

Analysis of Electrical Insulation Parameters of Nano Modified Corn Oil for Distribution Line Power Transformer Applications

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Abstract – Power transformer is one of the most expensive components in electrical network. Frequent breakdown of power transformers are reported mainly due to the failure of electrical insulation. Many researchers are working towards improving the electrical insulation properties of transformer oil. Present nano technology confirms that addition of nano fillers in the transformer oil provide superior electrical insulation properties. Recent concern towards environmental and fire safety of transformer operation has led to the development of natural ester based liquid insulation for power transformers. Hence it is important to evaluate the electrical insulation characteristics of nano modified natural ester based liquid insulation system. In this work, laboratory experimental works are carried out to understand the electrical insulation parameters such as power frequency breakdown voltage (BDV), volume resistivity, dielectric loss factor, relative permittivity, flash point, fire point, viscosity and lightning impulse streamer propagation characteristics of corn oil filled with SiO₂ nano fillers at different %wt concentration such as 0.01%, 0.05% and 0.1%. Lightning impulse withstand tests are conducted at both needle/plane and needle/sphere electrode geometry with 1.2/50 μ s waveform at both positive and negative polarity. It is noticed that addition of SiO₂ nano filler at lower %wt concentration in the range of 0.01% - 0.05% has significant influence in improving the BDV, volume resistivity, flash point, fire point, lightning impulse withstand and breakdown strength of corn oil. Results also reveal that the nano modified corn oil considerably reduces the dielectric loss factor and lightning streamer propagation velocity. Improvement in dielectric, thermal and LI streamer characteristics gives confident that nano modified corn oil may be considered for transformer applications.

Keywords: Power transformer, electrical insulation, nanofluid, BDV, dielectric loss factor.

1. Introduction

Electrical utilities give utmost preference for periodical evaluation of the electrical insulation characteristics of liquid insulation used in distribution line power transformers. Recent technological advancements have shown path to the development of natural ester based transformer oils considering its advantages over conventional mineral oils [1-7]. Chandrasekar et al., [1] analyzed the breakdown strength and PD characteristics of corn oil and palm oil. They have reported that corn oil has higher breakdown strength and partial discharge resistance than mineral oil. Senthilkumar et al., [6] have shown that the dielectric breakdown and partial discharge inception characteristics of thermally aged corn oil is considerably improved when compared with conventional mineral oil. In addition, recent developments in nanotechnology have also given horizons for the development of nanofluids as transformer insulation [8-18].

Prasad et al., [9] studied the dielectric characteristics of the nano-SiO₂ modified FR3 oil at different filler percentage concentrations. Many research papers are available in understanding the Lightning Impulse (LI) breakdown and withstand characteristics of conventional mineral oil [11-12]. However, in order to qualify nano modified natural ester insulating fluids for transformer applications and also to have a common dielectric clearance design, it should have similar LI withstand characteristics comparable with mineral oil. The AC, DC and LI breakdown characteristics of Fe₃O₄ and SiO₂ nanofiller added transformer oil were studied by T.S.Ramu et al. [11] and they have concluded that the dielectric breakdown strength of nanofluids greatly improved under all forms of voltages with considerable reduction in top and hot spot oil temperatures. Anandhan et al., [12] studied the LI characteristics of nano SiO₂ modified mineral oil and have shown that addition of nano fillers improved the lightning withstand and breakdown characteristics of mineral oil. Kevin J.Rapp et al., [13] studied the LI characteristics of Envirottemp FR3 fluid at both positive and negative polarity with quasi

uniform electrode configurations and concluded that impulse breakdown voltage of natural ester based fluid is similar to mineral oil. Arvind Shriram et al., [18] studied the PD signal Time-Frequency map and PRPD pattern characteristics of nano modified palm oil.

Considering these facts, extensive laboratory experiments are conducted in this paper in order to understand the BDV, dielectric loss factor, volume resistivity, relative permittivity, viscosity, flash point, fire point, LI withstand and breakdown characteristics of nano SiO_2 modified corn oil. Positive and negative lightning impulse voltage of standard time duration (1.2/50 μs) as per IEC standard is applied to needle/plane and needle/sphere electrode geometry. Dielectric, thermal and lightning impulse characteristics of nano modified corn oil are evaluated.

2. Experimental Setup

A. Preparation of Corn Oil Nanofluid

Corn oil available in the commercial market is utilized as a base fluid. Table 1 shows the physico-chemical and thermal properties of corn oil. Initially, corn oil sample was taken in a sealed steel container and thermally treated at 60°C for 24 hours inside a thermally controlled oven to remove the moisture content. Then the sample was allowed to cool in room temperature for 24 hours.

Table 1. Physico-chemical and thermal properties of corn oil as per manufacturer's data

	FP1 °C	FP2 °C	V @40°C mm ² /s	M %	SFA %	MUSFA %	PUSFA %
C	305	350	31	0.3	13.5	25.6	60.8

C-corn oil, FP1-Flash point, FP2-Fire point, V-Viscosity, M-Moisture, SFA-Saturated fatty acid, MUSFA-Monounsaturated fatty acid, PUSFA-polyunsaturated fatty acid

Nanofluid samples at different %wt SiO_2 concentrations, as shown in Table 2, were prepared as already discussed in Ref [9]. Magnetic stirrer and ultrasonicator were used in the preparation process as shown in Figure 1. In order to make the sample more stable, magnetic stirrer operation was performed initially for 45 minutes and then ultrasonication process was carried out for 20 minutes. This ensures the prevention of aggregations in the base corn oil and uniform dispersion of filler materials.

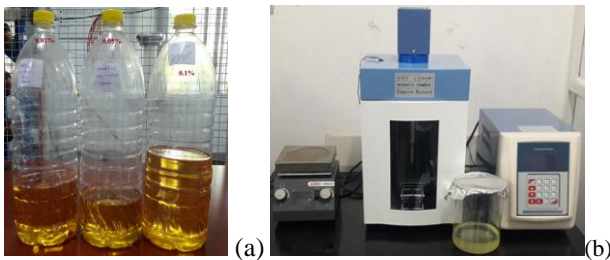


Fig. 1. (a) Nano silica modified corn oil at different %wt concentration of nanofiller (b) Photograph of magnetic stirrer and ultrasonicator used in the lab.

Table 2. Sample identity of nano-modified corn oil

Sample Identity	Detail
Type A	Pure corn oil
Type B	CO + 0.01% wt SiO_2
Type C	CO + 0.05% wt SiO_2
Type D	CO + 0.1% wt SiO_2

B. BDV, Viscosity, Flash Point and Fire Point Tests

Power frequency breakdown strength test was carried out as per IEC 60156 procedures using spherical electrodes at various electrode gap distances as described in Ref [1] and shown in Figure 2. Viscosity values of nano corn oils were measured using Redwood viscometer and test procedures were followed as already described in Ref [1]. Flash point and Fire points were measured using standard Pensky Martins open cup apparatus.

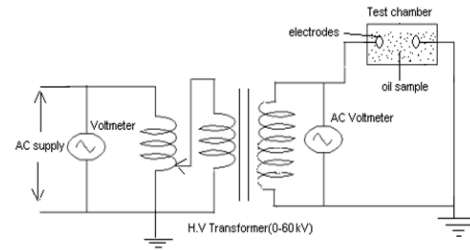


Fig. 2. Power frequency breakdown Strength Test Setup

C. Dielectric Loss Factor, Relative Permittivity and Volume Resistivity Tests

Dielectric loss factor, relative permittivity and volume resistivity tests were conducted for nano corn oils as per IEC 60247 using Eltel make test kit consisting of 3 terminal oil test cell as described in Ref [9]. Tests were carried out at different temperatures ranging from room temperature to 110°C.

D. Lightning Discharge Test Setup

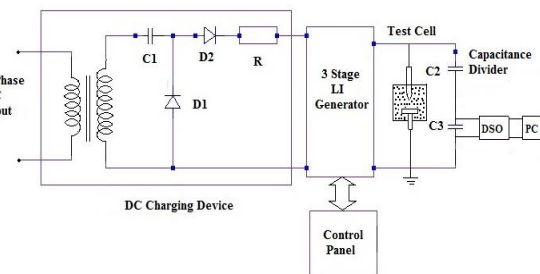


Fig. 3. Lab experiment setup used for generating standard 1.2/50 μs lightning impulse waveform

A transparent test cell consisting of a needle-plane (or) needle-sphere electrode system was filled with 200ml volume of nano corn oil. The top needle electrode was connected directly to the LI source. The bottom electrode was fixed firmly on the ground. The distance between the top needle and bottom plane electrode was kept at 5 mm (or) 10 mm. The schematic diagram of LI experimental

setup is shown in the Figure 3 consisting of a DC charging device connected to a 3 stage LI generator. In order to change the polarity of the LI waveform and to change the gap distance between the spark gaps, a motorized control panel is used.

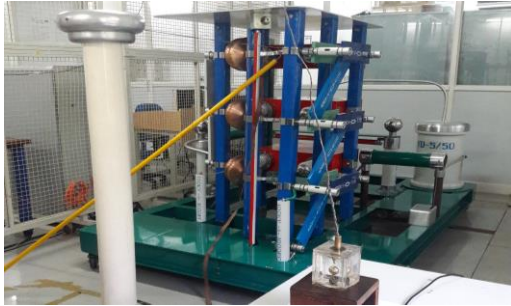


Fig. 4. Photograph of the laboratory experimental setup used for generating standard 1.2/50 μ s lightning impulse waveform connected with test cell

Photograph of three stage 300 kV Marx LI generator connected to the transparent test cell containing the liquid test specimen is shown in Figure 4. This Marx LI circuit charges the capacitor bank in parallel from the input d.c. source and discharges in series to deliver 1.2/50 μ s standard LI waveform. A standard high voltage 400 pF capacitor is used for voltage measurement. Tests were performed at room temperature and data is stored in PC integrated with digital storage oscilloscope.

3. Results and Discussion

A. Analysis of BDV Test Results of Nano Corn Oils

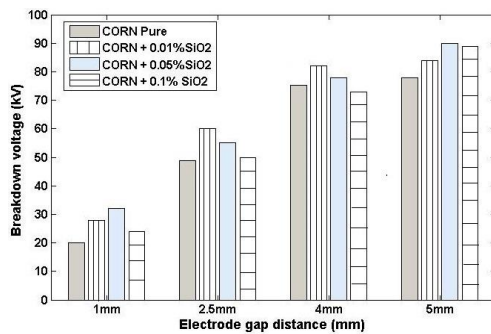


Fig. 5. BDV Test Results of nano corn oils at different gap distances

Figure 5 shows the breakdown voltage values of nano modified corn oils at different electrode gap distances. It is seen that type B and C sample shows higher BDV than other samples. In particular, significant increase in breakdown strength is observed with type B specimen with low concentration of filler material. However, type D specimen shows no significant enhancement in breakdown strength which may be due to the agglomeration of nano particles at higher concentration.

B. Viscosity, Flash Point and Fire Point Test Results of Nano Corn Oils

Figure 6 shows the viscosity, flash point and fire point results of nano modified corn oils. It is seen that there is no significant reduction in viscosity values when compared with virgin oil. In fact, a slight increase in viscosity is noticed with addition of nanofillers which is not so significant. However, due to the addition of SiO₂ nano fillers, considerable increase in flash point and fire point is noticed. There is no big improvement with respect to increase in %wt concentration of nanofillers.

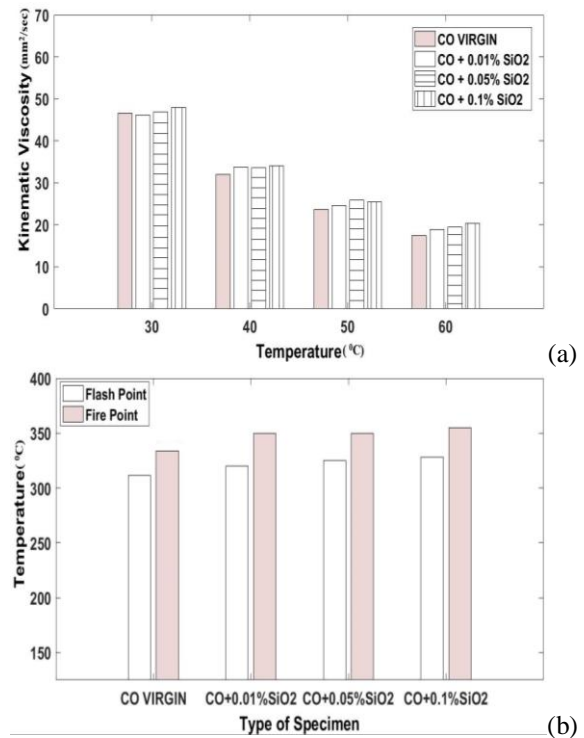


Fig. 6 a) Viscosity b) Flash and Fire point test results of nano corn oils

C. Analysis of Tan-delta, Dielectric Constant and Volume Resistivity of Nano Corn Oils

Figure 7 shows the tan-delta, dielectric constant and volume resistivity results of nano modified corn oils at different temperatures. Tan-delta values of nano SiO₂ modified corn oils are very less when compared with virgin oil. In particular performance of type C specimen with 0.05%wt concentration is much better than other specimens. Similarly in the case of volume resistivity, performance of 0.05 and 0.1%wt concentration are better than other samples. In the case of dielectric constant values, there is no significant improvement with addition of nano fillers except type B specimen.

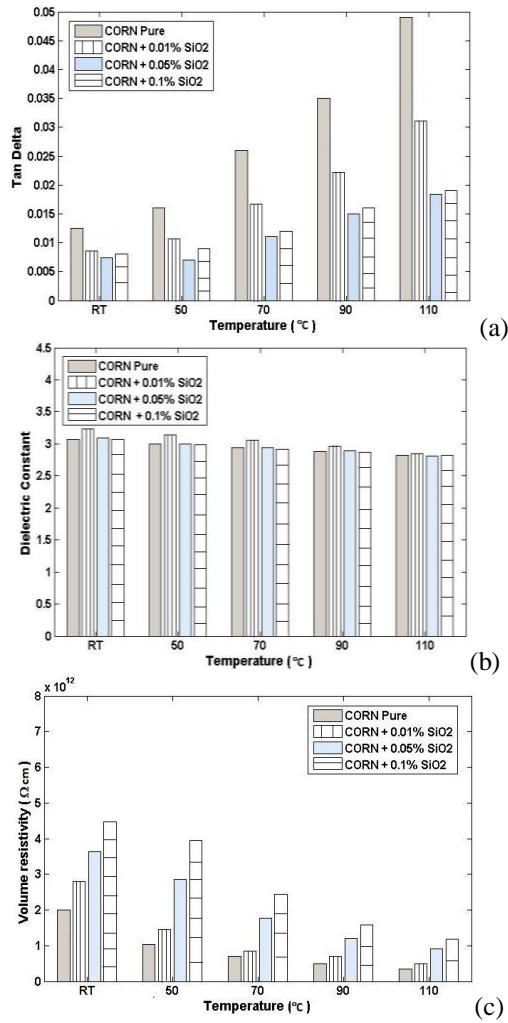


Fig. 7 a) Tan-delta b) Dielectric constant and c) Volume resistivity test results of nano corn oils at different temperatures

D. Analysis of LI Breakdown and Withstand Waveforms of Nano Corn Oils at Different Electrode Configurations

Initially the LI tests were carried out to know the breakdown and withstand waveforms of nano modified corn oil at different %wt SiO₂ filler concentrations and at different electrode configurations. Figure 8 shows the typical positive polarity LI withstand and breakdown waveforms of nano corn oils obtained at needle-plane electrode with 10 mm gap distance. It is observed that the front time and tail time of the generated LI waveforms are closely related with the standard 1.2/50 μs waveform. It is noticed that LI withstand and breakdown peak voltage of type C specimen is 116.45 kV and 120.25 kV respectively, which shows significant improvement when compared with other corn oil specimens. From the LI breakdown waveforms, it is noticed that tail time (T2) of 0.05%wt sample is considerably higher than other specimens. Similar trend of experimental results are obtained while maintaining the electrode gap distance as 5 mm.

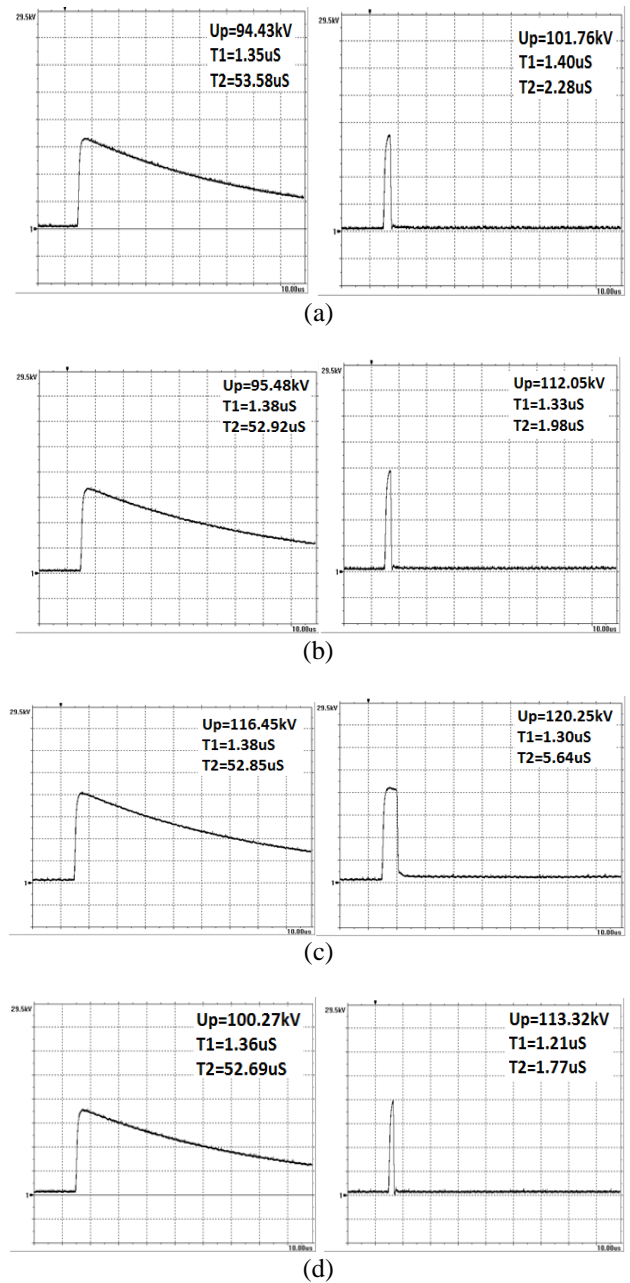


Fig. 8. Typical positive polarity lightning impulse withstand (left) and breakdown (right) waveforms obtained during needle-plane electrode with 10mm gap distance (a) Type A (b) Type B (c) Type C (d) Type D

Figure 9 shows the typical negative polarity lightning impulse withstand and breakdown waveforms of nano corn oils obtained at needle-sphere electrode with 5mm gap distance. In this case also, type C specimen (0.05%wt) shows significant improvement in both withstand and breakdown peak voltage. Performance of type D and type B specimen are very close to type C specimen. However, when compared with pure corn oil, significant improvement in LI breakdown and withstand capacity is observed with addition of SiO₂ nano fillers.

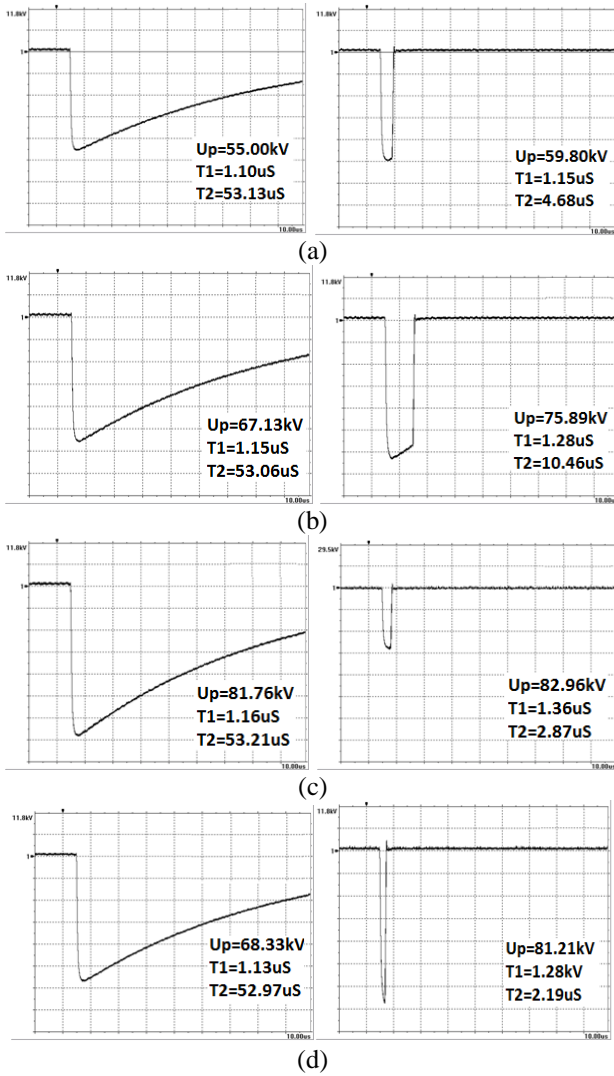


Fig. 9. Typical negative polarity lighting impulse withstand (left) and breakdown (right) waveforms obtained during needle-sphere electrode with 5 mm gap distance (a) Type A (b) Type B (c) Type C (d) Type D.

E. LI Breakdown Trend Analysis of Nano Corn Oils at Different Electrode Configurations

Since the breakdown phenomena of insulating oil under LI stress is highly non-linear and a statistical process, it is important to understand the breakdown voltage trend analysis of insulating oil with respect to increase in voltage and number of counts of operation. Experiments were carried out for all four specimens at both electrode configurations and at different electrode gap distances. Figure 10 and 11 shows the breakdown voltage trend pattern of type B specimen at different electrode configurations with 5 mm gap distance for both positive and negative polarity of LI waveform respectively. Failure and withstand voltages are shown in different markers. In general, irrespective of the type of specimen and polarity of LI waveform, it is clear that needle-sphere electrode configuration has higher breakdown voltage

when compared with needle-plane electrode for the similar experimental conditions.

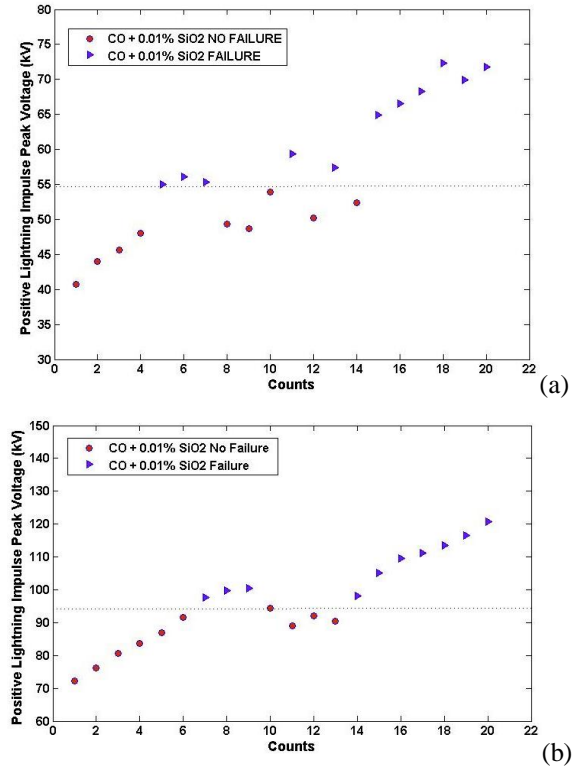


Fig. 10. Breakdown trend pattern of Type B specimen at positive polarity lighting impulse waveform obtained during (a) needle-plane (b) needle-sphere electrode with 5 mm gap distance

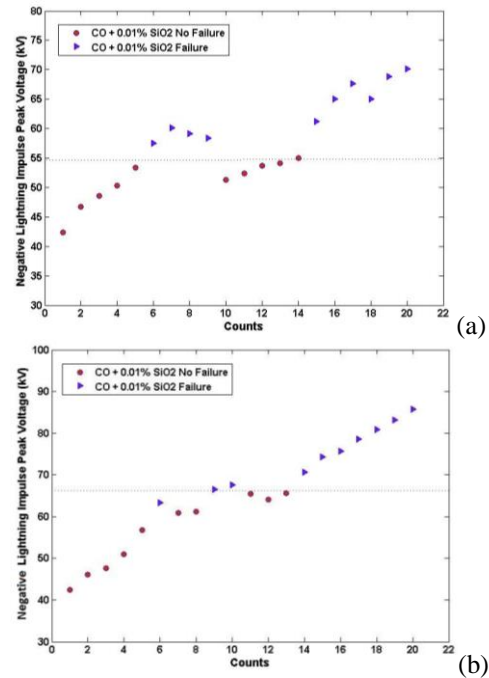


Fig. 11. Breakdown trend pattern of Type B specimen at negative polarity lighting impulse waveform obtained during (a) needle-plane (b) needle-sphere electrode with 5 mm gap distance

Based on the obtained results, a line of margin between withstand and breakdown voltage is drawn. LI voltage is applied for 20 counts at each polarity at both upper and lower limits of line of margin, in order to check the

repeatability of the test results. It is clear that mostly whenever the peak voltage of LI waveform crosses the limit of line of margin, then failure occurs. These test results are used to evaluate the mean breakdown voltage of nano corn oils at different electrode configurations.

F. Analysis of Mean LI Breakdown Voltage of Nano Corn Oils at Different Electrode Configurations

Based on the results of breakdown voltage trend analysis in the previous section, mean breakdown voltages of all specimens were evaluated. Figure 12 and 13 shows the mean LI breakdown voltage of nano modified corn oils at positive and negative polarity respectively. In general, it is noticed that nano modified corn oils show improved breakdown voltages at both positive and negative polarity of LI waveforms irrespective of the type of electrode and gap distance. This confirms that addition of SiO_2 nano fillers at lower %wt concentration will certainly improve the LI breakdown strength of nanofluid. In the case of positive LI, needle-plane electrode shows large difference in breakdown voltage at 5mm and 10mm gap distance, whereas in the case of needle-sphere electrode there is no big difference in results. At both positive and negative polarity, needle-sphere electrode breakdown voltage is higher than needle-plane electrode. When compared with nano modified mineral oil LI breakdown results reported in [12], it is noticed that nano modified corn oils show 50% improvement in positive LI breakdown strength at needle/plane geometry.

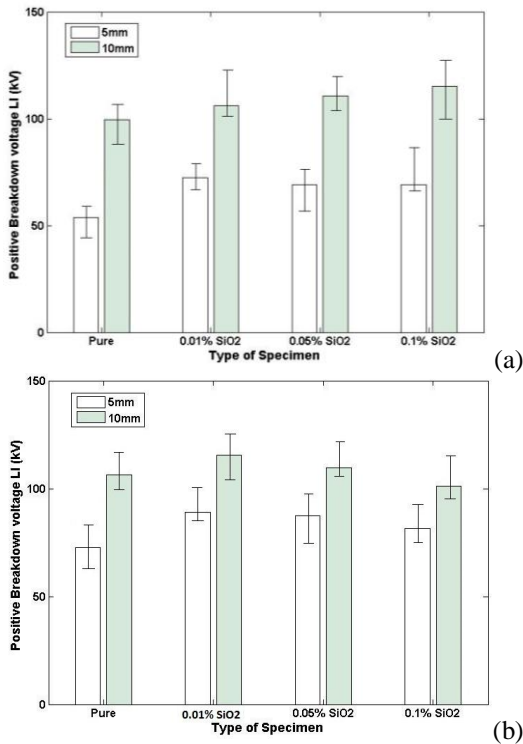


Fig. 12. Mean breakdown voltage of nano modified corn oils at positive polarity lighting impulse waveform obtained during (a) needle-plane (b) needle-sphere electrode at different electrode gap distance

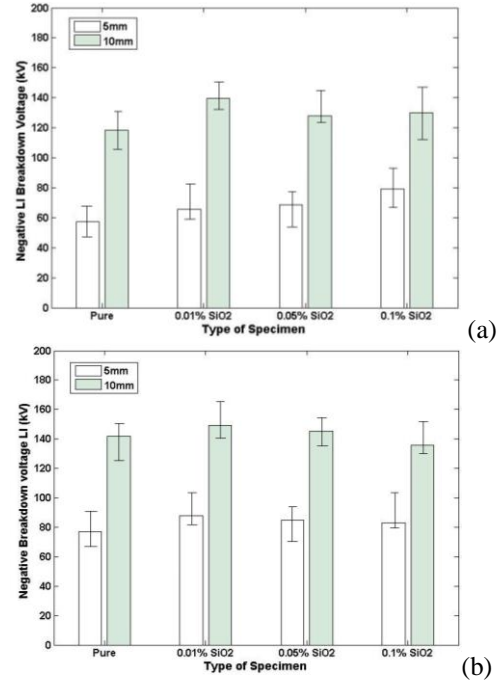


Fig.13. Mean breakdown voltage of nano modified corn oils at negative polarity lighting impulse waveform obtained during (a) needle-plane (b) needle-sphere electrode at different electrode gap distance

When compared with type B and C specimen, type D specimen shows slightly reduced breakdown voltage in most of the test conditions. This shows that addition of nano SiO_2 fillers above 0.1% wt concentration may lead to agglomeration of particles and may reduce the breakdown strength of nanofluid. In most of the test cases, performance of 0.01%wt and 0.05%wt concentration of nano SiO_2 filler specimen show better results than other specimens. In comparison with mineral oil results in [12], it is noticed that nano modified corn oils show 30% improvement in negative LI breakdown strength.

G. Influence of Voltage Stress on Front Time and Tail Time of LI Breakdown of Nano Corn Oils

The lightning impulse strength of the oil can be indirectly understood based on the speed of lightning streamer propagation in the oil medium. If the oil has higher LI strength, then naturally it will prohibit the speed of development of streamer in the medium, which can be evaluated based on the tail time (T2) of the lighting impulse waveform. Increase in voltage stress above breakdown strength will certainly reduce the tail time. In this study, influence of addition of SiO_2 nano fillers on the tail time of LI waveform with respect to increase in voltage stress is evaluated for nano modified corn oils at different electrode configurations. Figure 14 shows typical waveforms obtained for type A and type B specimen at needle-plane electrode with 10 mm gap distance. In the case of type A specimen, it is clear that when the LI peak voltage increases from 99 kV to 121 kV, then the tail time reduces from 2.4 to 0.6 micro seconds.

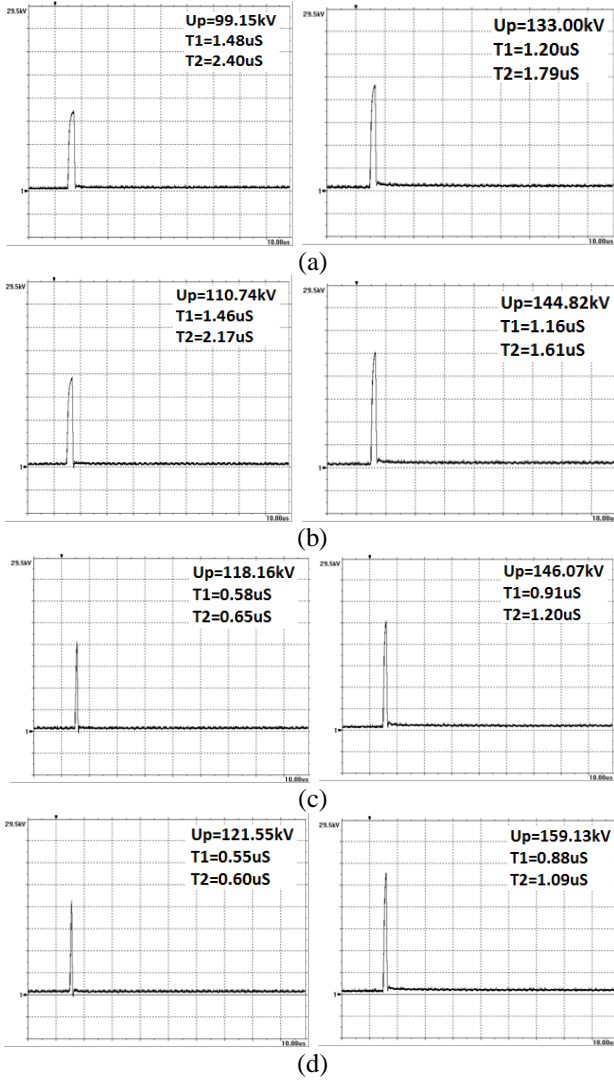


Fig.14. Typical positive polarity LI breakdown waveforms of Type A specimen (left) and Type B specimen (right) obtained at needle-plane electrode with 10 mm gap distance with increasing voltage stress

Whereas for type B specimen, it is seen that tail time lies in the range of 1.79 μs even at the peak voltage of 133kV, which shows significant improvement in the insulating strength of oil in prohibiting the growth of LI streamer in the medium. For type B specimen, test is continued until 159 kV peak voltage and it is noticed that T2 lies in the range of 1 μs . When compared with type A specimen, front time of type B specimen is significantly improved at all peak voltages. Similar trend of improvement in results are obtained for other nano modified oil specimens at both positive and negative polarity of LI voltage.

H. Analysis of Time to Breakdown of Nano Corn Oil at different Electrode Configurations

Test results of time to breakdown value of nano modified corn oils with respect to increase in voltage stress at 5 mm electrode gap distance are shown in Figure 15 and 16 at positive and negative polarity LI voltages. When the applied LI Peak voltage increases above breakdown threshold value, it is generally observed that the time to

breakdown value of nano modified corn oils show significant improvement when compared with pure oil.

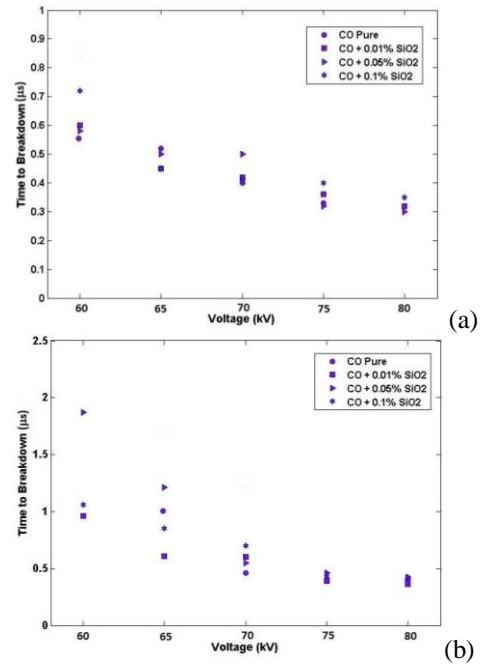


Fig. 15. Variations in time to breakdown value of nano modified corn oils at positive polarity LI waveform obtained during (a) needle-plane (b) needle-sphere electrode at 5 mm gap distance

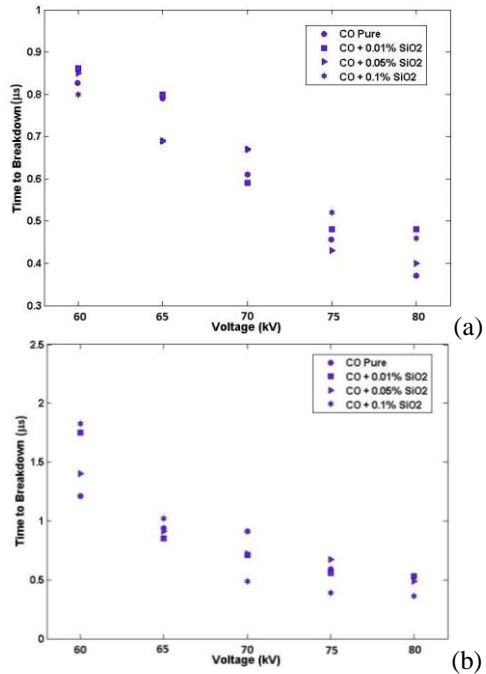


Fig. 16. Variations in time to breakdown value of nano modified corn oils at negative polarity LI waveform obtained during (a) needle-plane (b) needle-sphere electrode at 5 mm gap distance

Significant reduction in time to breakdown of all samples is noticed above 70 kV LI peak voltage for 5 mm gap distance. At higher operating voltages, time to breakdown value obtained with 0.01%wt sample is better than other specimens irrespective of the polarity and electrode arrangement. Also, time to breakdown values obtained

with needle-sphere electrode configuration is slightly higher than needle-plane electrode at both positive and negative polarity of waveform.

I. Analysis of Streamer Propagation Velocity of Nano Corn Oil at Different Electrode Configurations

Streamer propagation velocity is computed with the help of gap distance and time to breakdown value. Figure 17 and 18 shows the streamer propagation velocity of nano modified corn oils at both positive and negative polarity of waveforms respectively. It is possible to extract acceleration voltage of the LI streamer from the trend followed by streamer velocity with respect to increase in applied LI peak voltage. From Figure 17(a) it can be observed that above 70 kV, a sudden increase in velocity exists from 12 km/sec to 16 km/sec. From Figure 18(a) it is noticed that above 70 kV positive voltage, streamer velocity increases from 8 km/sec to 12 km/sec. Similar results are obtained in the case of needle-sphere electrode at both positive and negative waveforms. It can be understood that acceleration voltage of needle-plane and needle-sphere electrode configuration under both positive and negative LI waveform of nano modified corn oils is around 70 kV.

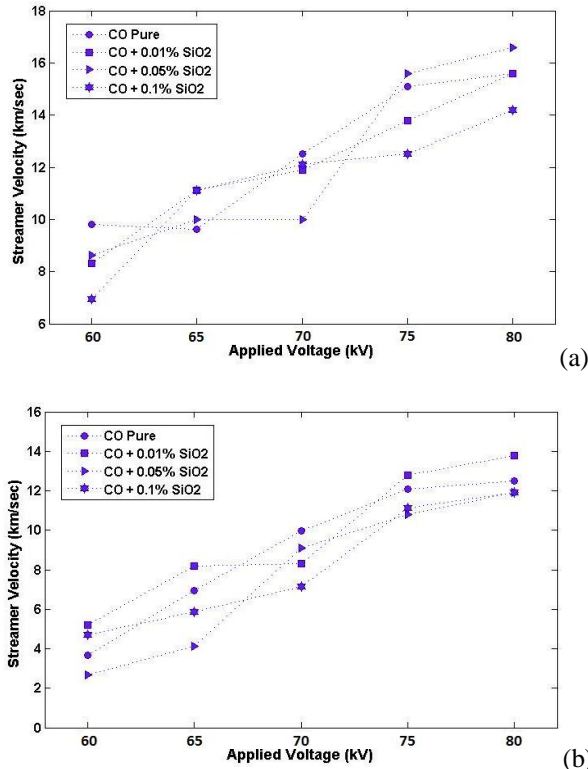


Fig. 17. Variations in streamer velocity value of nano modified corn oils at positive polarity LI waveform obtained during (a) needle-plane (b) needle-sphere electrode at 5 mm gap distance

Table 3 shows the acceleration voltage values of LI streamer at positive and negative polarity waveform of nano modified corn oils. In general, streamer velocity is slightly lower in the case of needle-sphere electrode

configuration, irrespective of the type of electrode and gap distance. It is also noticed that in the case of negative LI voltages, streamer velocity is lower in nano modified corn oils when compared with positive LI voltages. In general it is observed that nano modified corn oil shows slightly reduced streamer velocity when compared with pure oil.

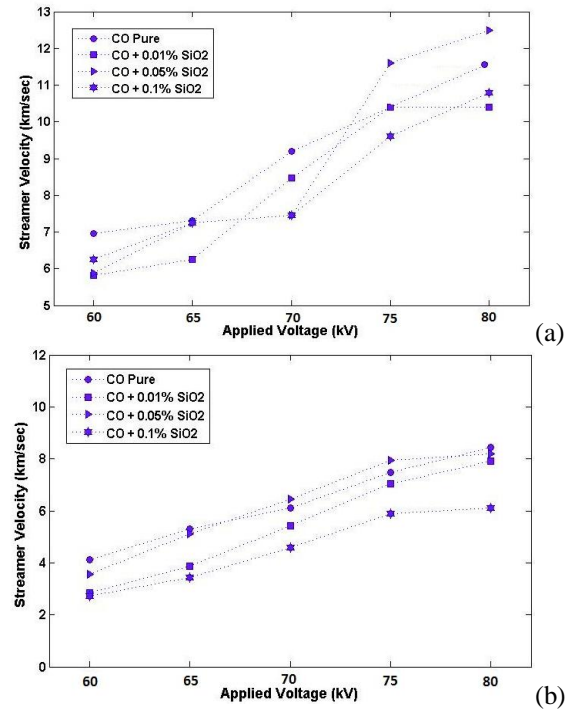


Fig.18. Variations in streamer velocity value of nano modified corn oils at negative polarity LI waveform obtained during (a) needle-plane (b) needle-sphere electrode at 5 mm gap distance

Table 3. Values of acceleration voltage of lightning impulse streamer at positive and negative polarity waveform of nano modified corn oils

Acceleration voltage (kV)	Needle-Plane		Needle-Sphere	
	5 mm	10 mm	5 mm	10 mm
Positive streamer	70	130	70	130
Negative streamer	65	125	65	130

From the above reported LI results of nano modified corn oils at different electrode configurations, it is noticed that addition of SiO₂ nano filler at lower %wt concentration in the range of 0.01% - 0.05% has significant influence in improving the LI withstand and breakdown strength of insulating medium. In addition, when the LI voltage is increased above breakdown voltage, then considerable increase in time to breakdown and reduction in streamer velocity is observed with nano modified corn oils. In comparison with Ref.[12] results of nano modified mineral oils at similar experimental conditions, 50% and 30% higher LI breakdown strength is seen at positive and negative polarity respectively for nano modified corn oils. These results confirm that addition of SiO₂ nano fillers in corn oil will certainly improve the LI breakdown strength and hence can be considered for outdoor power transformer applications.

4. Conclusion

Laboratory experiments on BDV, dielectric loss factor, volume resistivity, relative permittivity, viscosity, flash point, fire point, lightning impulse withstand and breakdown strength characteristics of nano modified corn oils at different %wt concentrations were carried out as per IEC procedures. Lightning impulse breakdown voltage, withstand voltage, time to breakdown, streamer propagation velocity and acceleration voltage of nano modified corn oils were evaluated at needle/plane and needle/sphere electrode geometry. It is noticed that addition of SiO₂ nano filler at lower %wt concentration in the range of 0.01% - 0.05% has significant influence in improving the BDV, volume resistivity, flash point, fire point, lightning impulse withstand and LI time to breakdown of corn oil. In addition, considerable reduction in tan-delta and LI streamer propagation velocity was noted in nano modified corn oils. However influence of nano fillers on the long term thermal performance of nano modified corn oil insulation is to be investigated in future studies.

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