Understanding the Surface Discharge Activity with Thermally Aged Nanofluid Impregnated Paper Insulating Material

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Abstract: SDIV of OIP material gets altered with thermal ageing temperature of OIP material, supply voltage frequency and the harmonic content in the supply voltage. The UHF signal radiated due to surface discharges formed under AC voltage, high frequency AC voltages and with harmonic voltages, have dominant frequency at about 0.9 GHz. Surface charge accumulation studies indicate that thermal ageing have high impact on amount of charge accumulation. Also number of layers of insulation have high charge trap density, which is ascertained through tdv/dt plot. The amount of charge accumulated is high with pressboard impregnated in titania nanoparticle dispersed transformer oil. The SD activity occurs at the rising portion of AC voltage and at high dv/dt's with harmonic AC voltages. More number of discharges occur with OIPs thermally aged at higher temperature. Physico-chemical changes clearly indicate not much of a change occurs with transformer insulation due to thermal ageing.

Keywords: Transformer oil, nanofluid, Surface discharge, UHF, charge accumulation

1. Introduction

In power system network, multiple components are present and transformer is one of the major component in it. Its safe operation decide the reliability of the power system network. Safe and reliable operation of high power transformers have direct impact on efficiency of electrical grid. Recent survey on failure of transformer indicates that improper insulation design is one of the major cause for failures of transformers [1, 2]. The conventional insulation in transformers used in transmission and distribution system is the mineral oil and paper. In recent times, ester oil is gaining importance to use as insulant in transformers. With the increasing power rating of transformers, the insulation designers are trying to identify insulant with high breakdown strength, high thermal conductivity with low loss factor. It is expected that the liquid insulation used in transformers should be good insulant and as well as coolant. The paper insulation in the windings should have good electrical, thermal and mechanical properties [3, 4]. EHV transformers generally use multi-layer paper oil gaps in order to increase breakdown electric field strength. Insulating paper possesses greater relative permittivity compared to transformer oil. The variation in resistivity of the material and variation in relative permittivity of the material can cause interfacial charge accumulation. In recent times, to achieve good thermal and electrical properties, nanofluids are gaining importance.

Zha et al. indicated that multilayer polyimide films have surface potential decay characteristics much slower than single layer [5]. The accumulated charges can enhance the tangential electric field thereby initiating surface discharge activity. Sokolov et al. have indicated that the creepage discharges in transformer insulation can cause carbonization of material [6]. In transformer insulation, one of the major cause for failure of solid insulating material is due to surface discharge activity causing carbonization of material. In addition, the accumulated charges can also alter the local electric field distribution in the material [7].

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During operation of the transformer, the solid/liquid insulation observes multi-stress ageing, which leads to moderate physical and chemical degradation, thereby accelerating the surface discharge activity [8-10]. Recently, the researchers have indicated that the incipient discharges formed inject current pulses with its rise time of about few nano seconds thereby forming electromagnetic waves in the Ultra High Frequency (UHF) range [11]. Thus it is essential to understand the impact of number of layers of insulation on the nature of UHF signal formed due to surface discharge activity and the variation in the frequency content due to surface discharges with number of layers of insulation.

Under normal operating conditions, the top and bottom oil temperature is about 65-70°C. When the transformer is overloaded, the temperature of transformer insulation shoots up abnormally. Earlier works indicate that the temperature can be as high as 180 ^{o}C. M-L. Coulibaly et al. have indicated that thermal ageing at 150 ^{o}C for 1000 hours drastically reduces the degree of polymerization of the material [12]. The reduction in polymerization of material can lead to reduction in mechanical strength of the material and its electrical properties [13]. The weakened part acts as a charge trap site. Thus it has become essential to identify insulating liquid which can meet our requirement without compromising the fundamental properties.

In recent times, with increase in use of power electronic devices and nonlinear loads, the supply voltage has been highly polluted having harmonics with different THD's [14, 15]. Thus, having design of transformer insulation with 50 Hz voltage, increase of supply voltage content having high frequencies can lead to failure of entire insulation. Pradhan et al, studied dielectric properties of material especially with sinusoidal and non-sinusoidal voltages at different temperatures and could conclude that the properties differs [16]. Thus it is essential to have insulation design with high breakdown strength with good thermal conductivity thereby not altering the fundamental properties of the material. To achieve this with advancement in technology especially by use of nano fillers, it should be possible. Thus in the present study, thermal ageing of Oil Impregnated Paper (OIP) material is carried out at near hotspot temperature. The performance of thermally aged OIP is characterized through surface discharge studies under AC and harmonic AC voltages with different THD's.

Considerable amount of work has been carried out by world over researchers to improve the thermal conductivity and dielectric strength of the transformer insulation system so as to extend their life expectancy and load handling capacity [17-21]. The addition of oxide nanoparticles in the transformer oils can allow one to achieve the life expectancy of transformer insulation. Atiya et al. observed that titania nanoparticles dispersed in transformer oil leads to improvement of its electrical strength [22]. A surfactant is added in order to achieve uniform dispersion and stability of the nanofluid [23, 24]. Thus it is essential to understand the surface charge accumulation of material aged in transformer oil and in nano fluid, its impact of surface charge accumulation. The study on this aspects are scanty. To understand the impact of temperature on variation in fundamental properties of the material, thermal ageing was carried out at 120 ^{o}C and 145 ^{o}C. The characteristic variation in transformer insulation due to thermal ageing can be ascertained only by carrying out certain physico-chemical studies including wide angle X-ray diffraction studies, Fourier transform infrared studies and by UV analysis [25]. Thus it is essential to understand the variation in transformer insulation, impact of nano filler on thermal ageing.

Having known all these, the following important aspects are studied (i) SDIV of OIP material thermally aged in transformer oil and in titania nanoparticles dispersed transformer oil, under AC and harmonic AC voltages with varying THDs. (ii) Charge accumulation studies on multi-layer thermally aged OIPs under AC & DC voltages. (iii) Characteristic variation in phase at which discharges occur under AC and harmonic AC voltages with THDs during surface discharge process need to be realized.(iv) physico-chemical diagnostic studies with thermal aged transformer insulation with nano fillers.

2. Experimental Studies

The experimental setup used for understanding the surface discharge activity on OIP insulating material is shown in Figure.1. The experimental setup can be sectionalized into three parts namely; the high voltage source, the test electrode, the UHF sensor connected to the high bandwidth digital storage oscilloscope.

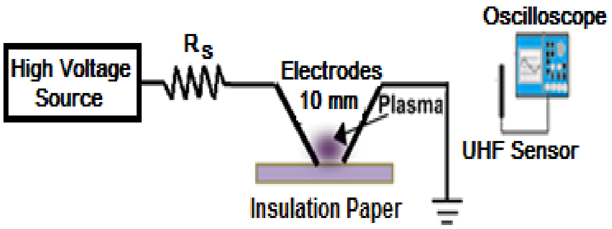


Figure 1. Experimental set up for surface discharge inception analysis

A. High Voltage Source

The high AC voltages of different frequencies were produced by use of Trek amplifier (Model 20/20C) with input to it from signal generator (Tektronix 3051C). Harmonic voltages with different THD's was generated using Aribrary Express software and fed to the signal generator. The voltage was applied to the test at the rate of 200V/s.

B. Test Electrode

The test electrode arrangement consists of two stainless steel electrode with its tip cut at 45° (according to IEC 60112 [26]) set on OIP insulating material. The electrodes are separated by a gap distance of 10 mm. One electrode is connected to the high voltage source through a resistance of 10 MΩ and the other electrode connected to ground.

C. Surface Charge Measurement

Figure 2 shows the experimental setup used to measure the surface charge accumulation on OIP material [27]. The sample was charged by non-contact corona discharge using needle plane electrode configuration at position 1. The injected charges get accumulated on the surface and might get trapped in defective sites, voids or in between layers. After charge spraying on OIP material at 7kV for 3 minutes under AC and DC voltages, OIP material was shifted to position 2. A gap distance of 2 mm was maintained between the sensor and OIP material, the sensor can measure the charge up to a radius of 5 mm on the OIP material surface. A gap distance of 2 mm was maintained between the sensor and the test specimen. The accumulated charge (Q) on the surface of the OIP was calculated using,

$$Q = V\frac{\varepsilon_0 \varepsilon_r A}{d} \quad (1)$$

Where A denotes the area of cross section of the sensor, V is the voltage measured by the electrostatic voltmeter, ε_0 and ε_r are the permittivity of free space and relative permittivity of the medium, respectively, and d is the gap distance between the sensor and the OIP material surface.

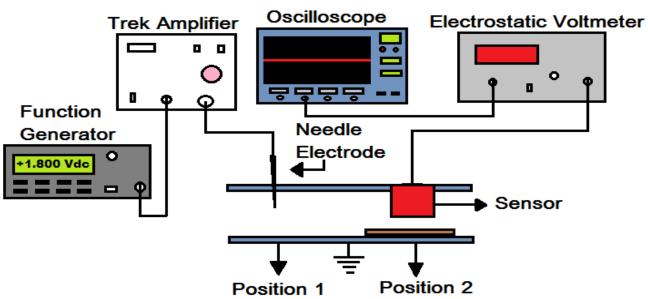


Figure 2. Experimental setup for charge accumulation

D. UHF Senor Unit

Non-directional broadband UHF sensor was used for sensing the radiated UHF signals due to surface discharge activity used in the present study is shown in Figure. 3. The sensor is placed at a distance of 20 cm away from the experimental set up in order to acquire the radiated signal during the discharge process. Judd et al., have described sensor characteristics and method to obtain its frequency response using UHF calibration system [28]. Figure. 3 shows the frequency response of the UHF sensor. The output is then connected to a high bandwidth digital storage oscilloscope for further analysis.

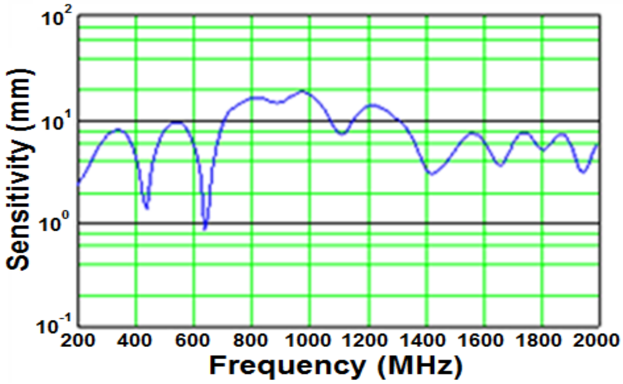


Figure 3. Frequency response of UHF sensor

E. Sample Preparation

To indicate the surface discharge process, the OIP material is immersed in oil and thermally aged. The thermal ageing is carried out at 120ºC and 145 ºC for 6 days and the material is used for further studies. Preparation of nanofluid is a major challenge. The process by which the nanoparticles are dispersed have high influence on performance of the insulating liquid. At first step, the titania nanoparticles (<15 nm, anatase) were dried in hot air oven to remove moisture. The known quantity of nanoparticles were added to transformer oil and magnetically stirred for 30 minutes and then the liquid is sonicated for proper dispersion of nanoparticles in liquid. Nanoparticles have high surface energy and have a tendency to agglomerate. To achieve stability and good dispersion behavior, Cetyl Trimethyl Ammonium Bromide (CTAB) was used as surfactant which caps the active surface area of nanoparticles and works against attractive Van Der Waals. At first stage, the liquid is left ideal for more than 10 days and no variation in color of liquid is observed. Figure. 4 shows the preparation process. The XRD studies were carried out using D8 Discover, Bruker axs Diffractometer using CuKα radiation of wavelength 1.5425 Å. FTIR analysis was carried out using PerkinElmer Spectrum 100 FT-IR Spectrometer. UV analysis was carried out using UV-VIS Spectrophotometer (Schimadzu).

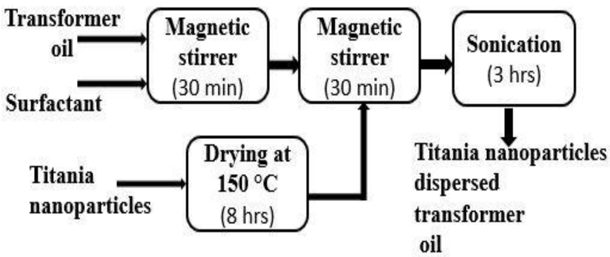


Figure 4. Preparation procedure of titania nanofluid with transformer oil as base

In the present study, TO represent transformer oil and NO represents titania particle dispersed transformer oil. Typical photograph of thermally aged OIP material in transformer oil and in titania nanofluid is shown in Figure 5. It is observed that not much colour change is observed with thermally aged specimen in transformer oil/ titania nnaofluid.

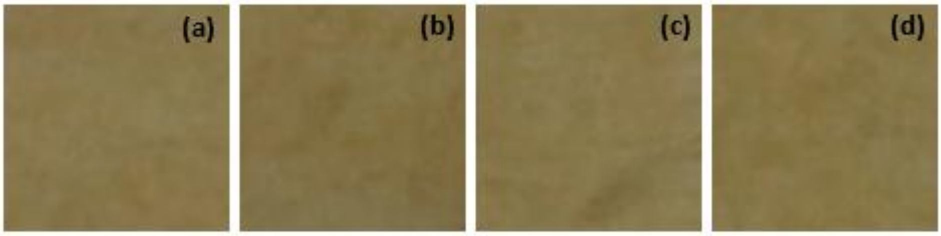


Figure 5. Photograph of the (a) Pure OIP in transformer oil, (b) Pure OIP in titania nanofluid, (c) OIP thermally aged in transformer oil, (d) OIP thermally in titania nanofluid at 145 °C.

3. Results and Discussions

A. Analysis of Surface Discharge Inception Voltage

Figure 6 shows the variation in SDIV of thermally aged OIP materials in transformer oil and titania nanofluid under high frequency AC voltage. It was observed that SDIV increases marginally with increase in supply voltage frequency. This could be due to the fact that at high frequency, the magnitude of applied voltage is time varying, minimum required electric field to initiate discharges could be achieved only when the applied voltage magnitude is high. Further it is observed that SDIV of OIP materials reduces with thermal aged specimens. The SDIV of OIP materials thermally aged at 145 °C is lower than that aged at 120 °C. Similar characteristics is observed with the OIP material aged in titania nanofluids. It was observed that reduction in SDIV with respect to ageing is more for OIPs aged in transformer oil as compared to OIPs aged in titania nanofluid. Sahitya et al. carried out Surface discharge analysis with copper supplied diffused OIP material. They have observed that on diffusion of copper sulphide to the OIP material, drastic reduction in surface discharge inception voltage is observed. They also have studied the nature of current pulses during surface discharge activity using high frequency current transformers. They have indicated that the current pulses generated in the positive and negative half cycles are different and are less than 1 ns [29]. Figure 7 shows the variation in SDIV of thermally aged OIP material in transformer oil and titania nanofluid under harmonic AC voltage with (a) 4%THDs and (b) 40% THDs. Marginal decrement was observed in SDIV with increase in harmonics and THD's for all OIPs. Decrement in SDIV is more for 145 °C thermally aged sample as compared to 120 °C thermally aged samples and % decrement was more in case of OIPs aged in mineral oil as compared to OIPs aged in titania nanofluid.

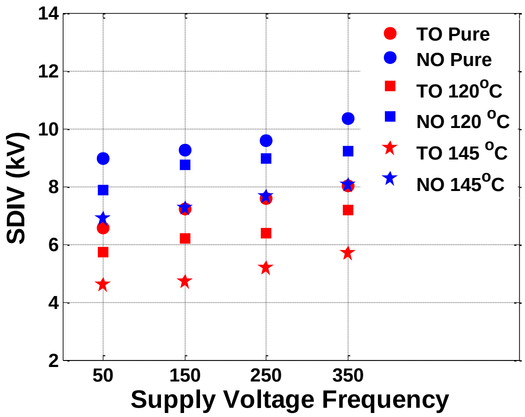
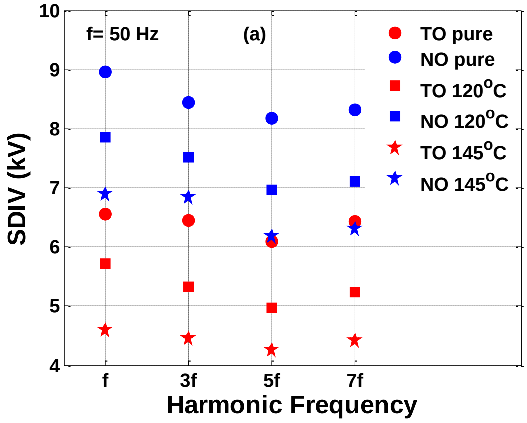


Figure 6. Variation in SDIV of thermally aged OIP material in transformer oil and titania nanofluid under high frequency AC voltages



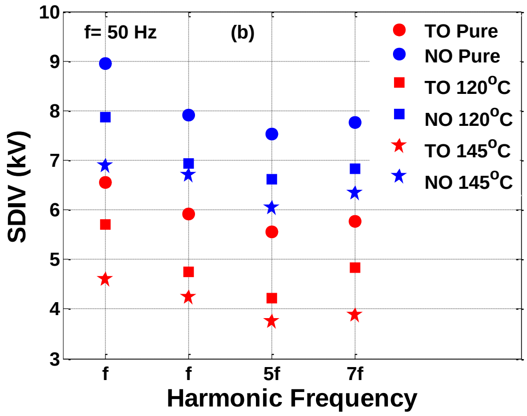


Figure 7. Variation in SDIV of OIP materials thermally aged in transformer oil and titania nanofluid under harmonic AC voltage with different THDs. (a) 4%THD and (b) 40% THD's Frequency Domain Analysis of UHF Signals

Figure 8 (a) and (b) shows typical UHF signal and corresponding FFT formed due to surface discharge activity with OIP material in titania nanofluid. It was observed that the characteristic frequency contents of the radiated signals due to surface discharge activity in nano OIPs lies in the UHF signal range having dominant frequency near 0.9 GHz.

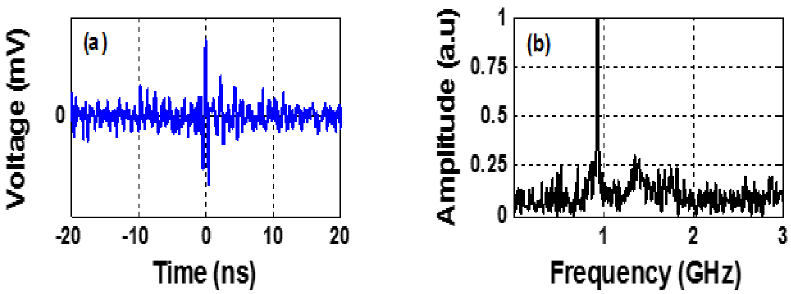


Figure 8. Typical (a) UHF signal formed due to surface discharge activity with titania nanofluid OIP material and (b) its corresponding FFT

B. Surface Charge Accumulation Analysis

Figure 9 shows the typical charge decay plots of OIP in transformer oil and with titania fluid. From the charge dissipation plots, it is observed that charge decays rapidly in the initial time and then decays slower with increase with thermally aged specimen. Initial accumulated charge is represented as Q_o and time constant of charge dissipation is represented as 'τ'. Table 1 shows the values of Qo and τ for different layers of thermally aged OIPs in transformer oil and titania nanofluid due to charge injection under AC and DC voltage profiles. It is observed that as the number of layer of OIPs increases, the corresponding values of Qo and τ increases. It is seen that initial accumulate charge and time constant value is more in case of –DC voltage profiles as compared to +DC, it could be because of paper structure which causes paper to trap charges and vary the decay rate. It is observed that OIPs thermally aged at 145 ^{o}C stores more initial charge and decays slower as compared to pure OIPs and OIPs thermally aged at 120 ^{o}C. Similar characteristic was observed with OIPs aged in transformer oil and titania nanofluid under AC and DC voltage profiles and layer wise. It was also observed that OIPs aged in titania nanofluid has more initial charge accumulation and decays slower as compared to OIPs aged in transformer oil.

Wu *et al.* studied space charge properties of oil-immersed-paper and have concluded that interface charge decreased with the increase of oil layer thickness. The cause for it is due to restraining charge migration inside the oil-paper insulation, which would lead to the electric field distortion [30]. Moisture content in oil-paper insulation have high impact on mobility of the charges. Moreover, the higher mobility of the charges leads to less slow moving charges trapped in the sample with higher moisture content [31]. Cheng et al. indicated that titania included OIP material have improved dielectric properties and space charge accumulation [32]. Chao tang indicated that space charge can have impact on charge accumulation, charge transportation process and charge distribution inside oil-paper. They also have indicated that the degree of polymerization is limited with titania included oil impregnated pressboard material [33].

Table 1. Measured values of initial charge accumulated and corresponding time constants for charge accumulation studies on thermally aged transformer OIPs (TO) and titania nanoparticles dispersed transformer OIPs (NO) for different layers due to charge injections under AC and DC voltages.

Days	Voltage profile	Layer 1		Layer 2		Layer 3	
		Q_o	T	Q_o	T	Q_o	T
TO Pure	AC	-4.12	1.41	-7.9	3.12	-10.6	4.12
	+DC	7.9	1.82	9.15	4.67	35.7	6.9
	-DC	-10.2	7.7	-16.2	8.23	-48.5	18.6
NO Pure	AC	-5.6	2.46	-17.9	5.12	-22.6	12.7
	+DC	15.5	8.15	21.3	8.6	54.2	19.2
	-DC	-24.6	12.6	-36.5	15.3	-54.4	27.8
TO 120 ^{o}C	AC	-5.25	3.75	-7.2	5.63	-23.6	8.3
	+DC	14.03	5.17	20.4	7.18	36.2	12.06
	-DC	-17.64	6.79	-35.3	12.83	-50.3	19.07
NO 120 ^{o}C	AC	-11.26	4.43	-23.8	7.32	-46.2	11.44
	+DC	18.7	7.22	38.7	8.5	51.6	15.6
	-DC	-27.3	9.34	-43.2	15.94	-60.8	27.56
TO 145 ^{o}C	AC	-7.9	6.5	-11.4	7.9	-35	22.5
	+DC	19.2	7.5	28.6	13.3	55.6	21.4
	-DC	-21.3	8.6	-42	14	-62.9	36.3
NO 145 ^{o}C	AC	-13	7.3	-27.7	13.2	-50.4	20.6
	+DC	22.3	12.9	44.9	16.2	61.8	22.6
	-DC	-33.6	15.1	-49.8	26.4	-71.7	46.1

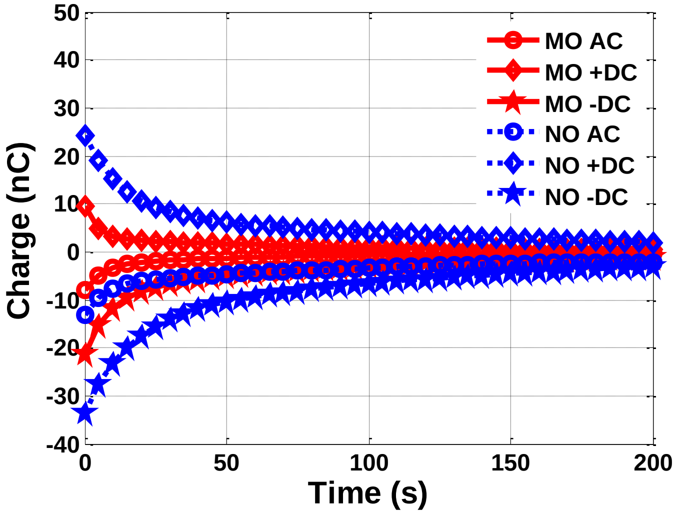


Figure 9. Typical surface charge decay plots of transformer OIP and titania nanoparticles dispersed OIP formed due to charge injection under AC and DC voltages

The tdV/dt vs t curve was proposed by Watson and the main aim of this curve is to understand the factors influencing charge trapping [34]. It shows the trend of interface charge dissipation and gives the clear pattern as compared to fundamental accumulated charge vs time plots. Llovera and Molinie have studied that the characteristic time constant and peak values display the charge behavior appearing on the tdV/dt vs t plots [35]. S. Kumara et al. have concluded that tdV/dt is proportional to the paper trap density at the energy of demarcation [36]. Additionally, log (t) is proportional to the paper trap energy gap. Hence, these curves are employed to study the trap energy distribution under various conditions. Characteristic time is defined as the time when the curve reaches the peak value. The double peak formation in tdv/dt plot indicates existence of two different time constants. Du et al. have indicated that the first peak (Figure) is due to charge decay due to shallow traps and the second peak formation, which occurs at later instant of time is due to deep traps. A right shift in characteristic time indicates an increase in time constant of charge dissipation and an increase in peak value indicates an increase in charge trap density [37]. The increase in intensity of t dv/dt is due to increase in charge trap density confirming number of layers have high impact on amount of charge accumulated.

When the layers of OIPs are charged with non-contact corona discharge, some of the charges get accumulated on surface and some get trapped in the interphase or bulk. The charge is firstly transferred from the surface to the bulk in the electric field and then gets trapped and detrapped, and via this process the charge reaches ground electrode. Figure 10(a) shows the typical tdV/dt vs log(t) for day 0 and day 6 thermally aged OIPs, and it is observed that aged sample shows higher peak and higher characteristic time as compared to unaged OIPs. It is also seen that in case of voltage profile, peak and characteristic time follows the sequence –DC> +DC> AC. Figure 10(b) shows a typical tdV/dt vs log(t) to show the effect of number of layers of OIPs. It is observed that peak and characteristic time follows the sequence Layer 3> Layer 2> Layer 1. Figure 10(c) shows typical tdV/dt vs log (t) to show the effect of thermal ageing. It is observed that the peak and characteristic time is higher for 145ºC aged OIPs as compared to 120 ºC aged OIPs and pure OIPs. Similar pattern was observed in case of OIPs aged with titania nanofluid. These characteristics are also supported by the trend of Qo and τ values indicated in table 1.

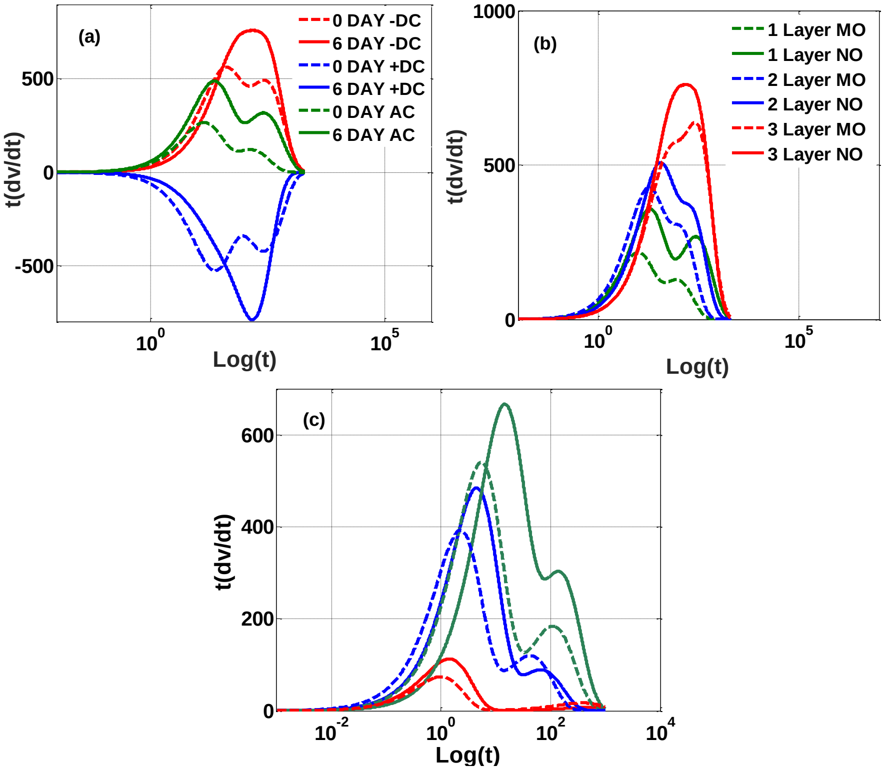


Figure 10. Variation tdV/dt curve of charge decay curve obtained under AC and DC voltage (a) AC and DC voltage profiles of virgin OIPs and thermally aged at 120 C, (b) layers for transformer OIPs and titanaia nanoparticles dispersed OIP materials of virgin material, and (c) with thermal aged material with three layers

C. Phase Resolved Partial Discharge (PRPD) Analysis

Figure. 11 shows the PRPD pattern formed due to surface discharge activity with thermally aged OIPs in titania nanofluid under AC and harmonic AC voltages with different THD's. It was observed that the surface discharge activity at the point of inception occurs at the rising portion of the applied AC voltages and with harmonic AC voltages when dv/dt is high. It is also observed that the number of discharges is less in case OIPs thermally aged at 120 °C as compared to 145 °C aged OIPs.

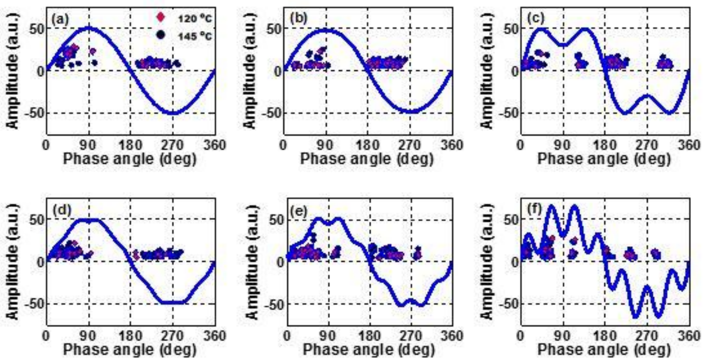


Figure 11. Typical PRPD pattern obtained at the point of surface discharge inception of OIPs thermally aged in titania nanofluid at 120 °C and 145 °C under (a) 50 Hz (b) 3f 4% (c) 3f40% (d) 7f4% (e) 7f10% (f) 7f40%

D. Physico-Chemical diagnostic Studies

Figure 12 shows the X-ray diffraction pattern of oil impregnated pressboard material. No characteristic variation is observed with the dried OIPs impregnated and thermally aged in transformer oil and titania. No indicative peak of titania is observed with OIP material formed with titania dispersed OIP material. Also thermal ageing of material have no impact on addition of new phases with the thermally aged OIP material. The XRD pattern indicates one amorphous peak and a crystallite peak. Liao et al. indicated that transformer OIP thermal ageing can cause reduction in crystallinity of OIP material. [38]. Crystalline regions are ordered and compact, while amorphous regions are disordered, irregular and deteriorate quite easily. The relative crystallinity of the transformer paper insulating material can be calculated using following equation [39];

$$Cr = \frac{a-b}{a} * 100\% \quad (2)$$

Where Cr is the relative crystallinity, a is the diffraction intensity of crystalline regions and b is the diffraction intensity of amorphous region. The intensity variation of virgin OIP material and the thermally aged material with variation in crystallinity of material is shown in Table-2. Only a marginal variation in crystallinity of material is observed due to thermal ageing.

Table 2. The Intensity and Relative Crystallinity of Different OIP Materials

OIP Samples	Intensity		Relative Crystallinity (Cr)
	A	B	
NO Pure	25640	63580	59.67%
TO Pure	25500	61940	58.83%
NO Day 6	19760	45860	56.91%
TO Day 6	49680	115000	56.64%

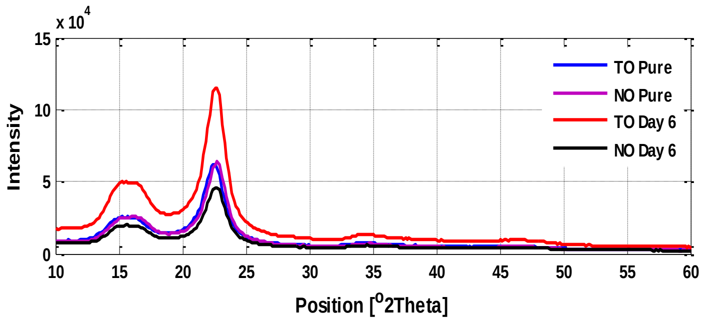


Figure 12. XRD pattern of dried paper insulation thermally aged in transformer oil and titania nanofluid for 6 days

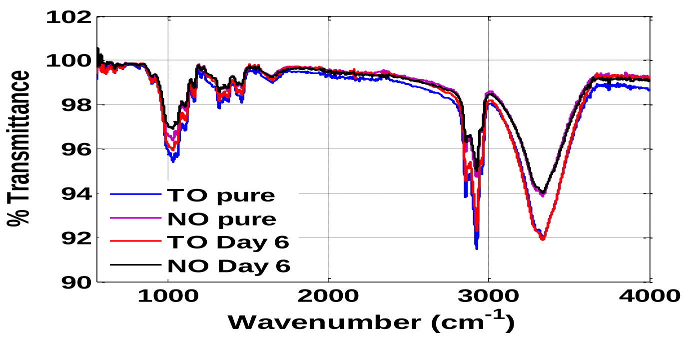


Figure 13. Spectral Response of dried paper insulating material thermally aged in Transformer Oil and titania nanofluid for 6 days using FTIR

Fourier Transform Infrared (FTIR) spectroscopy can provide any functional groups formed due to thermal ageing of material. and sample composition [40]. Figure. 13 shows the FTIR spectra of thermally aged OIP material in transformer oil and in titania nanofluid for 6 days at 145 °C. The FTIR pattern of thermally aged OIP and virgin material have no variations, indicating that no characteristic changes have occurred in the material.

Figure 14 shows the UV spectrum of thermally aged transformer oil and titania nanofluid using UV-VIS Spectrometer. It is observed that absorption peaks are located at nearly same wavelength for pure as well as thermally aged OIP materials. It is also observed that absorbance for titania nanofluid is lesser than transformer oil and same trend is observed after 6 days of thermal ageing.

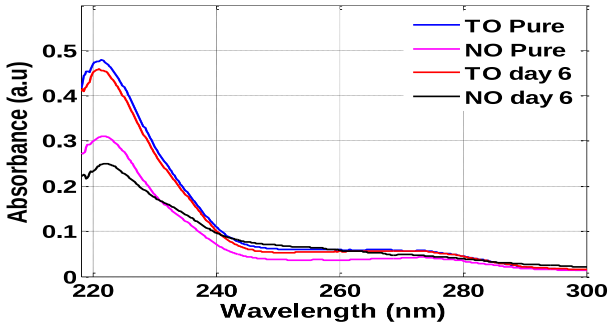


Figure 14. UV spectrum of thermally aged transformer oil and titania nanofluid

4. Conclusions

The important conclusions based on the experimental studies can be summarized as follows:

1. SDIV for nanofluid impregnated insulating material is higher than transformer OIP material. Characteristic variation in SDIV is observed under high frequencies and with harmonic voltages with different THDs. Thermal ageing of OIP material have reduced SDIV and its impact is less with OIP material thermally aged in titania dispersed transformer oil. The UHF signal radiated due to Surface discharges have dominant frequency at about 0.9 GHz. The characteristics is the same with harmonic voltages and with high frequency AC voltages.
2. Surface charge accumulation characteristics of the material is altered with thermal ageing temperature. The amount of charge acquired is less with OIP material aged in titania nanofluid. Number of layers of material have high impact on amount of charge accumulated and its decay time. Tdv/dt results indicate two different mechanisms by which the charge decay occurs with OIP material. Tdv/dt intensity is high with increase in number of layers of insulating material, indicating high charge trap density.
3. PRPD analysis shows that the surface discharge activity occurs at the rising portion of the AC voltage or harmonic AC voltages at the point of inception. More discharges are observed in OIP materials aged at 145 °C as compared to OIP materials aged at 120 °C.
4. Physico-chemical analysis clearly indicates that no characteristic changes are observed with transformer insulation, during the period of thermal ageing.

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