International Journal of the Physical Sciences Vol. 6(22), pp. 5109-5120, 2 October, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.681
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Influence of ultra violet radiation on the surface and leakage current of silicone rubber insulator

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Accepted 14 June, 2011

This paper deals with the surface degradation characteristics of 20 kV silicone rubbers (SiR). A chamber containing nine ultra violet (UV) lamps with intensity of 50 W/m^2 was considered as artificial ageing. There are many aging factors in the outdoor environment, but this paper studies the factors of UV that cause crazing, chalking, tracking and loosing hydrophobicity on the surface of insulator. Solid layer pollution method is applied according to IEC60507 standard and surface leakage current (LC) was measured to analyze its electrical characteristics. Fast Fourier Transformer (FFT) method was used to analyze the LC waveforms. Results show that UV has direct impact on the hydrophobicity of insulator surface. Supporting the results obtained from the leakage currents analysis, scanning electron microscope (SEM) and thermo gravimetric analysis (TGA) were used to observe the surface changes of silicone rubber and the dielectric loss.

Key words: Degradation, silicone rubber, leakage current, hydrophobicity, ultraviolet.

INTRODUCTION

Polymer degradation takes place as a result of various factors, which adversely affect the electrical and mechanical properties of polymers. Degradation may occur in the entire period of a polymer's life, for example, during its synthesis, processing and application. The most important sources that cause degradation of polymer are sunlight, heat, oxidation, mechanical stress, chemicals, moisture, radiation and biological sources. Combinations of these damaging processes may initiate conditions of degradation that are very complicated. These conditions cause decrease in the elongation and increase in brittleness of the material. It subsequently leads to loss of flexibility, development of cracks on the surface, discoloration and embrittlement. The process of aging depends on their intensities and the resistance present in a polymer. The most common form of radiation degradation is due to the ultra violet (UV) component of the sunlight. The sun is the principal natural source of UV radiation on the earth (Arora and Tripathi, 2004; Farzaneh, 2009). Utilities spend important amounts of money on preventive maintenance, which includes regular insulator washing and cleaning; although insulator washing is an expensive and time-consuming procedure. Laboratory studies and industrial experience have shown that insulator surface-leakage current, which is easily measurable, carries information about approaching flashover.

Leakage current (LC), which is driven by the source voltage and collected at the grounded end of the insulator, provides much useful information out of the many parameters describing the state of a contaminated insulator (Amarh et al., 2002; Suda, 2005). It was found that surface discharge has distinctive stages of development and that the upcoming flashover modifies the harmonic content. These findings suggested that the frequency signature of the leakage current may indicate the imminence of flashover (Otsubo, 2003). The LC provides information about the amount of contamination on a polluted insulator. The relationship between the leakage current and the discharge phenomena has been investigated

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Abbreviations: SiR, Silicone rubbers; **UV,** ultra violet; **FFT,** fast Fourier Transformer; **NaCl,** sodium chloride; **$CuSO_4$,** copper(II) sulfate; **THD,** total harmonic distortion; **TGA,** thermo gravimetric analysis; **SEM,** scanning electron microscope; **LC**, leakage current.

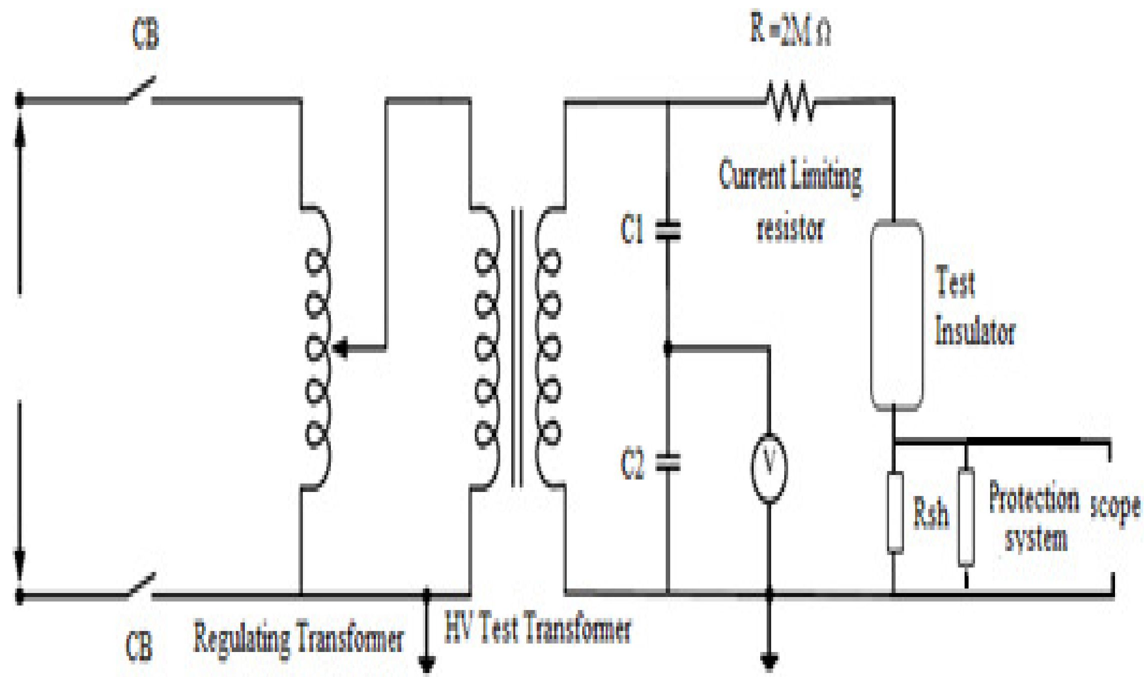

Figure 1. Schematic view of experimental setup.

on the polymer material under wet condition. In general, during aging test, two kinds of discharges that can evaluate the insulation performance are observed. One of them is corona partial discharge that occurs between water droplets. The other is dry band arc discharge that occurs between dry bands on the surface of the polymeric material that may cause tracking and erosion phenomena; although, its cumulative charge is much larger than that of a corona discharge (El-Hag et al., 2002; El-Hag, 2003).

In this paper, we present the relationship between frequency characteristics of leakage current waveforms and flashover occurrence at a siR insulator. According to the experimental results, there is a considerable correlation between 3rd harmonic level of the LC and occurrence of visible surface discharges.

EXPERIMENTAL TEST

High voltage test setup

A setup consists of 100 kV, HV transformer used for energizing the insulators to the required voltage stress and data acquisition system provided by the LC related information, that is, the time variation of LC such as maximum and average waveforms. Data acquisition consists of a digital oscilloscope to save data, back connected by Zener diodes (15 V) for overvoltage protection and a shunt resistor for measuring LC.

Pollution

A smooth pollution layer is coated on the silicone rubber (SiR) Insulator surface by a method of artificial contamination provided in (IEC 60507, 1991). According to this procedure, Kaolin powder is deposited after spraying a fine mist of water droplets on the surface. Afterwards, the insulator is immersed in the slurry of contaminants and dried. Kaolin composition consists of 40 gr kaolin, 1000 gr tap water and 10 gr Nacl, when the volume conductivity of tap water is 0.041 S/m.

Insulator characteristics

A SiR insulator of rating 20 kVL-L was used for laboratory artificial aging study. Figure 2 illustrates the photographs of actual insulators as well as test arrangements. Table 1 shows the characteristics of tested insulator.

LEAKAGE CURRENT ON CLEAN SURFACE

Initially, clean SiR Insulator was examined for rated voltages (20 kV) with applied voltage of 11.54 kV rms phase to ground. No visual discharges were observed under this test conditions. Figure 2a and 2b shows the typically obtained LC waveform for clean SiR Insulator. It should be noted that even at high contents of humidity, small LC flows on the insulator surface (Muniraj, 2009).

Table 1. Characteristics of insulator under test conditions.

Voltage class	20 KV
Leakage distance	770 mm
Shed diameter	100 mm
height	235 mm
Mechanical tension Strength	70 kN

Figure 2a**.** Photograph of tested insulator.

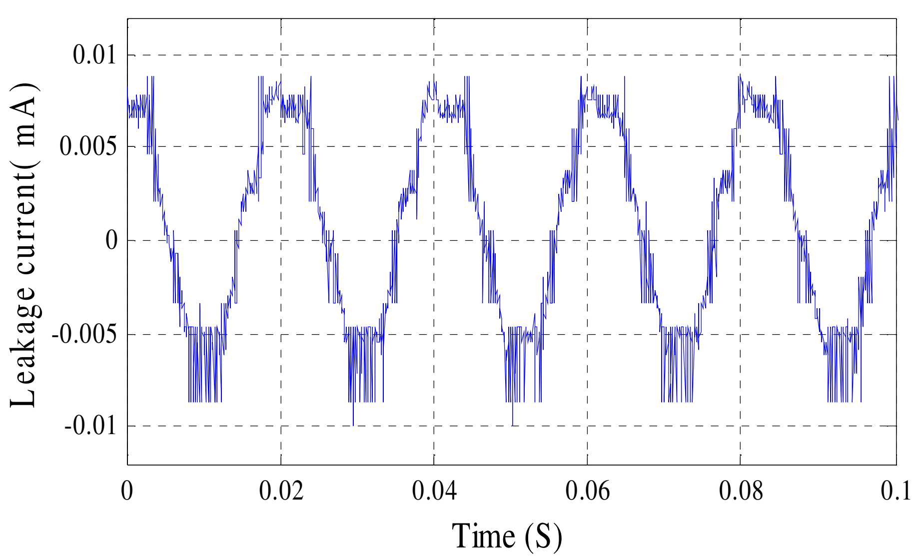

Figure 2b. Leakage current of 20 kV clean insulator.

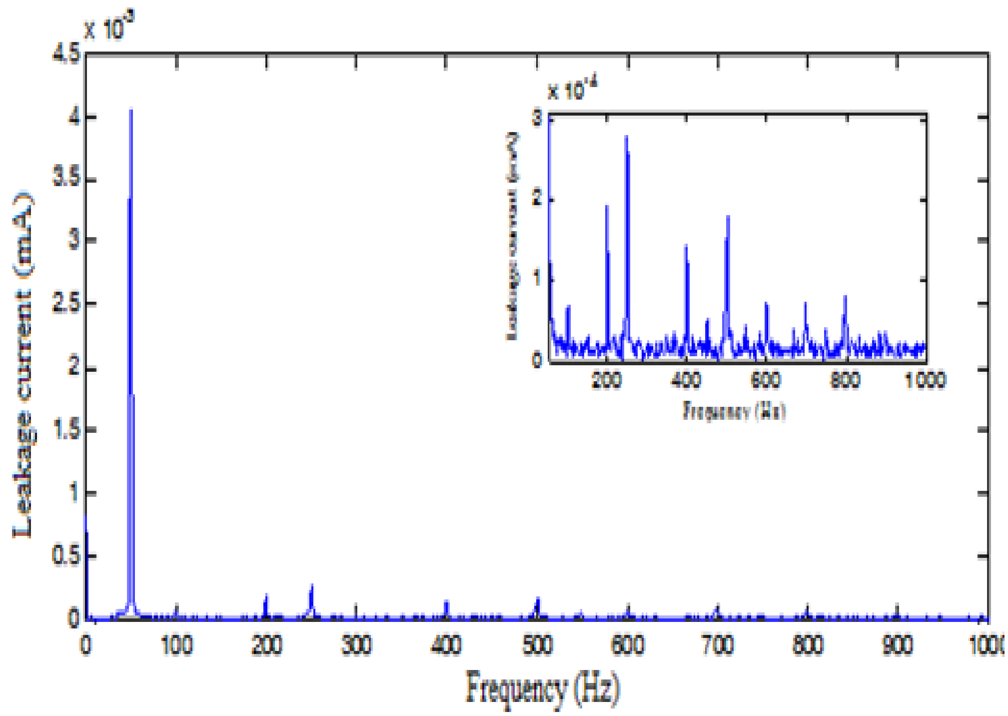

Figure 3. Frequency spectrum of leakage current on 20 kV clean insulator.

Figure 3 shows the frequency spectrum of the LC for clean surface. The LC on the clean surface contains the higher order harmonic components like 4^{th}, 5^{th}, and 7^{th}. It should be also noted that in clean condition, the 5^{th} harmonic component was always greater than the 3^{rd} harmonic. In the polluted dry condition the harmonic content does not change, that is, the total harmonic distortion (THD) is the same as clean condition (Figure 2).

LEAKAGE CURRENT ON POLLUTED SURFACE

When transmission lines passes near the coastal, desert and industrial areas, insulators are exposed to different types of contaminants such as sodium chloride (NaCl), copper(II) sulfate ($CuSO_4$) coming from the different sources and deposited on the insulator surface. Salt contaminations play a key role in SiR insulator ageing (Arora and Tripathi, 2004).

Artificial ageing tests must simulate actual conditions as much as possible. The goal is to evaluate degree of ageing deterioration of a SiR insulator by means of measuring magnitude of LC flowing through insulator surface. However, that conductive current flowing on the contaminated wet surface of SiR Insulator without any discharge would not deteriorate the surface so much compared with the case of corona discharge or dry band arc currents. The typical surface LC pattern has been recorded for the following three levels:

Conductive current

For completely wet surfaces, which were obtained in the pollution tests, LC also appeared to be sinusoidal (with no phase lag to the voltage waveform) but at higher level (Figure 4). The cases in which the hydrophobic properties were either partially lost or a weak dry band activity started, THD of LC could be high. Figure 5 shows the frequency spectrum of the LC during pollution surface condition. It is observed that the LC for polluted surfaces contains greater 3^{rd} harmonic components than other harmonic component. Figure 6 shows that insulator which is subjected to UV has more LC due to loss of hydrophobicity compare to non-aged insulator. Figure 7 shows the frequency spectrum of the LC on the polluted surface which is exposed to UV radiation. Even higher 3^{rd} harmonic content is observed for this case. Table 2 shows the magnitude of each harmonic in LC waveform for case A.

Dry band arcing

In this case, we have investigated the relationship between the LC and the discharge phenomenon on the wet SiR surface. In general, two kinds of discharges are observed in this case. One of them is corona partial discharge that occurs between water droplets, in which Si-C bonding of SiR is broken down by photon energy

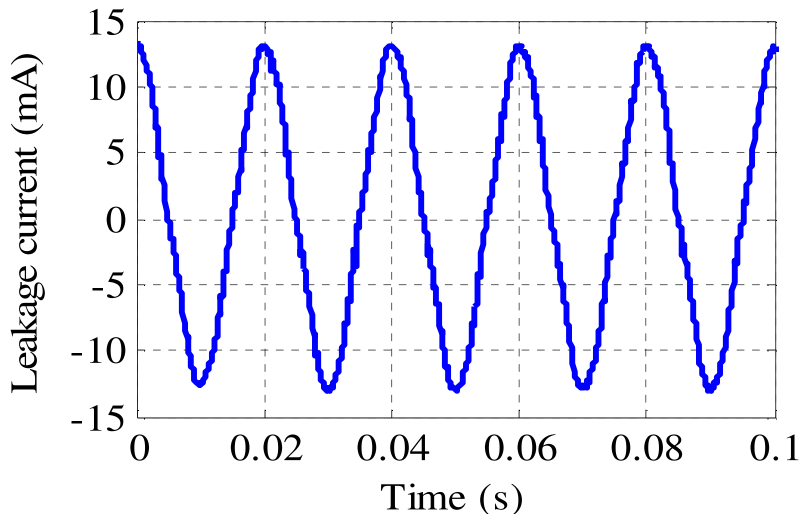

Figure 4. Leakage current of 20 kV polluted insulator.

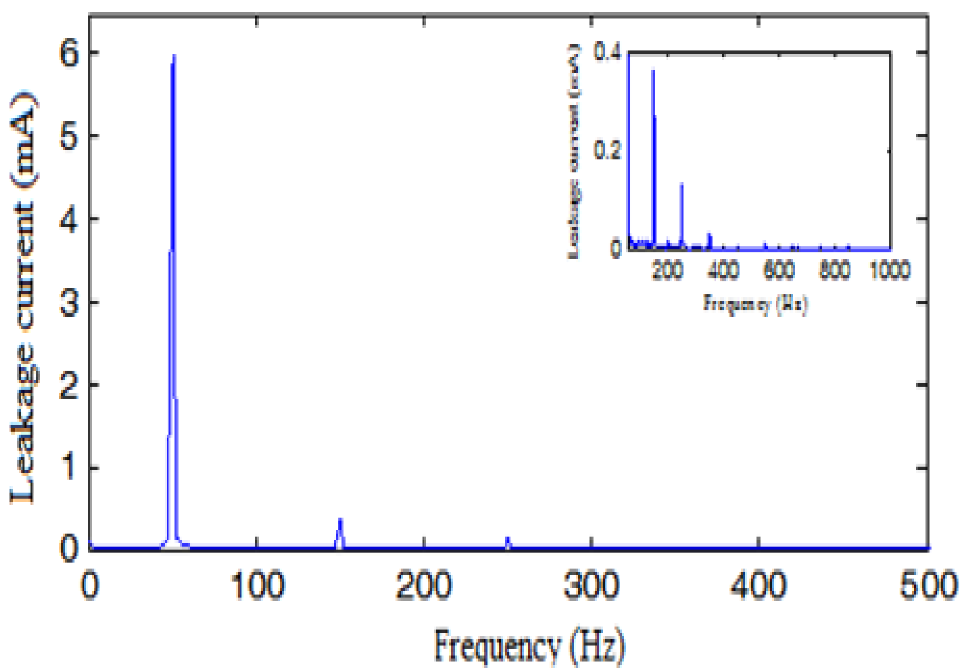

Figure 5. Frequency spectrum of leakage current on 20KV polluted insulator.

because the photon energy due to the corona discharge is larger than the bonding energy of Si-C. Therefore, the corona discharge activity on the hydrophobic surface can be used to define the insulation surface condition. The second is dry band arc discharge that occurs between dry bands on the surface of the polymeric material. Thus, the dry band arc discharge and the corona discharge influence the wet insulator performance. The multi-frequency waveform, shown in Figure 8 occurred during and prior to the visible discharge and, therefore, the discharge currents can be considered as a spike appearing on the crest of a nonlinear LC waveform. Figure 9 shows the frequency spectrum of the LC for the wet polluted surface condition. It is observed that the LC for wet polluted surface contains the greater 3rd harmonic components than case A. Figure 10 shows that insulator

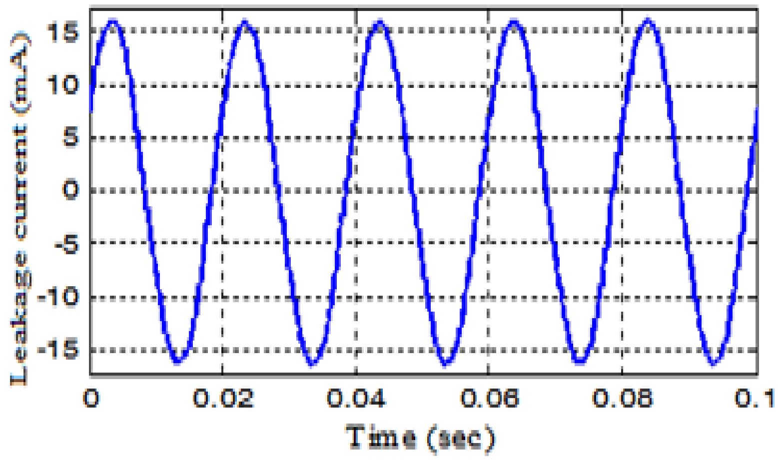

Figure 6. Leakage current of 20 kV polluted insulator Under UV.

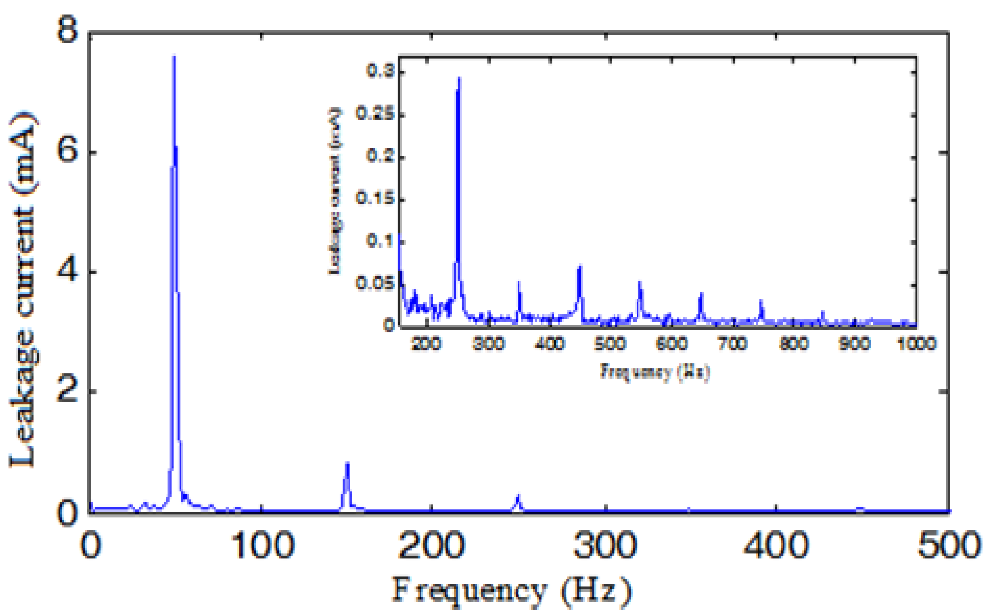

Figure 7. Frequency spectrum of leakage current on 20 kV polluted insulator under UV.

Table 2. magnitude of harmonics in LC waveform for case A.

Leakage current	With UV (mA)	Without UV (mA)
Maximum Value	15.97	13.08
1st harmonic	7.967	6.017
3rd harmonic	0.813	0.3684
5th harmonic	0.029	0.1314
7th harmonic	0.051	0.0336
9th harmonic	0.083	0.0113
11th harmonic	0.058	0.0103
13th harmonic	0.035	0.0048

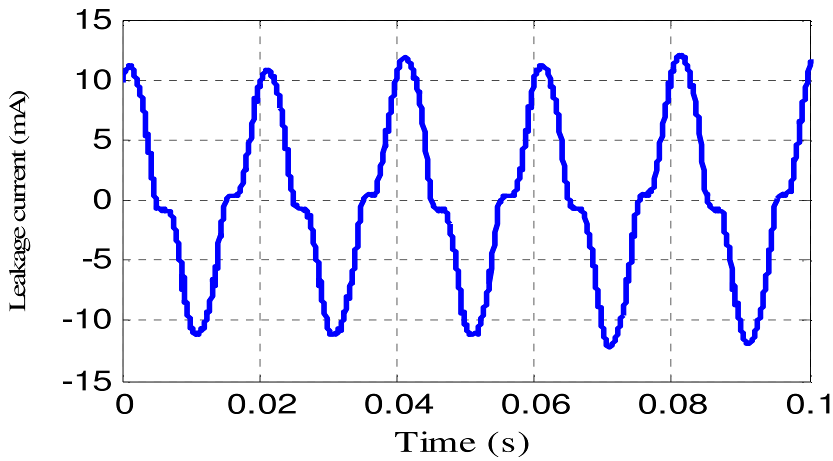

Figure 8. Leakage current of 20 kV polluted insulator contain dry band arcing.

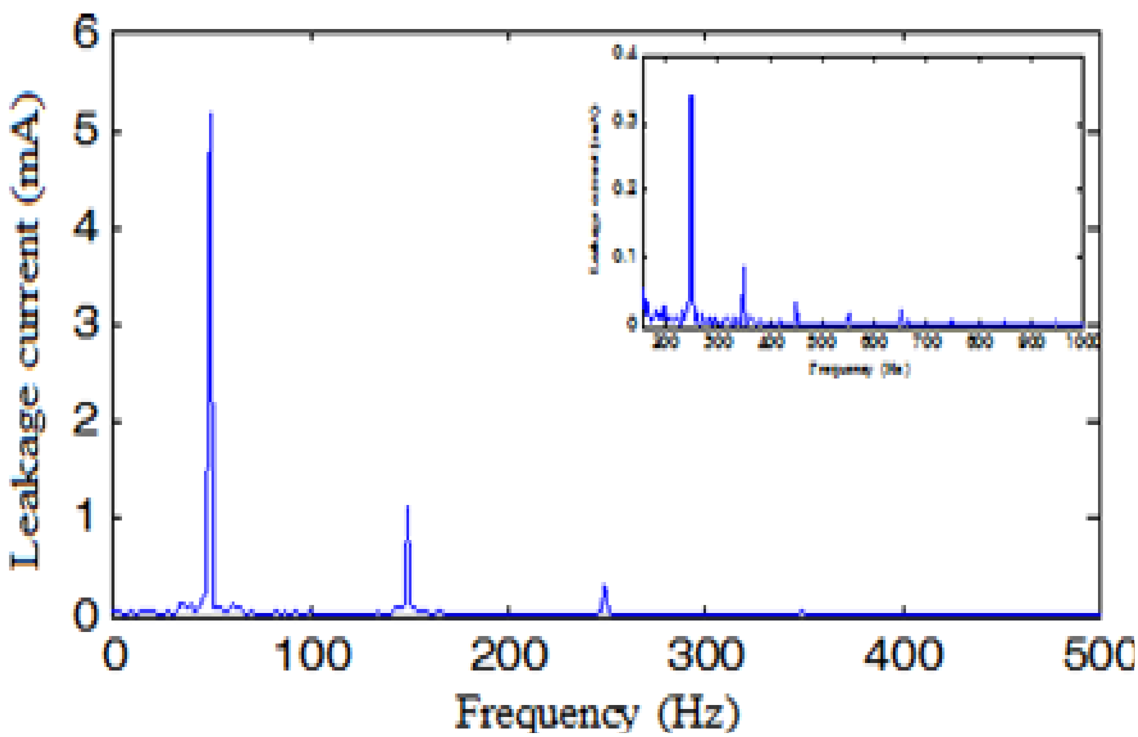

Figure 9. Frequency spectrum of Leakage current on 20 kV polluted insulator contain dry band arcing.

which is subjected to UV has more LC due to loss of hydrophobicity compare to non-aged insulator. Figure 11 shows the frequency spectrum of the LC for polluted surface exposed to UV radiation. Table 3 shows the magnitude of each harmonic in LC waveform for case B.

Fully formed arc with dry band arcing

With increase in the applied voltage, partial discharges will elongate along the surface and lead to fully formed arcs. This condition is just as the previous stage of the insulator flashover. Figure 12 shows the LC for this case. The Interesting point is that although the magnitude of the current is smaller than two previous cases (Figures 6 and 8), the 3rd harmonic component has increased in this case. comparing cases A and B. Figure 14 shows that insulator which is subjected to UV has more LC due to loss of hydrophobicity comparing to the non-aged insulator. Figure 15 shows the frequency spectrum of the

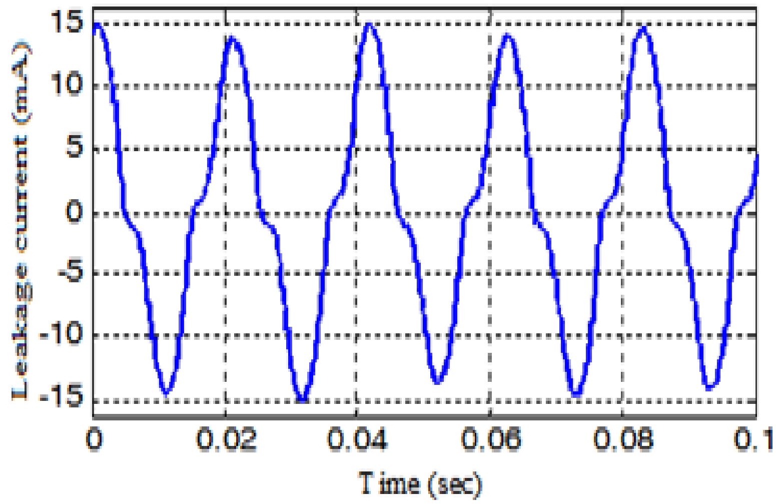

Figure 10. Leakage current of 20 kV polluted insulator under UV contain dry band arcing.

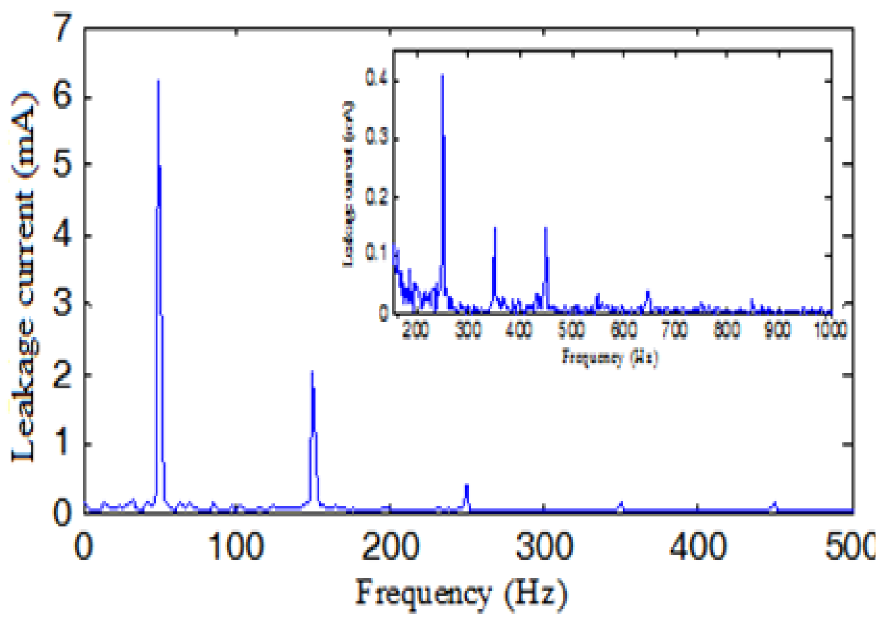

Figure 11. Frequency spectrum of Leakage current on 20 kV polluted insulator under UV contain dry band arcing.

Table 3. magnitude of harmonics in LC waveform for case B.

Leakage current	With UV (mA)	Without UV (mA)
Maximum value	15.1	11.76
1^{st} harmonic	6.34	5.167
3^{rd} harmonic	2.28	1.131
5^{th} harmonic	0.42	0.341
7^{th} harmonic	0.176	0.086
9^{th} harmonic	0.173	0.034
11^{th} harmonic	0.033	0.021
13^{th} harmonic	0.042	0.024

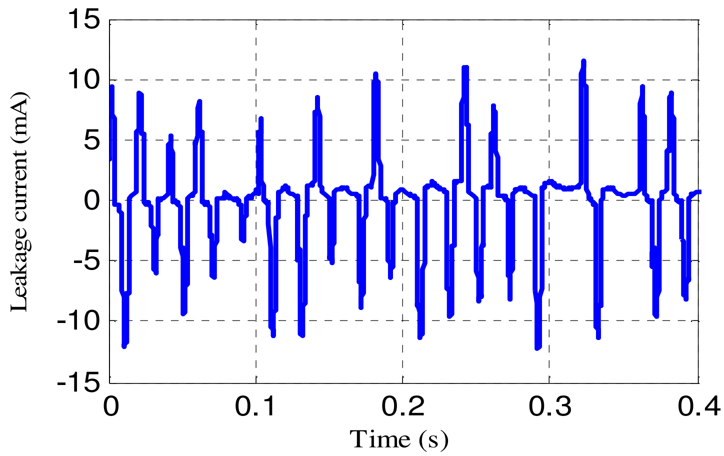

Figure 12. Leakage current of 20 kV polluted insulator contain fully formed arc with dry band arcing.

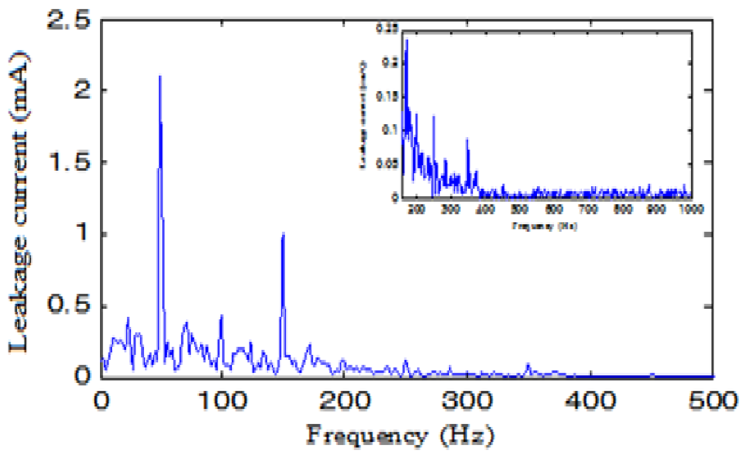

Figure 13. Frequency spectrum of Leakage current on 20 kV polluted insulator contain fully formed arcs with dry band arcing.

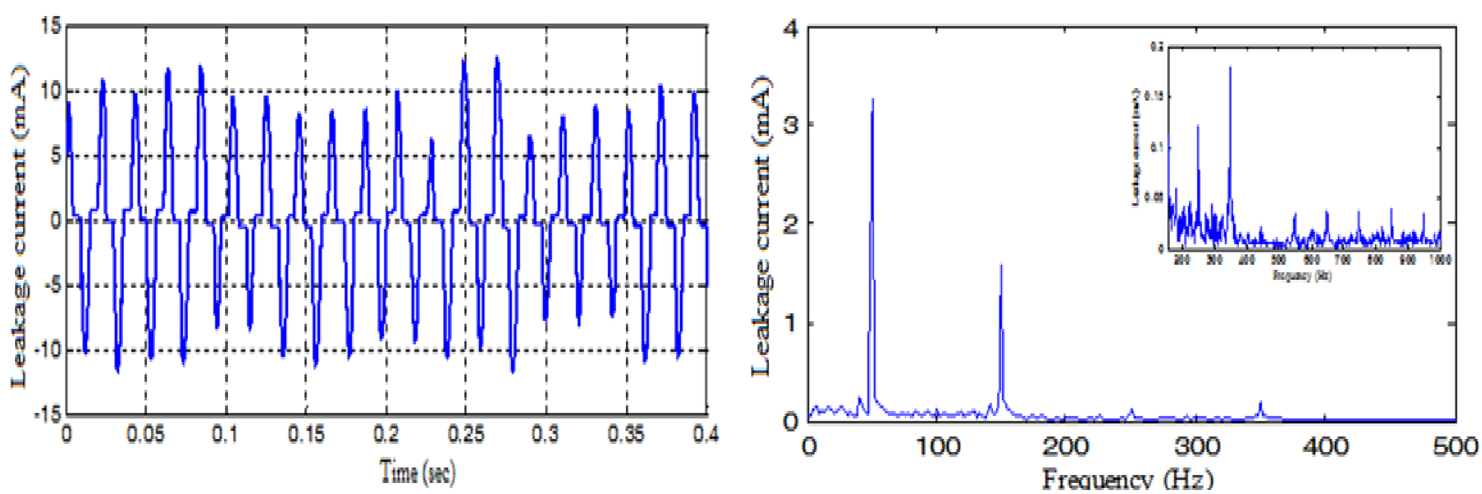

Figure 14. Leakage current on 20 kV polluted insulator under UV contain fully formed arcs with dry band arcing.

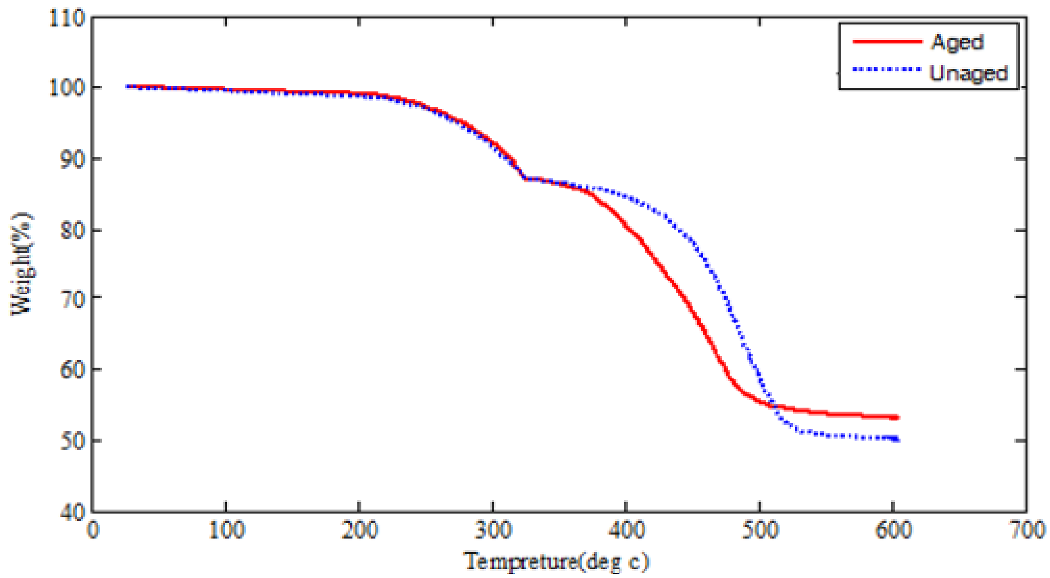

Figure 15. Frequency spectrum of Leakage current on 20 kV polluted insulator under UV contain fully formed arcs with dry band arcing.

LC during polluted surface exposure to UV radiation which has higher 3rd harmonic content. Table 4 shows the magnitude of each harmonic in LC waveform for case C.

TGA AND SEM ANALYSIS

Thermo gravimetric analysis (TGA) is a thermal analysis technique used to determine changes in weight of a sample in relation to changes in temperature. Figure 16 shows TGA of HTV-SiR which evaluate the thermal stability of SiR before and after exposure to UV. The measurement was carried out from 25 to 600°C in a nitrogen atmosphere. It can be seen that for the unaged SiR, the first onset temperature in 195°C with a weight loss of 12%, while the second onset temperature is 310°C with weight loss of 41%. After 65 days of exposure, the first onset temperature in 195°C with a weight loss of 12%, while the second onset temperature is 308°C with weight loss of 33%.

From the above results it can be suggested that change of weight loss in aged SiR is higher than unaged SiR. In addition, the first derivation of TGA curves was used to see precisely at what temperature decomposition began for both aged and unaged SiR, Figure 16.The first peak, which is not very strong, was noticed for both the aged and unaged silicone rubber around 1950 C. The second peak, which appears around 3100°C is caused by the liberation of the side chain (CH3) from the silicone backbone (Si-O-Si). Figure 16 Shows a significant difference in terms of the steepness that corresponds to the rate of weight loss.

Small samples (1 mm × 1 mm) were removed from the high voltage end of each insulator and their surface analysis was performed using scanning electron microscope (SEM). The analyses were made in high vacuum mode in order to avoid sample charging. SEM photographs were captured for analyzing surface condition for SiR Insulators at magnifications of 1000×. To compare the two surfaces (aged and new), the probing depth of the electron beam in materials was kept at 50µm. Figure 17 shows SEM results of new and aged samples. The overall visual observation is that there is no major degradation, such as cracking, however, it can be seen that these micrographs have different micro-structures. The unaged (new) samples have a smooth, more homogenous and less porous surface while the surface roughness and porosity increases with aging for aged SiR Insulators.

CONCLUSION

After an experimental test results on a 20KV SiR insulator, LC monitoring showed that third harmonic components of leakage current waveform is closely related to the pollution on the insulator, and ultraviolet emissions locally destroy the hydrophobicity of the surface insulator. Under clean conditions, no flashover occurred during the rated voltage tests. Taking a look at TGA analysis results, there is a shift in the figure for the aged sample and degradation starts in a lower temp-erature for the aged sample comparing to the unaged one. Also SEM analysis showed that the unaged sample has a smooth, more homogenous and less porous surface

Table 4. magnitude of harmonics in LC waveform for case C.

Leakage current	With UV (mA)	Without UV (mA)
Maximum value	13.5	12.1
1st harmonic	3.32	2.13
3rd harmonic	1.83	1.011
5th harmonic	0.124	0.1227
7th harmonic	0.16	0.0906
9th harmonic	0.043	0.017
11th harmonic	0.016	0.0132
13th harmonic	0.0129	0.0121

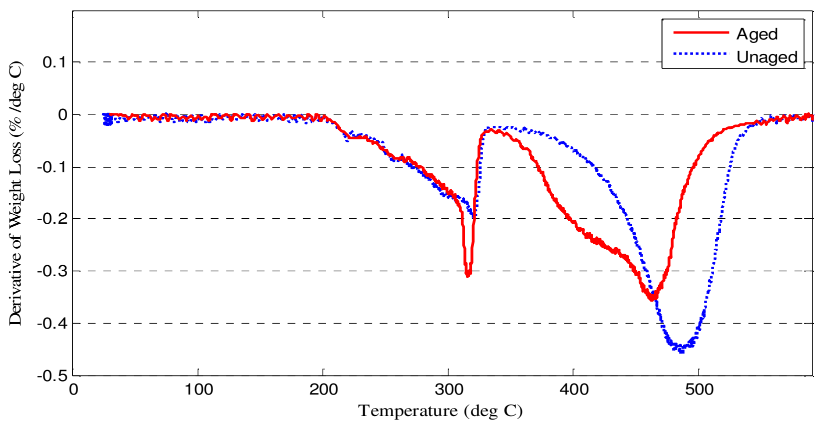

Figure 16. Derivative of Weight loss for aged and unaged polymer insulator.

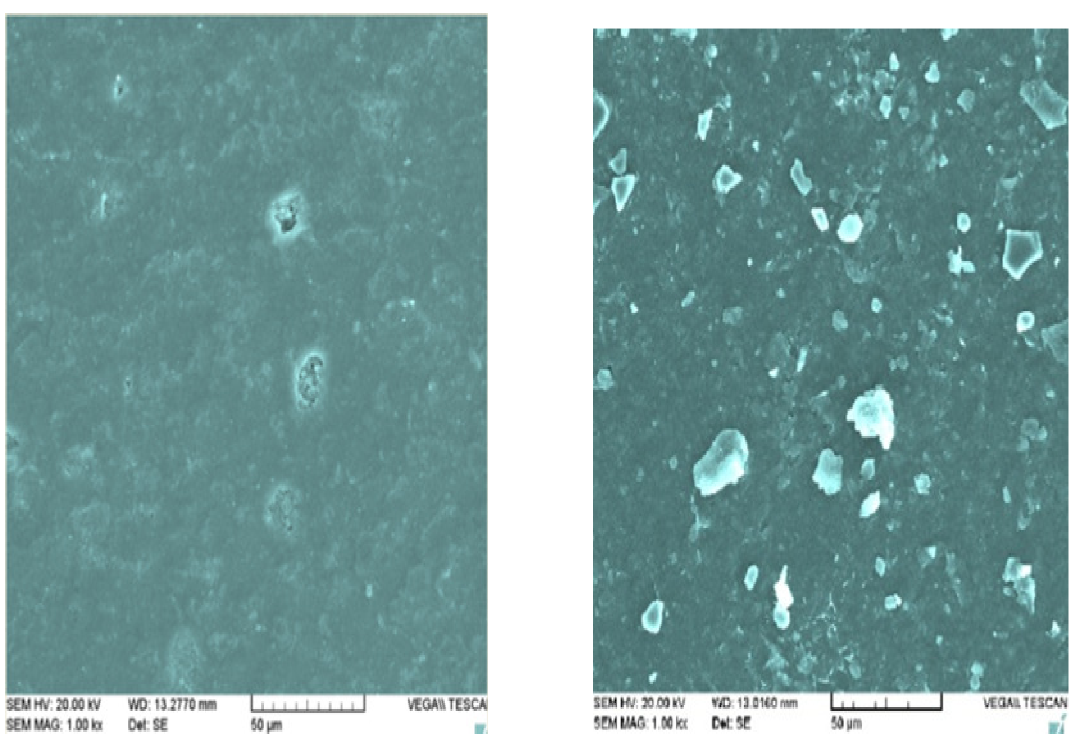

Figure 17. SEM analysis for aged and unaged SIR sample.

surface while the surface roughness and porosity increases with aging.

ACKNOWLEDGEMENT

This work was supported by the High Voltage Research Center, School of Electrical and Computer Engineering, University of Tehran.

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