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Tracking/Erosion Resistance Analysis of Nano-$Al(OH)_3$ Filled Silicone Rubber Insulating Materials for High Voltage DC Applications

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Abstract – HVDC technology has become popular as an economic mode of bulk power transmission over very long distances. Polymeric insulators in HVDC power transmission lines are affected by surface tracking and erosion problems due to contamination deposit, which pose a greater challenge in maintaining the reliability of the HVDC system. In addition, polymeric insulators are also naturally affected by aging due to various environmental stresses, which in turn accelerates the surface tracking and erosion problems. Research works towards the improvement of tracking and erosion resistance of polymeric insulators by adding nano-sized fillers in the base material are being carried out worldwide. However, surface tracking and erosion performance of nano-filled aged polymeric insulators for HVDC applications are not well reported. Hence, in the present work, tracking and erosion resistance of the nano $Al(OH)_3$ filled silicone rubber insulation material has been evaluated under DC voltages at different filler concentrations and aged conditions, as per IEC 60587 test procedures. Leakage current and contact angle measurements were carried out to understand the surface hydrophobicity. Moving average technique was used to analyze the trend followed by leakage current. Water aged specimen shows less tracking resistance when compared with thermal aged specimen. It is observed that nano-filler concentration of 5% is even sufficient to get better tracking/erosion resistance under DC voltages.

Keywords: Silicone rubber, Tracking resistance, Leakage current, Nano filler, Hydrophobicity

1. Introduction

In recent times, HVDC is the preferred technology for transmitting bulk amount of power over long distances. Polymeric insulators made of silicone rubber material are recently preferred in high voltage transmission systems, because of their excellent electrical properties [1]. However, failure of polymeric insulators due to tracking and erosion phenomena affects the reliability of the HVDC transmission system. Tracking or erosion occurs due to the electrical discharges across dry bands on the insulator surface under wet contaminated conditions. The impact of discharge varies with the surface electric field intensity and surface current magnitude, all of which are due to surface wetting and the degree of contamination. Once tracking or erosion occurs, the surface electrical insulation property is lost completely and it never recovers. In addition, polymeric insulators are also naturally affected by aging due to various environmental stresses, such as thermal stress, water absorption stress (due to fog, rain and moisture), etc., which in turn accelerates the surface degradation and tracking / erosion problems.

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In order to solve the problem of tracking and erosion of the insulation material, inorganic micro sized fillers are generally incorporated into the polymer materials and the results were reported in many papers [2-3]. Choosing proper filler is one of the most important aspects of silicone composite formulation and is based on the filler properties such as particle size, surface area, thermal and electrical conductivities. It is reported that microfiller contents from 30 to 65% by weight are necessary to achieve the required electrical properties for outdoor insulation applications. Nanotechnology has introduced the applications of nano fillers to enhance the electrical and mechanical properties of the insulating materials [4-5]. One of the advantages of nano sized fillers is their large specific surface area when compared with micro fillers.

Most of the tracking and erosion resistance studies carried out on polymer insulation are under the AC voltage [6-10]. Under AC voltages, it is easier to understand the surface degradation effects due to arcing from the third harmonic content analysis of leakage current (LC) [7]. Considering the recent advancements in HVDC technology, it has become necessary to understand the tracking/erosion phenomena with polymeric insulation materials under DC voltages [11-13]. The results of tracking phenomena of nano filled silicone rubber materials under DC voltages, in particular considering the effects of thermal and water absorption stress aged conditions, are scanty. Considerable databases have to be generated to identify a suitable insulation material for HVDC applications. In fact, due to greater accumulation of contamination over the insulators under the DC voltages, the problem of tracking phenomena is even more severe compared to that with the AC voltage and hence the tracking phenomena under the DC voltage has to be thoroughly understood.

Having known all this, in the present work, more care has been taken to understand the tracking phenomena in the nano filled silicone rubber materials by carrying out experiments according to IEC-60587 [14], under DC voltages, with ammonium chloride as the contaminant. In general silicone rubber offers good hydrophobicity for a long time providing high surface electrical resistance, which is attributed to its chemical stability and recovery phenomena due to diffusion of low molecular weight contents from bulk volume to the surface of the material [15]. However, hydrophobicity of material reduces due to water absorption and long term thermal stress. Therefore, influences of thermal and water ageing of specimen on the tracking resistance characteristics were also analyzed. The hydrophobicity of the nano filled silicone rubber materials were analyzed through contact angle measurement. The effect of aging & nano filler concentration of specimens on the tracking was analyzed through the LC measurement. Moving average technique was adopted to understand the trend followed by the LC during tracking process.

2. Test Specimen Preparation

Silicone polymer procured from Dow Corning, USA was used in the present study. $Al(OH)_3$ of size <50 nm, purity >99% supplied by Hefei Jiankun Chemical Industry was used for making nano-size filled silicone rubber specimens. The samples were prepared at different filler concentrations such as 5, 10, 20 and 30% by weight of the nano-fillers. The silicone polymer and fillers were weighed accurately and mixed thoroughly. After the addition of dicumyl peroxide curing agent, the mixture was stirred again, poured into a mould and degassed. In the pre-curing, which is mainly to impart dimensional stability, mould with the material was allowed to cure at relatively high temperature of 200˚C for 15 to 20 mins. During the post-curing process, which may be regarded as additional cross-linking under the influence of atmospheric oxygen, it is kept in uniformly air circulated oven at 170˚C for 16 hrs. Rectangular samples of size 34 cm×34 cm×5 mm were prepared from each composition and were cut into the appropriate size according to IEC-60587 test procedures.

3. Experimental Setup

Fig. 1 shows the schematic diagram of the experimental setup and the electrode configuration used in the study. The tracking resistance test on the nano filled silicone rubber material was carried out following the IEC-60587 inclined plane test method. The gap distance between the high voltage and the ground electrode was adjusted to be equal to 50 mm. The specimen was mounted at an angle of 45º and the contaminant was allowed to flow from high voltage to ground electrode over the surface of the plate specimen. 0.1N NH_4Cl was used as a contaminant. 0.02% weight non-ionic wetting agent (TritonX-100) was added to the contaminant to increase the surface wetting of the insulation material under test. The addition of nonionic wetting agent during tracking test is preferable because the hydrophobic effect of silicone rubber could be eliminated to certain extent.

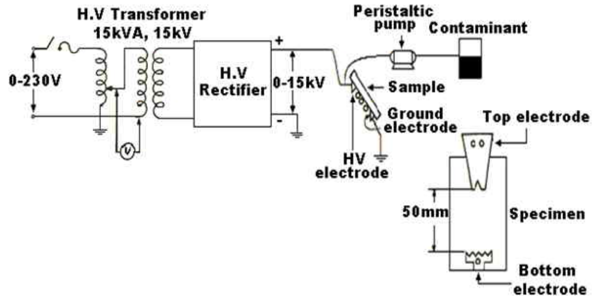


Fig. 1. Schematic diagram of tracking resistance experimental setup

The flow rate and conductivity of the contaminant was maintained at 0.6 ml/min and 2500 µS/cm respectively. DC voltage of 4.0 kV is connected to the top electrode and the bottom electrode is solidly grounded. Tracking time is evaluated as the time taken for the tracking path to reach 25 mm of gap within 6 hours. A set of six specimens were used to arrive at the tracking resistance of the material at a specified experimental conditions and the time to failure is the average of six failure times. The deviation in failure times in this set of experiments were within ±10% of the mean of the failure times. The leakage current (LC) measurement was carried out using a high frequency current transformer connected in the ground lead. A high sampling rate data acquisition system (NI, USB 6251, 1.25 MS/sec) was used in the present study. LC was measured at 5 kHz sampling rate. A software system developed for this data acquisition system provides the user with the complete LC waveforms for further processing. The investigations on tracking resistance were also carried out with nano filled silicone rubber samples aged under different conditions. Table 1 shows the details of test specimens used in this work.

3.1 Water aging

The silicone rubber samples were aged by placing the

Table 1. Details of test specimens

V	Virgin specimen
T	Thermal aged
WRT	Water aged at room temperature
W60	Water aged at 60°C

specimen in a water bath maintained at different temperatures, viz. 30 and 60º C for 240 hrs. The sample mass was taken out and contact angle was measured at the required instant of time during aging.

3.2 Thermal aging

The nano $Al(OH)_3$ filled silicone rubber samples were placed in a temperature controlled oven maintained at 250°C for 30 days. The oven was circulated with clean air. The initial colour of the sample was red and upon termination of aging, colour of the sample changed to pale red.

4. Concept of Moving Average Technique

The method of moving averages is widely used to understand the characteristic variation of data with time [16]. The basic understanding of a moving average is that it is the average magnitude of data at a specific point of time. The leakage current data captured over a period of time during the tracking test is highly nonlinear and intermittent in nature. In this case, instead of analyzing the raw data, it is better to discuss the average magnitude of current that moves with the addition of new data over a period of time, so that fluctuations with time are reduced and the characteristic variation of leakage current is smoothened out. Moving average current shows the stronger indication of the trend in the variation of leakage current magnitude over the period being analyzed. In the present work, a window consisting of k points was chosen to find the moving average using,

$$X_i = \frac{\sum_{N=i}^{N=i+k} Y_N}{k} \tag{1}$$

where X_i are the newly calculated moving average points corresponding to Y_N the raw data points. A 200 point window frame is used to smooth the LC data without missing any sharp variations.

5. Experimental Results and Discussion

5.1 Evaluation of tracking and erosion resistance

The tracking/erosion is basically a carbonaceous process. The silicone rubber insulators, on installation, surface of the material is highly hydrophobic, which maintains high surface electrical resistance of the material. However, in service, surface gets aged due to contaminations, electrical stress, thermal stress and water absorption stress; thereby the material slowly loses its hydrophobic nature. Therefore,

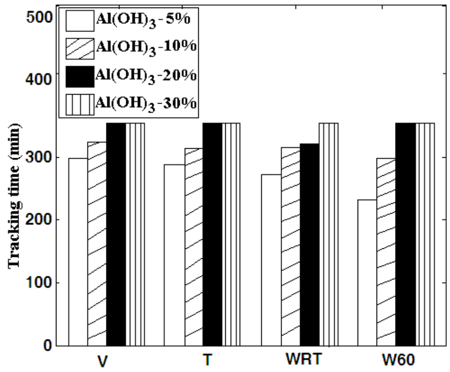


Fig. 2. Tracking time characteristics of nano $Al(OH)_3$ filled silicone rubber material at different filler concentrations and aged conditions

it leads to high leakage current flow under wet contaminated conditions, causing failure of material due to tracking/erosion. Fig. 2 shows comparison of the tracking time (which is a measure of tracking resistance of the material) of the silicone rubber specimen with nano sized $Al(OH)_3$ filler at different filler concentrations.

In general, no failure of the specimen is observed due to tracking when the nano $Al(OH)_3$ filler concentration goes above 10%, which shows that higher nano-filler concentration improves the physical properties of silicone compositions through molecular bonding with the silicone polymer. Nano sized $Al(OH)_3$ filler also acts as an arc quenching agent. At high surface temperatures due to dry band arcing, the degradation mechanism of filler material can be written as

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O \tag{2}$$

The formation of water molecules from the decomposition of filler material reduces the surface temperature of the silicone rubber material and hence avoids the surface degradation. Remaining Al_2O_3 material forms a protective layer for the base silicone polymer [11]. The filler is effective because it reacts either physically and / or chemically with the polymer to remove the degradation by-products formed by the dry band arcing from the surface of the material and hence the nano-filler helps in the prevention of total degradation of the material.

Tracking resistance is significantly higher in the case of virgin specimen when compared with aged specimens. Due to the harshness of the thermal aging, the tracking time of the thermal aged specimens is slightly reduced than the virgin specimens. This gives the information that a characteristic change in the surfacae of the material occurs due to thermal aging of the material. Water aged specimens show a considerable reduction in the tracking time when compared with other specimens. This clearly indicates that surface condition and nature of aging of the material plays a major role. In the case of water aged specimen, the saline water gets diffused into the body of the insulation

Table 2. Weight loss of nano $Al(OH)_3$ filled silicone rubber material at different filler concentrations

Filler concentration level (%)	Weight loss (%)			
	V	T	WRT	W60
5	0.165	0.390	0.767	0.983
10	0.184	0.294	0.489	0.978
20	0.179	0.212	0.376	0.789
30	0.032	0.129	0.131	0.238

enhancing the magnitude of leakage current flow during tracking studies, allowing early failure of material due to tracking.

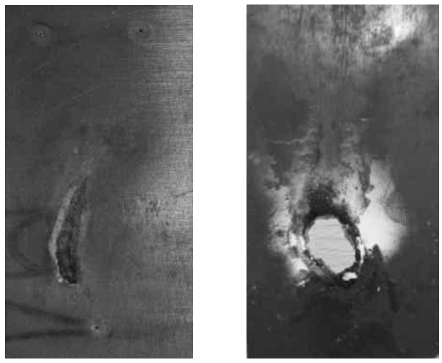
In order to understand the eroded volume of the material due to tracking test, the weight of the sample before and after tracking test were measured. Table 2 shows the comparison of the weight loss of the nano $Al(OH)_3$ filled silicone rubber material due to tracking test at different filler concentrations and different aging conditions. It is clear that irrespective of the type of filler, when the %wt nano filler concentration increases, the %wt loss of the material reduces. Water aged specimen shows considerable increase in weight loss when compared with other specimens. When the filler concentration increases above 10%, then significant reduction in eroded volume of the material is noticed and this is closely related with the earlier reported tracking resistance results.

Length of the tracked path also gives information about the surface tracking resistance of the polymeric material. After completing the tracking test, length of the tracking path of each specimen was measured and mean value of the tracking length is tabulated as shown in Table 3. It is observed that the aged specimen shows increase in mean value of tracking length when compared with virgin specimen. Also, considerable reduction in tracking length is observed when the filler concentration level increases above 10%. From the above reported results, it is observed that tracking time, eroded mass and tracking length of the silicone rubber material are closely related to each other and all these parameters gives significant information about the tracking and erosion resistance of the nano filled silicone rubber material.

Fig. 3 shows the photograph of failure of the material due to tracking and erosion during the test. Fig. 3(a) shows the tracked carbonized path and Fig. 3(b) shows failure due to bulk volume erosion of the material which occurs when large volume of material is eroded near to the ground electrode. This erosion condition mainly arises due to continuous long time floating arc near the ground electrode.

Table 3. Mean tracking length of nano $Al(OH)_3$ filled silicone rubber material at different filler concentrations

Filler concentration level (%)	Mean tracking length (mm)			
	V	T	WRT	W60
5	15.23	16.71	20.62	24.99
10	13.04	14.22	18.21	18.03
20	4.4	5.4	12.07	14.51
30	3.2	4.6	5.6	5.9



(a) (b)

Fig. 3. Photograph of 5% nano $Al(OH)_3$ filled silicone rubber specimen: (a) failure due to tracking; (b) failure due to erosion

5.2 Analysis of hydrophobicity of material

Contact angle measurement is an indirect measure of hydrophobicity of the insulation material. In general, if the contact angle of the material is above 90˚, it indicates that the material is hydrophobic and if the value is less than 90˚ it indicates that the material is hydrophilic. In the present work, contact angle was measured using electron microscope by liquid droplet method [17]. The size of the drop was about 1.5 mm in diameter. The contact angle is evaluated using the following equation,

$$\theta = 2\tan^{-1}\left(\frac{2h}{d}\right) \quad (3)$$

where d is the diameter of the liquid drop and h is the height of the liquid drop. After the water droplet is placed over the surface of the specimen, the contact angle is measured within 5 seconds. For each specimen, the contact angle was measured at six different locations and average of it is considered as the contact angle.

Fig. 4 shows that the variation in contact angle of the nano $Al(OH)_3$ filled silicone rubber material with respect to aging time at different water aging conditions. Reduction in surface resistance and hydrophobicity is mainly associated with the degree of water penetration in to the bulk volume. In order to understand the effect of temperature of water bath and for comparison purpose, the results of water aged sample at 90˚C temperature of water bath are also reported. In general, it is observed that the diffusion of saline water in the specimen with respect to aging time considerably reduces the contact angle. Irrespective of the nano-filler concentration level, when the temperature of the water bath increases, then considerable reduction in contact angle is noticed. However, when the filler concentration increases above

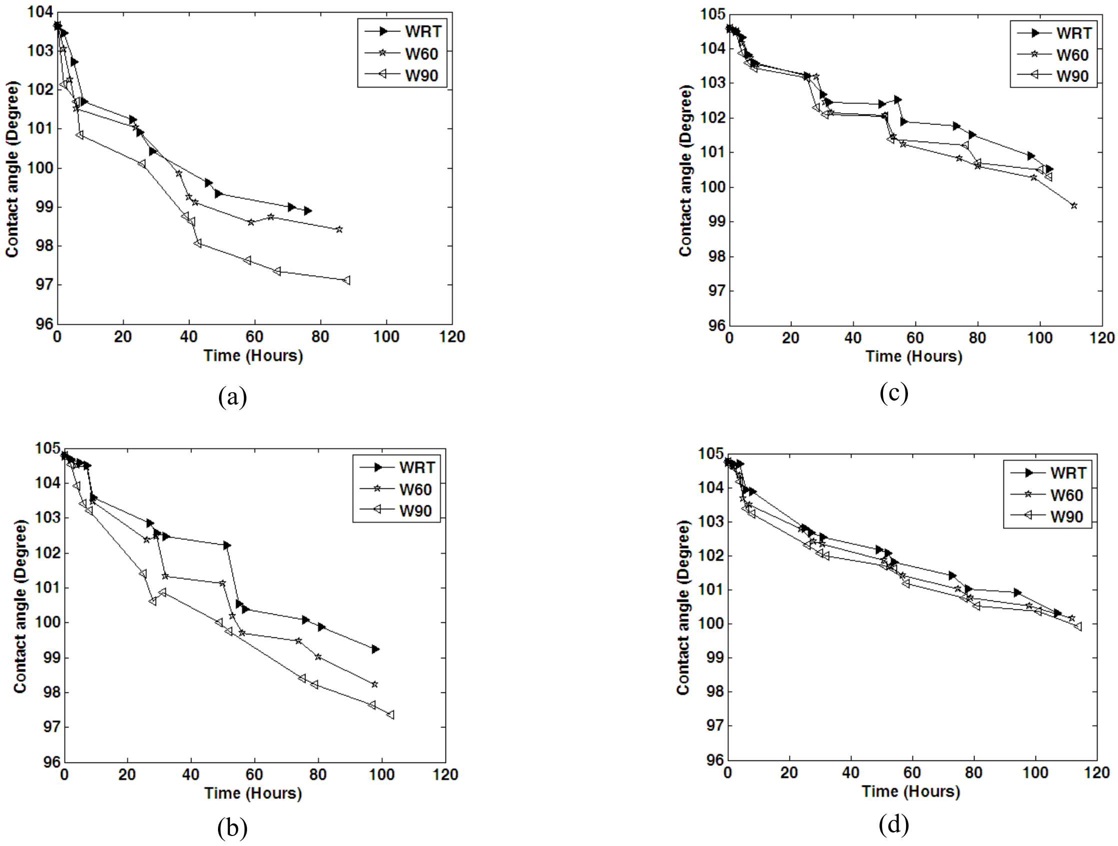


Fig. 4. Contact angle of nano filled SR material with respect to water aging time: (a) 5%; (b) 10%; (c) 20%; (d) 30%

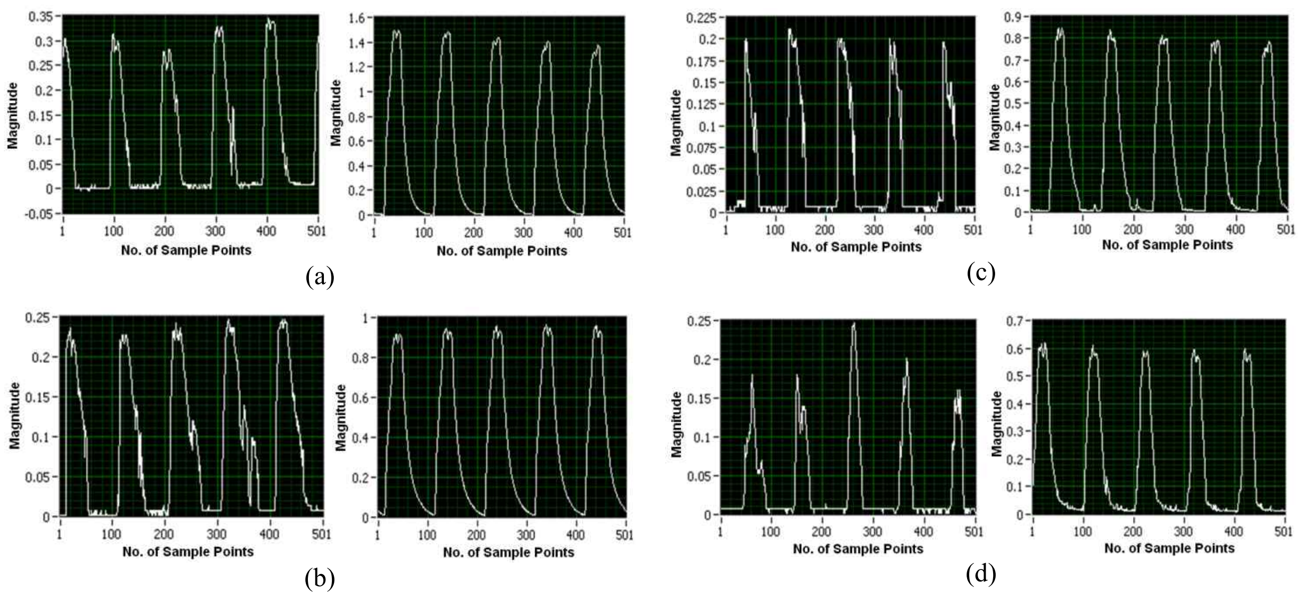


Fig. 5. LC signal of virgin SR obtained at initial stage (left) and final stage (right): (a) 5%; (b) 10%; (c) 20%; (d) 30%.

10%, then the nano composite silicone rubber material maintains the hydrophobicity and the value of contact angle is observed to be above 100˚ irrespective of the type of water aging. Comparing the tracking resistance results with the contact angle of the specimen, it clearly indicates that a reduction in the contact angle of the specimen correspondingly shows a reduction in the tracking time. It is also noticed that the nano $Al(OH)_3$ filler concentration above 5% is able to maintain contact angle above 90˚ i.e., the hydrophobicity of the silicone rubber insulation material for outdoor applications.

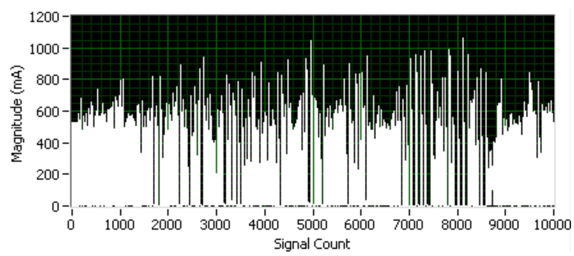
5.3 Leakage current trend analysis

Leakage current measurement and analysis provides useful information regarding the surface condition of the insulation material [18]. Chang et al., [19] studied the leakage current variation during tracking studies and concluded that magnitude of discharge depends on the surface wettability of the material. Fig. 5 shows the typical leakage current pattern of virgin specimen obtained during the initial and the final stage of tracking studies of silicone rubber specimen at different concentration level. LC signal pattern clearly shows that the magnitude of the LC signal is reduced as the filler concentration is increased. Figs. 5(a) & 5(d) clearly shows that, the magnitude of the LC pattern of the 5(d) is less than the magnitude of the LC pattern of the 5(a). In the LC pattern it is noticed that, surface electrical insulation property is improved by increasing the filler concentration on the SR material which is closely related to the tracking time results.

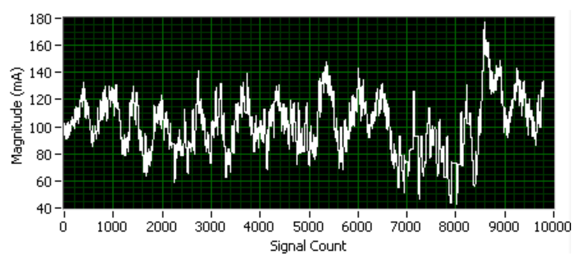
It is realized that during tracking studies, the surface discharge current magnitude is not constant and it varies arbitrarily as shown in Fig. 6(a). It is very difficult to come to a concrete conclusion based on the raw leakage current time domain data. Therefore, in order to understand the surface degradation of the nano filled silicone rubber insulating material under DC voltages, it is better to carry out the trend analysis of LC signals. El-Hag et al., [20] the condition of insulation structure by the measurement of leakage current adopting moving average measurement technique. They concluded that the moving average measurement technique could provide the tendency of current growth due to aging.

In this work, the trend followed by the LC pattern during the tracking process was evaluated using the moving average technique and a typical moving average plot is as shown in Fig. 6(b). The above reported characteristics of LC RMS plot and its moving average plot (Fig. 6) during tracking process shows that the surface condition of nano-composite insulating materials can be assessed by looking at the evolution of LC activity in the course of time.

Fig. 7 shows the moving average plot of LC signal of nano Al(OH)3 filled silicone rubber material at different aged conditions. It is observed that magnitude of leakage

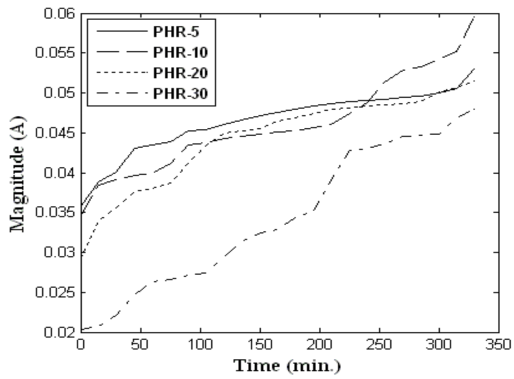


(a)

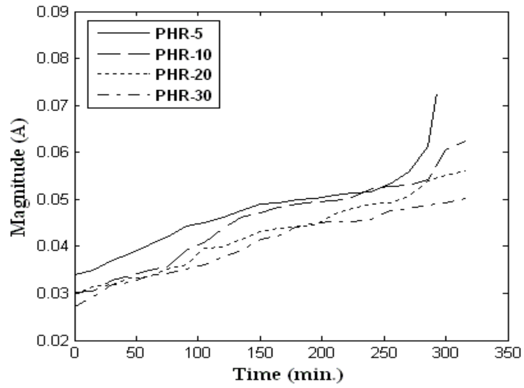


(b)

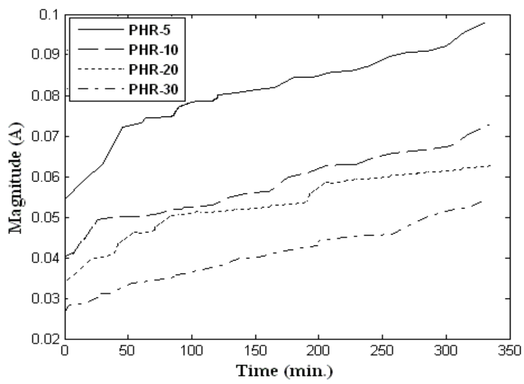
Fig. 6. Typical: (a) LC RMS plot and (b) moving average plot of nano size filled water aged SR material.



(a)



(b)



(c)

Fig. 7. Moving average plot of LC signal of nano size Al(OH)$_3$ filled silicone rubber: (a) Virgin; (b) Thermally aged; (c) Water aged at 60° degree

current flow in the un-aged specimen during the final stage of tracking experiment is around 50-60 mA. Under aged conditions, considerable increase in magnitude of leakage current (even more than 100 mA) is noticed and leads to severe dry band arcing which causes increase in surface temperature. This increase in local temperature leads to carbonization / polymerization / chain scission of the polymeric material. It is already reported that the accumulation of contaminants on the insulator surface under DC voltage is 1.2 to 1.5 times higher than that of under AC voltage for the same electric field conditions [11]. Therefore, under aged contaminated conditions and applied with DC voltages, high leakage current starts flowing in the conductive path formed by the contaminant leading to failure of material.

When compared with thermal aged specimen, in the case of water aged specimen it is noticed that the magnitude of current flow is continuous and increases the local temperature of the material. When water is absorbed into the bulk volume of silicone rubber material, ions or electrons in the contamination layer can migrate into the interior via absorbed water and develops leakage current through the bulk volume. Development of more leakage current promotes erosion and degradation of material. In addition, increased temperature of water bath (specimen W60) allows more water absorption by the material, which accelerates the degradation and leads to severe dry band arcing in the surface of material. In addition, increased surface roughness due to aging gives way for water particles to be held in the pits and cavities on the surface and leads to increase in leakage current and dry band arcing. Therefore, in the case of water aged specimens, occurrence of large number of high magnitude arcing on the surface is noticed, which causes faster tracking and erosion of the material.

It is also observed that irrespective of the type of aging, the magnitude of leakage current is significantly increased at lower filler concentration levels when compared with higher filler concentration levels. In general, relating the magnitude of current flow during tracking studies and the tracking time of the material, it shows an inverse relationship.

Therefore, the above reported characteristics of leakage current patterns during tracking process clearly show that the surface degradation of nano-composite insulating material due to tracking or erosion can be assessed by looking at the evolution of leakage current activity in the course of time. Also it is observed that the parameters such as tracking time, contact angle value and leakage current magnitude of nano composite silicone rubber insulation material are closely related with each other and it could be possible to understand the surface degradation of the material from the evaluation of these parameters. When compared with earlier reported results of micro filled silicone rubber materials [2-3], it is understood that the nano $Al(OH)_3$ filled silicone rubber material shows better tracking and erosion resistance characteristics under DC voltages. It is reported in literature that 40-60% of micro filler concentration is generally used in electrical industries to improve the tracking/erosion performance of silicone rubber material [11]. However, from the results of present work, it is also noticed that 5-10% nano filler concentration is enough to get better tracking and erosion resistance to get better performance of the material under DC voltages.

6. Conclusion

Experimental results on tracking and erosion resistance characteristics of silicone rubber material filled with nano size $Al(OH)_3$ fillers at different concentration levels under DC voltages have been presented in this paper. Influence of thermal and water aging of the nano filled silicone rubber material on the tracking resistance characteristics are studied. Water aged specimen shows less tracking resistance when compared with thermal aged specimen. The hydrophobicity characteristics of the nano filled silicone rubber material are evaluated using contact angle measurement at different aged conditions. Trend analysis of leakage current magnitude under DC voltages during tracking studies gives useful information about the surface degradation of the insulation material. It is realized that the tracking time and the leakage current magnitude shows an inverse relationship. In general, nano $Al(OH)_3$ filled silicone rubber material shows good tracking and erosion resistance under DC voltages as the filler concentration level increases above 5%.

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