Performance of Silicone Rubber Insulators under Thermal and Electrical Stress

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***Abstract*— In recent times due to several advantages, high temperature vulcanized (HTV) silicon rubber insulators (SIR) are being widely used for overhead high voltage transmission and distribution systems. However, over a period the insulator surface is exposed to high temperature in several places including desert areas, further accumulation of pollutants can alter the temperature distribution along the insulator. In the present work, effect of temperature on pollution performance of SIR insulators is attempted. A specially fabricated oven having a provision for high voltage connection and facility for measurement of leakage currents is made. Long term electro-thermal experimentation is carried out on various types of full scale insulator units. Further, study of migration of low molecular weight, recovery trends of hydrophobicity and the change in material properties using Scanning Electron Microscopy (SEM), Fourier transform infrared (FTIR) spectroscopy is carried out.**

I. INTRODUCTION

Silicone rubber (SIR) insulators are widely being accepted in electrical transmission and distribution sector owing to their promising features like unique hydrophobicity, better pollution performance, lower weight, ease of handling and installing, admirable resistance towards vandalism etc. [1]. Due to these advantageous properties of polymeric insulator, manufacturing industries are gradually capturing the larger share of the market over the conventional ceramic and glass insulators [1, 2]. In spite of superior performance, the long term reliability of polymeric insulators is still under investigation [3]. In the long run, surface degradation of such filled silicones are mainly caused by environmental stresses and electric activities [4, 5, 6]. One of the main environmental stresses is dry sunlight heating which influences the performance of SIR significantly in arid areas [6].

Thermal degradation studies of polymeric insulators have been extensively carried out by several researchers. Chang and Gorur [7] conducted thermal aging studies on HTV samples to investigate the effect of temperature on hydrophobicity recovery characteristics. The results indicate that high temperature accelerate the appearance of low molecular weight (LMW) on the surface of sample and thereby, causing a more rapid hydrophobicity recovery. Similarly, in [8], corona treated liquid silicone rubber (LSR) samples are exposed to different temperatures to evaluate the dynamics of hydrophobicity recovery process. Similarly, change in surface free energy of SIR is identified as one of the reasons for temperature dependent hydrophobicity in [9]. Though in literature [6, 10, 11], ultra violet (UV) radiation is also applied with electro-thermal stress, but it is found out that it does not play a major role in surface degradation of SIR for shorter duration of multi-stress aging tests [12].

Further, investigation on hydrophobicity transfer into artificial pollution layer was carried out in [8], reveal that diffusion of LMW and reorientation of molecular chains can be elevated by temperature. Researchers [13, 14] have conducted aging tests on polluted polymeric insulators and investigated the wettability class (WC) of full scale samples according to IEC Std.[15]. However, there is no standard pollution method available for polymeric insulators. CIGRE WG C4.303 [16] is working towards standardization of artificial pollution tests of polymeric insulators. Nevertheless, the literature available related to the effect of electro-thermal stress on pollution performance of full scale SIR insulators is scant.

The present work is focused towards the study of pollution performance on full scale HTV SIR Insulators under electro-thermal stress. The applied temperature parameter is selected based on the worst atmospheric temperature condition that a polymeric insulator can observe. A methodology has been proposed to achieve more uniform pollution layer on polymeric insulators compared to the method given in [16]. Also, leakage current (LC) is continuously monitored for different samples during the experiment and a significant change is observed in the characteristics of power frequency component of LC throughout the experiment for all the samples. Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscope (SEM) are effectively used to assess the relative performance of the samples.

II. EXPERIMENTAL DETAILS

A. Selection of Applied Parameters

The actual electric stress level for full scale HTV SIR test samples, having creepage length of 725 mm, has been calculated according to IEC Std. [17]. But determination of corresponding thermal stress parameter is based on the temperature profile of our country taken from European Centre for Medium-Range Weather Forecasts [18]. Temperature distribution is studied for different parts of the country and it is observed that unlike coastal areas, the meteorology of the inland arid Thar desert situated in Rajasthan are very hot, especially, the extreme west part of Thar is found to be the hottest place (maximum 51.5°C, average being around 47.0°C during summer) with sparse occasional rain or no rain at all for years. The values indicate that temperature spread over the years are quite higher as compared to the values recommended in the IEC Std. 61109 [19]. According to [6], about 12°C will be the temperature rise on the outdoor insulator surface with respect to ambient temperature due to continuous sun-light hitting on the surface in dry weather throughout summer. The applied stresses used for the experimental study are ac voltage of 21.0kV$_{rms}$, temperature 60.0°C and time duration is 500 hours.

B. Pollution Technique Adopted

Solid layer method is used as per IEC Std. 60507 [20] in which sodium chloride provides the conductivity and the clay helps the salt to be retained on the surface of the insulator for a long time. Salt of 10g/l for medium pollution and 15 g/l for heavy pollution is used [21].

CIGRE WG C4.303 [16] has come up with a method for applying pollution layer on polymeric insulator surface. It involves preconditioning of insulators before applying pollution slurry by spray method. Some literatures are available in which spraying method has been adopted in pollution testing of composite insulators [22, 23, 24]. However, in the present work, for full scale insulator units, it was observed that using preconditioning phase, creation of uniform pollution layer on SIR is almost impossible due to inherent hydrophobic nature of SIR surface. Pollution slurry forms discrete droplets on the surface and certain part of the contamination will be washed away by the jet from the spray nozzle. Hence, the key requirement before applying the pollution slurry is to make the SIR surface hydrophilic. Therefore, a modified dipping method is proposed for achieving uniform pollution layer on the insulator surface.

The insulator samples are cleaned and dipped in normal tap water for 24 hours so that water molecules get attached with the SIR surface and temporarily induce hydrophilicity on the insulator surface. After 24 hours uniform contamination layer can be applied by dipping the insulators in pollution slurry. Experiments can be performed as soon as the pollution layer gets dry or with some elapse time. In this paper, recovery phase is taken as 24 hours for all the samples.

C. Test Samples used

Commercially available full scale HTV SIR insulators with creepage distance of 725 mm have been used in this present work. The details of samples used in this experiment, are given in Table 1.

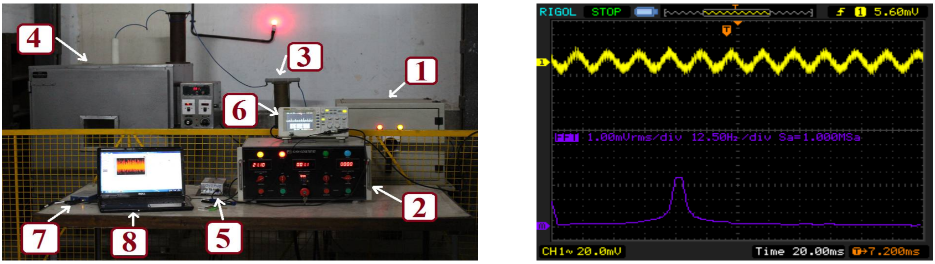
TABLE 1: TEST SAMPLE DETAILS

Name	Type	Condition
HTV 1	Fresh sample	Under electro-thermal stress
HTV 2*	24 hours dipped in tap water without pollution	
HTV 3*	Medium Polluted Sample	
HTV 4*	Heavily Polluted Sample	
HTV 5*	Heavily Polluted Sample	No stress is applied

*Samples with 24 hours recovery phase

D. Experimental Set-Up

Experimental arrangement for the present study is as illustrated in Fig 1(a). The set up consists of a specially fabricated oven having dimension of 750mm x 750mm x 750mm with a special provision made for high voltage (HV) lead and leakage current monitoring. The oven has a temperature control range up to 200°C. The HVAC source provides a continuously varying voltage of 0-30kV$_{rms}$, 50 Hz. The test set up is provided with an over current protection for safety. Fabricated shunt box is used at the ground side of test samples to tap voltage across a 1 kΩ for LC measurement of each treated samples. RIGOL DS1042C digital oscilloscope (40 MHz, 400 MSa/s) is used for real time LC monitoring. LC data acquisition with a very high sampling rate (500 kSa/s) is done using National Instruments compact DAQ-9171 operated in LabVIEW platform.



(a) (b)

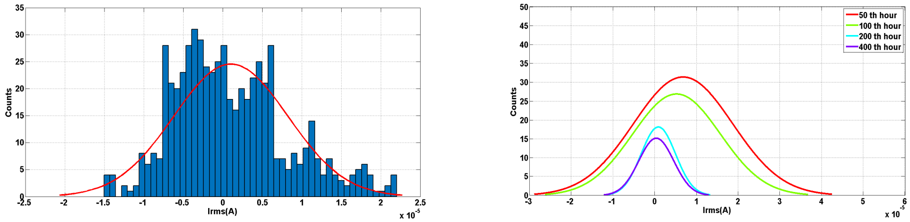
Fig. 1. (a) Experimental arrangement for electro-thermal aging studies.
1: HVAC source, **2**: Control panel, **3**: Current limiting resistor 15 kΩ, **4**: Furnace, **5**: Shunt box,
6: Digital Oscilloscope, **7**: NI cDAQ for LC measurement, **8**: NI cDAQ data acquisition in LabVIEW environment
(b) Leakage Current Waveform & FFT spectrum of HTV 1 at 430th hour

III. RESULTS AND DISCUSSIONS

A. *Leakage Current Analysis*

A typical leakage current waveform captured during the experiment is shown in Fig. 1(b). Also FFT spectrum corresponding to that LC wave is obtained from the digital oscilloscope. It is evident that 50 Hz component is dominating in LC and its variation, throughout the aging period, will be governed by surface resistivity of the treated full scale insulators, i.e., HTV 1, 2, 3, 4 samples.

Accordingly, the power frequency component of LC is taken into consideration and is processed employing histogram analysis technique. Histogram of the 50 Hz filtered data is plotted and a normal distribution is fitted to it using MATLAB as shown in Fig. 2(a). Significant variation in the normal distribution characteristics is obtained through out the test duration of 500h for all the treated samples. A typical variation in LC distribution of HTV 2 in shown in Fig. 2(b).



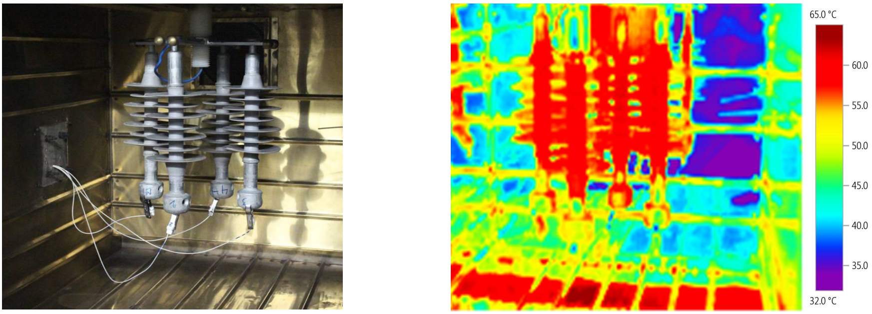
(a) (b)

Fig. 2. (a) Histogram and fitted Normal distribution plot of filtered LC for HTV 2 at 70th hour
(b) Variation in distribution of filtered LC over the experimental period for HTV 2

From Fig. 2(b), it is apparent that over the test period, base of histogram is decreased very rapidly up to almost 200 hours and then the variation got saturated.

B. Thermal Image Acquisition

During the experimentation, temperature is also monitored on the sample surface. A typical measurement carried out using a Testo 875 -1i model thermal imager on the insulator samples is shown in Fig. 3(a) – 3(b).



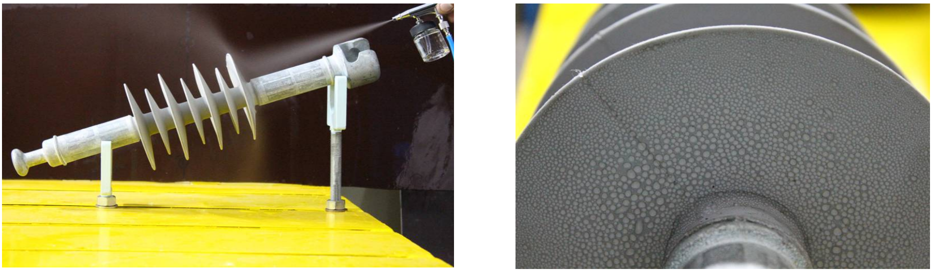
(a) (b)

Fig. 3. (a) Real Image (b) Thermal Image taken at 440th hour

It is noticeable from Fig. 3(b) that all insulator samples are uniformly stressed by thermal energy and the temperature variation along the insulators are approximately maintained near 60°C.

C. Wettability Class Measurement

Wetting nature of the test insulator surface has been examined using spray method as depicted in IEC TS 62073 [15]. 11 ml distilled water of conductivity 8 µS/cm is sprayed in 30 s over the test area of 69 cm^2 which is selected as the top-most and bottom-most shed of every test sample. According to [25], samples are kept at an inclination of 10°-35° from horizontal line during hydrophobicity class measurement as shown in Fig. 4(a). In order to make measurements comparable, all photographs are captured from approximately same distance using Canon EOS 700D with all camera parameters constant. A typical WC measurement carried on HTV 1 is shown in Fig. 4(b).



(a) (b)

Fig. 4. (a) Set Up for WC measurement of test samples using spray method
(b) WC 1 measured on bottom-most shed of HTV 1 at 290th hour

It is observed during the course of the experiment that polluted electro-thermally treated samples HTV 3, HTV 4 are recovering hydrophobicity at a faster rate compared to polluted untreated HTV 5 as shown in Fig. 5(a) – 5(f) which is in accordance with [7, 8, 9].

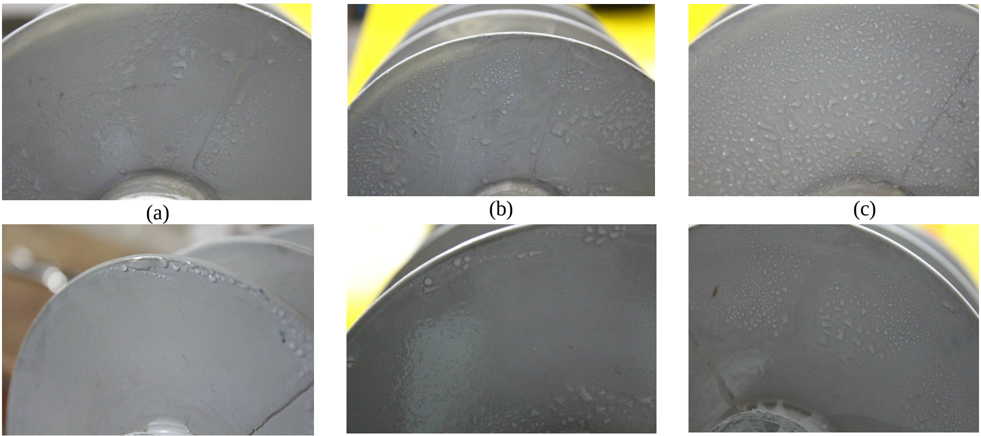

(a) (b) (c)
(d) (e) (f)

Fig. 5. (a) WC 7 on top-most shed of HTV 3 at 50th hour (b) WC 5 on top-most shed of HTV 3 at 300th hour (c) WC 3 on top-most shed of HTV 3 at 500th hour (d) WC 7 on bottom-most shed of HTV 5 at 50th hour (e) WC 6 on bottom-most shed of HTV 5 at 300th hour (f) WC 5 on bottom-most shed of HTV 5 at 500th hour

D. Fourier Transform Infrared Spectroscopy (FTIR) Analysis

In the present study, FTIR is performed on all test samples using Perkin Elmer FTIR/FIR spectrometer frontier model equipped with the MIRacle™ single reflection horizontal attenuated total reflection (ATR) accessory having diamond crystal. Each specimen is scanned sixteen times for accurate measurement and the average value is reported. Fig. 6 shows the IR transmittance spectrum for all the samples under investigation. Following bonds and their corresponding wave numbers are important for analyzing the thermal effect on SIR, C-H symmetric stretching in CH_3 at 2962 cm^{-1} in Fig. 7(b), CH_3 asymmetric stretching at 1260 cm^{-1} in Fig. 7(c), Si-O-Si symmetric stretching at 1008 cm^{-1} in Fig. 7(d) and Si-C symmetric stretching at 788 cm^{-1} in Fig. 7(e) [26]. Apart from the peaks mentioned above, the variation found in the region 3700 cm^{-1} to 3200 cm^{-1} characterizes the O-H bonding present in the ATH as shown in Fig. 7(a).

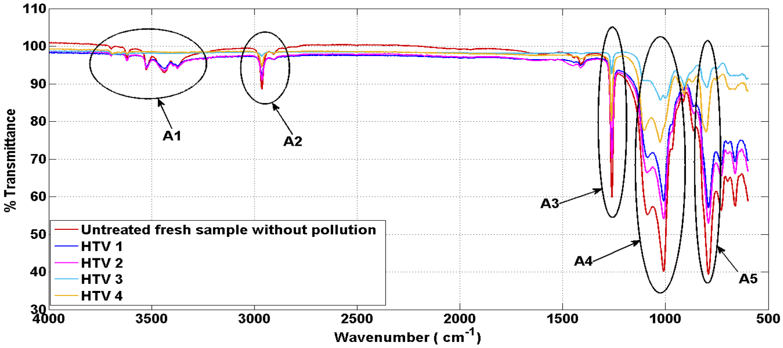


Fig. 6. FTIR transmittance spectrum of all samples used for the experiment at 500th hour

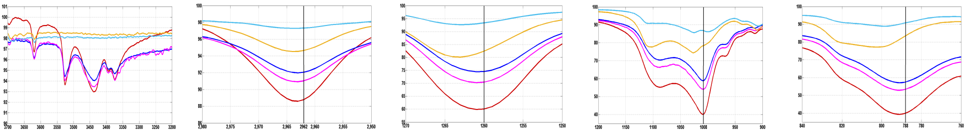

(a) (b) (c) (d) (e)

Fig. 7. (a) Inset A1 (b) Inset A2 (c) Inset A3 (d) Inset A4 (e) Inset A5 corresponding to Fig. 6.

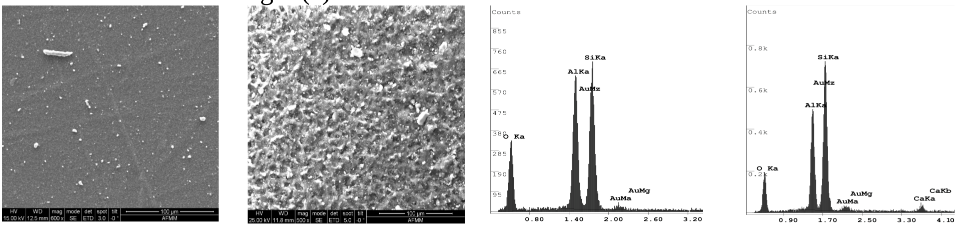
It is evident from Fig. 7(a) – 7(e) that rupture of molecular bonding occurred on SIR surface due to continuous dry heating throughout the experiment. In fact, the reduction in the Si-O-Si peak in Fig. 7(d) signifies the de-polymerization due to scission of main chain as a result of electro-thermal treatment. FTIR study also depicts that rupture of bonding at surface level is more for the polluted test samples HTV 3, HTV 4 compared to other samples. This may be due to LMW penetration into pollution layer during hydrophobicity recovery phase which causes higher splitting of surface level bonds.

E. Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Analysis (EDAX)

SEM is carried out using FEI make ESEM QUANTA 200 which is equipped with the EDAX detector to identify the elemental composition of the material under observation. The electron gun of the SEM is operated in the voltage range of 15-25 kV, in high vacuum mode. To avoid charging effect, gold coating of 10 nm thickness is given on the insulator samples by using gold sputtering technique.

SEM and EDAX analysis is conducted for all the test samples. Typical result in Fig. 8(b) shows HTV 1 whose surface roughness is found to be more than that shown in Fig. 8(a) for untreated fresh sample without pollution. This may be due to the same observation made from FTIR analysis that surface level bond breakage occurred on the sample during the electro-thermal treatment.

EDAX analysis for both untreated fresh and treated HTV1 sample is presented in Fig. 8(c) and 8(d) respectively. Fig. 8(c) shows peaks for silicone, aluminum, oxygen and gold. Aluminum is detected because of the added ATH filler and the gold because of the surface gold coating. For HTV 1, the EDAX result, in Fig. 8(d), shows significant decrease in the ATH content which is evident from the reduction in the peak corresponding to the aluminum in comparison to that of the untreated fresh sample without pollution. Reduction in the ATH will deteriorate the resistance to tracking and erosion of SIR [27]. It is also observed that EDAX for HTV 1 shows a decrease in the oxygen peak which is in agreement with the FTIR result showing O-H bond rupture with heat treatment as illustrated in Fig. 7(a).



(a) (b) (c) (d)

Fig. 8. SEM results of (a) Untreated Fresh Sample without pollution (b) HTV 1 at 500th hour
EDAX results of (c) Untreated Fresh Sample without pollution (d) HTV 1 at 500th hour

Typical SEM results on HTV 3 and HTV 4 is presented in Fig. 9(a) – 9(b) where pollution layer is clearly visible on the thermally treated insulator surfaces.

(a) (b)

Fig. 9. SEM results at 500th hour on (a) HTV 3 (b) HTV 4

IV. CONCLUSIONS

The important conclusions drawn from the present work:

1. Methodology proposed for applying pollution on SIR is believed to give uniform contamination layer on the insulator surface.
2. Effect of dry heating is clearly reflected in the characteristics of power frequency component of leakage current for all the test samples.
3. Wettability Class measurement clearly indicates the dependency of hydrophobicity recovery on temperature, with higher temperature, recovery process gets faster.
4. Both FTIR and SEM indicate surface level bond rupture on dry heating of the insulator samples. EDAX analysis gives the indication that with heat treatment, ATH content of HTV SIR will decrease and will significantly affect the long term performance of the polymeric insulator.

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