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Research Article

Aging Effect on Partial Discharge Characteristics of Olive Oil as an Alternative Liquid Insulating Medium

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Abstract: This study deals with the analysis of partial discharge characteristics of aged and aged with copper extra virgin olive oil. To confirm long-term reliability of transformers, it is essential to recognize the degradation characteristics of insulating oil in long-term operations, which are the dominant factors of the transformer dielectric strengths. This study is to identify how the PD characteristics of this oil changes and deteriorates with increasing age and what are the impacts on the electrical characteristics. The changes in the PD pattern and PD pulse due to the degradation of oil have been investigated with an innovative PD detection system PDBASEII. The Phase Resolved Partial Discharge (PRPD) pattern, time domain and frequency domain characteristics of PD pulses of vegetable oil was measured and they were compared with the mineral oil.

Keywords: Classification map, mineral oil, pulse spectrum, pulse waveform, thermal aging, vegetable oil

INTRODUCTION

Petroleum based mineral oils are the generally used fluids for electrical insulation and heat transfer in equipment like transformers, capacitors, circuit breakers, bushings etc. This is because the mineral oils have excellent dielectric properties such as high electric field strength, low dielectric losses and good long-term performance and obtained at reasonably low price. However, conventional transformer mineral oils or synthetic insulating liquids are usually non-biodegradable. In case of equipment failure or spillage, their decomposition is very slow and could cause serious contamination of soil and waterways. In addition, petroleum products are eventually going to run out. It was also reported that water absorption of paper under natural oils was much lower than mineral oil. Moreover, insulation life time of paper which is commonly used in a transformer is much longer when aged under natural oil compared to that mineral oils (McShane *et al*., 2001; Suwarno, 2007; Suwarno *et al*., 2008). Vegetable oils obtained from seeds, flowers and vegetables are biodegradable, non-toxic, environmental friendly and benign to aquatic or terrestrial. Based on the above, the alternative of liquid which is reliable, cost-effective and environmentally friendly was a target for several researchers in the last two decades. At the same time, it is essential to investigate how the electrical characteristics of these oil changes and deteriorate with increasing age.

Olive oil consist of 13.2% of saturated fatty acids, 73.3% of single, 7.9% of double and 0.6% of triple unsaturated fatty acids. Saturated fatty acids are chemically firm but of high viscosity. Triple unsaturated fatty acids are very unstable in oxidation but they have a low viscosity. Fluids with a high percentage of single unsaturated fatty acids are useful (Eberhardt *et al*., 2010).

In the pre break down stage, the partial discharge takes place in dielectric liquids implies the presence of high pressure gaseous cavities.

In many dielectric liquids, the breakdown strength rely on hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process which in other words means that a kind of a vapour bubble formed is responsible for the breakdown. Once a bubble is formed, it will get longer in the direction of the electric field under the influence of electrostatic forces. The volume of the bubble continues to be the same during elongation. Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the minimum value on the Paschen's curve for the gas in the bubble (Naidu and Kamaraju, 1996). To undergo discharge, these vapour bubbles need enormously high internal vapour pressure to supply sufficient number of charge carriers to maintain the electron or ion avalanches (Pompili *et al*., 2009; Pompili and Bartnikas, 2012). Under atmospheric pressure in cavities having depths of the order of 5 μm, even at 270 kV/cm after an elapse of 10^{-10} sec only 5 electron-ion pairs are produced (Novak and Bartnikas, 1995; Bartnikas, 2002), so there will be no PD activity in 5 μm cavities at atmospheric pressure. In order to sustain PD in such micro cavities, higher vapour

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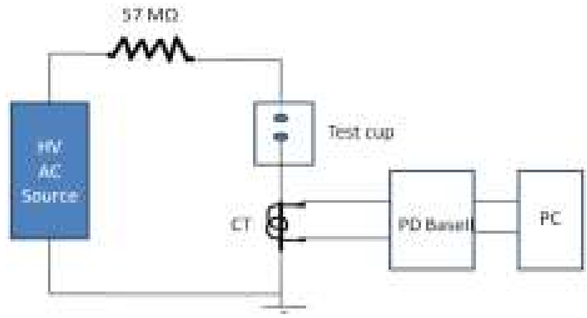


Fig. 1: Schematic diagram of experimental setup

pressure in the order of 50MPa would be required (Watson *et al*., 1998; Aitken *et al*., 1996). In the apparatus which operated under high voltage, the pressure within the micro bubbles generated in a liquid dielectric medium is close to this value. So the micro bubbles can freely be ionized to discharge and it can be detected by partial discharge pulse detectors. Further increase in voltage will lead to a rapid transition from the partial discharge process within the high vapor pressure cavity to streamer formation and finally to breakdown of the dielectric liquid gap.

If the applied voltage across the field enhancement site is maintained at the Partial Discharge Inception Voltage (PDIV), the vapor pressurized cavities will persist in reappearing and disappearing likely without ever precipitation breakdown streamer formation in the dielectric fluid. Nevertheless, it would be prudent to operate the dielectric liquid filled apparatus below the PDIV level and thereby avert possible molecular chain scission within the dielectric liquid to prevent its chemical degradation in the presence of partial discharges. The presence of PD pulse leads to breakdown streamer development and sludge formation in dielectric liquids. So it is important to analyze the PD properties of oils (Li *et al*., 2011a).

This study discusses about the PD characteristics of thermally aged olive oil (with and without copper) and the results obtained were compared with the mineral oil.

METHODOLOGY

To compare the PD characteristics of aged oil the PD test was conducted on virgin, aged and aged with copper of petroleum based mineral oil and olive oil. The experimental setup, as shown in Fig. 1 consisting of a high voltage transformer, test cup, potential divider and wide bandwidth PD analyzer Techimp PDBaseII were used for the present study. Digital systems for PD measurements permit to obtain many diagnostic indications about the insulating system degradation. The PD analyzer has been designed to collect a large number of PD pulses and separate them according to their waveform shape. The hardware is an Ultra-Wide Band (UWB) acquisition system with large storage capabilities and provided with a fast sampling rate (up to 200 MS/sec). Its software module allows deeper analysis and processing of the recorded PD data. The PD data can be achieved collecting not only PD pulse peak and phase, but also the PD pulse waveforms, thus adding the information from pulse shapes. The plane needle electrodes were arranged inside the test cup. The electrodes were arranged with a distance of 5 mm and it was maintained throughout the experiment. The diameter of the plane was 24 mm and the of needle tip with a radius of 0.05 mm.

Table 1: Electrical and chemical properties of samples

	Property			
Oil	AC breakdown voltage at 2.5 mm	Kinematic viscosity at 40°C	Flash point (°C)	Fire point (°C)
Mineral oil	30	12.00	140	160
Olive oil	36	33.82	300	330

The PD parameters were measured as a function of applied voltage. The applied voltage was increased in steps of 0.5 kV with the help of 100 kV/100 mA AC high voltage test set.

The test was carried out with six samples:

- Virgin mineral oil
- Aged mineral oil
- Mineral oil aged with copper
- Virgin olive oil
- Aged olive oil
- Olive oil aged with copper

The Electrical and chemical properties of the virgin oils are given in Table 1.

EXPERIMENTAL RESULTS

In this study, initially virgin mineral oil has been filled in the test cup and the applied voltage is raised in steps from 1 kV. The applied voltage is increased step by step till the Partial Discharge Inception Voltage (PDIV) is reached. It is generally necessary to exceed significantly the PDIV value in order to observe PRPD pattern of any liquid dielectrics. The PD measurement was carried out as a function of applied voltage. The PD measurement was carried out at each step from PDIV to till the continuous discharge occurs. Then tests were repeated for other samples also, to obtain the corresponding partial discharge pattern.

Partial discharge inception voltage: Transformer oil whether it is a mineral oil or vegetable oil has to withstand aging process. To determine the influence of the age on the PD characteristics of oils it is necessary to analyze its PDIV values. The PDIV value can be defined as the value of the applied voltage at which

Table 2: PD inception voltage of oils

	Category		
Oil	Virgin (kV)	Aged (kV)	Aged with copper (kV)
Mineral oil	10.6	5.8	8.7
Olive oil	8.5	9.4	13.9

either one PD pulse burst is found over an interval of 10 min or the PD pulse burst pulses recur at the rate of one or more cycles of the applied voltage wave (Pompili, 2009; Li *et al*., 2011b). The PDIV can be determined correctly in solid insulation and oil impregnated insulation because the voids commence discharge at defined voltage and the discharge process is regular. In the case of liquid dielectrics, the PD pulses emerge in pulse bursts and their repetition rate is irregular (Pompili, 2009).

The PD inception voltage of six samples was obtained and it is shown in Table 2. From the Table 2 it is very clear that the PDIV of mineral oil is getting affected and reduced due to aging. In the case of vegetable oils the PDIV value of aged with copper oil is higher than that of aged oils whose values are greater than virgin oils. The above result reveals that the aging factor did not affect the PD characteristics of vegetable oils instead it improved the dielectric character of the oil. Among the samples olive oil, aged with copper has shown good result. However, the deviation in PDIV is within acceptable limits.

Phase resolved partial discharge pattern: Investigation of partial discharge characteristics of vegetable oil is necessary before implementing in high voltage apparatus. Partial discharge patterns identification and analysis have been proven very useful for the diagnostics of the insulating condition of the high voltage apparatus. PD takes place when the local electric field surpasses the threshold value and produces a partial breakdown of the nearby insulating material. The high electric field necessary to produce a partial discharge is accomplished by utilizing a needle plane electrode configuration. Since the electric field under needle plane configuration is non uniform, it produces a maximum electric field (Abdul *et al*., 2011).

To confirm long-term reliability of transformers, it is essential to recognize the degradation characteristics of insulating oil in long-term operations, which are the dominant factors of the transformer dielectric strengths. Analysis of partial discharge characteristics of aged vegetable oil (extra virgin olive oil) to identify how the PD characteristics of this oil changes and deteriorates with increasing age and what are the impacts on the electrical characteristics will help us to conclude about the vegetable oils suitability in high voltage apparatus. The changes in the PD pattern and PD pulse due to the degradation of oils have been investigated with an innovative PD detection system PDBASEII.

The PD measurement was carried out as a function of applied voltage. The PD measurement was carried out at each step from PDIV to till the incessant discharge takes place. It has been noticed that from 1kV to the voltage below the inception voltage, PD signal is totally absent and noise signals are only there during this measurement. Then tests were repeated for virgin, aged and aged with copper oils to obtain the corresponding partial discharge pattern.

In this study, the PD pattern of oils at 14 kV, which is above the partial discharge inception voltage of all the samples is considered for comparison purpose.

The PD pulse analyzer Techimp PDBaseII supplies the time/frequency map classification and identification of the PD source using fuzzy inference engine (Contin *et al*., 2002). By examining the partial discharge distribution in the time frequency map, it is possible to discover the source of the PD activity that is, whether it is due to corona discharge or surface discharge or internal discharge. Perhaps the use of more advanced instruments having much shorter rise time and broad bandwidth would grant more meaningful results (Pompili *et al*., 1993). Since the hardware is fundamentally an Ultra-Wide Band (UWB) acquisition system with large storage capabilities, it is possible to collect a huge number of PD pulses and separate them according to the shape of their waveforms.

The phase resolved partial discharge pattern illustrates the phase and amplitude of the whole amount of the obtained pulses. The waveforms basically depend on the nature of the defect generating PD; pulses that have like shapes should belong to the same source and/or have the same position (Contin *et al*., 2002). Pulses having dissimilar shape are mapped in different areas of the time frequency map. Clusters containing signals with similar shapes are grouped in the map (Cavallini *et al*., 2005). With the help of a fuzzy inference engine of PD analyzer, the basic nature of the fault generating PD can be identified. The analyzer also gives the statistical parameters like kurtosis and skewness for every test. These parameters can be applied for pattern recognition purpose.

The PRPD pattern, time domain and frequency domain characteristics of PD pulses of vegetable oils were measured and they were compared with the mineral oil.

PRPD pattern of virgin oils: Before analyzing the results obtained for aged oils and aged with copper oils, investigating the characteristics obtained for virgin oils (mineral oil and olive oil) will make the analysis simpler.

Partial discharge inception voltage of mineral oil is measured as 10.6 kV. To find the corresponding PDIV of olive oil, the tests were repeated. Partial discharge inception voltage of olive oil under ac voltage is about 8.5 kV which is 2.1 kV lesser than that of mineral oil. However, the deviation in PDIV is within allowable limits.

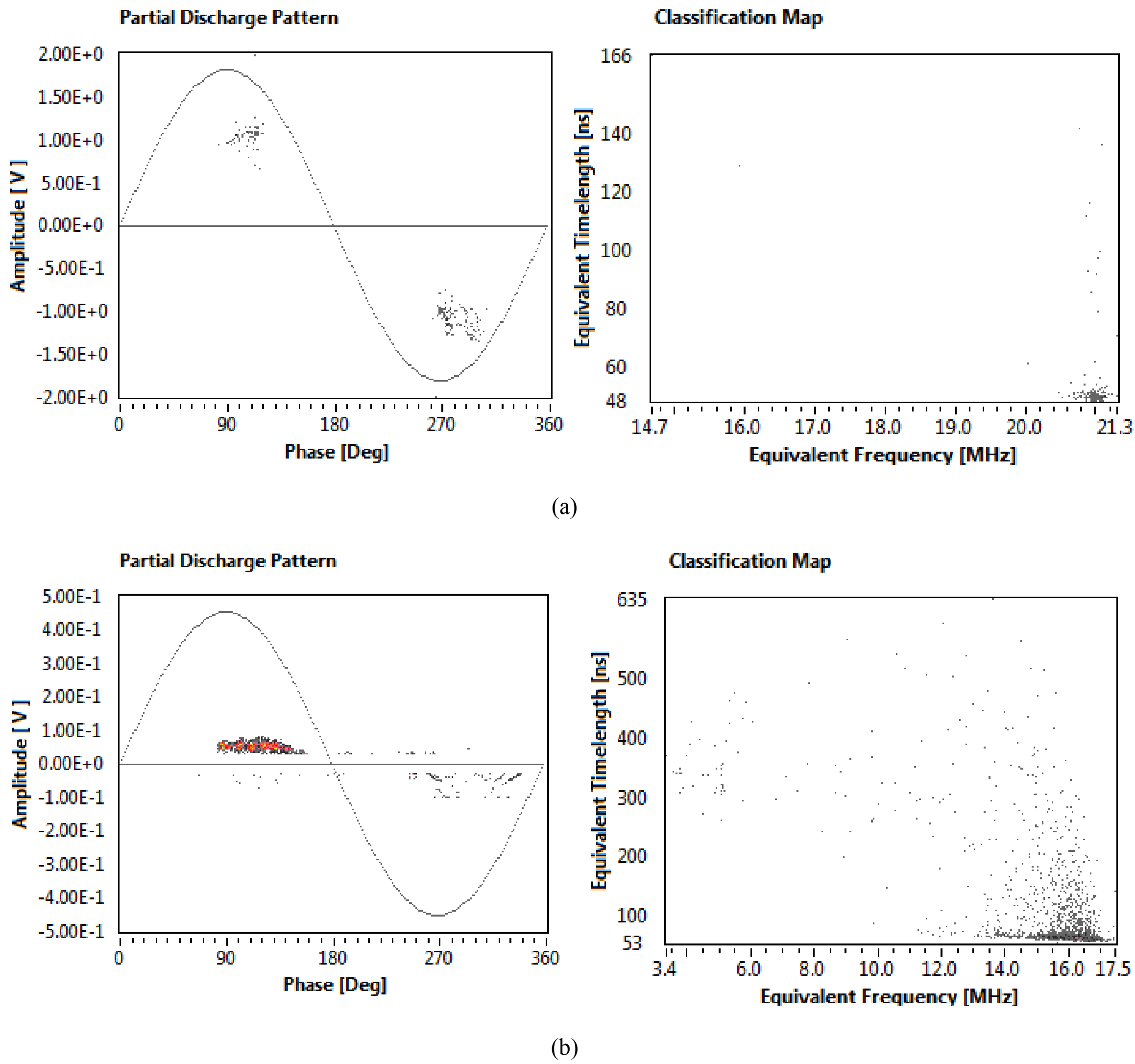


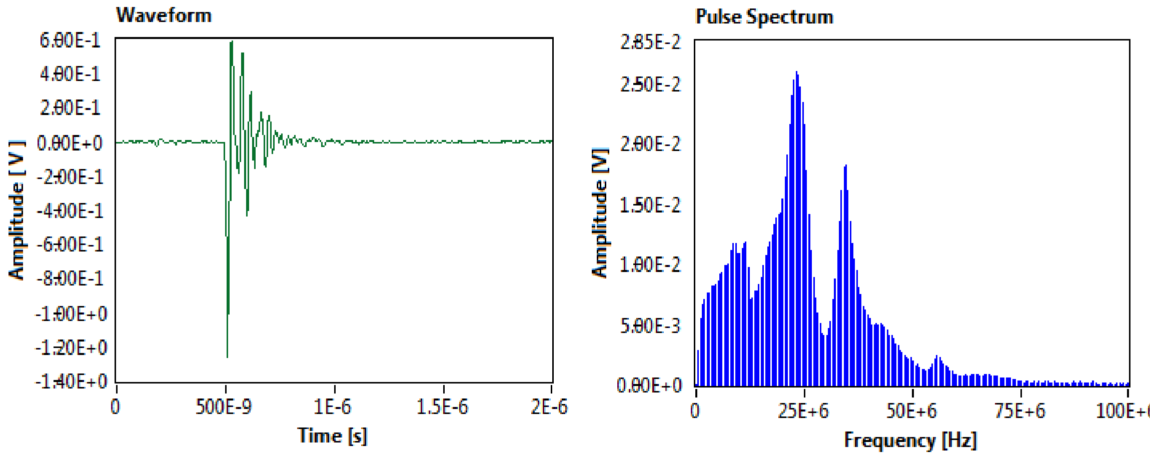
Fig. 2: Complete PRPD pattern and classification map of (a) mineral oil (b) olive oil

The phase resolved partial discharge pattern shows the phase and amplitude of the whole amount of the acquired pulses during the test. In this study, the PD pattern of oils at 14 kV which is above the partial discharge inception voltage of all the nine samples is considered for comparison purpose. Figure 2 shows the PRPD pattern and time frequency map of virgin oils with plane needle electrode obtained at 14 kV applied voltage. Using the innovative PDBASE II instrument, it is feasible to analyze the captured PD signals result in different modes such as:

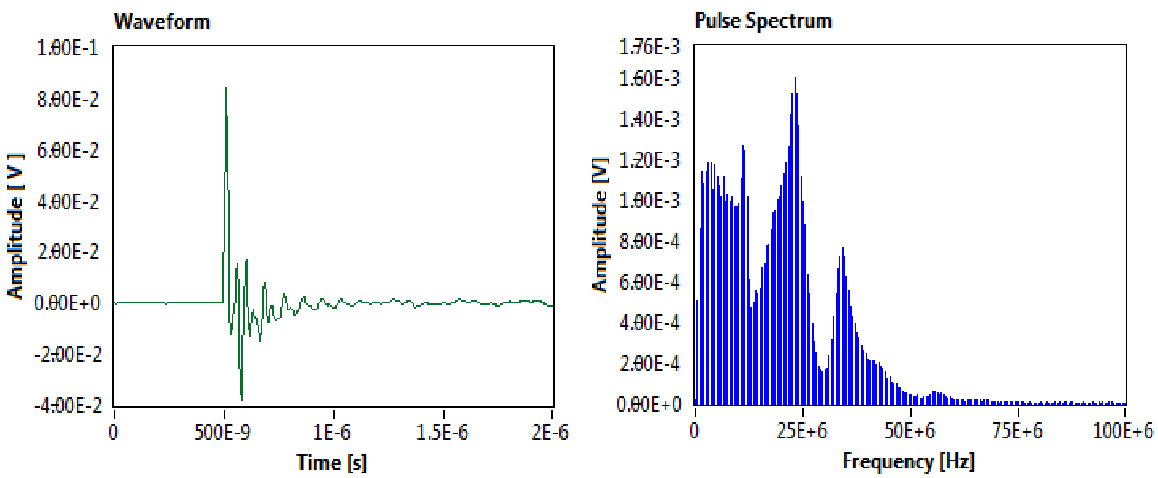
- Complete PRPD pattern
- Time frequency i.e., classification map
- PD pulse waveform
- Pulse spectrum

From the complete PRPD pattern of mineral oil obtained at 14 kV as shown in Fig. 2a, it is observed that in mineral oil the PD pulses emerge at the proximity of the voltage peaks as well as in positive and negative half cycles. The corresponding time frequency classification map (Fig. 2a) of the PD pulses shows clusters. The waveforms basically depend upon the nature of the defect produces PD; pulses that are having similar shapes should belong to the same source and/or have the same location (Bartnikas, 2002). With the help of PD analyzer, the clusters formed in the frequency band of 20.5-21.3 MHz are due to surface discharge and corona discharge. Typical PD pulse waveform and corresponding frequency spectrum obtained for mineral oil at 14 kV is shown in Fig. 3a. Peak value of the PD pulse waveform is 1.3 V and the pulse spectrum shows a peak around 25 MHz. During the experimental studies, both positive peak and negative peak PD pulses were detected.

For the same plane needle electrode configuration, the PRPD pattern analysis, for olive oil at 14 kV is



(a)



(b)

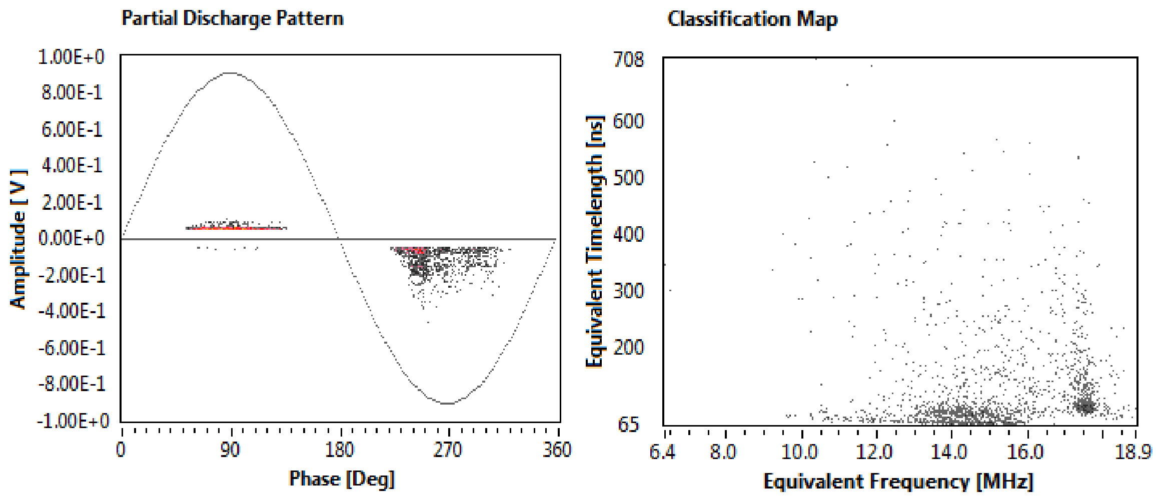
Fig. 3: PD pulse waveform and corresponding pulse spectrum of (a) mineral oil (b) olive oil

shown in Fig. 2b. In phase relationship to the applied ac voltage, the PD pulses start occurring from 80° or 260° and lie in the descending portion of the ac voltage waveform for olive oil. But most of the PD activity appears in the positive half cycle than negative half cycle. The classification map of olive oil Fig. 2b reports that there was a cluster in the frequency band of 14-17.5 MHz and the PD activity is purely due to internal discharge. PD pulse and corresponding frequency spectrum obtained for olive oil are shown in Fig. 3b. Pulse magnitude lies in the range of 0.09 V which is less when compared with mineral oil for the same applied voltage.

However, the results obtained for the vegetable oils are comparable with the mineral oil and this shows good signs for further proceedings (Banumathi *et al*., 2013; Banumathi and Chandrasekar, 2013).

PRPD pattern of aged oils: To implement biodegradable vegetable oils in high voltage apparatus, it is necessary to report their aging properties. This study discusses about the partial discharge characteristics of aged olive oil and castor oil and the results were compared with the mineral oil. To analyze the aging behavior, the oils were kept inside the oven for the period of one month. Since the transformer would not normally see temperatures in excess of 90°C an aging temperature of 150°C was used to accelerate ageing. After aging the PD test was carried out in the aged oils.

For aged mineral oil the partial discharge inception voltage is measured as 5.8 kV. To find the PDIV of olive oil the tests were repeated and it was measured as 9.4 kV. It was very clear that after aging the PD activity has started earlier in mineral oil. When compared to the vegetable oils also it is very earlier. But in vegetable oils the PD inception was taking place lately, i.e., the values are 1 kV greater than their corresponding virgin oil inception voltage.



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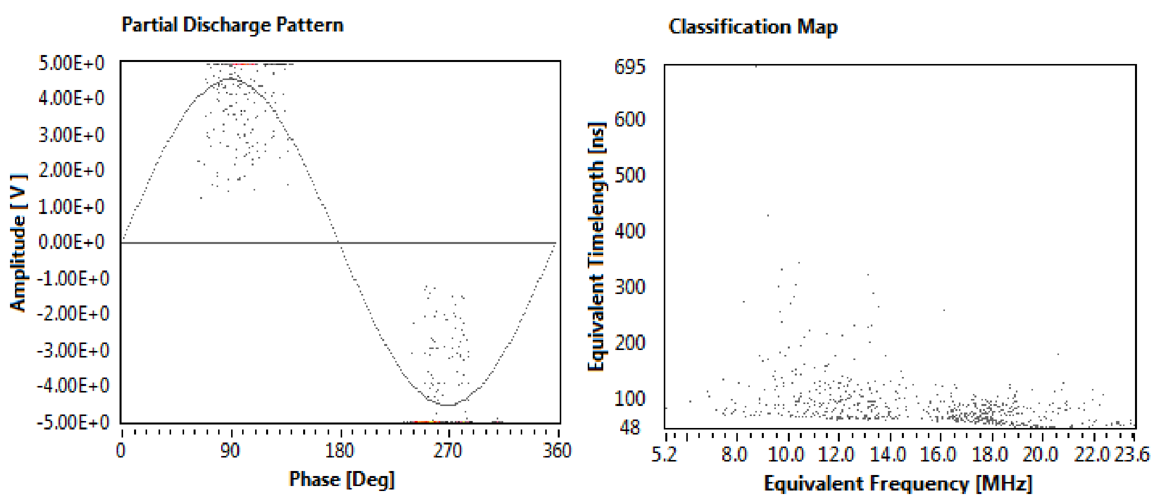


(b)

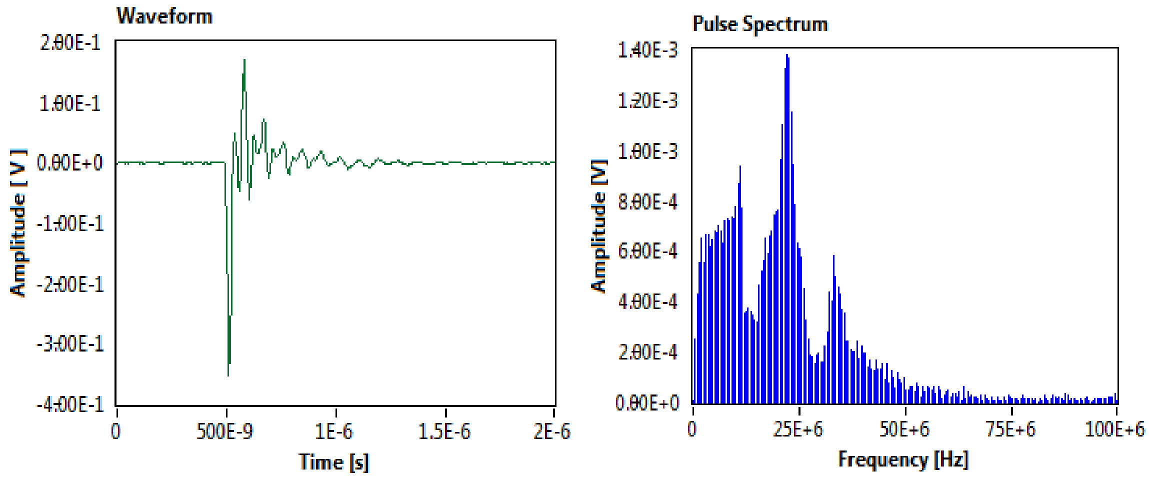
Fig. 4: Complete PRPD pattern and classification map of aged oils (a) mineral oil (b) olive oil

For aged oils also PRPD pattern captured at 14 kV is considered for discussion. Figure 4 shows the PRPD pattern and classification map of aged oils with plane needle electrode measured at 14 kV applied voltage. From the complete PRPD pattern of aged mineral oil Fig. 4a, it is observed that in mineral oil the PD pulses occupy the same region as virgin oil. But PD activity appears to be dominant in the negative half cycle. The corresponding time frequency classification map consists of two clusters and it is due to surface discharge and corona discharge.

The complete PRPD pattern and classification map of aged olive oil are shown in Fig. 4b. The PD pulse appears equally in both the half cycles and the distributions of pulses are same as virgin olive oil. The classification map reports that the cluster is due to corona discharge and surface discharge.

Typical PD pulse waveform and corresponding frequency spectrum obtained for aged oils are shown in Fig. 5. Among the aged oils pulse magnitude obtained for olive oil is high. The corresponding pulse spectrum obtained for the aged oils show the peak around 25 MHz. These results show that even after aging the PD characteristics and further studies of vegetable oils are within the acceptable limit.

PRPD pattern of oils aged with copper: A Power transformer is composed of several materials which include copper and mineral oil. Mineral oil undergoes chemical reactions with copper during operation at high temperatures, overloading etc., leading to corrosion. Corrosion may lead to the formation of contaminants and it will be dissolved in the oil. This will affect the dielectric properties of oil. So in addition to fresh oil



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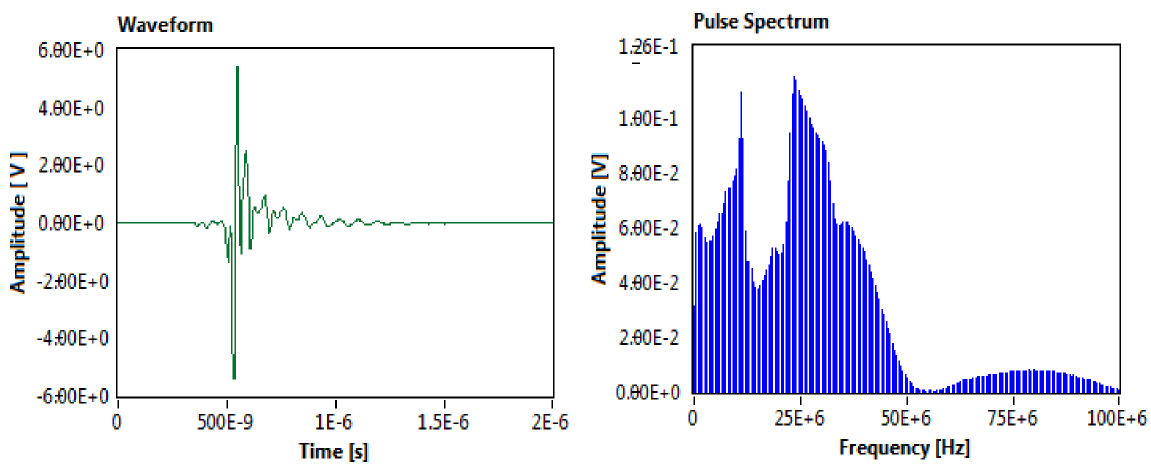
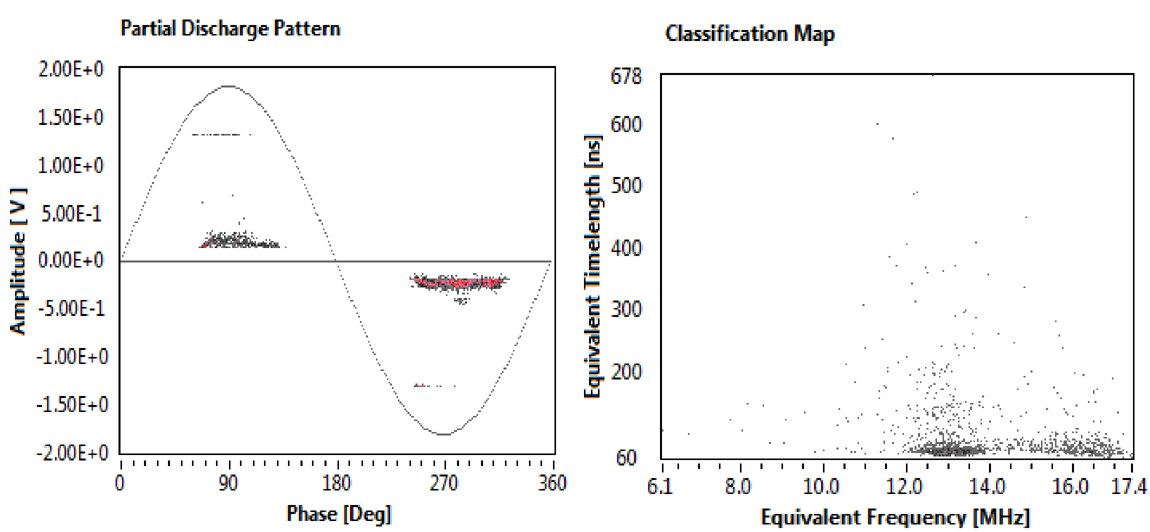


(b)

Fig. 5: PD pulse waveform and corresponding pulse spectrum of aged oils (a) mineral oil (b) olive oil



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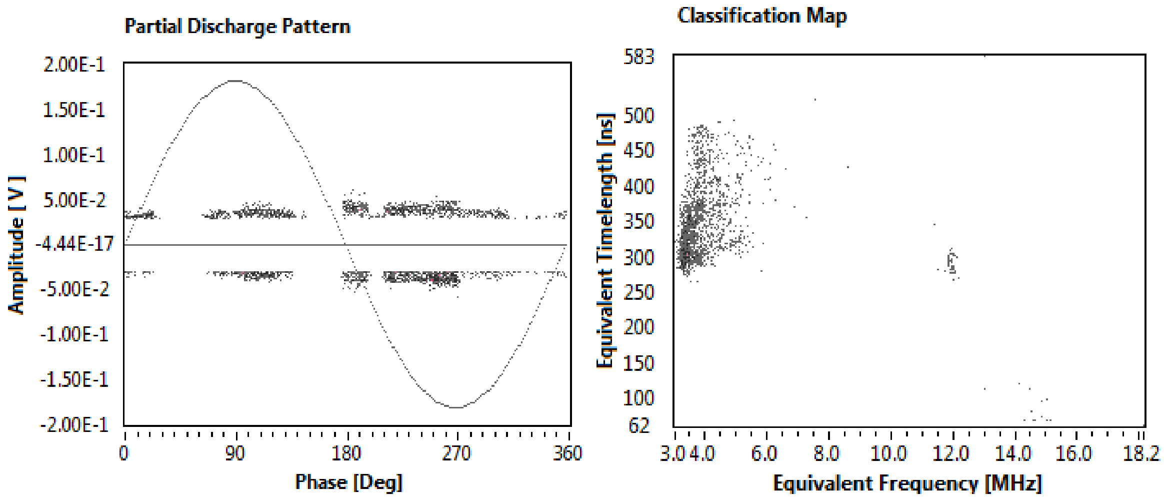
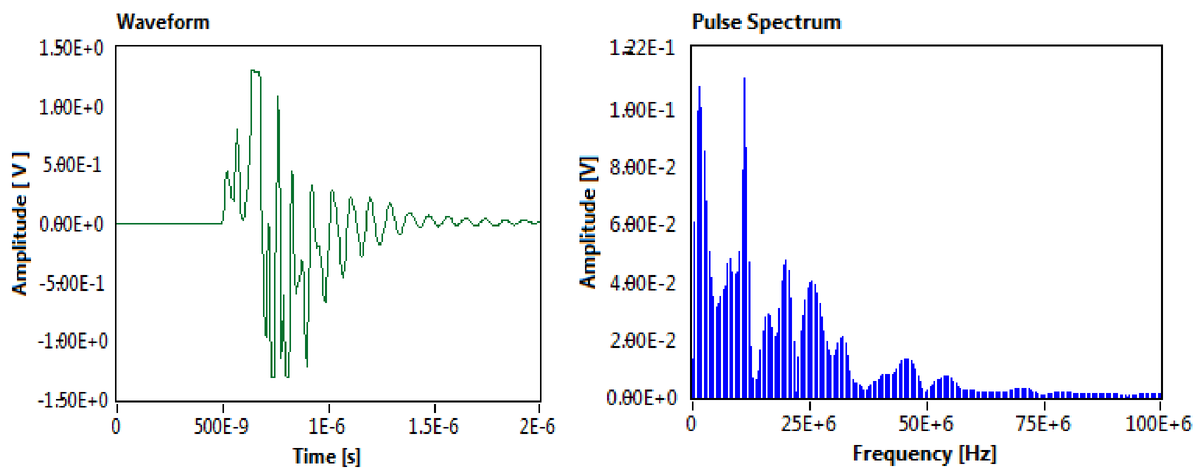


(b)

Fig. 6: Complete PRPD pattern and classification map of AWC oils (a) mineral oil (b) olive oil



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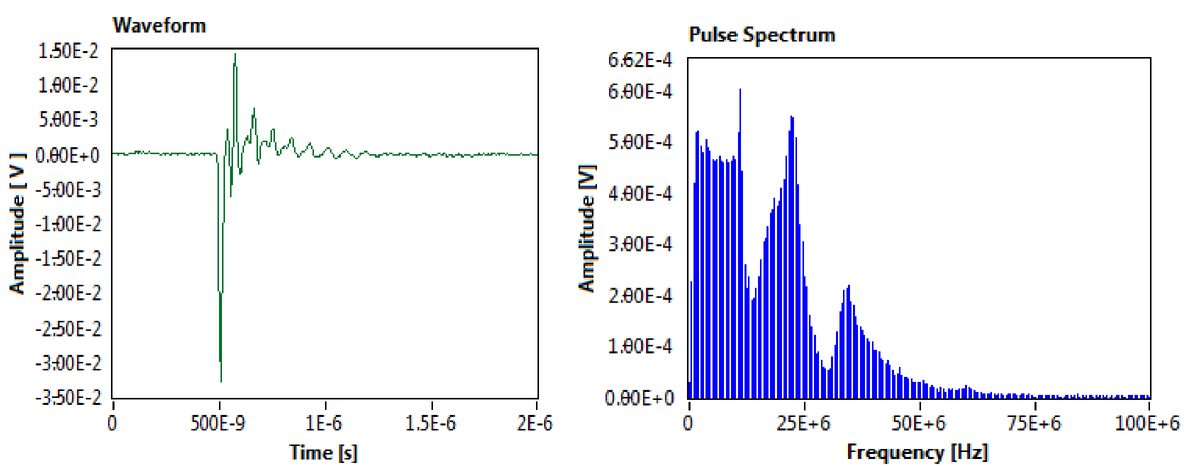

(b)

Fig. 7: PD pulse waveform and corresponding pulse spectrum of AWC oils (a) mineral oil (b) olive oil

one set of oils (mineral oil and olive oil) in a separate vessel were kept inside the oven with copper material. Copper was added to the samples to assess its effect on oil aging.

The PD test was repeated with the oils, Aged With Copper (AWC) to analyze their partial discharge characteristics. The PDIV values of oils are given in Table 1. The PDIV values are higher than aged oils. Olive oil has highest PDIV value of 13.9 kV. It gives more interest to analyze its characteristics.

For AWC oils also PRPD pattern captured at 14 kV is considered for discussion. Figure 6 reports the PRPD pattern and classification map of aged oils with the same electrode configuration measured at 14 kV applied voltage. From the complete PRPD pattern of AWC mineral oil Fig. 6a, it is observed that in mineral oil the PD pulses occupy the same region as virgin oil. The PD pulse appears equally in both the half cycles. The corresponding time frequency classification map results resemble the classification map of aged mineral oil. The PD activity is majorly due to surface discharge and corona discharge.

The complete PRPD pattern and classification map of AWC olive oil are shown in Fig. 6b. The PD pulse appears equally in both the half cycles. But the PD activity is very less when compared to other oils. The classification map reports that the cluster AWC olive oil is mainly due to corona discharge.

PD pulse waveform and corresponding frequency spectrum obtained from AWC mineral oil (Fig. 7a) shows that the peak value of the PD pulse waveform obtained from olive oil (Fig. 7b) is very less when compared to mineral oil. This shows good sign about the oil.

CONCLUSION

In this study the PDIV and PD characteristics obtained for virgin, aged and aged with copper olive oil were discussed and compared with the mineral oil. The results show that:

- PDIV values of aged and AWC olive oil are higher than mineral oil.
- The PD characteristics and source for PD activity of olive oil is also comparable with the mineral oil.
- The amplitude of PD pulse of AWC olive oil is very less than AWC mineral oil.

So it gives more interest to analyze the other factors of olive oil to confirm its suitability in high voltage applications.

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