Quantification of surface erosion in polymeric insulating material under electrical stress using FTIR, SEM and edge detection

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Abstract: Silicon rubber (polymeric) insulators are extensively preferred in overhead power transmission networks due to their superior performance over the conventional insulators. The surface degradation is an important concern for the insulators as it is organic in nature. The degradation may be caused by a variety of factors like electrical and environmental stresses which will result in the failure of the insulator. This paper discusses the surface erosion study of silicon rubber by applying 3.5 kV voltages (AC and DC with both the polarities) as per IEC 60587. To quantify the surface erosion, Fourier transform infrared (FTIR) and scanning electron microscopy (SEM) have been used. Further, the results are verified by edge detection techniques using Sobel and Prewitt edge detection algorithm. The study revealed that the surface erosion is more with positive DC voltage than AC and negative DC which demands the introduction of appropriate filler materials to enhance the surface properties of the silicon rubber.

Keywords: silicon rubber insulator; surface degradation; erosion; IP test; Fourier transform infrared; FTIR; scanning electron microscopy; SEM; edge detection.

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1 Introduction

The silicon rubber (SR) insulators are widely preferred in overhead transmission lines because of their better performance than ceramic and glass insulators. Being lighter in weight, SR insulators are very flexible to install (Costea and Baran, 2012). They exhibit outstanding hydrophobicity that makes it the first choice for the outdoor and overhead applications. However, the carbonaceous tracks may be formed over the surface of SR materials due to partial discharge and dry-band arcing. Additionally, electrical discharges, corona, and environmental factors may cause the surface erosion of the material. The performance of the SR material is degraded due to aging and other factors. In polluted surrounding, the SR insulators demonstrate poor performance and may fail (Amin and Salman, 2016; Gorur et al., 1992; Zhang et al., 2012; Amin et al., 2007). The system voltage, i.e., AC or DC, also plays an important role in degradation of the material. The inclined plane test as per IEC 60587 is preferred to study the performance of the polymeric insulator under laboratory conditions (IEC6058, 2007-05). Introduction of nano sized particles in base SR matrix can enhance thermal, mechanical, and chemical properties at the little cost of electrical property. This can reduce the rate of failure of SR insulators, thereby improving the reliability of the transmission network.

Kaaiye and Nyamupangedengu (2017) tried to compare the effects of AC and DC voltage on SR insulator under polluted conditions. They used Fourier transform infrared (FTIR) and scanning electron microscopy (SEM) analysis to understand the surface degradation due to the AC and DC test voltages. They found that when applied voltage and pollutant flow rate is increased, more severe surface erosion is found. Reddy et al. (2015) experimented on polymeric insulators to study the surface degradation due to tracking and erosion through IP test. The authors examined that more acidic pollutant resulted in more surface erosion in all the tested samples. Ashitha and Ganga (2017) used the IP test to mimic the polluted conditions in laboratory to analyse the effects of UV radiations on surface erosion. SEM analysis was carried out to figure out the surface erosion. They concluded that the presence of UV radiations reduced the surface erosion by decreasing the dry band arcing. Ghosh and Khastgir (2018) predicted service life of SR insulators through natural and accelerated aging. The authors found that there is loss of desired properties of SR due to electrical discharges, thermal aging, etc. Biswas and Veena (2019) studied the performance of SR insulator through DC IP test with UV radiation aging. The degradation was confirmed through FTIR spectra by revealing the stretching of a few bonds. They concluded that with an optimum filler concentration, the surface degradation can be reduced significantly. To improve the thermal properties of silicone rubber materials, Ghunem et al. (2021) suggested the use of fillers as flame-retardant to reduce the surface discharge and decrease the erosion of the materials. Alqudsi et al. (2021) proposed that the fumed silica and its interaction with SR were found effective in suppressing the erosion of the material by controlling the depolymerisation in the material.

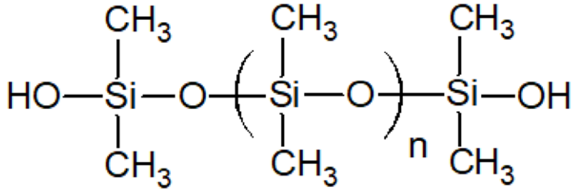
In this work, the inclined plane test as per IEC 60587 has been carried out on virgin SR insulator by applying 3.5 kV AC and DC voltages with both the polarities for three hours. The samples were weighted before and after the IP test to study the surface erosion due to electrical stress. FTIR and SEM analysis were used to understand the changes in surface condition after the IP test. Further, to validate the surface erosion, edge detection technique is used on SEM images.

2 Experimental procedure

2.1 Material and samples

The SR insulator is widely used in overhead transmission and distribution network in Gujarat, India. The insulator used for experimental work was HTV SR, polydimethylsiloxane (PDMS), with other additives like alumina (ATH), fumed silica and pigments. The polymer composite consists of a polymer PDMS which has a base of silicon and oxygen atoms with two methyl groups (CH_3) attached to the silicon atom creating the repeating unit of the polymer as shown in Figure 1.

Figure 1 PDMS structure (see online version for colours)



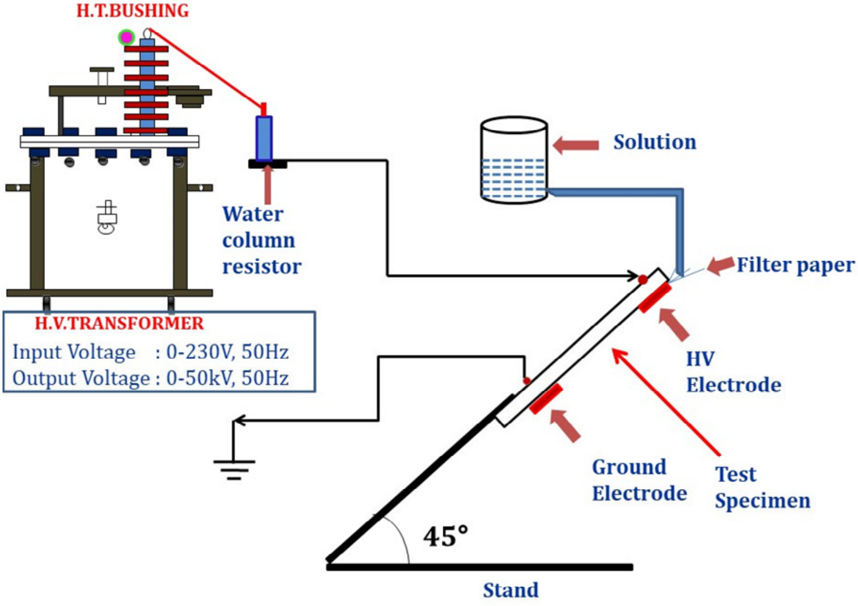
$$HO-Si(CH_3)_2-O-\left(Si(CH_3)_2-O\right)_n-Si(CH_3)_2-OH$$

The samples were cut from the SR insulator string with the dimensions 120 mm × 50 mm × 6 mm as per IEC 60587.

2.2 Test setup

Figure 2 shows the schematics of the test setup at High Voltage Engineering Laboratory. It consists of a single-phase stepup transformer, 230 V/50 kV, with diode rectifier along with a filter to produce the required DC voltage.

Figure 2 Inclined plane test setup (see online version for colours)



The samples were mounted on 45° inclined plane stand with the help of two electrodes, the upper electrode was HV and the bottom one was ground electrode. The contaminant is prepared as per the standard with 0.1% of ammonium chloride (NH_4Cl) and 0.02% of a non-ionic wetting agent Triton x-100 in distilled water. The contaminant is allowed to flow through the filter papers over the surface of the samples at a flow rate of 0.30 ml/min. The samples were tested by applying 3.5 kV AC (RMS) and 3.5 kV DC with both the polarities (positive and negative) continuously for three hours. The weight of the samples was noted before and after the IP test to calculate the surface erosion due to the arcing. During the test, visual observations have been made to study the arcing intensity and length of the arc over the surface of the SR samples. After the test, FTIR and SEM analysis were carried out to examine the effects of electrical stresses.

2.3 Analysis

FTIR spectroscopy is a powerful technique to sense the changes in molecular structure by scanning the specimens through infrared (IR) frequency (from 4,000–400 cm^{-1}). The FTIR spectrum is a plot of IR frequencies against the intensity of transmission/absorption. Some of the chemical bonds of the material absorb particular frequencies of emitted energy and by quantifying the transmitted and absorption frequencies of test sample, certain bonds can be decided. This technique is highly helpful in generating evidence about the presence or absence of certain functional groups in the material. The tested samples have been analysed using FTIR spectroscopy with the help of Perkin-Elmer make Spectrum GX having a range 10,000 cm^{-1} to 370 cm^{-1}.

The surface morphology of the samples has been carried out using scanning electron microscope XL30 ESEM with EDAX. The SEM images can be used to understand the surface degradation of the material due to electrical stress. Further, the Sobel and Prewitt edge detection algorithms were implemented using MATLAB on generated SEM images to count the number of edges which reflect the surface erosion (Rani et al., 2020; Acharjya et al., 2012). The techniques work by calculating the gradient of image intensity at each pixel within the SEM image. It helps in differencing each pixel from darker to brighter. Sobel operator offers swift execution and simultaneously it provides the same output during execution over an image (without modifying the original image). It is the method of stable edge detection. It is a 3 × 3 convolution kernel. Sobel uses two masks with 3 × 3 sizes, one helps in estimating the gradient in X-direction and other for Y – a direction in gradient. This technique is a row edge detector.

Table 1 Mask filter for Sobel algorithm

–1	0	+1	+1	+2	+1
–2	0	+2	0	0	0
–1	0	+1	–1	–2	–1
	Gx-horizontal			Gy-vertical	

The kernel can be applied separately to input image for obtaining gradient component in each orientation. The magnitude or strength of the edge is calculated by

$$|G| = \sqrt{G_x^2} + \sqrt{G_y^2}$$

In the case of Prewitt algorithm, the following mask filter is used to sense the edges is given in Table 2. The remaining process to count the edges is same as Sobel algorithm.

Table 2 Mask filter for Prewitt algorithm

–1	0	+1	+1	+1	+1
–1	0	+1	0	0	0
–1	0	+1	–1	–1	–1
	Gx-horizontal			Gy-vertical	

3 Results and discussion

The surface erosion is characterised by three methods viz., visual observation of the surface, FTIR spectrum analysis and SEM analysis. Further, edge detection techniques are used on SEM images to count the number of edges to validate the results.

3.1 Visual observations

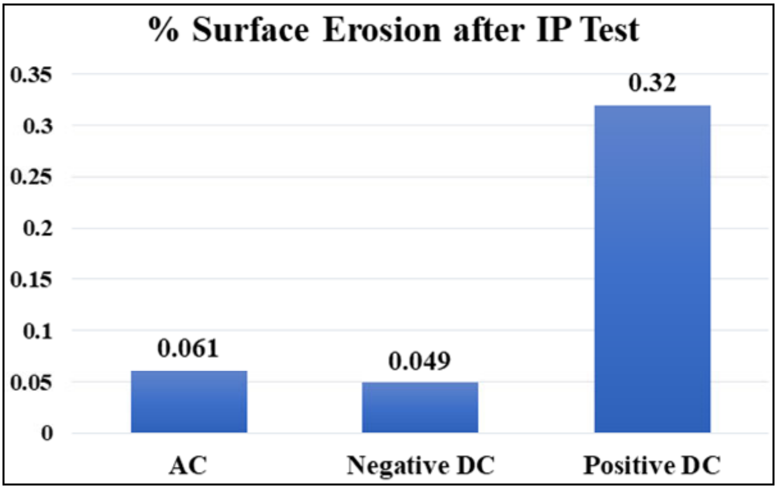
Figure 3 shows the surface conditions of the samples after IP test. The effects of types of voltage can be seen from the surface of the samples. In all the three samples, the intensive arcing is observed near the ground electrode and the carbonaceous tracks are visible on the surface due to the arcing. The arc intensity was found maximum during the test with positive DC supply. All three samples get burnt near the bottom electrode due to continuous arcing during the test. A comparison of the area near the ground electrode reveals that the deeper mark is left in the sample with positive DC voltage than AC and negative DC. From the visual observations, it can be concluded that more erosion is found with the positive DC voltage followed by AC and DC voltage stress.

Figure 3 (a) 3.5 kV AC (RMS) (b) 3.5 kV DC (–Ve) (c) 3.5 kV DC (+Ve) (see online version for colours)

(a) (b) (c)

This is also verified by comparing the weight of the samples before and after the test which is shown in Figure 4. The surface erosion is 0.061%, 0.049%, and 0.32% with AC, negative DC and positive DC test voltages, respectively.

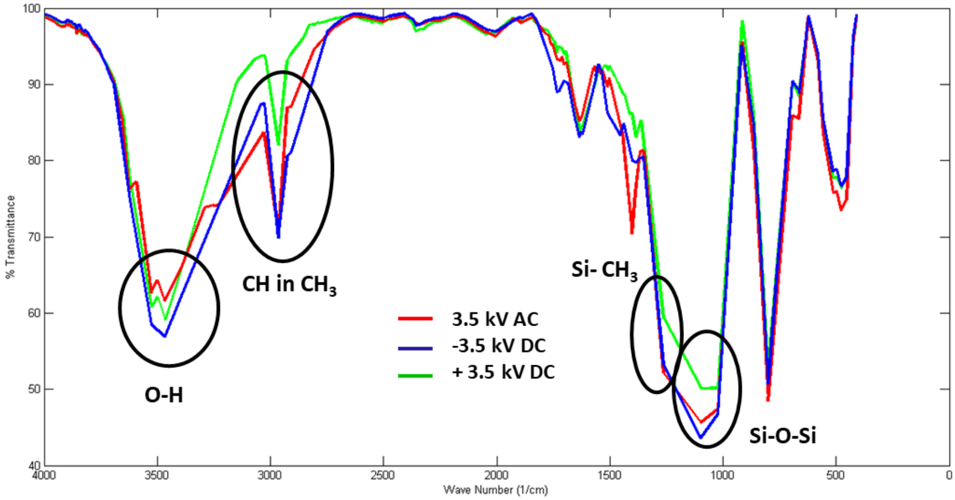
Figure 4 Surface erosion after IP test with AC, –Ve and +Ve dc voltages (see online version for colours)



3.2 FTIR analysis

The comparison of FTIR spectra of AC, negative DC, and positive DC test voltage is presented in Figure 5. The raw data were obtained after FTIR analysis and with the help of MATLAB a comparative graph is plotted.

Figure 5 FTIR spectrum after IP test with Ac, –Ve and +Ve DC voltages (see online version for colours)



The stretching of various bonds is visible in Figure 5. A few bonds such as O-H (3,700–3,200 cm^{-1}), CH in CH$_3$ (2,962–260 cm^{-1}), Si-O-Si (1,100–1,000 cm^{-1}), and Si-CH$_3$ (1,270–1,255 cm^{-1}) are extremely useful in assessing the effects of electrical stress on the SR material (Verma and Reddy, 2018).

It can be observed that the bonds correspond to Si-O-Si around wave number 1,096 cm^{-1} have been decreased more in the sample tested with positive DC voltage than other two samples. This change is indicating the depolymerisation of the SR insulating material. This may be increased with the increase in applied voltage and the duration for which the voltage is applied. Around the wave 2,961.65 cm^{-1}, reduction in CH peak is found. The continuous arcing on the surface of the samples caused the formation of the tracks which changes the polymer structure of the material.

3.3 SEM analysis

Figure 6 shows the SEM images (at 50 µm) clearly indicating the changes on the surface of the samples. Figure 6(a) shows the original SEM images captured at 50 µm level, whereas Figures 6(b) and 6(c) show the edge detected images using Prewitt and Sobel algorithm respectively in MATLAB.

The detected edges represent the intensive changes in the depth of tracks on the surface of the material. The comparison of the edge count is shown in Figure 7. The edges detected by both the techniques are almost similar. The higher count of edges indicates the rougher surface depicting more erosion compared to less edge count. As seen, the number of edges is found to be more in the sample tested with positive DC voltage than AC and negative DC voltages.

Figure 6 SEM images with edge detection and edge count, (a) unprocessed images as received from instrumentation centre (b) images with edge detection by Pewitt algorithm (c) images with edge detection by Sobel algorithm

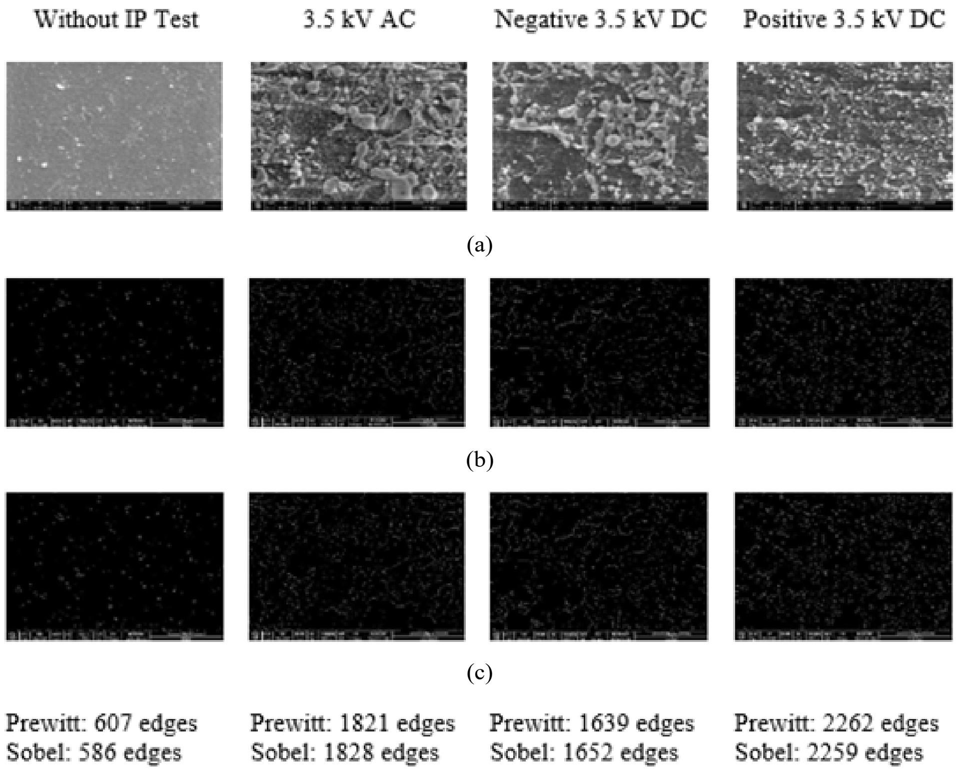
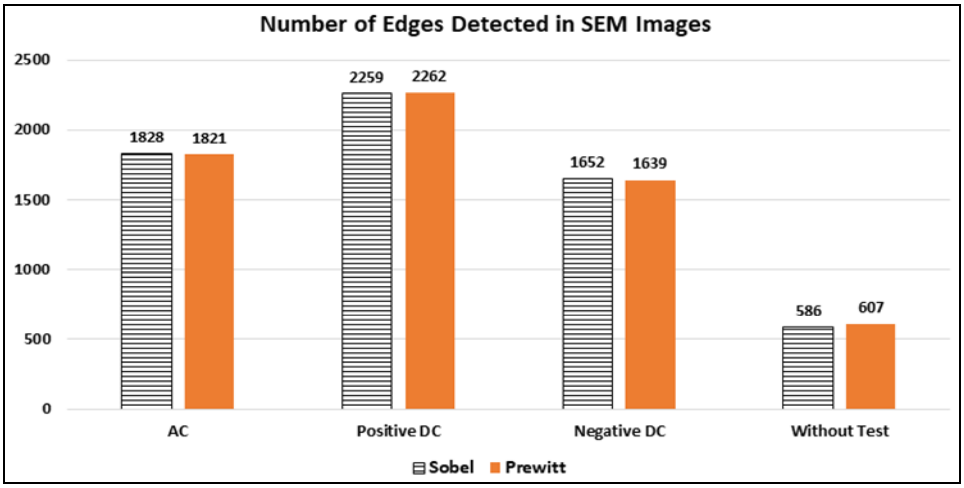


Figure 7 Edge count by Prewitt and Sobel method (see online version for colours)



When the voltage is applied between the electrodes mounted on the surface of the insulator, it results in the dry-band arcing due to the continuous flow of the pollutant. The thin film of the pollutant provides the conducting path to the charges and current flows causing the surface to heat. The degradation of the material is initiated due to this heat which creates the tracks on the surface which results in erosion of the surface. In DC tests, the positive electrode erodes significantly more than the negative electrode due to electrolysis. When the upper electrode is positive, the electrolysis process of releasing metallic ions may enhance the electrical conductivity. As a result, positive DC tests have greater average leakage current, are more irregular and produce deeper erosion and greater sample mass loss as compared to their equivalent negative DC and AC tests. To slow down the degradation of the material, appropriate fillers should be introduced in the base material so that the resistance to tracking and erosion, and thermal properties of the polymer insulating material can be enhanced (Xue et al., 2018; Nazir et al., 2018).

4 Conclusions

From the experimental study on SR insulator used in overhead system with inclined plane test and edge detection techniques, the following conclusions can be drawn:

- The type of voltage affects the surface degradation mechanism in polymeric insulator. The positive DC voltage caused the highest degradation of the sample followed by AC and negative DC voltages.
- Maximum (0.32%) erosion of the material is found with positive DC voltage whereas it is 0.061% and 0.049% with AC and negative DC voltage, respectively.
- FTIR study revealed the stretching of various bonds like Si-O-Si, CH in CH_3 and OH indicting the surface erosion due to electrical stresses.
- SEM images (at 50 µm) show the surface condition of the material after IP test. The SEM images supported the results derived through weight comparison before and after IP test and FTIR analysis. The SEM image of a sample with positive DC test is found with rougher spots indicating more erosion compared to other test voltages.
- Additionally, edge detection technique with Sobel and Prewitt algorithm supports the outcome of SEM and FTIR analysis presenting the greater number of edges with positive DC test voltages than AC and negative DC.

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