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Breakdown Characteristics of Unused Transformer Oil and Olive Oil under AC and DC Voltages at Different Temperature Rate

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Abstract: This project aim is to investigate the breakdown characteristics of unused transformer oil and olive oil under AC and DC voltage at different temperature rate. HVAC and HVDC breakdown tests are carried out alongside with the hemisphere electrode arrangements. The high voltage test is done in order to observe the performances of the oil samples to attain the highest breakdown AC and DC voltages. In addition, this project needs to be done to see if olive oil as one of the vegetable oil can be an alternative for the conventional transformer oil. Commonly used transformer oil is made from mineral oil and it is declining day by day as its use increases. So as a precaution studies are done with vegetable oils to replace the mineral oil-based transformer insulation fluid. In this study, each oil sample is tested at different temperature rate and has recorded different value of breakdown voltage from the experiment. The gap distance between electrodes is constant and oil samples are heated at different temperature ranges. More voltage is needed to breakdown at higher temperature rate. Both the unused transformer oil and olive oil have linearly increased AC and DC breakdown voltages when subjected to higher temperatures. However, it is found that the highest AC and DC breakdown voltages are recorded at the highest temperature range and when the insulating medium used is olive oil. Moreover, the obtained AC and DC voltages are then be used to study the electric field in FEMM software.

Keywords: High Voltage Alternating Current (HVAC), High Voltage Direct Current (HVDC), Finite Element Method Magnetics (FEMM), breakdown tests

1. Introduction

In today's era of globalization, the use of technologies have increased in human's daily life where the demand for electrical energy also has increased. Thus, importance to the electrical energy should be given more especially when it comes to electrical insulation in order to avoid any leakages, failures, accidents and others. In that case, transformer insulation is also important in the electrical energy system because it functions to step up and step down the voltages.

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Liquid insulation is widely used in high voltage system for the transformers where usually mineral oils are being used as an insulation. Mineral oils are poorly biodegradable and might vanish in the future [1]. The mineral based transformer oil is a non-renewable source and gives bad impact to the environment if it is unused or disposed because it is difficult to degrade [2].

Therefore, the researchers try to seek for the substitution of mineral oils since they give negative impacts to the environment. Besides, the high flash point characteristics and extensive production around the world are the main reasons for using mineral oils [3]. Basically, a good insulating liquid must have high breakdown voltage, good chemical stability, low dielectric losses, reasonable price, stable at high temperature and act as an excellent coolant for the transformer [4]. Over the years, transformer oils that are mineral oils based are extensively used to preserve the core and windings of the transformer which are fully immersed inside the oil. The mineral oils are extensively used to produce transformer oil because it act has an excellent coolant, low dielectric losses, low cost, great dielectric strength, longer life span and its availability. Thus, using the right oil guarantees transformer durability and life span. Moreover, the mineral oil is mostly originated from non-reusable fossil fuel that will affect the nature [5].

Hence, vegetable oils are the appropriate substitute for the mineral oils since they are obtained naturally from seeds, flowers and other parts of the vegetables itself [6]. Many researchers and industries are performing investigations on vegetable oils to be used as insulating oils for the transformer since they are biodegradable and do not cause pollution [7]. When comparing the mineral oil with vegetable oil , mineral oil has higher pour point, higher viscosity and low oxidation stability. Therefore, if the mineral oil is replaced with vegetable oil then well-preserved surrounding can be ensured [8]. In addition, it enables more studies and industries relating biodegradable oil to grow well for the future undertakings.

So, in that case for this project olive oil is used as the vegetable oil because it is produced naturally from plants which are biodegradable. Olive oil also has higher temperature stability and a higher pour point than mineral oil. It has higher fire point and reduces the impact of transformer fires. The leaks and spills of olive oil does not harm crops and aquatic lives. It is also a very bad conductor of electric charge and that makes it to be used as coolant and insulating medium in transformers. Moreover, it is highly biodegradable and cheap in price. Even though research has been done for various vegetable oils to measure their dielectric properties, it is believed that olive oil has not received much attention yet for its suitability as insulating fluid in transformers. These are the reasons behind using olive oil as an insulating oil for this project, also tested and compared with an unused transformer oil. Normally the oil in a transformer is subjected to continuous heating temperatures of about 95oC [9]. The temperature ranges has been varied until 110oC because the standard heat limit is about 95oC. Meanwhile, the variation of temperature ranges help in observing the increment and decrement of AC and DC breakdown voltages. More voltages required to breakdown oils at higher temperature because there is lower viscosity in the oil which makes it less resistance to the conventional heat flow of oil.

2. Research Method

This research has two stages where the first stage is the HVAC and HVDC breakdown tests and the second stage is the simulation for electric field intensity analysis of the oil samples. The oil samples have been tested under AC because it is important in generating a continuous variable AC test voltage at power frequency [10]. HVAC are designed for testing all types of electrical insulations up to the highest voltages, preferably of electrical apparatus used in power transmission and distribution systems. This test is mostly done to check on the high voltage withstand of an insulation to avoid damages to the transformer.

Meanwhile, the oil samples have been tested under DC voltages because high-voltage direct-current (HVDC) power transmission is the most controlling application for line-commutated converters that available today [10]. In high-power and long-distance applications, these systems become more economical than conventional AC systems. They can link two ac systems operating unsynchronized or with different nominal frequencies, that is, 50 Hz to 60 Hz. They have very good dynamic behavior and can interrupt short-circuit problems very quickly.

As for the second stage, the electric field intensity has been obtained for the oil samples at different temperature ranges by using FEMM. FEMM is said to be an open source of source finite element analysis software package that can aid in solving low frequency electrostatic problems. This software addresses two dimensional planar and axisymmetric domains. Besides, the FEMM software also addresses the linear and non-linear period harmonic low frequency magnetic and magnetostatic difficulties and lined electrostatic complications.

This software is extensively used to find numerical solution for electric field problem because this software has various and simple tool to solve the problem of electric field. In order to have a good results from the solution of an electrostatic problem it is important to design the model well. The FEMM has panel for nodes, line, arc segments, list of materials and others for the user to design a desired model on the geometry space to draw. The obtained results can be evaluated from the contour plots.

2.1 HVAC and HVDC Breakdown Tests

The AC and DC breakdown voltage measurement methods are referred to the TERCO instruction in the high voltage laboratory and conducted according to the ASTM D1816-12(2019). In these methods, the voltage is increased until the breakdown occurs to the oil samples and the breakdown voltage value has been recorded. In this experimentation, the kind of olive oil used is extra virgin since it has light texture and there is good heat flow through it. The oil samples have been heated to ±5 oC of a particular temperature range few minutes earlier before placing it in the test cell so that during the high voltage test the temperature remains within the set temperature range.

The experiment has been repeated with the same oil sample and temperature for six times. Each oil sample has been heated to the desired temperature before the placing it for the breakdown test. Also, it has been always made sure that the temperature is within the desired temperature range for all the six times of repetition of breakdown test. The unused transformer oil and olive oil have been heated at temperature ranges of 27oC, 50oC - 60oC, 60oC - 70oC, 80oC - 90oC and 100oC - 110oC.

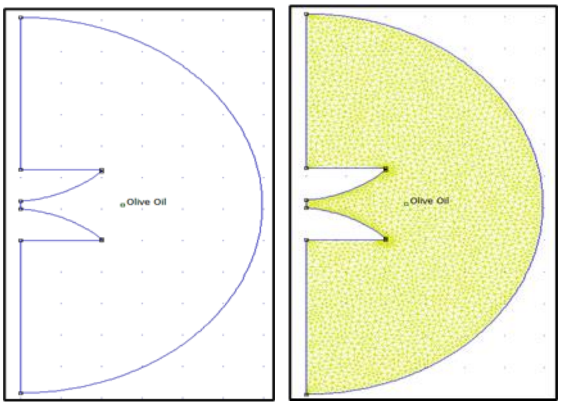
Fig. 1 - The HVAC breakdown test setup

Fig. 2 - The HVDC breakdown test setup

2.2 Simulation for Electric Field Intensity Analysis

The analysis of electric field between the hemisphere electrodes with two different oil samples is done by using FEMM Version 4.2 software. The model of electrode arrangement is created in two-dimensional plane (2D) with the axisymmetric domain [11]. The analysis of electric field for the unused transformer oil and olive oil are replicated by the software with altered dielectric constants.

The outcomes from software development are observed then analyzed. Besides, the data from graphs are clarified briefly with practical explanation which is associated to the project’s purposes. The errors occurred are detected once simulating the model, hence it is resolved at that point by checking the simulation properties and then simulated again until the verified results are obtained.



(a) **(b)**

Fig. 2 - The model of hemisphere electrodes in FEMM (a) before meshing condition; (b) after meshing the model

3. Results and Discussion

The results of the AC and DC collapse in voltage of the oil samples are discussed. Besides, the effect of breakdown voltage to the electric field intensity of the oil samples is also considered.

3.1 Breakdown Voltage of Different Type of Oils

The HVAC and HVDC experiments show that the breakdown voltage is affected by dissimilar type of oils and temperature ranges. Each temperature range has resulted in different value of breakdown voltage. The breakdown voltage is calculated based on average value from six recorded values with a fixed gap distance of 2.5mm [4]. The Table 1 and 2 show the average of AC and DC breakdown in voltages of unused transformer oil and olive oil at different temperature.

Table 1 - Average value of AC breakdown voltages of unused transformer oil and olive oil at different temperature ranges

	AC Breakdown Voltage (kV)	
Temperature Range	Unused Transformer Oil	Olive Oil
27ºC	15.86	15.14
50ºC - 60ºC	25.83	33.11
60ºC - 70ºC	32.09	42.87
80ºC - 90ºC	35.07	44.12
100ºC - 110ºC	38.62	46.98

Table 2 - Average value of AC breakdown voltages of unused transformer oil and olive oil at different temperature ranges

	DC Breakdown Voltage (kV)	
Temperature Range	**Unused Transformer Oil**	**Olive Oil**
27ºC	26.07	26.77
50ºC - 60ºC	37.79	42.69
60ºC - 70ºC	40.49	45.55
80ºC - 90ºC	42.08	47.19
100ºC - 110ºC	43.06	39.53

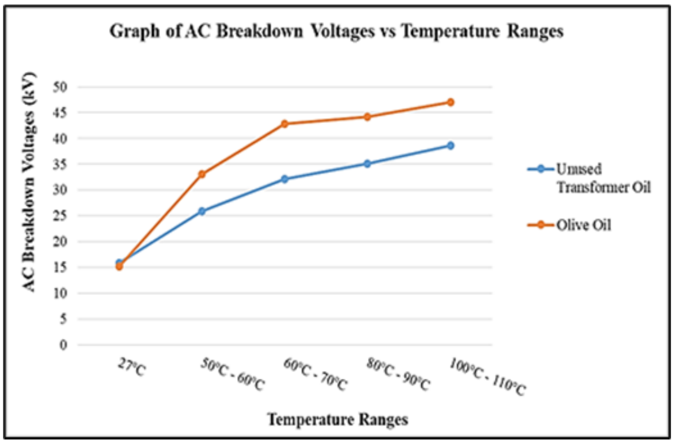


Fig. 4 - The graph of AC breakdown voltages versus temperature ranges for unused transformer oil and olive oil

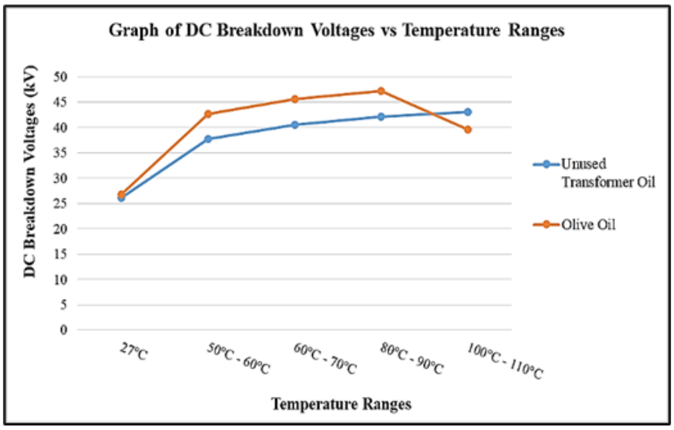


Fig. 5 - The graph of DC breakdown voltages versus temperature ranges for unused transformer oil and olive oil

Figure 4 and Figure 5 show the graphs of AC and DC breakdown voltages versus temperature ranges. The breakdown voltage results obtained for the HVAC breakdown test show that both the unused transformer oil and olive oil can be subjected to continuous heating temperatures of about 110°C. However, the olive oil has higher breakdown voltages at most of the temperature ranges when compared to the unused transformer oil.

This shows that the olive oil can be a good insulating medium for the transformer when compared to unused transformer oil at an AC condition. While, the breakdown voltage results obtained for the HVDC breakdown test has indicated that the unused transformer oil can be subjected to continuous heating temperatures of around 110°C and for the olive oil of about 90°C. But then at a DC condition, the olive oil can still be a good candidate for the use in transformer since at the DC breakdown test it has resulted in higher breakdown voltages until 90°C when compared to the unused transformer oil.

In addition, the circulation of heat can be facilitated well by the olive oil at higher temperatures as the viscosity of the oil is reduced and at the same time it might be able to withstand the heat at an overload condition [12]. Besides, the drop in breakdown voltage of olive oil for the temperature range of 100°C - 110°C can be due to the presence of moisture in the testing cup since the oil is heated first in a metal cup then poured into the testing cup [13, 14]. Besides, breakdown voltages are found to be higher in olive oil than in mineral and rapeseed oil [15-16].

3.2 Simulation Outcomes of Electric Field Intensity for HVAC and HVDC breakdown tests

More effects on electric field intensity specifically at the upper bound as the high voltage value obtained from the breakdown test is applied to it. The output from the simulation are contour plots and X-Y graphs as shown in Figure 6, Figure 7 and Figure 8. The electric field intensity at upper bound of AC and DC breakdown test for unused transformer oil and olive oil with a fixed 2.5mm gap spacing at different range of temperatures are illustrated in Table 3 and Table 4.

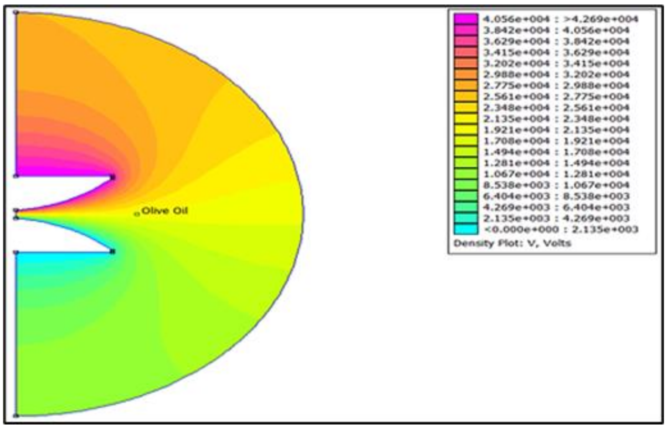


Fig. 6 - The breakdown voltage is contour plotted for the olive oil under DC breakdown test at a temperature range 50ºC - 60ºC

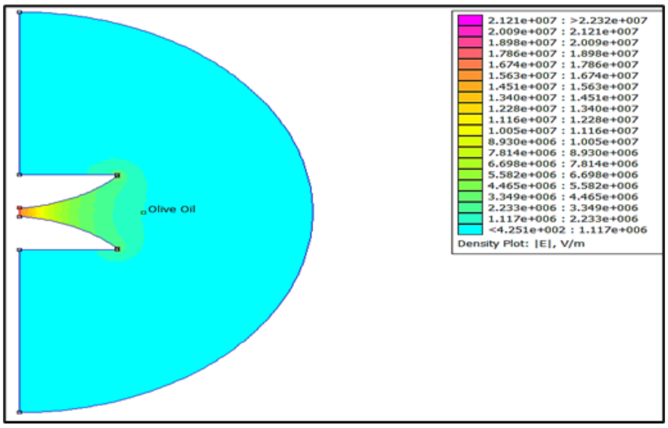


Fig. 7 - The electric field intensity is contour plotted for the olive oil under DC breakdown test at a temperature range of 50ºC - 60ºC

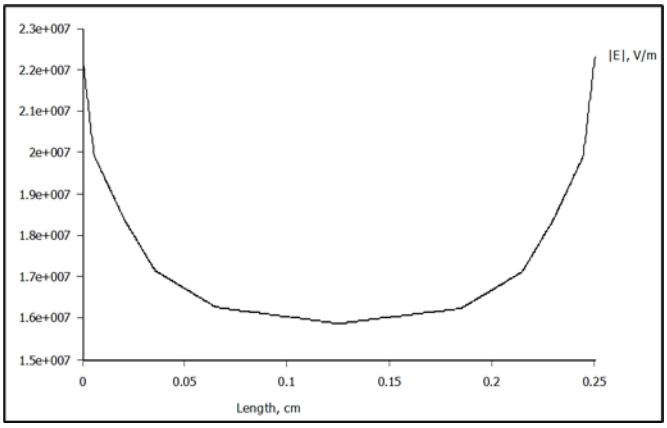


Fig. 8 - The graph of electric field intensity for the olive oil under DC breakdown test at a temperature range of 50ºC - 60ºC

The voltage and electric field intensity contour plots for both AC and DC voltages obtained from the breakdown test have the same contour color arrangements and shape of graph. But then, the differences can be seen from the values of voltage and electric filed intensity where they are seen from the legends and X-Y axis. When breakdown occurs at both AC and DC voltages, the electric field intensity of the oil samples still seems higher at the upper bound when compared to the lower bound and formed a parabolic shaped graph. The breakdown voltage contour plot in FEMM simulation, each colours signifies a different value of voltage concentration. These colours can be denoted at the colour bar positioned at the right side of the window in which the maximum voltage value is symbolized by magenta whereas the blue colour characterizes the lowest voltage density.

While, the contour plot for electric field intensity shows that the most intense electric field is between the electrode because of the applied AC and DC voltages. The blue contour away from the electrodes shows fewer electric field intensity at that particular part.

Table 3 - The electric field intensity at upper bound for unused transformer oil and olive oil in AC breakdown test

Temperature	DC Breakdown Voltage (kV)	
	Unused Transformer Oil	**Olive Oil**
	E (kV/cm)	E (kV/cm)
27ºC	8294040.08	7917489.05
50ºC - 60ºC	13507884.95	17314931.47
60ºC - 70ºC	16781572.90	22418940.27
80ºC - 90ºC	18339973.87	23072629.92
100ºC - 110ºC	20196458.26	24568271.84

Table 4 - The electric field intensity at upper bound for unused transformer oil and olive oil in DC breakdown test

Temperatures	HVDC breakdown test	
	Unused Transformer Oil	**Olive Oil**
	E (kV/cm)	E (kV/cm)
27ºC	13633393.76	13999417.56
50ºC - 60ºC	19762406.98	22324808.96
60ºC - 70ºC	21174381.02	23820450.88
80ºC - 90ºC	22005876.84	24678091.70
100ºC - 110ºC	22518371.12	20672281.52

The results show that the olive oil has highest value of electric field intensity at upper bound under both HVAC and HVDC breakdown tests. This is because the olive oil has higher AC and also DC breakdown voltages when compared to unused transformer oil. Besides, it is clear that if there is higher breakdown voltage then the electric field intensity at the upper bound of electrode is also higher.

4. Conclusion

In conclusion, by means of the temperature increases, the AC and DC breakdown voltage rises too. From the AC and DC breakdown tests that have been done, it is clearly seen that the olive oil has resulted in higher breakdown voltages for most of the temperatures rise when compared to the unused transformer oil. Whereas, the examination of the electric field of the oil insulation by using FEMM has shown that the increase in breakdown voltage of oil samples also increases the electric field intensity of the oils at a fixed gap distance of the electrodes. In this project, the olive oil has higher electric field intensity at the upper bound of high voltage electrode because it has higher AC and DC breakdown voltages than unused transformer oil. Thus, the olive oil can be a good alternative to replace the mineral oil for the use in transformers.

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