International Journal on Electrical Engineering and Informatics - Volume 5, Number 4, December 2013

Partial Discharge and Conduction Current Signature Analysis for the Assessment of Transformer Oil Behavior under Accelerated Stress Condition

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Abstract: Performance and serviceable life of oil filled transformers are primarily governed by the behavior of insulating oil. Such transformers, during operation, may experience several stress evolving operating conditions. Deterioration in the performance of oil filled transformers are directly associated with the degradation of oil during the course of operation with different loading conditions. Further, the oil characteristics undergo appreciable variations since the chemical compositions in the oil are subjected to variations. Partial Discharges (PD) in insulating oil is one of the proven indices which exhibit the changing characteristics of oil. PD activity in oil insulating medium is influenced by several factors that are invariably directly correlated to the physics and chemistry of the insulant. The proposed article focuses on assessing the PD activity in different transformer oil insulations under different applied voltages. Further, the investigations also confined towards the correlation of PD phenomenon with Conduction Current (CC) through insulating oil. Various categories of iso-paraffin base and naphthenic base transformer oil have been taken into consideration which include new untreated oil, thermally degraded oil, oil degraded with transient signals and mixture of oil with solid dielectric materials. Detailed analysis based on experimental studies reveals that the dynamics of PD activity in degraded oil display unique discharge signatures when compared with new untreated oil. Also, it is evident that the PD activity is enhanced with the oil which contains a mixture of solid dielectric materials and with thermally degraded oil. Further, simultaneous measurement of conduction current and partial discharge activity in oil depicts that the dynamics of oil degradation is well observable in conduction current wave and correlation of both signatures yields better results interms of understanding the changes in oil behavior with time.

Keywords: Oil Insulation, Partial Discharge, Conduction Current

1. Introduction

Oil insulation forms an integral part of power transformers, distribution transformers and instrument transformers. Such insulating liquids are usually subjected to different stresses during real time operation. Intended lifetime of any oil filled power apparatus, most of the times, is influenced by the unintentional operating conditions like transient overvoltages, short circuits due to momentary faults and permanent faults, overloading due to sudden load additions and unplanned outages of other in-service transformers, arcing due to tap changing operations along with the regular planned loading strategy etc. Performance of oil insulation is also influenced by its inherent physics and chemistry [1]. Insulating oil always has a tendency of exhibiting largely varying characteristics due to different internally and externally originated stress conditions. Such stress conditions may immediately exhibit as Partial Discharges (PD) in oil insulation which in turn aggravates the degradation process and initiates changes in key dielectric parameters. Further, assessment of PD activity creates possibilities to evaluate the

Received: October 24th, 2013. Accepted: December 2nd, 2013

physical condition of the oil insulant. PD in oil serves as an indicator of ageing process and it is the common factor which relates various sources of ageing like electrical, thermal and chemical causes. Moreover, it is possible to obtain time resolved and instantaneous status of discharge conditions through proper PD measurement and data acquisition [2]. Although any new insulating oil possess healthy dielectric parameters at the beginning phase, it is hard to foresee the degradation dynamics. Moreover, the rate of deterioration of oil insulation depends on the operating condition to which it is subjected, apart from natural ageing process associated with every insulating medium. Other fundamental parameter which is well connected with various source of ageing is conduction current through oil, since it is the controlling factor for insulating oil performance [3]. The ideology behind the investigation undertaken in this article is that the mode through which the oil is degraded plays a major role in the oil dynamics. Hence, the scope of study is confined towards ascertaining the PD activity in various degraded insulating oils at different applied voltages and the results were statistically compared. The investigation also intended to explore the possibilities in correlating PD and conduction current phenomenon.

2. Partial Discharge and Conduction Current Phenomenon

According to International Electrotechnical Commission (IEC 60270), Partial Discharge (PD) is a localized electrical discharge that only partially bridges the insulation between the conductors and which may or may not occur adjacent to a conductor [4]. Occurrence of PD in an insulation system is due to the inevitable consequence of localized electrical stresses in the insulation or on the surface of the insulation. Such discharges emerge as pulses of high frequencies with fast attenuation rate [5] usually exhibited in the rage of a few nano-seconds to a few tens of micro-second. The discharges appear as tiny arcs capable of causing deterioration of the insulating material by the energy impact of accelerated ions leading to dissociation of chemical bonds in the dielectric. Furthermore, the number of discharge events and deterioration depends on the magnitude of applied voltage and material used. Several research studies have been reported to analyze and comprehend PD behavior which broadly categorizes the phenomenon either as a deterministic process or as a stochastic process [6]. Classical approaches were dealt with the measurement of mean value of PD in pC since computational difficulties are minimal. However, partial discharge activity has inborn stochastic behavior due to variables like magnitude of PD pulses, time and pattern. According to [6], there are several factors which govern the stochastic behavior such as the growth rate of cavities in liquids, presence of ionizing radiation, probability of electron injection, electrical field strength, space charges etc. Moreover, it is evident and appropriate that the entire process of assessing PD is carried out based on statistical analysis due to the inherent statistical nature of electron avalanche.

Conduction current flowing through the oil insulation also serves as one of the effective indicator of oil degradation. The conduction process in the oil relies on its quality, electrode configuration, gap spacing, applied voltage, time of test duration etc. Further, conduction phenomenon is also governed by the chemical composition of the oil. Based on the source of ageing/stress, oil insulation exhibits different characteristics and thereby influences the conduction mechanism. Henceforth, the observation of conduction current signature can be correlated with other degradation assessment mechanisms like partial discharge signatures.

3. Description of Experimental Setup And Experimentation Process

A. Partial Discharge Measurement for different applied voltages

For the experimentation process, six different category of insulating oil has been considered as mentioned in Figure 1. Among the six oil samples, one new sample and a sample from an in-service transformer are used. The remaining samples were subjected to accelerated ageing process which include thermal ageing at 120ºC for 8 hours duration, degradation through lightning impulse signals, oil with the mixture of solid dielectric materials and oil mixed with the moisture. The details of oil samples and their preparation procedures have been listed in Table 1.

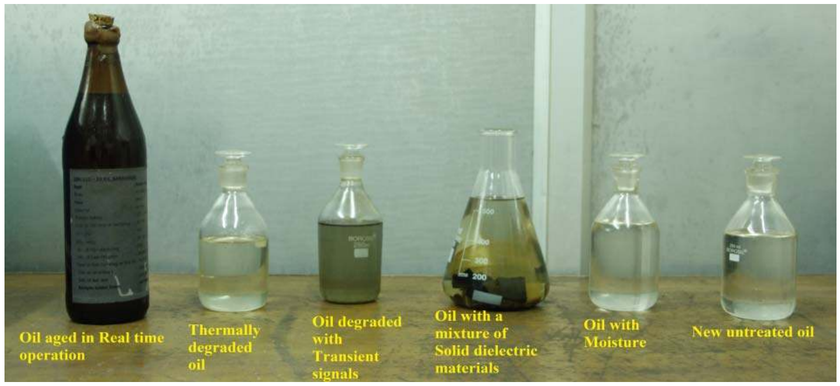

Figure 1. Different Oil samples used in experimentation process

All the samples have been tested for the partial discharge behavior. PD stressing experimental setup comprises a High Voltage Test Transformer, 1000 pF coupling capacitor, coupling quadripole for pulse acquisition and measurement and a Perspex® container of capacity 500 ml connected with a needle- plane configuration equipped with suitable provisions for adjusting the gap between the electrodes. Figure 2 shows the experimental setup used for performing PD stressing experiment. The circuitry for PD testing and measurement is also depicted in Figure 3. The gap spacing throughout the experimentation process is maintained at 10 mm. The needle tip radius is in the order of 200 µm. The PD data acquisition procedure includes the measurement of Discharge Inception Voltage (DIV) and the subsequent acquisition of PD data, in steps, for each 2 kV, from the instant of commencement of discharge activity [7]. The test voltages considered for experimentation range from 13 kV to 21 kV. Furthermore, in order to facilitate comparison of status of PD in oil samples, voltage across the electrodes have been maintained identical in all the samples. The data acquisition setup includes a Tektronix Digital Storage Oscilloscope integrated with PD Gold® software to measure time-resolved and phase-resolved PD patterns. PD Measurement and Data Acquisition System and a typical PD waveform obtained during investigation are shown in Figure 4 and Figure 5 respectively. PD acquisition system is precisely calibrated every time prior to the recording of PD data.

B. Simultaneous Measurement of Conduction Current and Partial Discharge in oil

Figure 2. Setup for PD stressing experiment

Conduction Current and Partial Discharge activity has been simultaneously measured using the experimental circuitry shown in Figure 3 below. In this case, the same oil samples that have been used as mentioned in Table 1. All the samples were subjected to electrical stress by applying a test voltage of 20 kV between a needle-plane electrode configuration with 10 mm gap. Each sample has been tested for the time duration of 4 hours. Measurement of Conduction Current and Partial Discharge activity were made every 20 minutes time interval.

Table 1. Oil Sample Classes and Preparation Process

Sample Description	Sample Preparation Process	Quantity
New untreated Oil Sample	New Iso-Paraffin base Oil sample procured from an oil supplier.	All the oil samples tested with 500 mL capacity oil container
Moisture mixed Oil sample	2 mL of Moisture mixed with the new oil.	
Oil with a mixture of solid Dielectric material	New oil is mixed with Pressboard, Kraft Paper, Cotton Tape, Mica Sheet, Copper Conductor wrapped with Paper and tape. The sample is heated in a oven to facilitate disintegration of solid compounds into oil.	
Oil degraded with Transient signal	Oil sample is subjected to 500 Lightning Impulse Voltage shots generated from a Marx Impulse Voltage Generator.	
Thermally degraded oil	Oil under test is subjected to accelerated thermal ageing process in an air circulated thermal oven capable of heating upto 250ºC with tolerance level of ± 2ºC. The heated oil sample was cooled down to room temperature before subjecting them for PD measurement	
Oil aged under Real time operation.	One naphthenic based oil sample is taken from an in-service transformer working since 2004.	

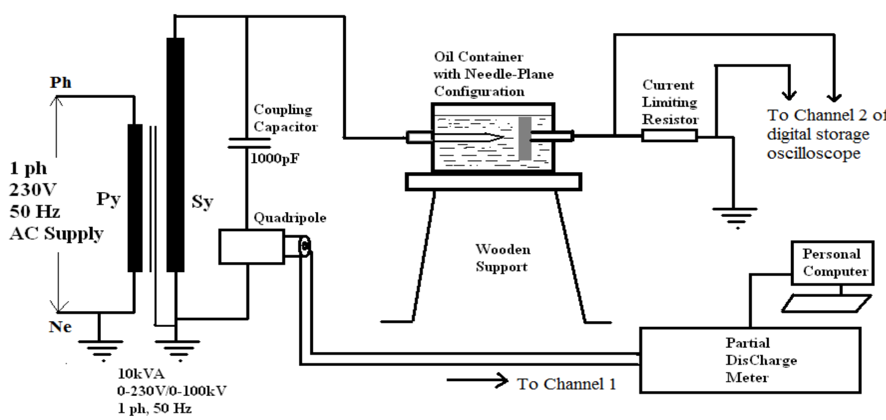

Figure 3. Circuitry for PD Testing and Measurement of Conduction Current

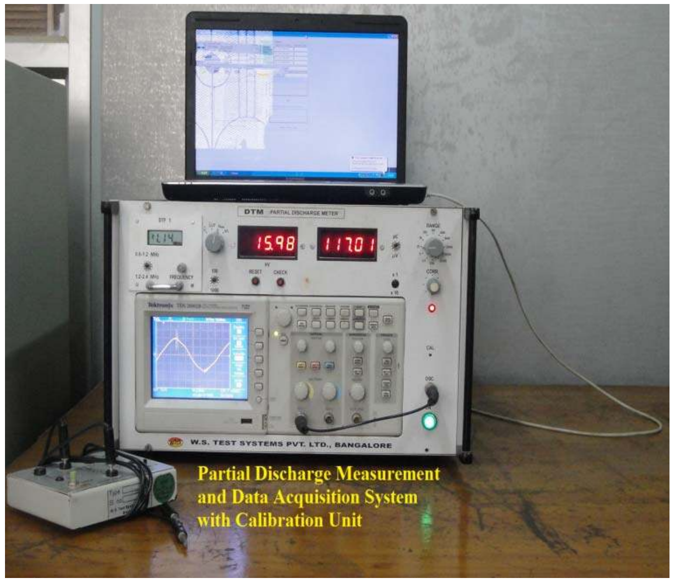

Figure 4. Partial Discharge Measurement and Data Acquisition System

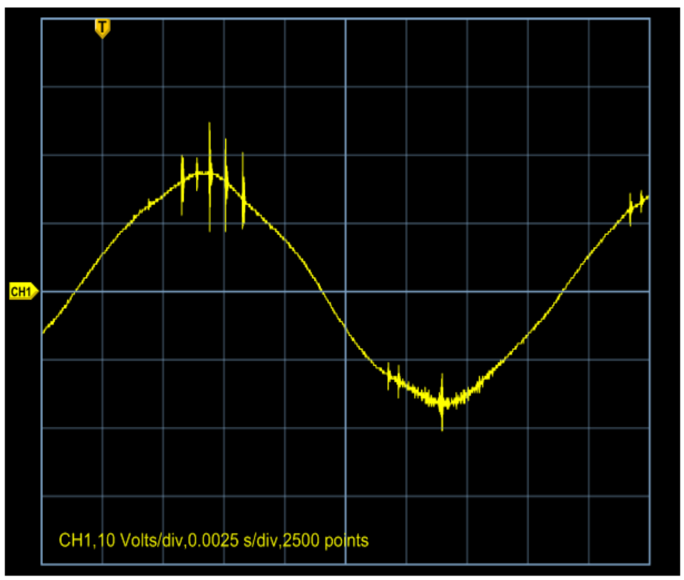

Figure 5. Typical PD waveform obtainedduring investigation

4. Observations and Analysis

A. Partial Discharge Analysis

Experimental studies carried out on various oil samples mentioned in Table 1 include the measurement of Discharge Inception Voltage (DIV), measurement of PD data and computation of statistical parameters. Table 2 shows the DIV of the oil samples under study for the gap spacing of 10 mm. From Table 2, it is perceptible to note the existence of closeness in the DIV values of all oil samples irrespective of their physical characteristics. Though, the values DIV does not vary appreciably, the PD behavior in oil samples is entirely different with the increase in the applied voltage across the electrodes.

Table 2. DIV values of different oil samples

Oil Sample Description	Discharge Inception Voltage (DIV) (kV)
New untreated Oil	11.2
Oil mixed with moisture	11.4
Oil mixed with solid dielectric materials	12.6
Oil degraded with transient signals	12.6
Thermally degraded Oil	11.2
Oil aged under real time operation	11.8

A.1 Two Dimensional Phase Plot of PD activities

1. Since the oil samples possess unique physical characteristics owing to the degradation treatment, PD activity in oil exhibit diverse characteristics at different levels of voltages. The variations of PD activity are plotted as a 2-dimensional phase plot to enable better understanding of the intensity and dispersion of discharge pulses. Figure 6 shows the variation of PD at different voltages in a new untreated oil sample. It is obvious from the plot that there is no increase in the PD pulses even when the voltage level is increased substantially from the DIV. It is also evident during studies that the discharges are discerned only at higher voltage levels which are considerably beyond the DIV.

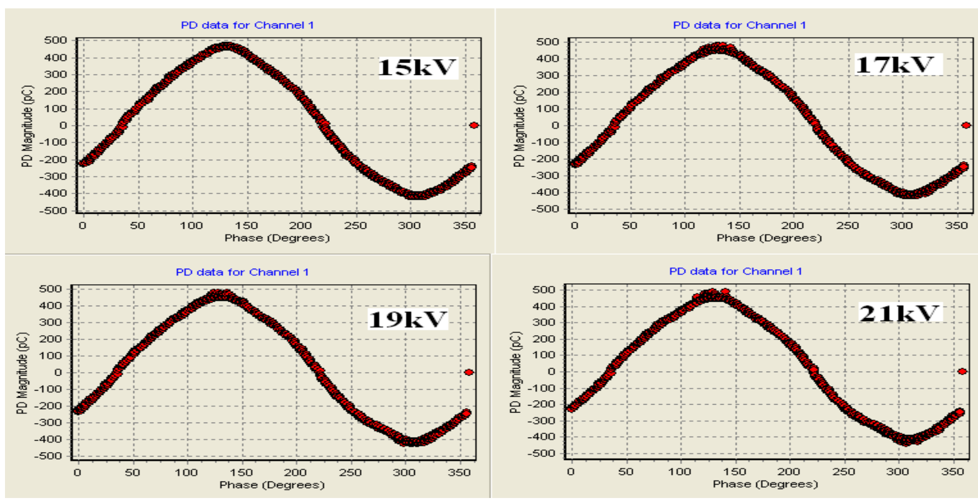

Figure 6. 2D Phase Plot of PD Activity in new untreated oil

2. Furthermore, the PD behavior in case of the oil sample which has been mixed with solid dielectric materials and the sample which is subjected to thermal degradation are exactly similar when compared with the oil sampled from an in-service transformer. In all the three oil samples the discharges aggravates intensely with the increase in applied voltage across the electrodes. From the observation of phase plot of the three samples it is evinced that the role of solid dielectrics and temperature variations conspicuously display enhanced PD activity at higher voltages. Further, it is observed that the discharge pulses tend to concentrate (distribute) more on the positive peak of the voltage wave. Such behavior is not found in new insulating oil. This may be attributed to the theory related to suspended particle mechanism [8] and the role of Van Hoschff's [9] characteristics of breakdown in liquid dielectrics leading to alignment of particulate impurities. This inturn leads to enhanced PD in degraded oil samples. Figure 7 shows the discharge activity in the three degraded samples at 21kV voltage level.

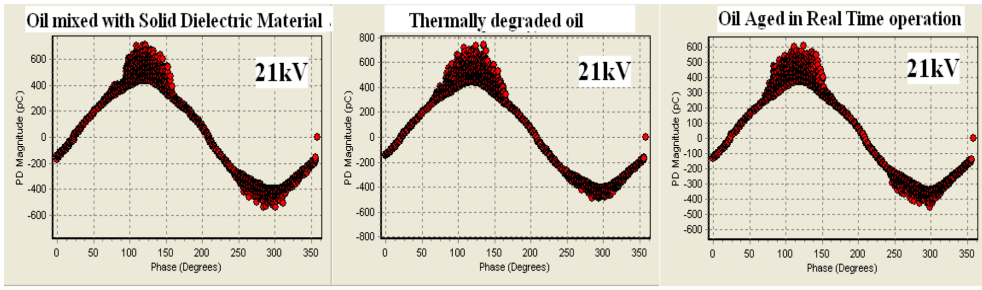

Figure 7. 2D Phase Plot of PD Activity – A Correlation with Real time sample

3. Among six samples, degradation studies have been conducted using Lightning Impulse Voltage to facilitate better understanding on the role of transient signal in PD occurrence. Figure 8 reveals that the PD pulses increases as the applied voltage increases but the crowding of pulses occurs only in the negative peak of the voltage wave which is in sharp contrast with the samples degraded by other mechanisms. This phenomenon could be related to the influence of polarity- effect [4] on discharge pulses and associated degradation.

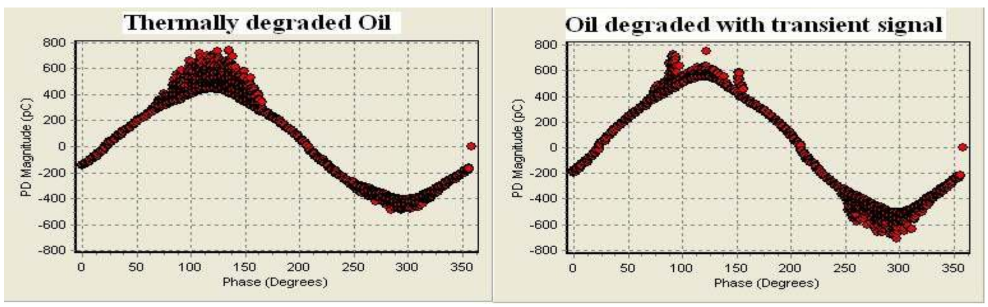

Figure 8. 2D phase Plot of PD Activity - Role of Temperature and Transient signals in PD

4. The role of moisture is also studied by mixing 2 mL of water content in new untreated oil. It is observed during sample preparation that the water droplets clearly settled at the bottom of the container and it hardly drifts even when the applied voltage is raised. The PD data recorded for this case shows that the there is no substantial changes in the pulses and pulse pattern of the waveform. The probable reason for such behavior may be due to the role of space charge effect leading to the elongation of water droplet, influenced by the interfacial tension effects [10], electrostatic pressure etc.

A.2 Statistical Analysis on PD Data

PD data acquired from oil samples are statistically analyzed in order to have insights on the dispersion and distribution of PD data at different applied voltages. Among various statistical moments, two higher order moments (Skewness and Kurtosis) were computed and the following palpable observations are made similar to a study reported in [11]-[12]-[13] to ascertain the statistical characteristics of PD.

I. Skewness

The plot displayed in Figure 9 provides information on the extent of skewness of the PD data to facilitate the degree and direction of asymmetry for different voltages under consideration.

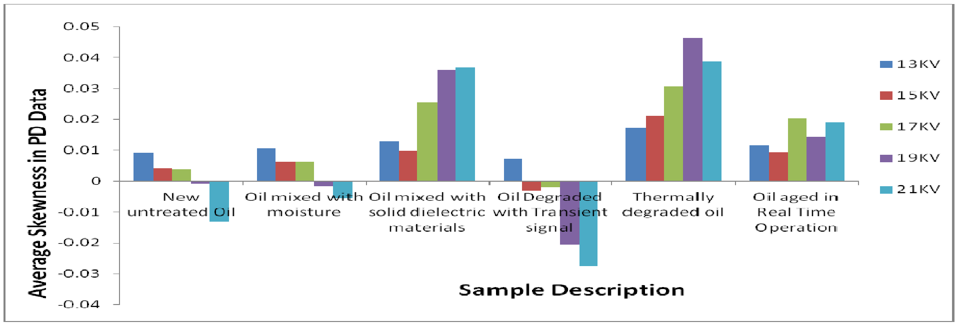

Figure 9. Average Skewness in each oil samples at all voltage levels

1. It is observed in all samples that the skewness data increases in either positive or negative magnitude for increase in the applied voltage across the electrodes. This again reiterates the direct dependency of PD pulses on applied voltage.
2. In the plot shown in Figure 8, the samples 3, 5, and 6 exhibit similar behaviour i.e. the skewness is completely positive which gives the information about crowding of pulses in positive half cycle. This graph can well be related with Figure 6 which displays the PD pulse pattern for all the three samples.
3. The samples with lesser values of skewness enhance the fact that new oils are always less prone to intense discharges as PD pulses are very less even at the voltage level much beyond the value DIV. Also, the histogram of skewness portrays that the pulses in the new oil at high voltages concentrates on the negative peak of voltage wave. This is evidently due to corona like discharges in fresh oil which are bereft of impurities.
4. The oil which is degraded with Lightning Impulse voltage produces more negative skewness when compared with other oils. It is apparent from the data that the crowding of PD pulses occurs mostly at negative peak when the oil samples are exposed to transient signals.

II. Kurtosis

Figure 10 shows the Kurtosis values of PD data for different voltages. This data gives the information about the distribution of PD data whether it is pertaining to peak distribution or flat distribution.

1. The graphical view of samples 1 and 2 gives almost constant values of kurtosis. These values are corresponding to the new untreated oil and oil mixed with moisture. The negative values portrays that the data distribution is very flat and the constant values shows that there is no chance for the distribution to get converted into peak distribution. This can be related to the physical condition of the oil with very less discharge pulses and the pulses are not intense even when the voltage is raised.
2. Identical to skewness data, the sample 3, 5 and 6 displays similar characteristics in kurtosis data as well. In all the three samples, it is noteworthy that the kurtosis values have a tendency to approach towards positive values. Though it does not reach positive value for the voltage under consideration, it shows that there exist possibilities for the flat data distribution to switchover to peak distribution. This clearly indicates more discharges are likely at higher voltages in the samples which are influenced by solid dielectric materials and temperature.
3. The sample degraded with transient signal also reveals that the distribution of data is very flat for the levels of applied voltage considered. Also, the kurtosis characteristics of the oil affected by transient signal are distinct when compared with other samples. This shows that the role of transient voltages in oil degradation is very unique which is on par with other degradation mechanisms.

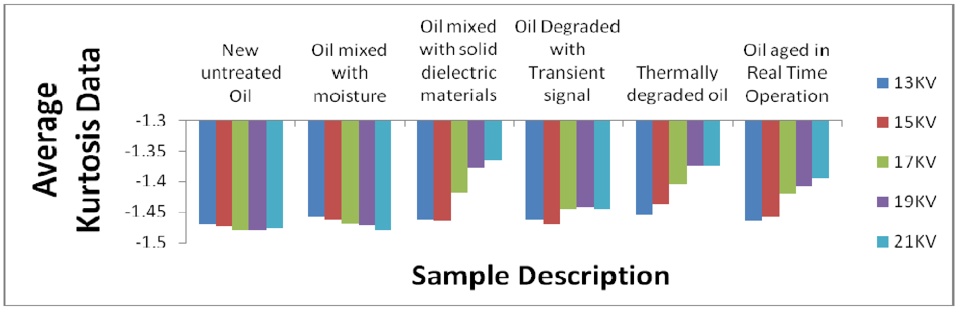

Figure 10. Average kurtosis in each oil samples at all voltage levels

B. Partial Discharge and Conduction Current Signatures

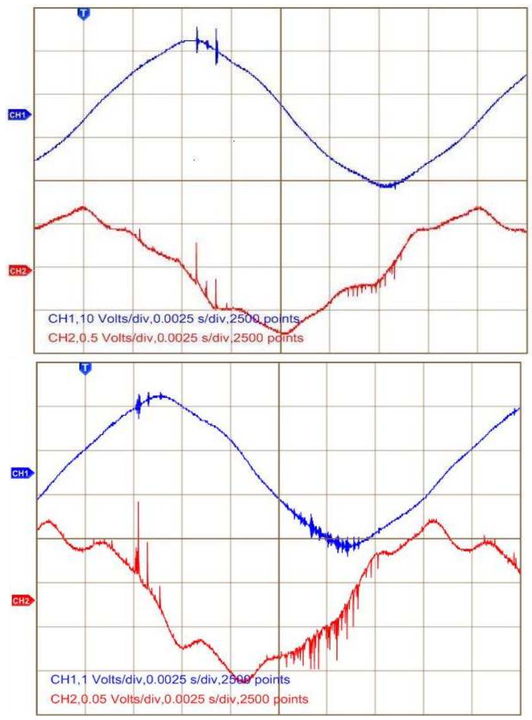

Figure 11. Partial Discharge and Conduction Current Signatures obtained during experimentation

As per the experimental investigations mentioned in section 3.2, all the oil samples were subjected to a constant test voltage. During the experimentation for 4 hours, both partial discharge and conduction current signatures have been recorded. It is pertinent to note that the variation in the conduction current pulses coincides with partial discharge pulses in every time instant. Figure 11 shows the signatures of partial discharge pulses and conduction current pulses.

1. It is observed that there is a notable variation in the number of discharge pulses as time increases. Further, there is a huge shift in the PD pulse position from the peak towards zero crossing of the voltage wave with the increase in the time of applied voltage. Shifting of PD pulses is very evident in all samples but exhibits different pattern in each sample.
2. Conduction current wave also displays similar characteristics as like partial discharge signature. In addition to variation in the number of pulses, it is also possible to note current pulses of different magnitudes with the increase in time of applied stress.

3. From the simultaneous measurement of PD and conduction current, both number of pulses and magnitude of discharge pulses were noted.

5. Conclusion

The investigation to assess the partial discharge activity in transformer insulating oil is driven by the ideology to carry out assessment on the impact of different modes of degradation that influence the PD behavior in oil. For the experimentation, five different voltage levels have been considered and all oil samples have been subjected to PD stressing process. The following conclusions are drawn from studies conducted on fabricated laboratory models.

1. PD behavior of transformer oil mixed with solid dielectric materials and the oil subjected to thermal stresses are matching with the one, aged under real-time operating condition. It can be concluded that the role played by temperature and solid dielectrics like Pressboard, Kraft Paper etc during PD activity is very well construed through the investigations during statistical and experimental analysis. This conclusion is drawn based on the fact that the oil in an in-service transformer may certainly be exposed to both temperature variation due to different loading condition and solid dielectric materials.
2. New transformer oils are less prone to Partial Discharge phenomena when compared with the degraded oil upto a particular level of applied voltage across the electrodes. Though there is no much deviation in the DIV of new samples and the degraded samples, the difference in PD magnitude matters the most when the voltage reaches a level well beyond DIV.
3. Role of transient signals like lightning impulse and/or switching impulse voltages may also influence the PD behavior in a distinct way when compared with the other degradation processes.
4. PD dynamics in different oil samples are unique and the dynamics of non-linearity in PD behavior is visualized through the experimentation.
5. Simultaneous measurement of partial discharge and conduction current signatures provide information about both magnitude and number of pulses which are the key parameters associated with the dynamics of oil degradation.

6. Acknowledgement

The authors of this work are extremely grateful to Prof. R.Sethuraman, Vice- Chancellor, SASTRA University, Dr. S. Vaidhyasubramaniam, Dean- Planning and Development, SASTRA University and Dr. S. Swaminathan, Dean- Sponsored Research and Director-CeNTAB, SASTRA University for the support and motivation extended to them during the course of the research. The authors are also grateful to Dr. B. Viswanathan, Dean/SEEE, SASTRA University for many useful suggestions, discussion and motivation. The authors of this paper also wish to thank SASTRA University for providing fund for this work under the Research & Modernization Fund [RMF] Scheme and their extensive support to carry out this work. (Ref.: Project No.:6, Letter Ref. No. R & M/006/ SEEE-003/ 2008-09, Dt: 20/11/2008 and Ref.: Project No.:10, Letter Ref. No. R & M /0010/SEEE-005/2009-10, Dt: 25 October 2010)

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