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AC Breakdown Voltage Test of Vegetable Oils Analyse by AI-Driven Statistical Analysis

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ABSTRACT

Transformers are also vital in electrical delivery to the consumers they are used in the process. Conventionally, transformer insulating fluids have been filled with standard mineral oils (MO) due to their fine dielectric strengths and cooling performances. In this work, the prospect of the two biodegradable oils, palm oil (PO) and rice bran oil (RBO), as the new dielectric fluids for transformers was investigated using the stringent method. The key elements of the methodology involved considering and analyzing oil data as an output while employing new AI-based algorithm analysis in certain areas. The findings of this research indicate that Natural Ester Oils (NEOs) have several benefits and one of them is the fact that they can self-disintegrate and minimize the possibility of fire outbreaks. The statistical analysis conducted by employing the characteristics of AI is useful for understanding the reliability and effectiveness of ester oils in a given circumstance and hence, the possibility of using these oils as a viable MO replacement in the transformer context. Thus, it can be pinpointed out that RBO yields maximal breakdown voltage of 100 KV; and average breakdown voltage was significantly higher than MO. Like in the case with MO, breakdown voltages of blends consisting of PO and RBO were found to be comparable. The trends in breakdown voltage distribution also provide the evidence that esters are going to have the performance characteristics as close to MO as possible. As it has been discussed, NEOs, especially PO and RBO, are economically effective in the long term and ecologically beneficial for transformer insulation.

Keywords: *Transformer; AI; palm oil; rice bran oil; mineral oil*

1. Introduction

Transformers have a crucial role in ensuring efficient transmission of electricity to consumers [1]. It is crucial to prioritize the development of transformers that are dependable, efficient, and capable of meeting the increasing power demands of our expanding world. The use of standard mineral oil (MO) in transformer insulating fluids has been a long-standing practice due to their effective dielectric properties and cooling capabilities [2]. However, MO have significant ecological and operational drawbacks, which is why there is a quest for environmentally friendly alternatives. The laboratory experiments demonstrated that Palm oil (PO) and Rice Bran Oil (RBO) exhibit similar biodegradability, renewability, and dielectric properties as mineral oils. This suggests that these natural ester oil (NEO) could be potential alternatives to MO [3].

MO, although widely used, pose challenges in terms of their impact on transformer performance and environmental sustainability [4-6]. There are some significant issues with them, though. They are

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not biodegradable and come from non-renewable petroleum sources, making them highly hazardous in case of leaks or spills. The oxidation of MO over time can lead to the production of sludge and acids, which can negatively impact the insulating properties of the oil and the overall integrity of the internal components in a transformer. The flame propagation in these situations can greatly increase the risk of danger. For instance, if there are any faults or if the temperature is too high, it could lead to fires with serious consequences. Furthermore, MO undergoes degradation and necessitates ongoing monitoring and maintenance, such as regular purification of tools in the laboratory through filtration and replacement. This can be a costly and time-consuming task to manage [7-9].

There was an incident in 2015, a transformer containing mineral oil exploded in New York's Indian Point Energy Centre [10]. The explosion was caused by minor oil decay, which affected its dielectric force and led to arcing, ultimately resulting in failure. Then, in 2023, there were two cases: one in Malaysia in May and another in Bangkok in August [11,12]. Also, this year, 2024, a transformer exploded again in India, and four were injured [13]. This incident serves as a reminder of the significance of dependable and environmentally-friendly insulating fluids in improving transformer safety ratings.

Natural Ester Oil (NEO) such as PO and RBO have numerous advantages compared to MO [1,14-16]. These products are sourced from renewable materials and are biodegradable, which helps to minimise environmental contamination in case of leaks or spills. This suggests that vegetable-based materials could be viable options for transformer insulating fluids, according to Ravinsky *et al.,* [17] ester oils possess excellent thermal conduction properties and higher flash points, making them a safer and more efficient option for transformers operating under heat stress conditions. This statement highlights the fact that they generally produce fewer acidic by-products and sludge compared to mineral oils. As a result, transformers can have a longer lifespan and require less maintenance [9,17,18].

In this research, artificial intelligence (AI) will be more widely adopted. AI is extensively used to improve both accuracy and efficiency in statistical analysis. Using AI algorithms, particularly in Google Colab (with Python) [25], helps expedite data analysis and has many other benefits. Some process a considerable amount or size of data, discover very complicated patterns, and make accurate predictions with the help of different statistical models [26].

Artificial Intelligence (AI) has been widely adopted for statistical analysis in the past few years, as it provides greater reliability and quick data processing. Using AI tools, researchers can automate the analysis process, reducing human errors and providing more in-depth information regarding the performance of ester oils under different conditions [26].

In brief, oil serves as a critical element for transformer design and performance by delivering insulation, efficient cooling, and longer life [27]. The following section will discuss liquid-filled transformers, their properties as fundamental natural esters, and an analysis of their use for existing electrical power systems. This paper seeks to review the insulation properties of natural ester oils in detail and with precision by carrying out AI-driven statistical analysis, aiding the future development of transformer technology in more environmentally friendly insulating materials.

2. Methodology

2.1 Pre-Treatment Oil

The potential of two biodegradable oils, palm oil (PO) and rice bran oil (RBO), as new dielectric fluids for insulating transformers, has been evaluated with a thorough methodology. The method consisted of measuring oil data as an output and using new AI-based algorithm analyses in some key areas. The breakdown voltage (BDV) was measured according to standard procedures using the BAUR DTA 100C device that enabled precise and reproducible results [1].

The oils were characterized in a comparative way with six different parameters: market MO was Hyrax Oil that also involved two samples of natural ester oil (PO = palm oil and RBO - rice bran oil) and mixture from both palm oil together with rice bran oil that were mixtures, PO/RBO (50/50%, 70/30 and 30/70%). The oils were warmed in the moment estimates had been carried out. After that, the oil samples were heated for 60 min at 100°C. The heating is done to mimic the thermal stress that oils could endure when transformers are working [2].

The oils were then filtered to remove any unwanted particles. This stage was very important since it removes impurities which can change the dielectric properties of oils and make a raw material for BDV tests. Breakdown voltage measurements were performed using 12.5 mm diameter spheres with a gap of 2.502 ±0.005 mm according to IEC 60156 conditions The oil was then homogenised (stirred) mechanically in the test vessel, to drive off any entrained air bubble [3]. Removing air was an important step to get clean voltage readings and prevent any anomalies or instability in the results.

2.2 Experimental Test

The AC breakdown voltage test begins with the careful preparation of the oil samples, including MO, PO, PO, and a combination of PO and RBO. These samples are thoroughly pre-treated to meet the required standards. The test setup utilizes the BAUR DTA 100C oil tester, which complies with all international and national standards, including IEC 60156 [30]. This ensures the reliability and standardization of the test results. Fifty readings were taken for each oil sample to make the results both accurate and reproducible. However, only 30 readings that has smallest standard deviation were taken to analyse. The methodology used herein minimized the variation among replication, hence making it a more conducive method to compare dielectric strength for different oils.

Oil sample is put into the test vessel and all parts are submerged entirely. This step is important to ensure that no air bubbles remain in the measurement cell which could lead to mis usage or detection of lower breakdown voltages. In the testing vessel there is a stirrer to mix up the oil and prevent air pockets being formed, thus retaining homogenous test conditions throughout [31].

The electrodes, having a sphere diameter of 12.5 mm, are set up so that there is a gap of 2.5 mm between them, in accordance with IEC 60156 [30]. This distance is necessary to make the results comparable and reliable because various oil samples may have different conductive properties. After setting up the gap, the AC breakdown voltage test is performed by slowly increasing the voltage on the electrodes and noting the voltage at which survey begins. Every 50 readings are obtained for each individual oil however, in this study, only 30 readings with the best standard deviation are choose to proceed with further statistical analysis.

By following this meticulous procedure, the study aims to achieve accurate and repeatable measurements of the dielectric strength of the various oil samples, contributing valuable data for the assessment of their suitability as transformer insulation materials.

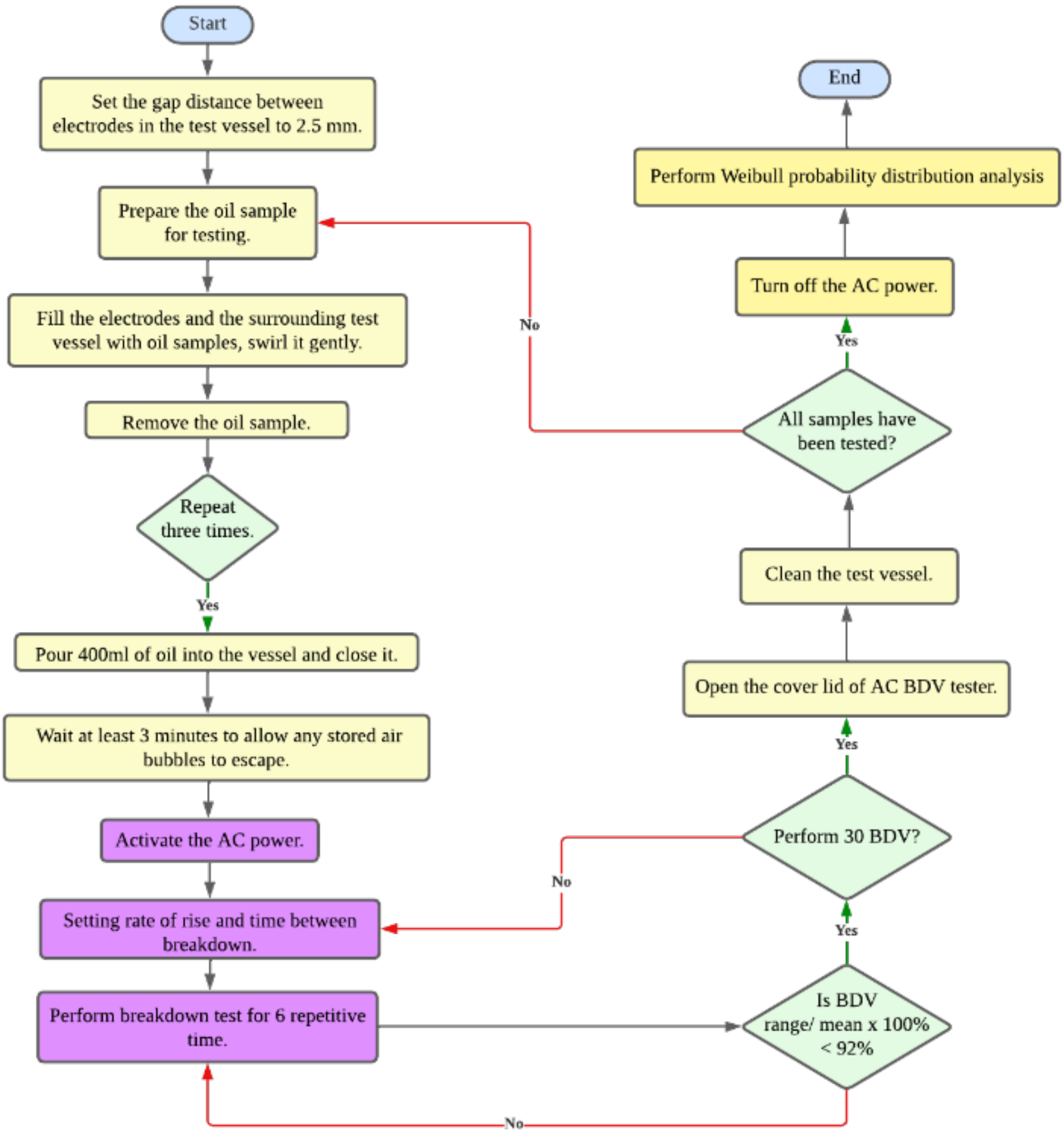

Fig. 1. Flowchart of the AC breakdown voltage experiment process

2.3 Data Analysis

The analysis of breakdown voltage data is conducted through a systematic approach designed to ensure accuracy and derive meaningful insights [24]. It begins with data collection, where relevant data points are gathered from experiments or field measurements. Following this, data reprocessing ensures data integrity and consistency. Exploratory Data Analysis (EDA) is then employed to summarize data characteristics and identify patterns using graphical methods like histograms and scatter plots. Subsequently, distribution fitting, including both normal and Weibull distributions, assesses the data's statistical properties. Model evaluation validates the fit of these distributions to the data. Artificial intelligence techniques enhance analysis by providing predictive capabilities and deeper insights into breakdown voltage behavior [26]. Result interpretation concludes the process, summarizing findings and their implications, which are crucial for decision-making and further research. This structured methodology ensures comprehensive understanding and effective communication of breakdown voltage insights across relevant fields and applications.

Data collection is the initial step where breakdown voltage data is gathered from relevant sources. This data is stored in a structured format, typically a CSV (Comma-Separated Values) file, to maintain organization and facilitate further analysis. Ensuring accurate and comprehensive data collection is essential for robust analysis and informed decision-making in electrical engineering applications. In data reprocessing, Python [25], along with libraries such as Pandas, Matplotlib, and Seaborn, plays a crucial role in cleaning, transforming, and preparing collected breakdown voltage data for analysis.

In data reprocessing, these Python libraries work synergistically to preprocess and visualize breakdown voltage data efficiently. They enable researchers and engineers to clean and transform raw data into a structured format suitable for in-depth analysis and interpretation, thereby facilitating informed decision-making and advancing research in electrical engineering applications [25].

Then, the Exploratory Data Analysis (EDA) employs various visualization techniques such as scatter plots, boxplots, histograms, and Weibull plots to unveil the distribution and characteristics of breakdown voltage data. These visualization techniques play a pivotal role in EDA by providing intuitive and insightful ways to explore, summarize, and interpret breakdown voltage data. They help researchers and engineers uncover patterns, outliers, and underlying relationships within the data, facilitating informed decisions and further analysis in electrical engineering and reliability studies.

3. Conclusions

When analysing the data, the following conclusion can be made, the highest breakdown voltages were from RBO that is 100kV.Furthermore, the average breakdown voltage of RBO is much greater than that of MO. But in some series of measurements, it can be observed that the breakdown voltage of 0.5PO0.5RBO, 0.7PO0.3RBO and 0.3PO0.7RBO is comparable with the breakdown voltage of MO. The RBO has the most skewed distribution following with 0.5PO0.5RBO.

From the data, it can be concluded that the ac breakdown performance of the natural esters oil, at low probabilities was comparable to mineral oil. Therefore, considering transformer insulation, it is likely that designs intended to use MO will be suitable for esters.The kurtoses of the esters were slightly lower than that of mineral oil, indicating that outlying ester breakdown voltages are unlikely to be more frequent than when occurring in mineral oil. This suggests esters are likely not to be less reliable than mineral oil as dielectrics.

Considering the effectiveness of esters as dielectrics, this shows that these oils can be as capable as mineral oil in acting as transformer insulation.

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