Surface Analysis of Polymeric Insulator Used in Overhead Transmission System under Corona Discharges

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Abstract **Polymeric insulators used in overhead transmission systems are subjected to corona discharge occurring from metallic end fittings and line components. This corona discharge affects the performance of insulating material along with other factors like pollutants and electrical stress. Corona penetration on the surface of the material for a longer duration can cause the failure of the insulator string. The work focuses on the study of corona discharge on high-temperature vulcanised (HTV) silicon rubber insulating material using digital image processing. The average pixel intensity and luminosity content of the corona discharge under different voltage levels have been computed with the help of corona images. The Hough transformation technique is employed to calculate the corona streamer spread angle in MATLAB. The virgin and artificially acid-aged samples, after corona treatment, were analysed using the Fourier transform infrared (FTIR) analysis and scanning electron microscopy (SEM) to quantify the degradation due to corona and acid aging. It is found that the aged sample shows more degradation in terms of hydroxylation and de-polymerization compared to virgin samples.**

Keywords* — *Corona, acid aging, surface degradation, silicon rubber, scanning electron microscopy, image processing, hydroxylation, depolymerization.

I. INTRODUCTION

Polymeric insulators are becoming widely popular in overhead power transmission networks due to their superior properties. They are replacing the conventional ceramic and glass insulating materials due to the numerous advantages of polymeric materials [1,2]. Being lighter in weight, the composite insulators are convenient to install. They exhibit good hydrophobicity, high mechanical strength-to-weight ratio, and lower maintenance cost [3]. Despite all these merits, polymeric insulators are more prone to experience degradation due to the environment along with the electrical stresses [4]. The key electrical factors which enhance the degradation mechanisms in the polymeric insulators include erosion due to tracking, dry band arcing, and corona discharges over the surface of the material [5]. Most insulator failures are because of brittle fracture, which occurs mainly due to corona discharge near the end fittings, which leads to the infiltration of moisture and acid formation [6,7]. Environmental factors like UV rays, rain, humidity, snow, and ice combined with electrical stresses could accelerate the degradation of the insulators and shorten their life [8].

Corona is a luminous discharge caused due to ionization of air surrounded by an electrode whose voltage gradient exceeds the critical value [9]. The effect of corona includes the generation of audio noise, radio interference, power loss, etc., adding to the list, the corona has been identified as a potential threat to the long-term operation of high-voltage polymeric insulators. The degradation depends on the intensity of the corona and the power released by the discharge [10-14]. Research on the application of image processing techniques to study the discharge phenomenon and its quantification is discussed in the literature [15,16]. A detailed review of tools used for outdoor polymeric insulators is presented in [17]. The application of digital image processing for the analysis of corona discharge is gaining a lot of attention nowadays [18]. High dynamic range (HDR) imaging can be used to measure the luminance of a scene using a digital camera [19]. The corona images' average pixel intensity and luminosity content can be calculated using the image processing technique [20]. The corona spread angle can be computed from digital images using an appropriate tool [21].

In the present work, digital images of the corona discharge

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on the different polymeric insulator samples, virgin and aged, are taken under numerous voltage levels. These digital images are analysed with the help of digital image processing in MATLAB to understand the degradation of the samples due to corona. The study the effects of corona on the surface of the material, the samples were subjected to corona penetration under a 10 kV AC RMS supply for 15 hours. The Fourier transform infrared (FTIR) analysis and scanning electron microscopy (SEM) are carried out to quantify the mechanism.

II. EXPERIMENTAL ARRANGEMENT

The schematic of the experimental set-up for corona treatment is shown in Figure 1. It consists of a transparent chamber housing the needle and ground electrodes. The needle electrode is connected to an autotransformer (0-30 kV).

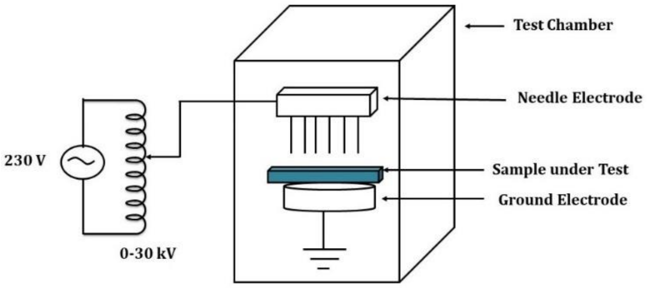

Fig. 1 Schematic of Test Set-up

The polymeric (HTV silicon rubber) sample under test is kept between the needle and ground electrodes with a 3 mm spacing between the sample and needle electrode.

The samples are prepared by cutting from the polymeric insulator string received from the manufacturer. The tests are performed on two types of samples, viz. virgin and artificially aged. For aged samples, the acid of pH 3.3 is prepared, and the samples are kept in the acid for 48 hours then samples are exposed to corona discharge in the test chamber.

Corona images are taken with the help of a DSLR camera under a darker ambiance so that the surrounding light does not disturb the intensity of corona discharge. Corona images are captured at various voltage levels, 6 kV to 16 kV in the varying steps of 2 kV AC RMS, and the images are analysed with the help of the MATLAB image processing tool. From the digital images, the corona spread was understood by mean pixel intensity and luminosity content. The corona discharge with various voltages is shown in Figure 2. During the ionization process, some electrons are in a free state and may act together with the electric field. Subsequently, the electrons are accelerated, and an electron shedding to other atoms could take place, which leads to a chain effect. It can be seen that the discharge intensity is increased with the rise of applied voltage. This is because the electric field is amplified at the tip of needles due to increased potential. This concentrated field yields the ionization of air in the gap between the sample and the upper electrode.

Fig 2 Corona Discharge on the Surface of the Insulator with Different Voltage Levels

III. IMAGE PROCESSING TECHNIQUES

The pixel intensity is calculated using MATLAB digital image processing and the intensity profile is plotted along the reference line in the corona digital image is shown in Figure 3. The reference line, Figure 3 (a), starts from the tip of the needle emanating the corona discharge to the surface of the sample receiving the discharge. The pixel intensity is computed for all the test voltage levels in MATLAB and plotted as shown in Figure 3 (b).

It can be observed from Figure 3 (b) that with the rise in voltage, pixel intensities are increasing; indicating that more ionization leads to the larger emission of light at higher voltages. To quantify the observation the average pixel intensity (Iavg) and the luminosity content of the corona images are calculated. The method first selects the region of interest (ROI) from the corona image and crops it appropriately. Then the images are converted from RGB color space to YCbCr color space. This conversion is carried out because YCbCr color space gives the luminosity component (Y) of the image which is helpful in the extraction of corona plasma spread. The process is shown in Figure 4.

The average value of the pixel intensity in an image is the mean of the processed digital image I(M,N) which is calculated by equation (1).

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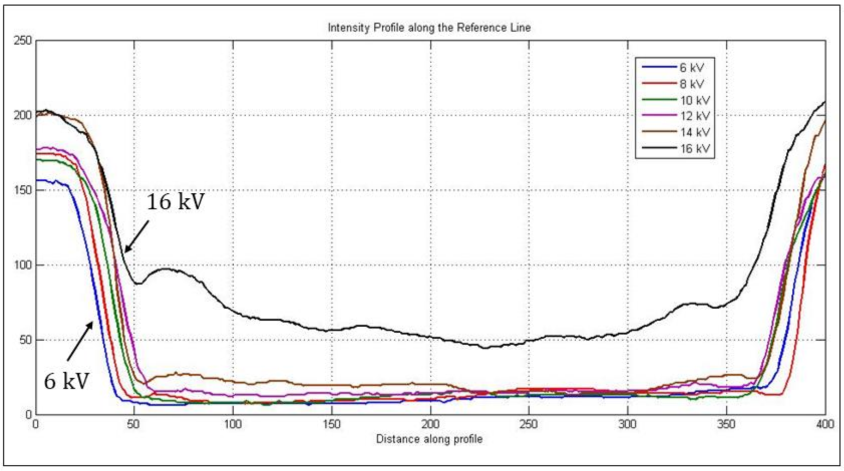
$$I_{avg} = \frac{1}{M \times N} \sum_{m=1}^{M} \sum_{n=1}^{N} I(m,n) \qquad (1)$$



(a) (b)

Fig 3 (a) Reference Line along the Corona Discharge; (b) Intensity Profile of Pixels along the Reference Line

The luminosity content of the image is calculated using equation (2) in which R, G, and B are red, blue, and green components of the color image respectively.

$$Y = 0.2162 \times R + 0.7152 \times G + 0.0722 \times B \qquad (2)$$

The streamer spread angles of the corona discharge with different voltage levels are also calculated. First, extract the corona plasma spread region as discussed above. Then crop the region near the corona needle tip to outline the discharge of streamers. Hough transformation is applied to the cropped region to identify the lines along the edges. The principle of the Hough transform is given below. Let 'n' refers to the number of pixels found along the edge of an image. The goal is to compute the number of pixels that lie in a straight line. The Hough transform is carried out in the following manner [22].

1) Consider a point x_i, y_i, and a straight line $y_i = ax_i + b$, there could be a number of lines passing through this point but common to all of them is the parameter a, and b.

2) Imagining this in parametric space (a_i, b_i) instead of in xy space, b = -ax + y, considering x, and y as parameters and a, and b as variables. Each point in xy space will result in a line in the subsequent parametric space.

3) The lines for all image points in parametric space are obtained and thereby the intersection points are calculated. The point with the greatest number of intersections in space will give the corresponding set of points in xy space which lies on a straight line.

The angle between all the lines is computed using (3).

$$\lambda = \tan^{-1}\left|\frac{m_1 - m_2}{1 + m_1 \times m_2}\right| \qquad (3)$$

where m_1 and m_2 are the slopes of two lines respectively. The maximum angle is assigned for the given crop region as the spread angle.

IV. RESULTS AND DISCUSSION

A. Analysis of Corona Discharge using Digital Image Processing

The average pixel intensity values, computed by equation (1), under different voltages are plotted as shown in Figure 5. It is observed from the plot that the Iavg is increased as the supply voltage is increased.

This is because the corona discharge is rising with the increase of the electric field causing a more intense luminous glow around the tip of the needles in the HV electrode. After 14 kV, the intensity of the corona discharge is exponentially increased due to accelerated electrons which produce an ample number of electrons that results in intense corona discharge which can be seen from the figure.

The luminosity content, calculated by equation (2), is plotted as shown in Figure 6. From the graph, it is evident that the luminosity content in the corona digital images is increased with the applied voltage.

Corona spread angles calculated with the help of the Hough transformer are plotted as shown in Figure 4. It is observed from the figure that the spread angle is

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increased with the rise of the given voltage indicating that more surface area is receiving the corona penetration when the supply voltage is increased.

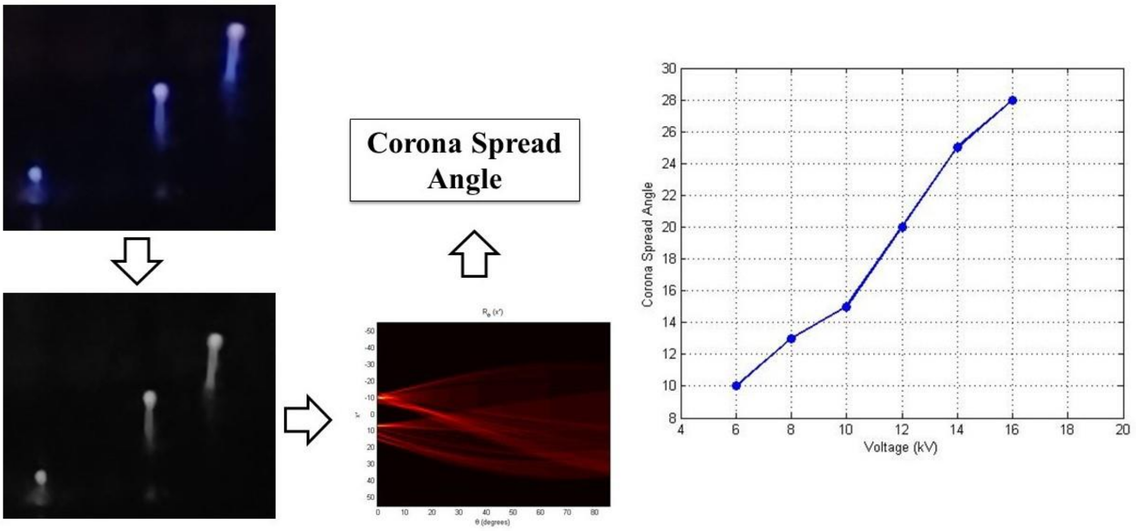

Figure 4 (a) Detection of Hough Lines; (b) Streamer Spread Angle

The virgin and artificially aged samples with acid aging were subjected to corona discharge for 15 hours at a 10 kV supply voltage. The surface conditions of both samples after testing are shown in Figure 8. The spots due to corona penetration on the surface of the samples are visible. The surface of the sample treated with the acid exhibits more changes in the form of surface roughness as seen. The roughness is quantified by converting the digital images into binary images and the number of edges is calculated in MATLAB. The number of edges in a virgin sample is found to be 41133 whereas in an aged sample 76732. The greater number of edges indicates the level of roughness. Despite the same voltage levels, the sample treated with acid shows more surface degradation than a virgin sample due to the impact of acid. From the above analysis, it is understood that the digital image processing technique can be considered a non-destructive and low-cost method for the condition assessment of polymeric insulators as it can provide many important details about the degradation of the surface due to corona discharge and the technique can also be used for the analysis of other factors affecting the performance of insulating materials.

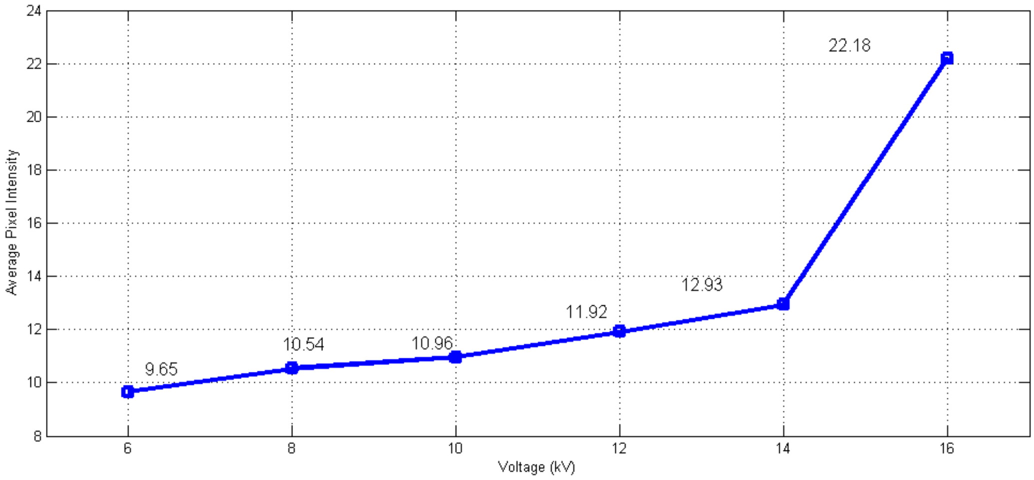

Fig 5 Average Pixel Intensity of Corona Image

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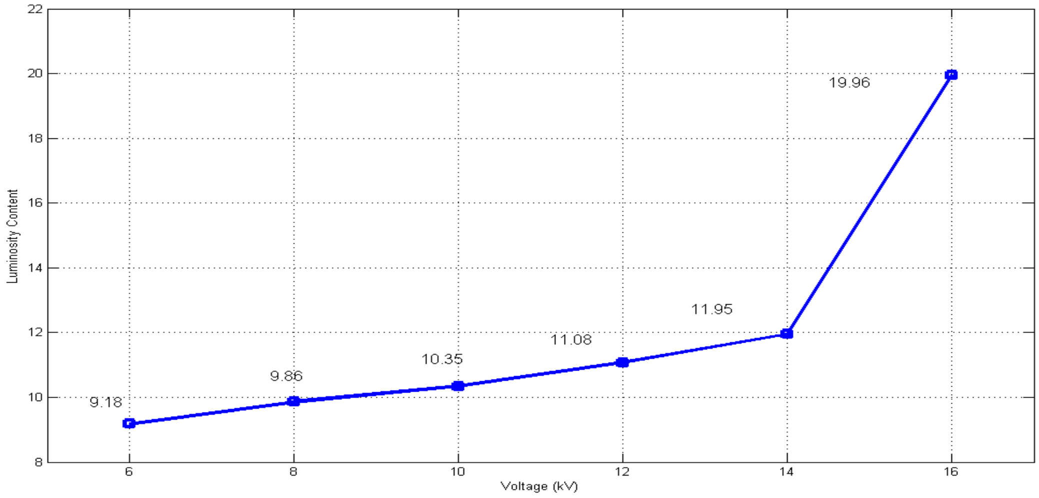

Fig 6 Luminosity Content in Corona Images

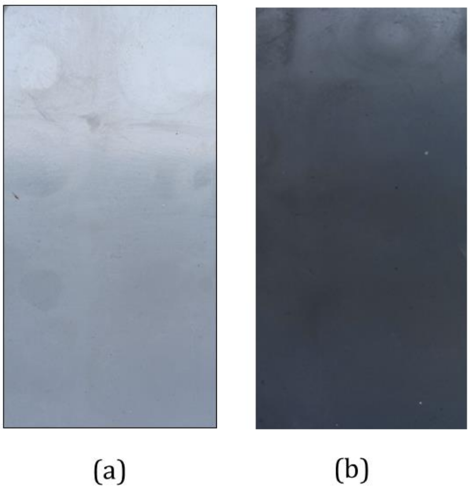

Fig 7 Surface Condition of Samples after Corona Discharge

B. Fourier transform Infrared (FTIR) Spectroscopy

The Fourier transform Infrared (FTIR) analysis provides information about the formation and stretching of various bonds in the material structure due to electrical and other stresses. In the present work, the FTIR analysis is carried out using Perkin Elmer Spectrum GX Range: 10,000 cm^{-1} to 370 cm^{-1}. The material under investigation is Polydimethylsiloxane (PDMS) which has chemical bonds with corresponding peaks in the infrared (IR) spectrum as given in Table 1.

Figure 8 shows the IR spectrum of samples without and with acid aging. The peak around 1008 cm^{-1} specifies the Si-O-Si (region 1 in the figure), which is the main chain of the PDMS polymer. The reduction in the Si-O-Si peak indicates the de-polymerization due to the scission of the chain because of corona discharge on the samples.

Regions 2 and 3 in the figure show the symmetric stretching of CH in the CH_3 bond and OH in ATH respectively. This indicates the formation of hydroxylation. Also, the stretching of bond CH_3 in Si-CH_3 around 1500 cm-1 suggests the formation of nitric acid on the surface of the samples due to corona penetration. These effects reduce the hydrophobicity of the material. The combined effects will result in the creation of cracks on the surface which can work as a permanent housing for dirt and other particles forming the conducting film along with moisture.

This conducting film may result in partial discharges and flashovers which can degrade the material and reduce the mechanical strength of the insulator string. It is seen that the sample with acid aging exhibits comparatively more degradation due to the combined effects of corona and acid.

TABLE I. CHARACTERISTIC IR ABSORPTION PEAKS FOR PDMS [23].

Bond	Wave Number (cm^{-1})
C-H symmetric stretching in CH_3	2962-2960
Si-O-Si symmetric stretching	1100-1000
OH in ATH	3700-3200

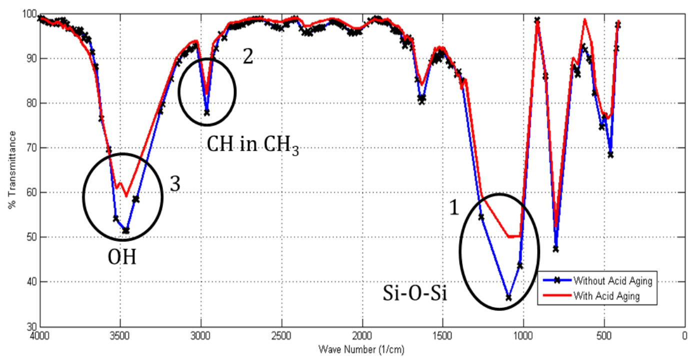

Fig 8 FTIR Spectrum of Samples Without and With Acid Aging

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C. Scanning Electron Microscopy (SEM)

The morphological changes on samples that are corona treated with and without acid aging are analyzed using scanning electron microscopy (SEM). SEM images provide qualitative estimates of the type and extent of the degradation. Roughness can be characterized on the surface with many large changes in depth, which in the micrographs appears as large, rapid changes in the value of the pixels. In this work, the SEM is performed using XL 30 ESEM machine. Figure 9 shows the SEM images and their binary images of samples without and with acid aging after corona treatment.

It is obvious from the SEM figures that the surface of the sample without acid aging shows more roughness compared to the sample without acid aging. Thus, the severity of damage is more in the case of acid aging treatment, which agrees with that of the FTIR results. However, SEM being a qualitative method, making a quantitative inference from it is a difficult task. Hence an attempt is made to obtain the total number of edges from the SEM images using MATLAB. The number of edges is found to be 4751 in samples without acid aging whereas in the case of acid aging it is 11546. If the corona penetration continues for a longer duration, this roughness may create cracks in the surface of the material which will lead to the failure of the insulator.

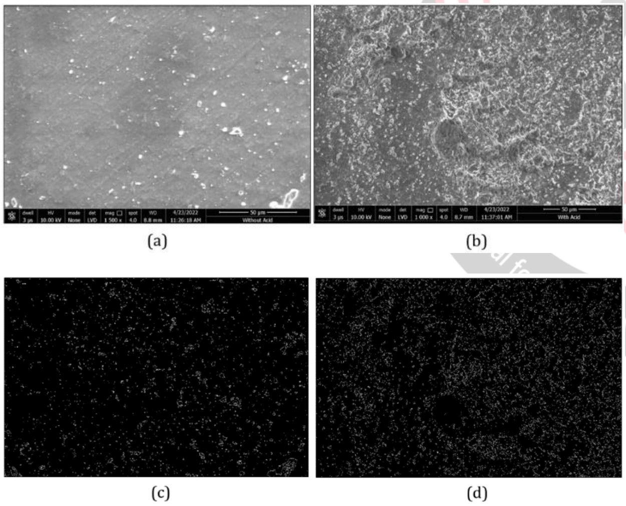

Fig 9 SEM Images (50µm) (a) without Acid Aging;

(b) with Acid Aging; (c) Edge Detection without Acid Aging; (d) Edge Detection with Acid Aging

V.CONCLUSIONS

The behaviour of corona discharges without and with acid treatment was studied for polymeric insulator degradation. The following important observations are made:

1) The average intensity and luminosity content increase as the voltage level rises. With 6 kV and 16 kV, the average pixel intensity is 9.65 and 22.18, respectively. With 6 kV and 16 kV, the luminosity content is 9.18 and 19.96, respectively.
2) As the voltage level rises, so does the corona spread angle, resulting in more corona plasma spread on the material's surface. In the absence of acid aging, the corona spread angle is determined to be 10o at 6 kV and 28º at 16 kV.
3) More edges (11546) are discovered on the surface of acid-aged samples than on untreated samples (4751), indicating that acid treatment accelerates the surface breakdown process in polymeric insulators.
4) FTIR analysis confirms the above observations. Acid aging resulted in more depolymerization than non-acid aging samples. Furthermore, the OH bond stretch indicates a brief loss of hydrophobicity because of corona discharge. SEM research backs up the conclusion by revealing increased surface roughness in acid-aged samples.

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