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Investigations on Partial Discharge, Dielectric and Thermal Characteristics of Nano SiO_2 Modified Sunflower Oil for Power Transformer Applications

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Abstract – The reliability of power transmission and distribution depends up on the consistency of insulation in the high voltage power transformer. In recent times, considering the drawbacks of conventional mineral oils such as poor biodegradability and poor fire safety level, several research works are being carried out on natural ester based nanofluids. Earlier research works show that sunflower oil has similar dielectric characteristics compared with mineral oil. BIOTEMP oil which is now commercially available in the market for transformers is based on sunflower oil. Addition of nanofillers in the base oil improves the dielectric characteristics of liquid insulation. Only few results are available in the literature about the insulation characteristics of nano modified natural esters. Hence understanding the influence of addition of nanofillers in the dielectric properties of sunflower oil and collecting the database is important. Considering these facts, present work contributes to investigate the important characteristics such as partial discharge, lightning impulse, breakdown strength, tan-delta, volume resistivity, viscosity and thermal characteristics of SiO_2 nano modified sunflower oil with different wt% concentration of nano filler material varied from 0.01wt% to 0.1wt%. From the obtained results, nano modified sunflower oil shows better performance than virgin sunflower oil and hence it may be a suitable candidate for power transformer applications.

Keywords: Sunflower oil, Nanofluids, Partial discharge, Lightning impulse discharge, Dielectric and thermal characteristics, Power transformer.

1. Introduction

Insulating oil plays a major role in high voltage transformer applications as a dielectric and cooling medium. Conventionally used mineral oils are obtained by fractional distillation and subsequent treatment on crude petroleum. The major drawbacks of mineral oil are more toxic, poor biodegradability, serious contamination of waterways and soil due to spillages and also low flash and fire points at 150°C. Many researchers identified vegetable oil as an alternative solution for mineral oil [1-13] because it is environmental friendly, non-toxic, biodegradable and also it's flash, fire point is above 300°C. Earlier research works show that sunflower oil has similar dielectric characteristics compared with mineral oil. BIOTEMP oil which is now commercially available in the market for transformers is based on sunflower oil.

The aim towards nanofluid research makes the electrical researchers to develop latest and futuristic electric insulation systems which have the capacity to operate at the higher voltage levels.

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A nano sized material which gets evenly dispersed in the virgin or base fluid known as nanofluids have enhanced thermal property and dielectric strength and results are reported in many papers [14-22].

Partial discharge (PD) diagnostics is considered as an important tool for understanding the degradation and remaining life time of liquid insulation in transformers. PD pulse initiates as a result of sludge formation and streamer development in liquid dielectrics [23]. The main origin of partial discharge is sharp particles or edges, cavities, and presence of voids in insulation [24]. Understanding the partial discharge characteristics of nano modified vegetable oils, in particular, sun flower oil in the laboratory level is important.

Normally transformers are used in outdoor application and hence understanding their lightning impulse withstand strength with nanofluid insulation becomes more important for the better insulation design [25, 26]. Lightning impulse test is essentially needed for power transformers as a routine test in factory as per IEC standard 60076-3. The insulation placed inside the transformers are mostly exposed of quasi-uniform electric field [27] and hence the alternate nano modified sunflower oil insulation system should tend to accept the electrical strength in a quasi-uniform field.

Hence, before choosing the nano modified natural ester based sun flower oil as a liquid dielectric for power transformers, it is important to analyse its electrical partial discharge, dielectric breakdown strength, physical and thermal characteristics. By considering this, in this paper, the experimental investigations were carried out for sunflower oil and SiO_2 nano modified sunflower oil with variation of nano fillers from 0.01wt% to 0.1wt% concentration. A variety of tests like Partial Discharge along with its time and frequency domain analysis, Lightning impulse, Breakdown strength, Tan-Delta, Dielectric Constant, Volume resistivity, Capacitance, Viscosity, Flash point and Fire point were conducted and the results obtained from these tests are reported.

2. Experimental Techniques

2.1 Nano fluid preparation

In this work, commercially available branded sunflower oil was treated as base oil and the same brand oil was maintained for entire research work. Initially, oil samples were filtered in order to remove the presence of impurities and dust particles in the sample. The insulative SiO_2 nano particle was added at the concentration level of 0.01wt%, 0.05wt% and 0.1wt% with the base oil and it was subjected to stirring process using magnetic stirrer for 20 minutes to avoid sedimentation of nano fillers in the oil and then again subjected to ultra-sonication treatment for 5 min to disperse nano fillers uniformly and completely in the base oil. Then the nano modified sunflower oil and virgin sunflower oil was treated thermally by using hot air oven to avoid the presence of moisture content in the test sample before testing. All the tests were performed under room temperature.

2.2 Partial discharge, lightning impulse, breakdown strength, viscosity, flash and fire point

The two major types of PD that occur in a transformer are corona and surface/interface discharges. Corona discharge may develop due to the existence of conducting particle floating in the liquid insulation. Whereas surface/interface discharge discharges occur at the interface of the oil and pressboard materials. The Fig. 1(a) shows the schematic diagram of experimental setup used in this present study to monitor the partial discharges developed between needle-plane electrode configurations in order to simulate the corona discharges. The electrodes are located in the 200 ml volume of transparent test cell surrounded by the liquid dielectric. The needle electrode was connected to the top portion of high voltage supply and plane electrode was grounded at the bottom. This needle-plane electrode was separated at a gap distance of 5mm. In order to get a stable PD pattern, 1.5 mm thick pressboard was placed upon the plane electrode. PD signals are collected by High Frequency Current sensor which is connected around the

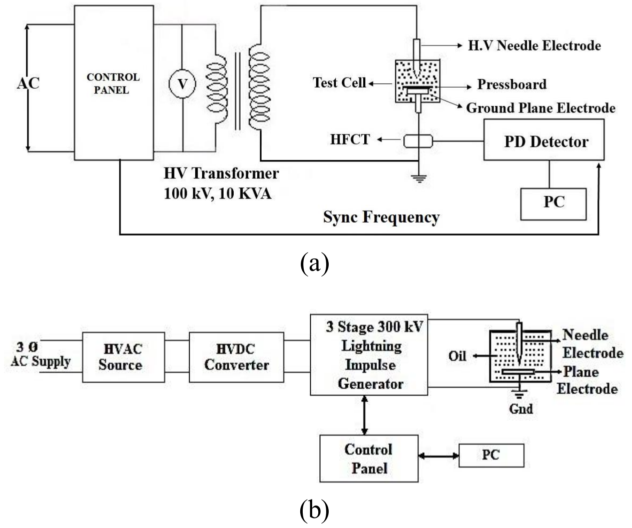


Fig. 1. Schematic diagram of the experimental setup for needle-plane electrode configuration (a) PD test, (b) 300 kV, 3 stage Lightning Impulse

ground connection of test cell to the PD detector using coaxial cable. Similarly PD waveforms are monitored using PC which is connected with PD detector.

Fig. 1(b) shows the block diagram of experimental setup used in this present work to understand the lightning impulse characteristics of nano oils and virgin oil. A 200 ml volume of test sample is filled in the transparent test cell containing needle-plane electrode configuration with gap distance of 10 mm maintained constant. A high voltage lightning source was connected to needle electrode and plane electrode was solidly grounded. PC was connected with the control panel to direct the impulse generator and also to obtain the impulse waveform of test sample.

The lightning impulse source used in present research work operates on the basis of Marx circuit and delivers the 1.2/50 μs of standard lightning impulse to the connected test sample. Measuring of LI voltage was carried by using the standard high voltage measuring capacitor of 400 pF. The measuring capacitor was connected to the digital storage oscilloscope so that the waveform is obtained by using PC integrated with digital storage oscilloscope.

The electric strength at the time of breakdown was known as dielectric strength or breakdown voltage. This breakdown voltage strongly depends up on the physical and chemical parameters like viscosity, acidity present in the oil and also influenced by dissolved gases like oxygen or carbon dioxide, dust, fibers and especially ionic impurities [28-30]. As per IEC standard 60156, BDV test was measured by using 100 kV rated BDV apparatus. A standard mushroom type electrode was located in the transparent test cell filled with test sample of 450 ml volume and it is maintained with a typical clearance of 1 mm, 2.5 mm, 4 mm, and 5 mm. Test voltage was applied to the electrodes and it continuously increases at a constant slew rate of 2 kV/s till the breakdown occurs. The corresponding BDV reading was observed.

Viscosity has a strong influence on both breakdown properties and thermal properties [31, 32]. Depending up on the oils viscosity, temperature inside the transformer gets varied. Viscosity test was measured using Redwoods viscometer. Oil cup was filled with the test sample at particular level. Water bath was made to heat at uniform temperature. When the oil and water reach the particular temperature then ball valve was lifted above the orifice hole.

Stop watch was started at the same time and the oil was allowed to pass through it. 50 cc of oil was collected in volumetric flask and the measured seconds for 50 cc of oils were converted to the kinematic viscosity of the oil.

The flash point is the minimum temperature when there is a sufficient concentration of vapour of flammable liquid in air to sustain burning when there is a source of ignition. The fire point is the temperature at which the vapour of the liquid present in air continues to burn at least 5 seconds even after removing the source of ignition. Presence of contaminations also has a significant effect on the flash and fire point, particularly if the contaminant is relatively more volatile. In this work, Pensky Martins open cup apparatus was used to determine the flash and fire point. Test oil was filled in the test cup to the required level. The test flame was shown near to the test oil and as the temperature increases, it was recorded by thermometer. At one temperature, test sample starts to vaporize and that minimal temperature was noted as a flash point and once the vapor starts to burn continually above that minimal temperature, then that temperature was noted as fire point.

2.3 Tan-delta, dielectric constant, volume resistivity and capacitance

Dielectric dissipation factor is also called as Tan-Delta which is mainly used to find out the insulation quality. By measuring this parameter on periodical basis, it is possible to know the rate of deterioration of the oil and it will be helpful to replace the insulation before failure and for preventive maintenance schedule.

The dielectric constant, which is also called as relative permittivity, is generally influenced by contaminants, moisture levels present in the insulation and electrical frequency [33]. Dielectric constant reading shows how the insulation becomes polarized when subjected to the voltage. Volume resistivity is useful to find out the leakage current occurring through the whole body of insulation. Volume resistivity was obtained by applying 500 V D.C continuously for 60 seconds.

Capacitance can be evaluated using empty cell reading and dielectric constant (ε). By measuring electrical properties like capacitance on regular basis, it is possible to ensure the unexpected breakdown. These electrical properties may change due to ageing effect. In general, capacitance value obtained from the new insulation is taken as benchmark reading. Then by measuring and comparing the periodical reading of capacitance of that same insulation with the benchmark reading, the capacitance of the aged insulation can be obtained. All the above tests are conducted at room temperature, 50°C, 70°C, 90°C and 110°C by using Eltel 50 Hertz instrument. This instrument operates on the basis of null detector by balancing the bridge. All these test are conducted as per IEC 60247 standard.

3. Experimental Results and Discussion

3.1 Partial discharge test results of nano modified sunflower oil

In this test, needle-plane electrode configuration was used and in order to simulate the stable partial discharge signals, pressboard material was used above the plane electrode. The supply voltage was increased at each step by 1 kV till the PD signal was detected. To examine the PD behaviour, all the nano sunflower oil samples and virgin oil sample were tested upto 30 kV. The Rate of PD pulse occurrence is erratic and appears to be pulse bursts, hence it is difficult to determine the Partial Discharge Inception Voltage (PDIV) in liquid dielectrics. The lowermost voltage at which PD starts to initiates at least one PD pulse over an interval of 10 minutes and it is made to appear in PD measuring system for the applied voltage is known as PDIV.

The PDIV value of virgin and nano sunflower oil is shown in the Fig. 2. It is seen that the PDIV value of nano modified sunflower oil rises above the virgin sunflower oil PDIV value. However while increasing the concentration of nano filler from 0.01wt% to 0.05wt% the PDIV value starts to increase but while moving from 0.05wt% to 0.1wt% of nano filler concentration there is a slight reduction in its value. This shows that PDIV value strongly depends up on the concentration of nano filler used in the base oil sample. In general the PDIV value depends up on the type of base oil, type of nano filler with its concentration level used.

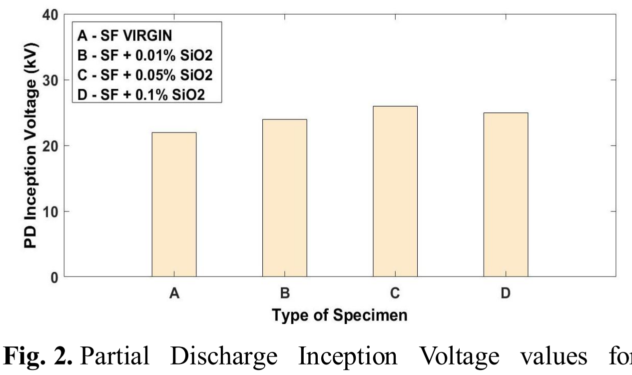
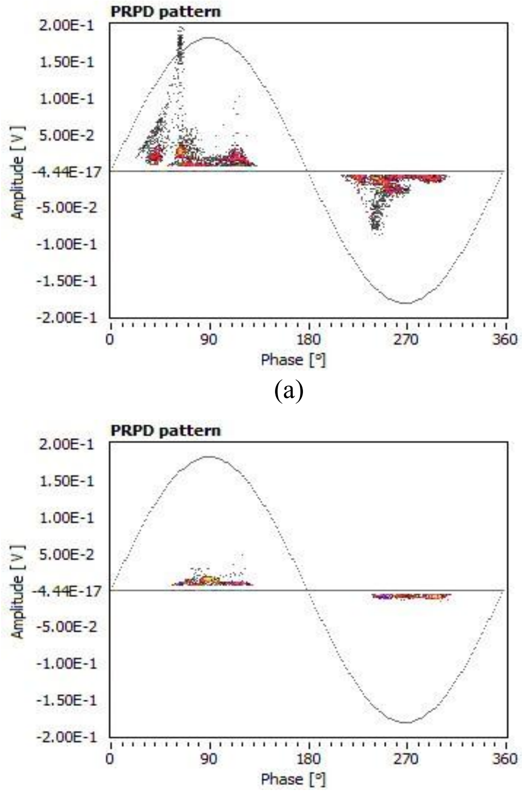
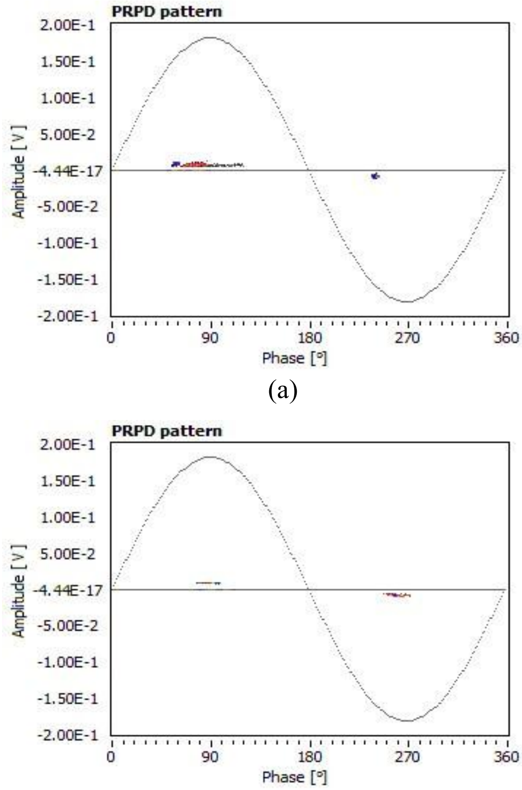


Fig. 2. Partial Discharge Inception Voltage values for virgin and nano modified sunflower oil samples



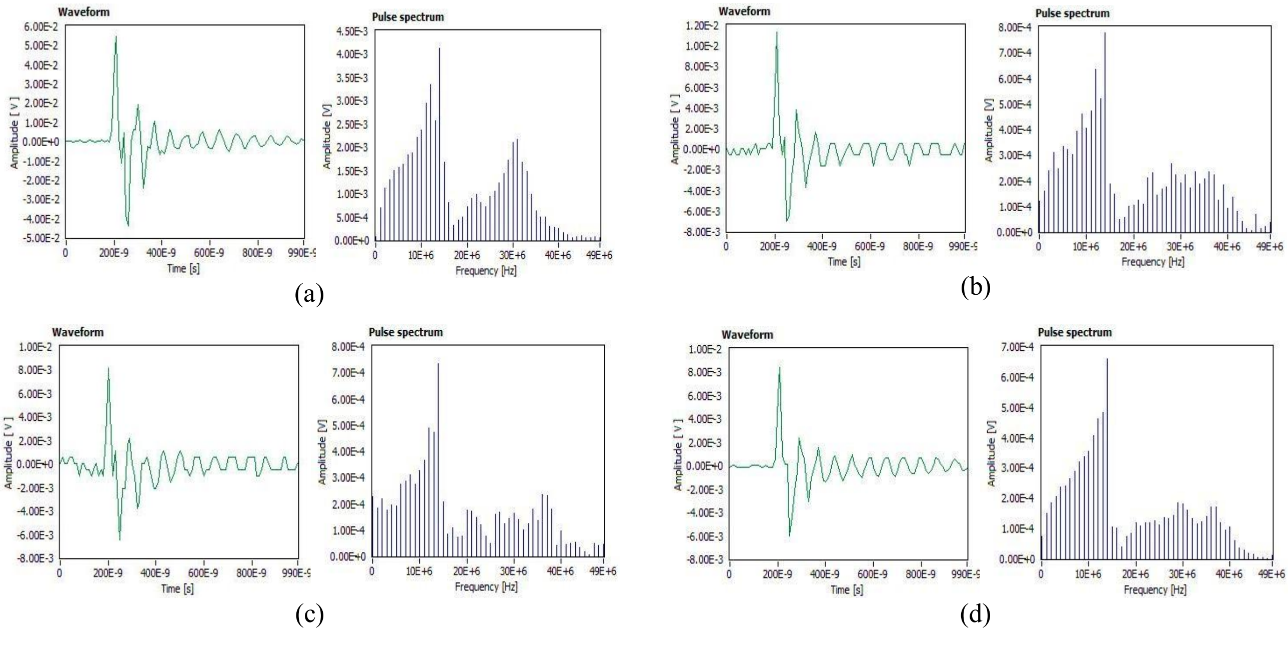
(b)

Fig. 3. Partial discharge pattern was obtained for needle-plane electrode configuration of (a) SF Virgin (b) SF+0.01wt% SiO_2. Test Voltage 30 kV.



(b)

Fig. 4. Partial discharge pattern was obtained for needle-plane electrode configuration of (a) SF+0.05wt% SiO_2 (b) SF+0.1wt% SiO_2. Test voltage 30 kV



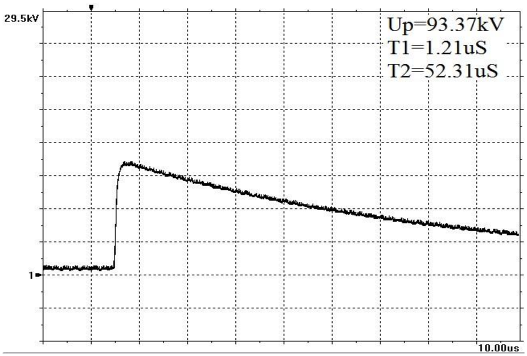
(d)

Fig. 5. Partial discharge pulses and corresponding frequency spectrum obtained for needle-plane electrode configuration of (a) SF Virgin (b) SF+0.01wt% SiO_2 (c) SF+0.05wt% SiO_2 (d) SF+0.1wt% SiO_2.Test voltage 30 kV

Fig. 3 and 4 shows the partial discharge pattern obtained for needle-plane electrode configuration for virgin oil and nano modified sunflower oils, at a test voltage of 30 kV. In general it can be observed that nano modified sunflower oil shows the lower PD magnitude than the virgin sunflower oil at 30 kV. It is seen that 0.1wt% concentration of nano sunflower oil sample shows low level of PD pattern which means development of PD pulse is low. But in the virgin oil the PD pattern is very high and reaches its peak amplitude of nearly 0.2 V. From this it was clearly noted that while adding the nano filler above 0.05wt% then there is a significant decrease in PD values while compared to virgin and other nano samples, which is due to the insulative SiO_2 nano particles absorbing moisture contents present in the oil and enhances PD characteristics.

Information about condition of insulating oil can be obtained while analysing each PD pulses in time and frequency domain basis. Generally shape of PD pulse, rise time, frequency spectrum and equivalent time length are required to understand the time-frequency characteristics of PD signals.

Fig. 5 depicts the PD pulses with its corresponding frequency spectrum obtained from needle-plane electrode configuration for different oil samples. It is seen that in sunflower virgin oil the peak magnitude of pulse spectrum reaches nearly between 4 mV. Whereas 0.01wt% of nano sunflower oil shows the PD pulse reaches at 0.8 mV. From this it was noted that while adding the nano filler from 0.01wt% to 0.1wt% to the sunflower oil then there is an improvement in peak amplitude of pulse spectrum while compared to the virgin sunflower oil.



(a)

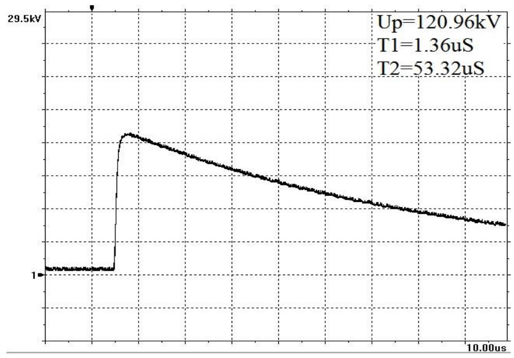
(b)

Fig. 6. Positive LI waveform (a) Virgin oil withstand (b) Virgin oil breakdown

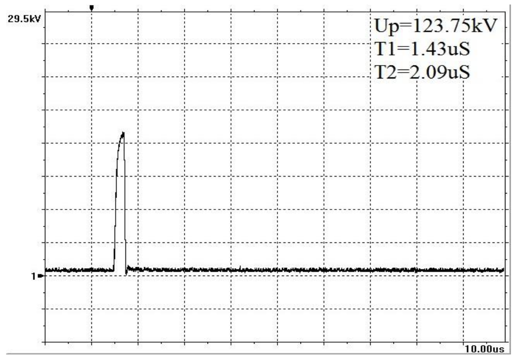
3.2 Lightning impulse test results of nano modified sunflower oil

The Lightning impulse voltage of positive polarity was used to compare the virgin sunflower oil and nano sunflower oil samples. Fig. 6(a) and (b) shows the typical waveform of positive LI withstand and breakdown waveform of virgin sunflower oil.

Similarly Fig. 6(a) and (b) also shows the average peak value of voltage applied (Up), along with the up time (T1) and down time (T2) of the lightning impulse voltage applied. It is seen that the virgin oil sample has the capacity to withstand up to 93 kV peak LI, whereas it starts to breakdown when the applied LI peak goes above 95 kV. Tests were repeated with 20 different oil specimens of



(a)



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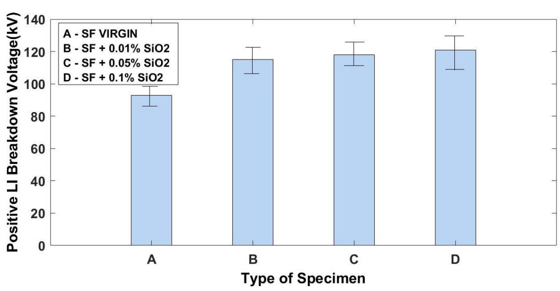


(c)

Fig. 7. (a) 0.1wt% SiO_2 nano sample withstand (b) 0.1wt% SiO_2 nano sample breakdown. (c) Comparison of Positive LI breakdown voltage of virgin oil specimen with different nano oil specimen

same type, so that minimum, maximum and average breakdown voltage can be computed.

Similarly Fig. 7(a) shows the typical average positive impulse withstands of 0.1wt% sample and Fig. 7(b) shows average breakdown waveform of 0.1wt% SiO_2 modified sunflower oil sample. This type of oil sample shows higher LI breakdown strength, which is closer to 121 kV and it attains breakdown at 123 kV. Significant increase in breakdown strength is observed with increase in nano filler concentration. Similar results are also obtained with 0.01 wt% and 0.05wt% concentration samples.

Fig. 7(c) shows the comparison of positive lightning impulse breakdown strength of nano modified sunflower oils at different wt% concentrations along with virgin sunflower oil. It also shows the average, minimum and maximum value of breakdown strength obtained with test specimen. It is noted that 0.01wt% oil shows higher percentage increase in breakdown strength when compared to base oil. However percentage increase in LI breakdown strength is not so significant with 0.1wt% concentration. From the positive polarity LI studies, it is noted that in general, nano modified sunflower oil has higher breakdown strength than the pure sunflower oil.

3.3 Breakdown strength, viscosity, flash and fire point of nano modified sun flower oil

From the result shown in Fig. 8(a) the nano filler of 0.01wt% concentration shows positive improvement in breakdown withstand strength than the virgin sample at all the tested electrode gap distances. In general, from the results of breakdown strength, it is noticed that the 0.1wt% concentration sample shows significant improvement in withstand strength than the all other nano samples and virgin sample. From this result it is clearly noted that while increasing the nano filler concentration from 0.01wt% to 0.1wt% there is an improvement in breakdown voltage withstand strength.

Fig. 8(b) shows that at 30°C virgin oil is viscous than the other nano modified oil samples. While the temperature increases to 40°C than the viscosity of 0.01wt% of nano modified sunflower oil shows less value than the virgin and other nano modified sample. Similarly at 50°C and 60°C the viscosity of 0.01wt% becomes lesser than the other samples. This shows that addition of nano filler up to 0.01wt% may also improves the viscosity. If the nano concentration level increases above the 0.01wt% than there is a slight increase in viscosity but lesser than the virgin oil.

The flash and fire point limits may vary based on the oxidant, pressure and minimum oxygen concentration required for the combustion reaction [34]. From Fig. 8(c), it is clearly noted that nano modified sunflower oil has positive result in fire point and flash point while compare to the virgin oil. If the nano filler concentration level increases from 0.01wt% to 0.1wt% then there is an increase in flash and fire safety level of the insulation.

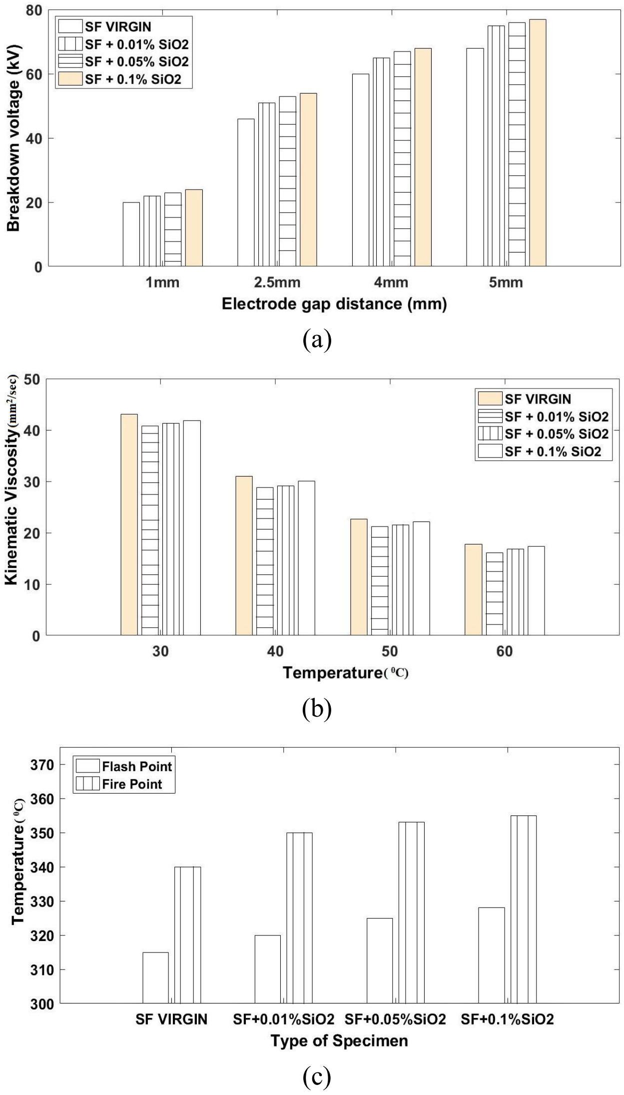


Fig. 8. Comparison of Virgin sunflower oil with nano modified sunflower oil (a) Breakdown Strength, (b) Viscosity, (c) Flash and Fire point

3.4 Tan-delta, dielectric constant, volume resistivity and capacitance of nano modified sunflower oil

Fig. 9 shows the experimental tan delta analysis of virgin sunflower oil along with nano modified sunflower oil at different temperatures. From the results, virgin sunflower oil shows high level of deterioration which means high level of imperfection present in the virgin oil sample. 0.01wt% nano sample shows less amount of deterioration while compared to the virgin oil. The 0.05wt% nano sample shows very less amount of imperfection and deterioration while compared to 0.01wt%, 0.1wt% and virgin sample. These results clearly show that the amount of dielectric loss through the nano modified oils enhanced better than virgin oils, due to the presence of hygroscopic insulative SiO_2 particles. The key role of SiO_2 nano particles is to absorb the water contents in the oil, which

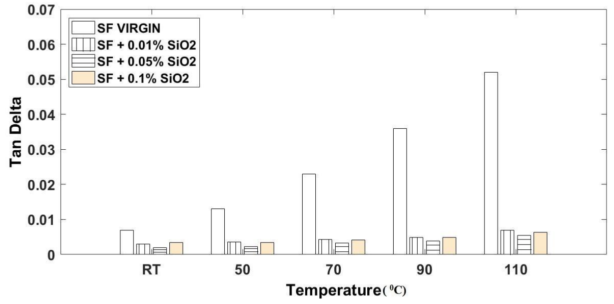
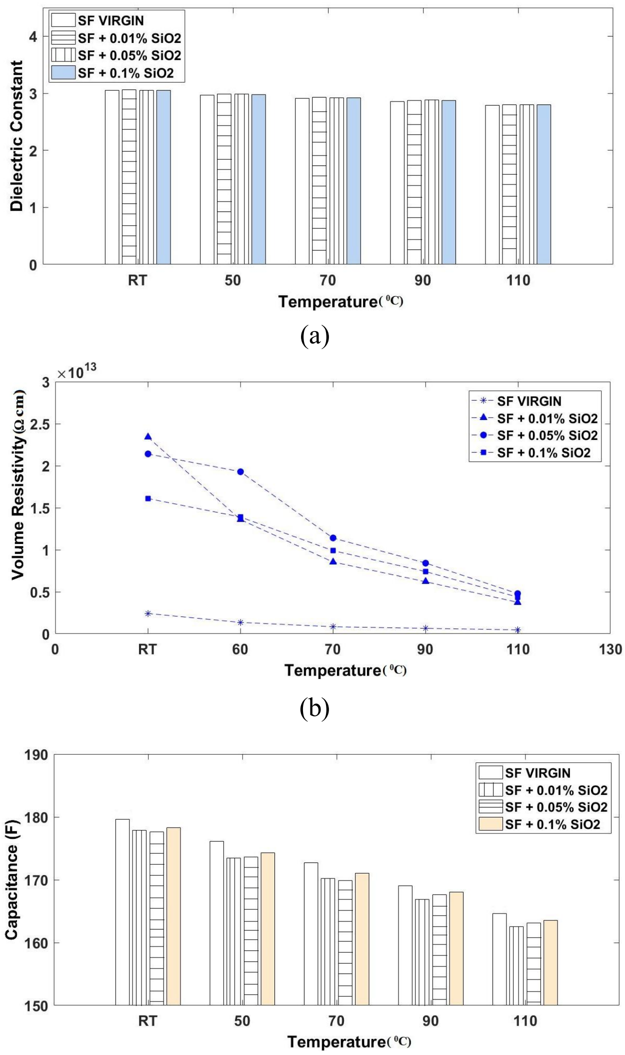


Fig. 9. Tan-Delta test for virgin sunflower oil and nano modified sunflower oil at different temperature



(a)

(b)

(c)

Fig. 10. Comparison of Virgin and nano modified sunflower oil at different temperature (a) Dielectric constant, (b) Volume Resistivity, (c) Capacitance

reduces the dielectric loss in the medium.

By comparing virgin sunflower oil with nano modified sunflower oil the dielectric constant shows nearly equal to each other. From Fig. 10(a) the dielectric constant at room temperature for virgin oil shows 3 as same as the entire nano sample. At 50°C and 70°C the dielectric constant shows 2.9 for virgin and also for all nano samples. At 90°C it shows 2.8 for entire samples and at 110°C the virgin, 0.01wt% and 0.1wt% of samples show 2.7 of the dielectric constant whereas for 0.05wt% of nano sample shows 2.8.

Volume resistivity varies greatly with the purity, ageing of the liquid insulation, time of the applied voltage, and sometimes with the amplitude of the applied stress. Fig. 10(b) shows volume resistivity results and it shows that sunflower virgin oil has low resistance in all temperature while compared to all other nano samples. 0.01wt% of nano sample shows high resistance while compared to virgin. 0.05wt% of nano sample shows higher resistance while compared to all other nano and virgin sample. This result also shows that up to 0.05wt% of nano concentration, it increases its volume resistivity while moving above 0.05wt% level the volume resistivity value starts to decline.

Fig. 10(c) shows the capacitance for virgin sample and nano sample at different temperature. At room temperature 0.01wt% of nano sample shows nearly equal capacitance value to 0.1wt% but higher than the 0.05wt% of sample. The capacitance value gets increased in 0.1wt% while compared to 0.05wt% and 0.01wt% of nano sample at all tested temperatures.

4. Conclusion

In this paper, the dielectric experimental investigations were carried out for SiO_2 modified sunflower oil and virgin sunflower oil. Based on the experimental results it was seen that while adding the nano filler from 0.01wt% to 0.1wt% of nano SiO_2 to base sunflower oil then there is an improvement in PD pattern, pulse spectrum, positive lightning impulse withstand strength, breakdown voltage strength and thermal characteristics than the virgin sunflower oil. Viscosity of the 0.01wt% of nano sample shows much improvement than the virgin and other nano samples. In the case of Tan-delta and volume resistivity, up to 0.05wt% of nano filler concentration there is an improvement in its performance. However while moving above 0.05wt% to 0.1wt% then the performance starts to decline slightly. Dielectric constant of nano sunflower oil samples show value nearly equal to virgin oil sample. In general while considering all experimental results it can be observed that the nano modified sunflower oil samples have much better insulation property than the virgin oil sample. From the experimental results, it seems that nano sunflower oils have enhanced dielectric performance than the mineral oil. While increasing the nano filler concentration above 0.1wt% level then the electrical performance starts to decline which may be due to agglomeration taking place in the nanofluids. Further research work on aging studies may find whether this oil is suitable for long term transformer applications.

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