminate microbubbles, and lower conductive particle content to improve dielectric strength. After purification, samples were conditioned at $25 \pm 2^\circ\text{C}$, and all containers and electrodes were cleaned with isopropyl alcohol to avoid contamination. The BDV test was performed using an automatic tester equipped with 12.5-mm spherical electrodes set at a 2.5-mm gap, with an AC 50-Hz voltage applied at a rise rate of 2 kV/s. Each sample underwent six successive BDV measurements as required by IEC 60156, with electrode cleaning after each breakdown event to maintain consistency.

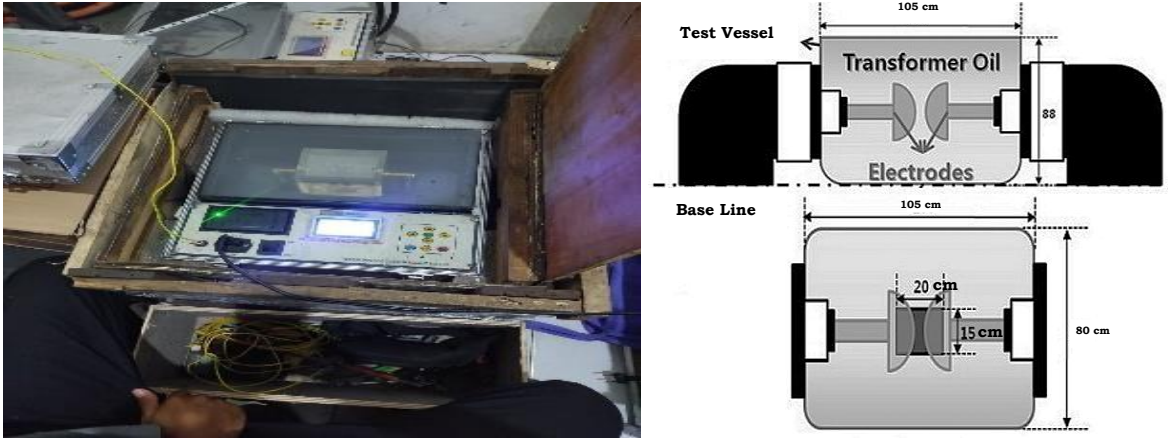


Figure 1. Breakdown Voltage Tester for Transformer Oil

The final BDV value was obtained from the arithmetic mean of all tests, and the results were analyzed to assess the influence of contamination and the effectiveness of purification, with comparisons made against IEC 60422 condition limits to determine the oil’s insulation quality and suitability for continued service. The breakdown voltage of insulating oil can be calculated or evaluated using the following equation:

$$E = \frac{V}{d}$$

Where,

E = Dielectric strength (kV/mm)

V = Measured breakdown voltage (kV)

d = Electrode gap distance (mm)

This equation provides an estimate of the average electric field required to initiate electrical breakdown across an oil-filled gap. A good BDV value typically adheres to relevant standards (such as IEC 60156), with minimum acceptable values for new oil often exceeding 30 kV, depending on equipment specifications and operational requirements.

Figure 1 shows the equipment and schematic diagram of a breakdown voltage (BDV) tester used for assessing the dielectric strength of transformer oil. The left side of the figure depicts the actual test apparatus, consisting of a high-voltage generator, digital measurement interface, and an enclosed oil test cell equipped with electrodes. The device applies an increasing AC voltage to the oil sample until electrical breakdown occurs, automatically recording the breakdown voltage.

The right side of the figure illustrates the schematic design of the test vessel and electrode arrangement. The diagram indicates dimensions of the test chamber, with a typical gap distance of 2.5 mm between hemispherical electrodes submerged in the oil. This standardized configuration ensures consistent electric field distribution during testing. The BDV test helps identify contamination or degradation in the oil by measuring the voltage level at which dielectric failure happens, providing critical data for maintenance and quality control of power transformers.

2. Purification Process of Transformer Oil

During the purification process, the entire train will remain stationary while the used transformer oil is drained from the tank. The oil will then be pumped into a double-stage vacuum insulating oil regeneration and filtration machine for thorough purification and treatment. The purification procedure consists of five main stages performed in repetitive cycles: primary (coarse) filtration, heating, vacuum separation, regeneration, and fine filtration. Once the filtration unit begins operation, the used transformer oil is drawn into the primary filter due to pressure differential, effectively removing large particulate impurities before entering the heating phase.

During heating, water molecules in the aged oil gain kinetic energy and become more diffusive as the temperature rises. Thermal heating combined with filtration is considered one of the most effective methods for removing contaminants, especially moisture and dissolved gases in transformer oil [30]. The heated oil subsequently passes into the vacuum separator, where a vacuum pump facilitates moisture removal. Water content is extracted under vacuum either as vapor or condensed into liquid with the aid of a heat exchanger.

The next critical stage is the regeneration process, essential for restoring degraded transformer oil. Oxidation by-products increase the oil's acidity, reduce its interfacial tension, and lead to sludge formation [31]. The regeneration process effectively removes polar contaminants, deep oxidation products, and free carbon particles while also improving the oil's color and appearance [32]. The final step is fine filtration, which eliminates residual microscopic impurities down to 5 μm and larger. The entire purification cycle is typically repeated several times or continued until the treated oil achieves a minimum breakdown voltage of 30 kV, as specified by IEC 60296 standards (Fluids for electrotechnical applications – Mineral insulating oils for electrical equipment). Figure 2 summarizes the overall flow of the transformer oil purification process.

3. Weibull Distribution Analysis

In probability theory and statistics, the Weibull distribution is a continuous probability distribution widely used for reliability analysis and life data modeling. It is named after its originator, Waloddi Weibull, a Swedish physicist who introduced it in 1951 [33]. The Weibull distribution is defined using two key parameters: the shape parameter and the scale parameter. In the context of transformers, dielectric probability analysis of insulating oil is often related to evaluating insulation failure risk and estimating the oil's service life.

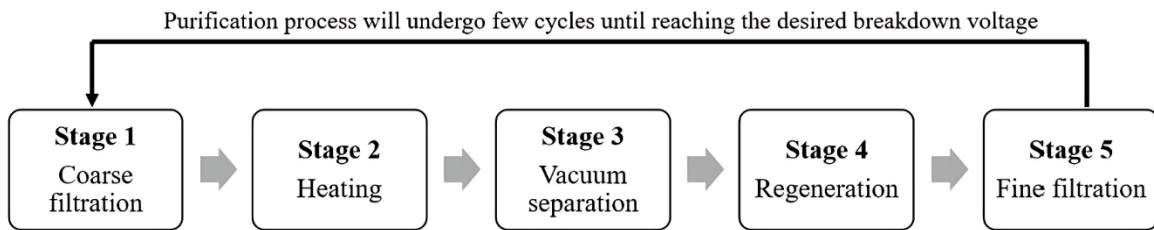


Figure 2. Double-Stage Vacuum Insulation Oil Regeneration Filtration Machine process

The Weibull model is employed to describe the distribution of time-to-failure data and is particularly useful for calculating the probability of dielectric failure in transformer oil. The cumulative distribution function (CDF) of the Weibull model can be expressed as follows:

$$f(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^\beta} \quad (2)$$

Where,

$f(t)$ = probabilitas kegagalan pada waktu

α = parameter skala (mean atau umur rata-rata dari sistem)

β = parameter bentuk yang menunjukkan sifat distribusi

Results and Discussion

1. Breakdown Voltage Test Result

Breakdown voltage (BDV) is a critical parameter used to evaluate the dielectric strength and overall quality of transformer insulating oil. It provides an indication of the oil's ability to withstand electrical stress without experiencing dielectric failure. A high BDV value typically reflects low contamination levels, minimal moisture content, and reliable insulating performance, which are essential for the safe and efficient operation of power transformers.

In this section, the BDV test results for three different transformer oil samples Shell Diala S4, Pri Apar, and PSP are presented and analyzed. These oils are widely used in the industry and may exhibit different dielectric characteristics depending on their formulation, condition, and history of service. By comparing the BDV values obtained from standardized testing procedures, this analysis aims to assess the relative quality of these oils, identify potential issues such as contamination or aging, and support decisions for maintenance or replacement.

Figure 3 illustrates the comparison of breakdown voltage (BDV) test results for three types of new transformer oils: Shell Diala S4, PSP, and Pri Apar. The graph plots the breakdown voltage values (in kV) measured over multiple testing cycles, highlighting the performance consistency and relative dielectric strength of each oil sample. From the result, it is observed that Shell Diala S4 generally shows higher and more variable BDV values compared to PSP and Pri Apar, with several peaks exceeding 60 kV during certain tests. In contrast, PSP and Pri Apar exhibit more stable but slightly lower BDV readings, typically clustered around 30–50 kV. These variations may reflect differences in oil formulation, purity, and inherent dielectric properties. Higher BDV values suggest better insulating performance and lower susceptibility to electrical breakdown under stress. Such comparative testing is essential for selecting suitable transformer oils to ensure reliable insulation, minimize failure risk, and support long-term operational safety.

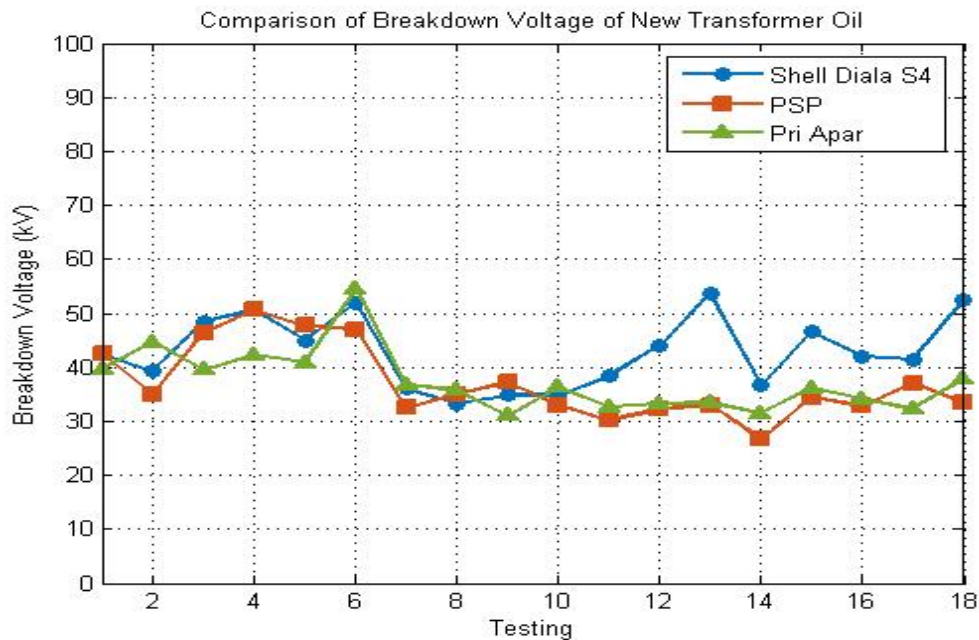


Figure 3. BDV Test Result on each oil with new condition

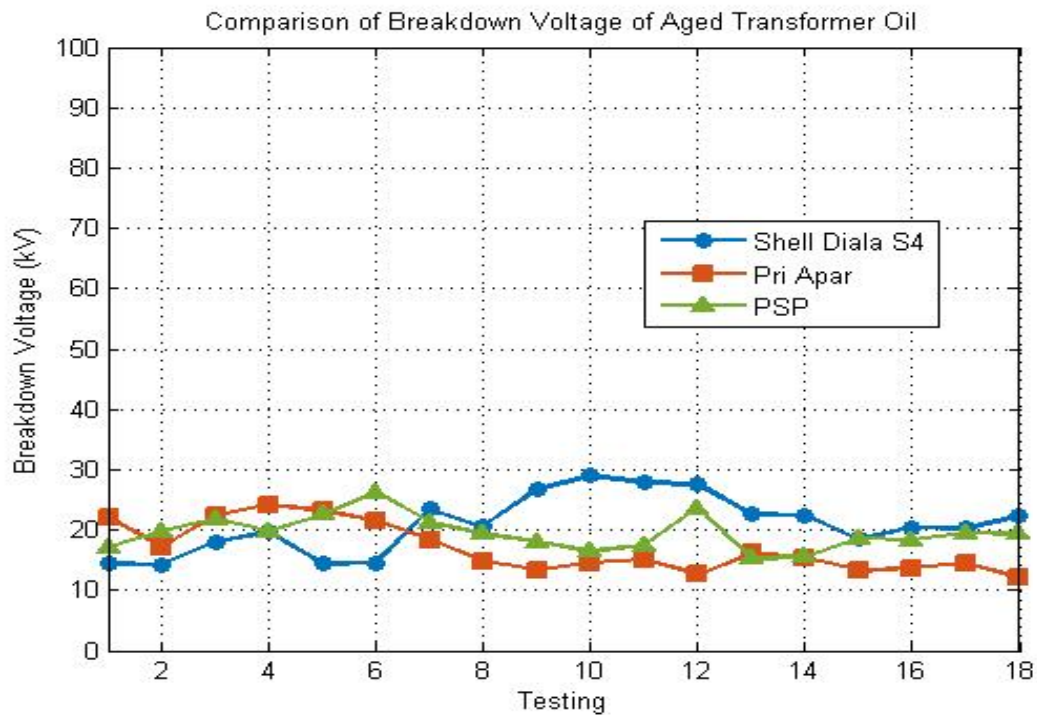


Figure 4. BDV Test Result for Aged Tranformer Oil

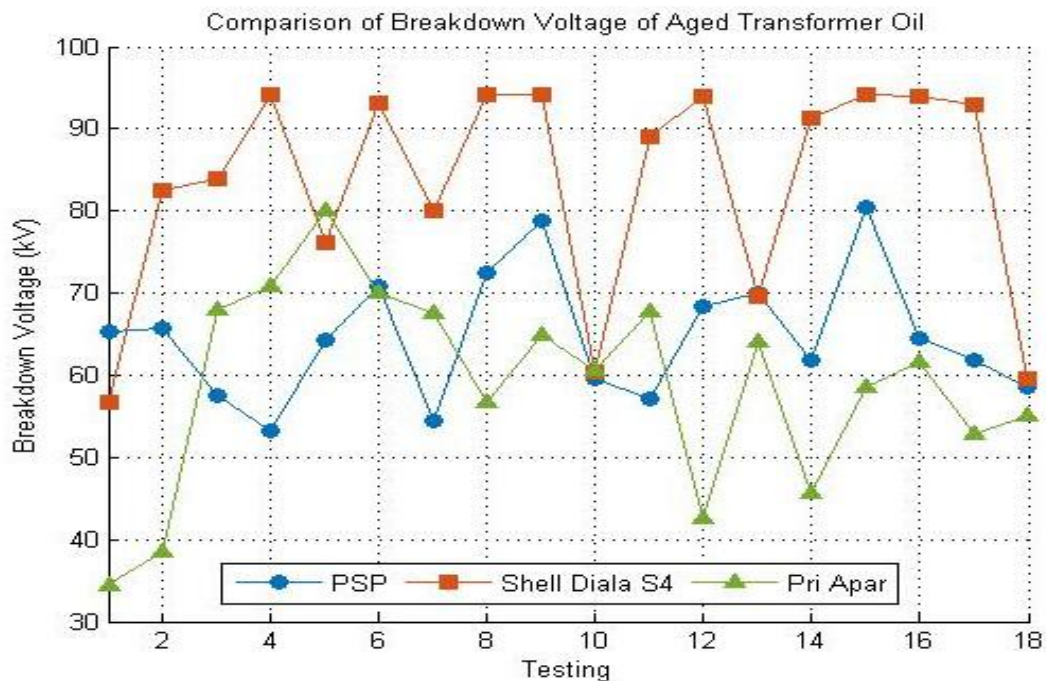


Figure 5. BDV Test Result for Purified Tranformer Oil

Figure 4 shows the comparison of breakdown voltage (BDV) test results for aged transformer oils of three different types: Shell Diala S4, Pri Apar, and PSP. The graph plots BDV values (in kV) measured over multiple testing cycles, illustrating the performance degradation and dielectric strength reduction associated with oil aging. Compared to the new

oil results, the BDV values for all three samples are noticeably lower and more consistent at reduced levels. Shell Diala S4 generally maintains slightly higher BDV values relative to Pri Apar and PSP, with most readings ranging between 15 kV and 30 kV. Pri Apar and PSP display even lower and more stable readings, often remaining close to or below 20 kV. This decline in breakdown voltage highlights the impact of aging on transformer oil properties, including increased contamination, moisture content, and chemical degradation. The lower BDV values indicate reduced insulating performance, underscoring the need for timely monitoring, purification, or replacement to ensure safe and reliable transformer operation.

Figure 5 illustrates the comparison of Breakdown Voltage (BDV) test results for three types of transformer oils PSP, Shell Diala S4, and Pri Apar after undergoing a purification process. The data is based on 18 individual tests for each oil type. The results show that Shell Diala S4 consistently exhibits the highest breakdown voltage values, often exceeding 90 kV, indicating excellent dielectric performance after purification. In contrast, Pri Apar oil demonstrates greater fluctuation and generally lower BDV values, with several measurements falling below 60 kV. Meanwhile, PSP oil shows intermediate performance, with BDV values ranging between approximately 50 kV and 80 kV. This trend suggests that the effectiveness of the purification process varies depending on the oil type. Shell Diala S4 remains stable and superior, while PSP and Pri Apar oils show more significant variations, which may be attributed to the initial oil condition and the purification method.

2. Weibull Distribution Analysis

Weibull Distribution Analysis is a statistical method used to evaluate the reliability and failure characteristics of materials or systems. In transformer oil testing, it helps estimate breakdown voltage performance and predict insulation failure probability. This method provides key parameters such as shape and scale, enabling a deeper understanding of dielectric strength consistency and the impact of aging or purification processes (Widagdo et al., 2025).

Figure 6 presents the Weibull probability plot for new transformer oils Shell Diala S4, PSP, and PRI APAR based on their AC Breakdown Voltage (BDV) performance. The plot includes a 95% confidence interval and shows cumulative probability versus breakdown voltage. From the graph, Shell Diala S4 demonstrates the highest reliability, indicated by its rightmost position on the plot, suggesting it has the highest breakdown strength among the three oils.

The shape and scale parameters for Shell Diala S4 are also the largest (shape: 7.339, scale: 45.70), signifying consistent and strong dielectric performance. In comparison, PSP and PRI APAR have lower scale values, indicating weaker breakdown voltage characteristics. Particularly, PRI APAR shows the lowest scale parameter (39.89) and a higher dispersion in failure probability, suggesting less reliability under high voltage stress.

The Anderson-Darling (AD) test results and corresponding p-values demonstrate that all data sets conform well to the Weibull distribution. Among them, Shell Diala S4 exhibits the lowest AD value, indicating its superior statistical stability and consistency compared to the other oils tested. This finding strengthens the reliability of Shell Diala S4 as a dielectric medium. Based on the Weibull analysis, Shell Diala S4 can be regarded as the most dependable new transformer oil in terms of dielectric strength performance, ensuring greater operational safety and long-term stability for power equipment. Following Shell Diala S4, PSP oil ranks second, offering reasonable performance but with slightly less consistency. PRI APAR shows the lowest ranking among the three, though it still fits the Weibull model. Overall, the analysis emphasizes the importance of Shell Diala S4 as the most reliable option, supporting its potential as a preferred choice for transformer insulation applications.

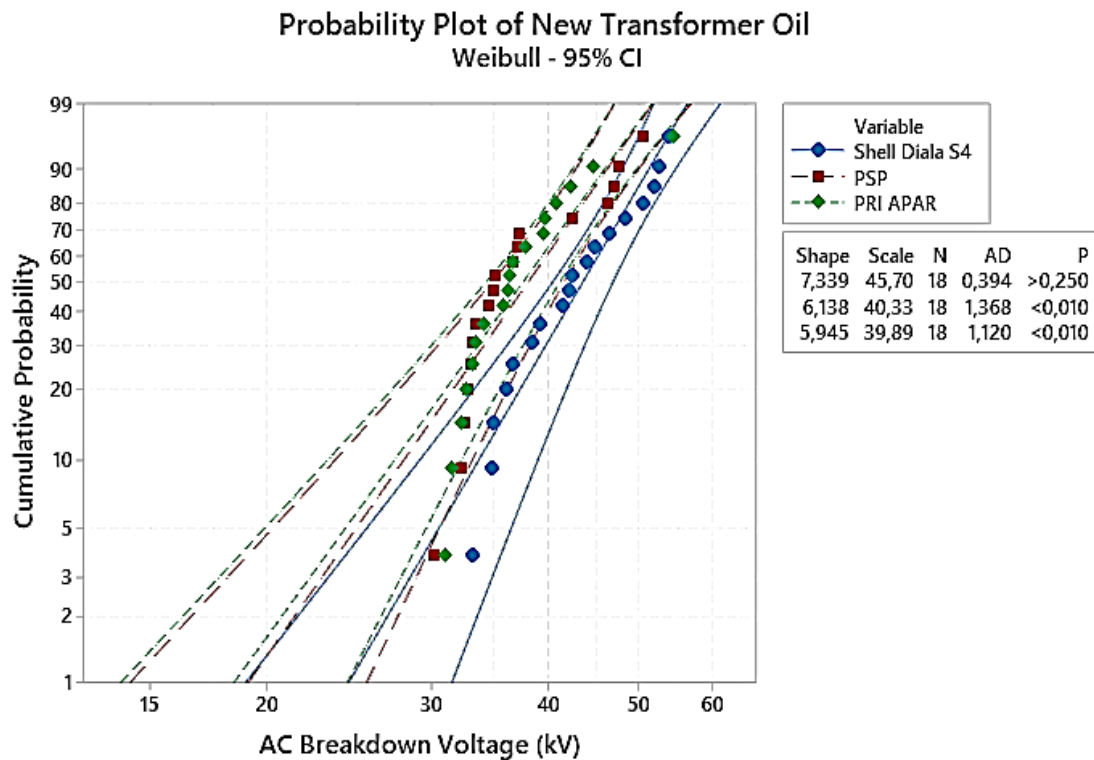


Figure 6. Weibull Probability for New Transformer Oil

Probability Plot of Aged Transformer Oil
Weibull - 95% CI

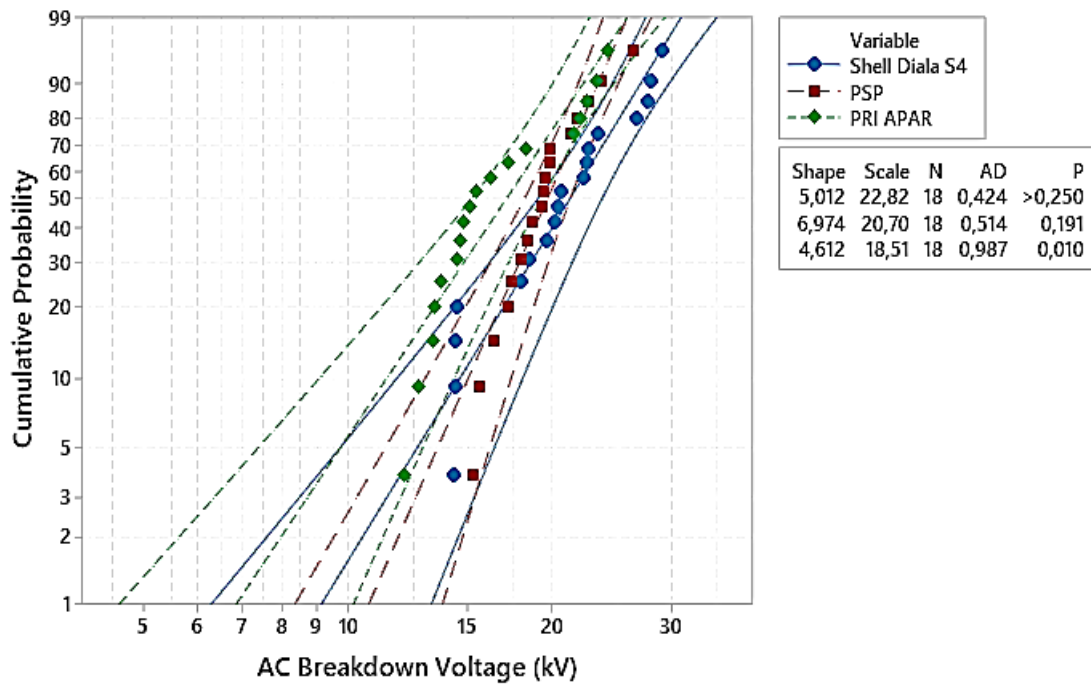


Figure 7. Weibull Probability for Aged Transformer Oil

Probability Plot of Purified Transformer Oil
Weibull - 95% CI

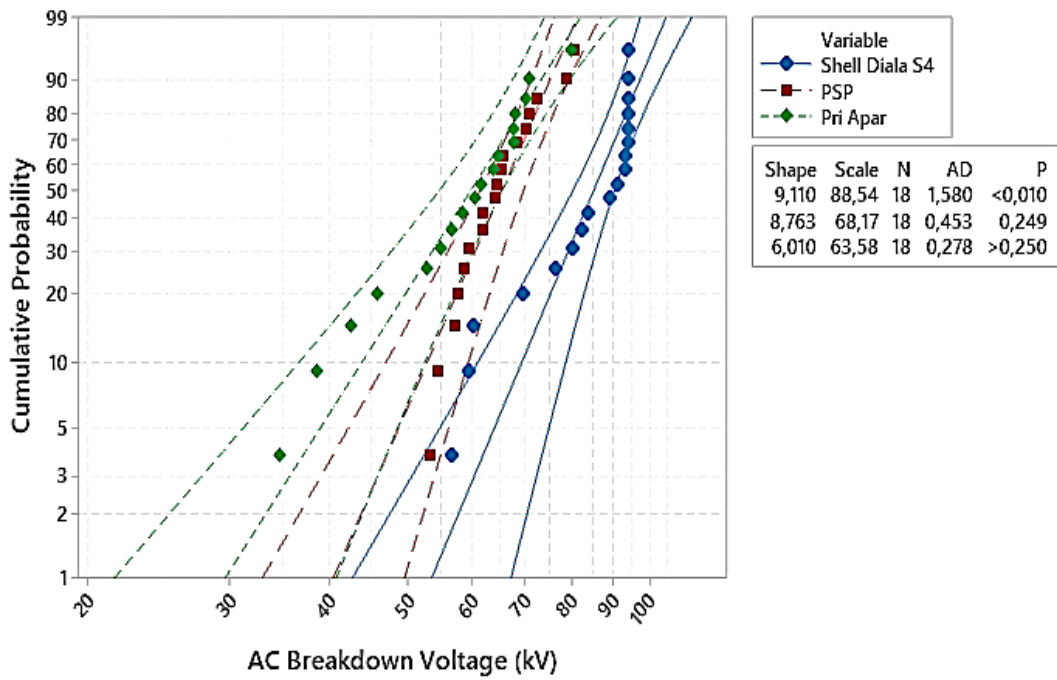


Figure 8. Weibull Probability for Purified Transformer Oil

Figure 7 presents the Weibull probability plot for aged transformer oils Shell Diala S4, PSP, and PRI APAR based on their AC Breakdown Voltage (BDV) characteristics. The plot statistically evaluates insulation reliability against cumulative probability with a 95% confidence interval. The results clearly show that aging significantly decreases the dielectric strength of all three oils compared to their new condition. Shell Diala S4 still demonstrates superior performance, though it shifts leftward, with a scale parameter of 22.82 and a shape parameter of 5.012, indicating wider spread and reduced consistency due to aging. PSP and PRI APAR show even further degradation in dielectric performance. Notably, PRI APAR exhibits the lowest scale parameter 18.51, reflecting the most severe decline in breakdown voltage after aging. Its flatter curve also implies higher variability in failure events, suggesting lower reliability under stress. The Anderson-Darling (AD) test confirms that all data sets fit the Weibull distribution, with p-values above 0.05, validating the model. In conclusion, while all oils degrade with age, Shell Diala S4 maintains better breakdown strength and reliability than PSP and PRI APAR, making it the most robust option under prolonged use.

Figure 8 shows the Weibull probability plot for purified transformer oils Shell Diala S4, PSP, and Pri Apar based on their AC Breakdown Voltage (BDV) values. This plot provides a statistical reliability analysis after the purification process, using a 95% confidence interval. From the graph, it is clear that purification significantly improves the breakdown performance of all oil types compared to their aged conditions. Among them, Shell Diala S4 stands out with the highest scale value (88.54 kV) and shape parameter of 9.11, indicating both high dielectric strength and consistency after purification. The steep slope also reflects strong reliability. PSP oil shows moderate improvement, with a scale value of 68.17 kV and a shape parameter of 8.763, suggesting better performance and tighter failure distribution compared to its aged state. Meanwhile, Pri Apar oil also benefits from purification, reaching a scale value of 63.58 kV, though it remains less consistent (shape = 6.010) than Shell Diala S4. The Anderson-Darling (AD) test results show that all data sets fit the Weibull distribution well, with p-values well above 0.05, validating the model's use for reliability estimation. In conclusion, purification restores and enhances the dielectric properties of all transformer oils, with Shell Diala S4 again demonstrating the best performance in terms of both strength and statistical consistency.

Conclusion

The results of this study demonstrate that purification plays a significant role in restoring the dielectric quality of aged transformer oil. The observed improvements in breakdown

voltage 70% for Shell Diala S4, 50% for PSP, and 47% for Pri Apar confirm that purification can effectively recover key insulation properties to levels approaching, or in some cases exceeding, those of new oil. These findings contribute to a better understanding of transformer-oil recovery mechanisms and highlight the importance of moisture and contamination removal in maintaining dielectric reliability.

The implications of this work extend to asset management strategies in distribution systems. Aged transformer oil poses a heightened risk of dielectric failure, yet this risk can be substantially mitigated through routine purification, making it a cost-effective preventive maintenance measure. Based on its consistently superior post-purification performance and stronger resistance to degradation, Shell Diala S4 is recommended for critical and long-term applications. Meanwhile, PSP and Pri Apar remain viable for medium-risk environments, provided they are supported by more frequent monitoring and scheduled purification cycles. Overall, the study reinforces the necessity of integrating purification into regular maintenance programs and offers evidence-based guidance for selecting suitable insulating oils to enhance transformer reliability and service life.

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