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Analysis of Surface Condition of Polymeric Insulators for High Voltage Power Transmission Line Applications Using Partial Discharge Analysis

V. Jayaprakash Narayanan [1],Dr.S. Chandrasekar [2] A.Vanitha[3]
[1]*Assistant Professor,Gnanamani College of Technology,Namakkal, Tamil Nadu, India*
[2] *Member IEEE, Professor, Gnan Expert R&D Centre, Department of EEE, Gnanamani College of Technology, Namakkal, Tamil Nadu, India*
[3]*Assistant Engineer, TNEB, Govt of Tamil Nadu,India*

ABSTRACT :*In recent decays polymeric insulators are mostly preferred for high voltage power transmission line applications. However, severe pollution deposits on the surface of the insulator and aging of the polymeric insulators due to thermal and ambient stresses lead to reduction in its insulation strength. This paper deals with analysis of partial discharge characteristics of high voltage polymeric insulators with the aim to understand the influence of thermal aging at different pollution conditions. In this work, laboratory based tests are carried out as per IEC 60507 under ac voltage, at different humidity and at different contamination levels using sodium chloride as a contaminant, on virgin and thermal aged polymeric insulator. Partial discharge signals are acquired through a PD monitoring system which is able to collect the PD waveforms along with patterns. Time domain and frequency domain characteristics of PD pulses are studied to understand the influence of thermal aging of polymeric insulator. From the obtained results, we could infer that the performance of outdoor polymeric insulator reduces with thermal aging, which will lead to surface erosion and degradation of the insulating material.*

KEY WORDS*: power transmission line, insulator, silicone rubber, partial discharge, frequency spectrum, pollution severity.*

I. INTRODUCTION

Porcelain and glass have traditionally been widely used as the insulating materials for high voltage power transmission line applications and their advantages and drawbacks are well known. However, in recent times, the polymeric insulators have replaced ceramic units due to wide range of reasons such as light weight, easy transportation and installation, high mechanical strength to weight ratio, combat to vandalism , aesthetic appearance and superior insulation performance [1,2]. During the last three decades the privilege to use the polymeric insulators has tremendously increased globally. When these polymeric insulators are installed in coastal areas, the salt and airborne particles are deposited on their surfaces and the pollution builds up gradually. Under dry conditions, these deposits do not decrease the surface insulation strength, whereas in wet weather condition a conductive layer is formed which results in flow of leakage current. The density of leakage current is non-uniform over the surface of the insulator and due to flow of leakage current sufficient heat is developed leading to formation of dry bands in the surface. Formation of dry bands causes redistribution of voltage along the insulator surface giving rise to strong electric field intensity across the dry bands which create electric arcs (or) partial discharges (PD) across the dry bands.

This dry band arc will cause erosion and surface degradation of insulating material in polymeric insulators. When the surface resistance is low enough, these dry band arcs will grow along the insulator profile and may eventually cause insulator flash over. Preventive maintenance by washing the insulator surface is one of the ways to reduce the flash over, but it is cumbersome and costly. Therefore, several studies have been performed to optimize the maintenance times. But it resorts to pollution charts which are widely used and are liable to abnormal seasonal and weather variations. The conventional Equivalent Salt Deposit Density (ESDD) method has been proposed, but it looks both time consuming and difficult to practice [3, 4]. At present, the common technique to detect the pollution severity is by means of analysis of leakage current. It indicates the surges occurring near the current peaks of dry band arcing phenomena [5]. For a given insulator, evolution of leakage waveform depends essentially on the changes occurring at the surface pollution layer and surface wetness of the insulator. Sarathi et al, [6] have proposed the multi resolution decomposition technique as an effective tool to understand time-frequency characteristics of leakage current signals and to identify the surface condition of the insulation. The dry band arcs are a precursor of flash over; hence the partial discharge detection will provide better mechanism to effectively assess the surface condition of the outdoor polymeric insulator [7]. When these polymeric insulators are installed in outdoor transmission lines, they are also affected by severe weather conditions such as high temperature, large daily and seasonal variations and high humidity levels and UV radiations throughout the year. In addition to surface degradation by partial discharges due to pollution, polymeric insulators are also subjected to aging which is due to the high temperature and UV which results further deterioration of the electrical insulation performance of the material. Determination of irreversible changes due to aging is a complicated process. It depends on the form of housing, design of insulator and environmental condition. Aging can lead to increased leakage current and which may result in earlier flash over under wet and contaminated conditions.

Gorur et al [8] proposed a methodology based on the surface resistance measurements to identify the surface degradation of polymeric insulators and concluded that surface resistance can be used as an indicator of aging of non ceramic insulator, but minimum value of surface resistance cannot be specified. Que et al [9] presented a methodology based on voltage–current phase angle measurements to understand surface degradation and aging of polymeric insulators. In general polymeric material offers good hydrophobicity for a long time. The long term maintenance of hydrophobicity is attributed due to its chemical stability and recovery phenomena resulting from diffusion of low molecular weight contents from bulk volume of the insulator to the surface of the material [10]. Hydrophobic polymers are characterized by high electrical surface resistance which however decreases due to water absorption during ageing and with increasing environmental temperature and contamination build up. Kumagai et al [11], have shown that cross linking, branching, interchanging of silanol groups are the most dominant chemical reactions in silicone rubber polymeric materials and the byproducts of oxidation restrict the diffusion of mobile low molecular weight chains to bulk volume, which decreases the recovery speed of hydrophobicity of polymeric materials and accelerates ageing process.There are several field investigations with the polymeric insulators which provide useful and real time information about their performance but the information about their performance under thermal aged conditions is rather limited**.** Hence, expectation of performance and life time of thermally aged insulator in reference to laboratory test is considerably important, requiring the comparison of virgin and thermal aged insulators. Considering these facts, this paper implies the effects of conductive pollution on PD activity through laboratory experiments performed on virgin polymeric insulator and on thermal aged polymeric insulator at different pollution levels and at different relative humidity conditions. Typical PD waveforms along with PD patterns have been collected through an innovative PD detection system. The time domain and frequency domain characteristics of PD pulses observed on virgin and thermal aged polymeric insulators are compared.

II. EXPERIMENTAL SETUP

2.1 Test Specimen

A 11kV polymeric insulator with leakage distance 300 mm and core diameter 70 mm was used for laboratory experiments. Figure 1 shows the photograph and sketch of the polymeric insulator used in this study.

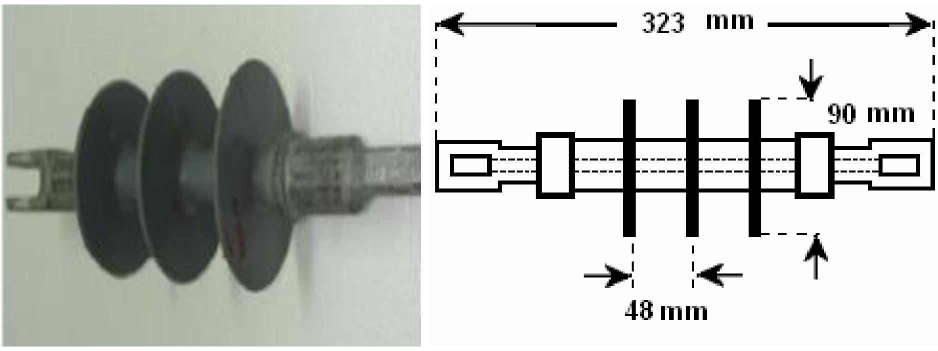


Figure1. Photograph and sketch of the 11kV Silicone Rubber Insulator

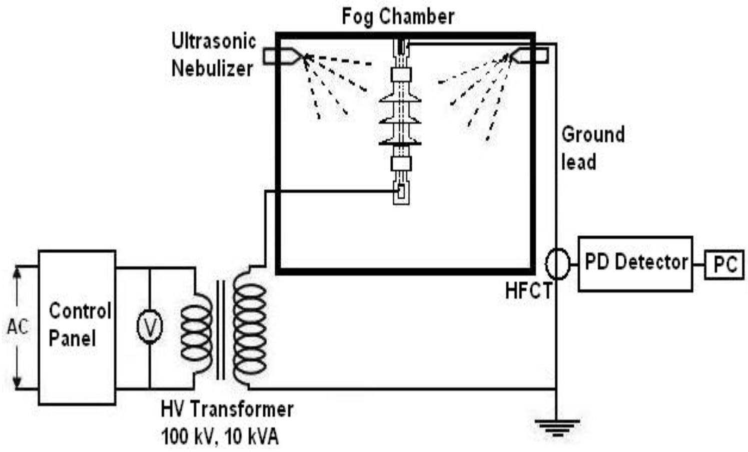


Figure 2 Schematic diagram of the experiment set up

Figure 2 reports the schematic diagram of the experimental set up. The test insulator was suspended vertically inside the fog chamber (1.5×1.5×1.5 m). The test voltage was 11 kV rms, 50Hz. Tests were conducted as per IEC 60507 clean fog test procedure. Before tests, the insulator surfaces were cleaned by washing with isopropylic alcohol and rinsing with distilled water, in order to remove any trace of dirt and grease. To reproduce the saline pollution typical of coastal areas, a contamination layer consisting of sodium chloride was sprayed over the surface of the polymeric insulator such that the salinity spread uniformly over the surface. The concentration of Nacl salt was varied to give Equivalent Salt Deposit Density (ESDD) in mg/cm^2 to 0.06 (lightly polluted), 0.08 (moderately polluted), and 0.12 (heavily polluted). Accelerated thermal aging of the polymeric insulator was carried out in the laboratory by keeping the specimen inside the temperature controlled hot air oven at 150° C for a period of 1440 hour. Four ultrasonic nebulizers were used to maintain the required relative humidity level inside the fog chamber. Relative humidity inside the fog chamber was measured using the wall-mount Hydrothermal instrument.

PD measuring system : PD signals were picked by connecting a high frequency current transformer (HFCT) around the ground connection of the test cell. HFCT is a clip on device clamped around the ground lead and it has a 50 MHz frequency bandwidth which is sufficient to cover the entire range of PD. Output of the HFCT is connected to the PD detector. Partial discharges were detected through a large bandwidth system, PDBASE II (TechIMP Systems, Italy) able to sample the complete PD waveforms at a sampling rate of upto 1 GSa/s and bandwidth of 0-500 MHz. The sensitivity ranges from 2 mV/div to 5V/div. PDBASE II also provides large number of digitized PD pulse waveforms and it is able to separate them according to the PD waveform shape by means of fuzzy classification tool [10-13]. No coupling capacitor was inserted in parallel to the test specimen. The PD pulses were sent to a remote PC for further processing.

TEST PROCEDURE

Laboratory tests were carried out in the following test conditions.

[1] Virgin silicone rubber insulator with clean dry and wet surface.
[2] Virgin insulator with different pollution levels, 0.06 ESDD, 0.08 ESDD and 0.12 ESDD at a constant relative humidity
[3] Virgin insulator with constant pollution level at different relative humidity from 50% to 100%.
[4] Procedures (ii) and (iii) repeated for thermal aged polymeric insulator.

IV. RESULTS AND DISCUSSION

4.1 PD test results of clean insulator surface

In order to understand the difference in PRPD pattern between the clean surface and polluted surface, initially both virgin and thermal aged silicone rubber insulator specimen was tested without applying any pollution with an applied voltage of 11kV rms at clean surface conditions. Insulator specimen was kept inside the fog chamber and tested for both clean dry surface and clean wet surface condition without applying any pollution and the relative humidity level was varied from 50% to 100%. Typical PRPD patterns obtained with the clean surface condition at 100% RH is shown in figure 3. The sine waveform used in the PRPD pattern obtained is used as a phase reference signal and its amplitude is not given in vertical scale. It is observed that during both clean tests, there is no significant discharge. Only high frequency noise signal is present in this test.

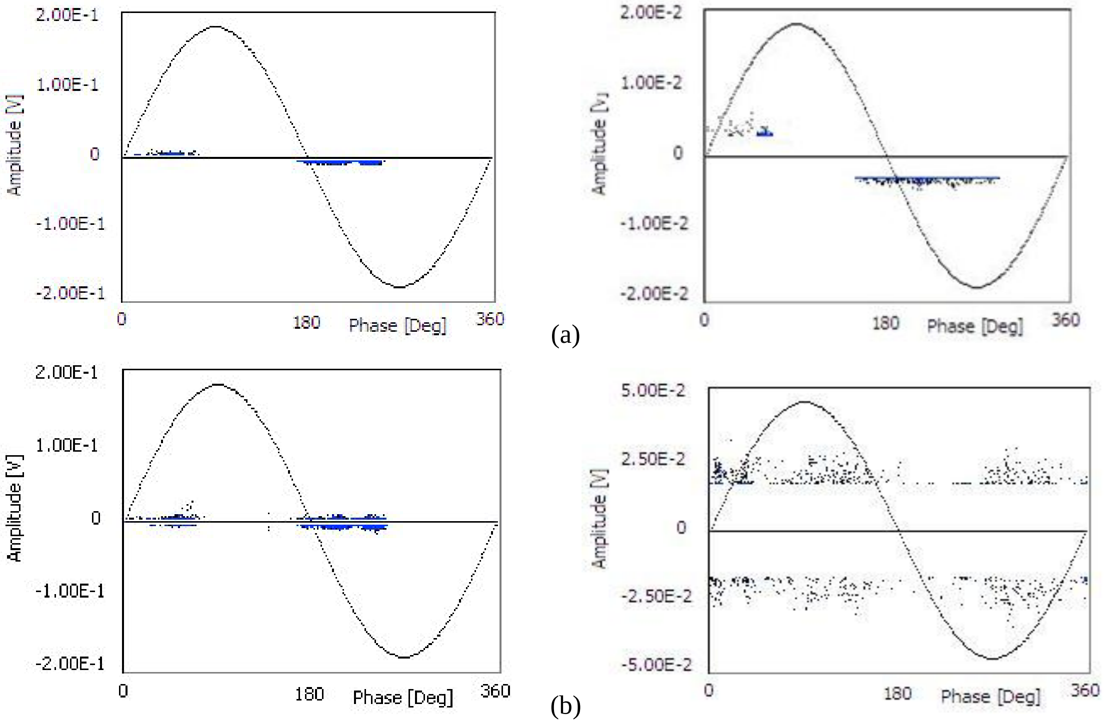


Figure 3 Typical PRPD Pattern of 11 kV polymeric insulator virgin (left) and thermal aged (right) obtained at 100% RH (a) Clean dry (b) Clean wet surface

Typical PD pulse and corresponding frequency spectrum obtained at clean surface condition is shown in figure 4. From the results, it is observed that PD signal is completely absent and low magnitude noise signals are only present during this measurement. Frequency bandwidth of the noise signal was observed in the range of 20-25 MHz.

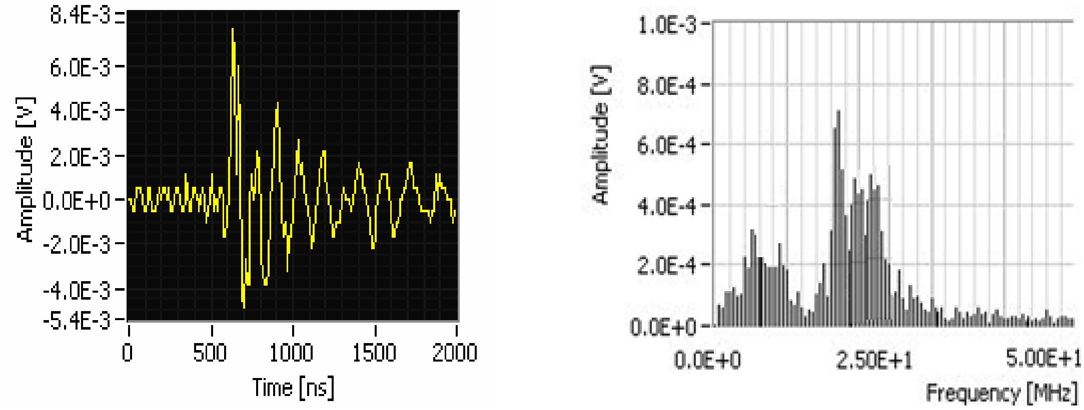


Figure 4 Typical PD Pulse and corresponding frequency spectrum at clean surface condition

4.2 PD test results with varying pollution at constant relative humidity

Insulators located in coastal areas and industrial areas are mainly affected by deposit of pollution on the surface. This deposit of pollution on the surface increases considerably with respect to time period. Hence it is necessary to understand the partial discharge characteristics with respect to increase in pollution level on the surface of insulator. In this test, the PD measurement is carried out on both virgin and thermal aged insulator specimens, by keeping the sample under different pollution level at a constant relative humidity. Typical PRPD pattern obtained at 90% relative humidity is shown in Figure 5. The contamination level is varied from 0.06 ESDD to 0.12 ESDD in this set of experiments.

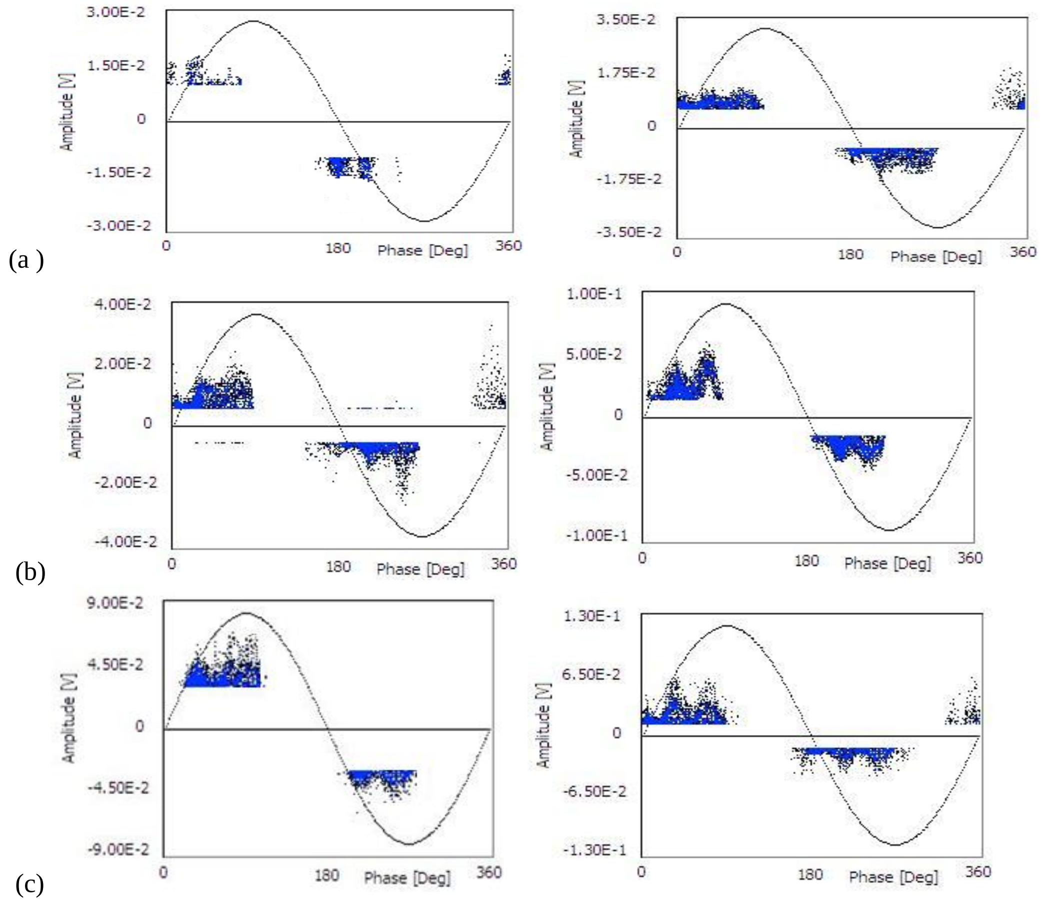


Figure 5 Typical PRPD Pattern of 11 kV polymeric insulator virgin (left) and thermal aged (right) obtained at 90% RH (a) 0.06 ESDD (b) 0.08 ESDD (c) 0.12 ESDD

By comparing the above PRPD patterns of virgin and thermal aged specimens, it can be inferred that the magnitude of PD increases considerably with thermal aging at all pollution levels. With respect to increase in pollution level, the magnitude of PD increases and dispersion of PD amplitude in the pattern also increases. Occurrence of PD pulses in both positive and negative half cycles is noticed. However, the number of PD pulses at high pollution (0.12 ESDD) is reduced considerably when compared with 0.08 ESDD. This may be due to the formation of long arcs occuring in the surface of the insulator during high pollution, which dries the surface quickly and therefore it takes some more time for the initiation of another PD pulse after surface wetting. Photograph of short duration PD pulses and long duration PD pulses of thermal aged specimen observed during the experiments at 95% relative humidity level are shown in Figure 6.

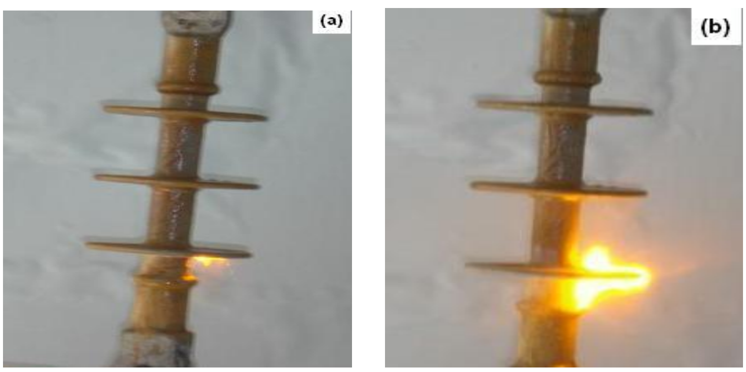


Figure 6. Photograph of 11 kV silicone rubber insulator thermal aged specimen at 95% relative humidity (a) Short duration PD observed at 0.08 ESDD pollution (b) Long arc observed at 0.12 ESDD pollution

PD test results with varying relative humidity at constant pollution

In this test, both virgin and thermal aged polymeric insulator was tested at constant pollution level 0.06 ESDD and the relative humidity inside the fog chamber was varied from 60% to 100%. Figure 7 shows the typical PRPD pattern obtained at 0.06 ESDD at different relative humidity levels of virgin and thermal aged specimens. From the PRPD patterns, it can be identified that the magnitude of the PD and number of PD pulses increases with increasing relative humidity. This is mainly, because at high relative humidity, the collection of water droplets along the surface of the polymeric insulator is more, causing high leakage current which leads to the heating of surface and causes more dry bands along the surface. Due to increase in electric field strength across the dry bands, more number of PD pulse occurs. It is also noticed from the PRPD patterns that with respect to increase in relative humidity level, the dispersion of PD pattern increases, which shows a feature typical of surface discharge phenomena. Occurrence of large number of partial discharges on the surface of polymeric insulator causes surface degradation and erosion of the material, which leads to reduction in electrical insulation strength.

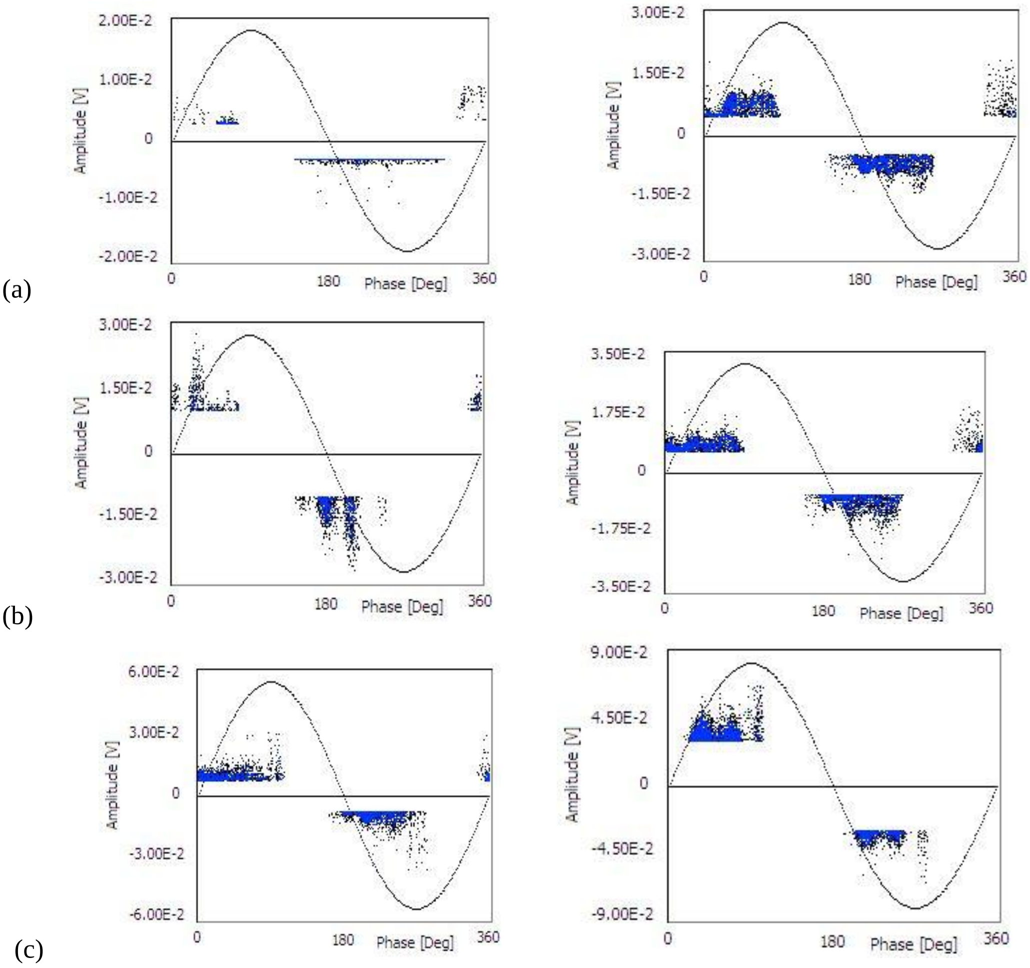


Figure 7 Typical PRPD Pattern of 11 kV polymeric insulator virgin (left) and thermal aged (right) obtained at 0.06 ESDD (a) 60 % RH (b) 80% RH (c) 100% RH

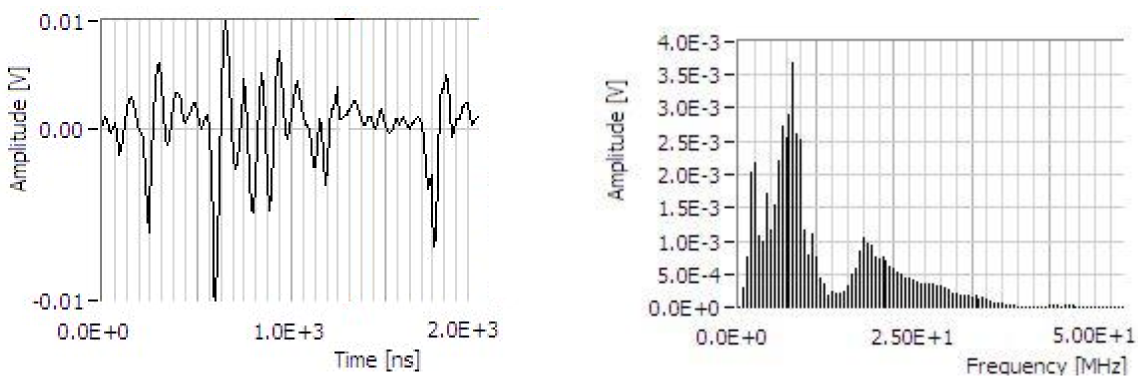
PD pulse and frequency spectrum analysis

Understanding the PD pulse characteristics and its frequency domain analysis is important in order to develop a better diagnostic system for the surface condition analysis of the outdoor polymeric insulators. In the present work, during the experimental studies, individual PD pulses were also captured simultaneously at different pollution conditions and stored in PC for further frequency domain analysis. Typical PD pulses and its corresponding frequency spectrum of virgin and thermal aged silicone rubber insulators obtained at different surface pollution conditions are shown in figure 8 and figure 9. From this analysis it is observed that,

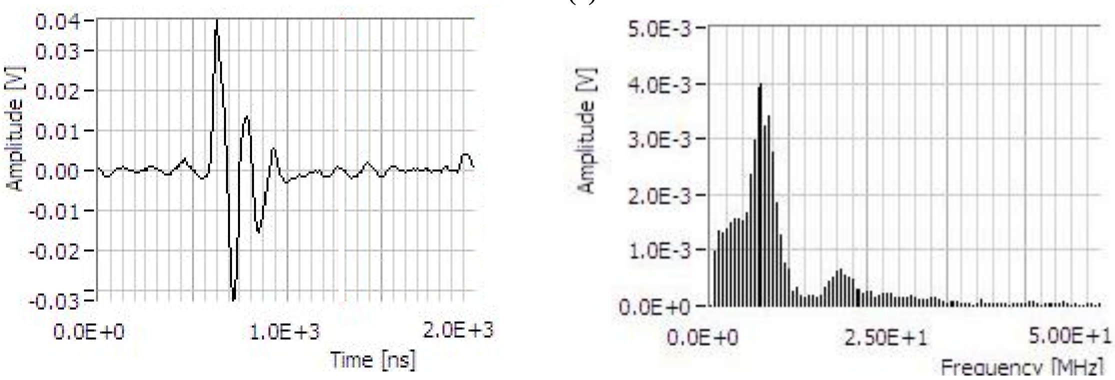
[1] PD pulse amplitude increases with increase in pollution level for both virgin and thermal aged specimens

[2] Short duration discharges (Figure 8 b and 8 c) are mostly observed in virgin specimens

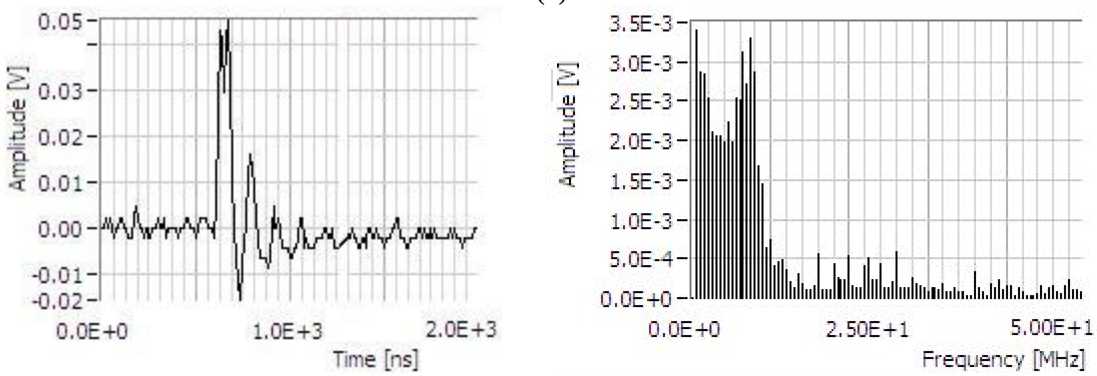
[3] Long duration discharges are observed at heavily polluted conditions (0.12 ESDD) in thermal aged specimens (Figure 9 c)
[4] Time length of PD pulses increases considerably with respect to increase in pollution level in both virgin and thermal aged specimens
[5] Rise time of PD pulses increases considerably with respect to increase in pollution
[6] At lightly polluted conditions (0.06 ESDD), the high frequency content (15-25 MHz) is also noticed in the frequency spectrum of the PD signal.
[7] With respect to increase in pollution level from 0.06 ESDD to 0.12 ESDD, the magnitude of high frequency content (15-25 MHz) significantly reduces and the dominant frequency content shift towards 5-10 MHz.
[8] Energy content of the PD signal increases at long arcs observed in thermal aged specimens and this will increase the surface local temperature of the thermal aged specimens, which will lead to faster erosion and degradation of the polymeric material.



(a)

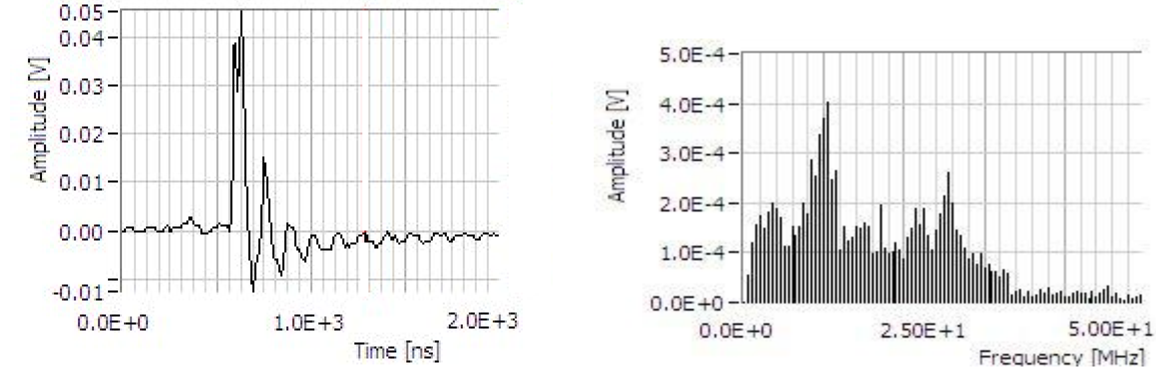


(b)

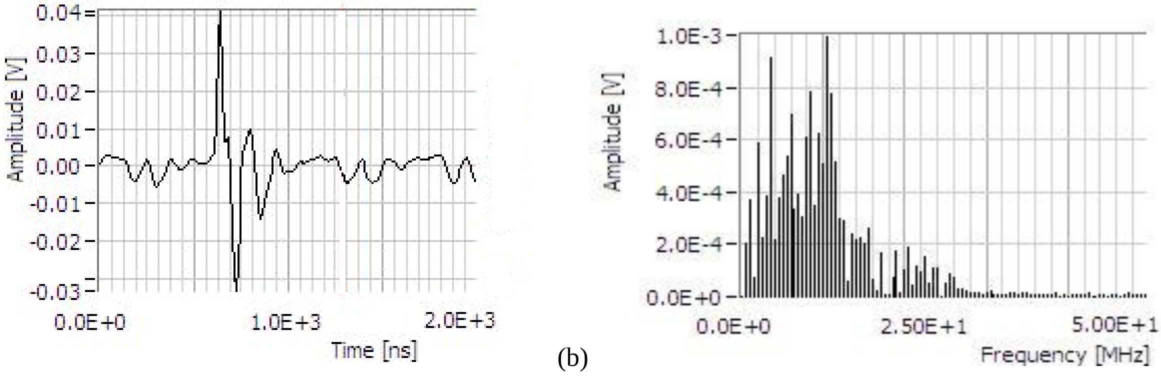


(c)

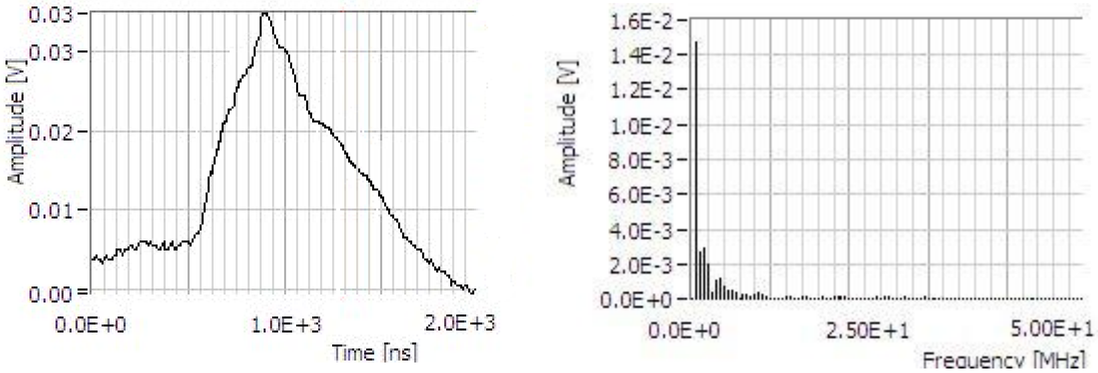
Figure 8 PD Pulse and Frequency Spectrum of Virgin Polymeric Insulator obtained at 90% RH
(a) 0.06 ESDD (b) 0.08 ESDD (c) 0.12 ESDD



(a)



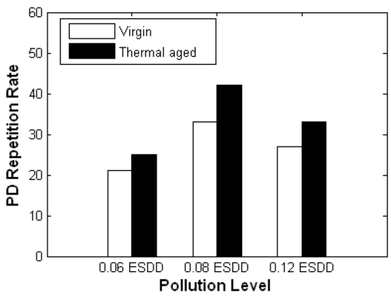
(b)



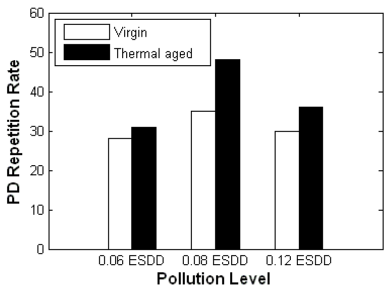
(c)

Figure 9 PD Pulse and Frequency Spectrum of thermal aged Polymeric Insulator obtained at 90 % RH (a) 0.06 ESDD (b) 0.08 ESDD (c) 0.12 ESDD

Analysis of repetition rate of PD pulses



(a)



(b)

Figure 10. PD repetition rate of virgin and thermal aged polymeric insulator at(a)80%RH and (b) 100 % RH

Repetition rate of the PD pulses (pulses/sec) is a good indicator of pollution severity on the surface of the insulator and it is also indirectly a measure of surface degradation of the polymeric insulators. In the case of outdoor polymeric insulators, the PD appear in pulse bursts and their repetition rate is irregular. The PDBASE II analyzer gives repetition rate for each measured PRPD data. Figure 10 shows the plot between repetition rate and pollution level of virgin and thermal aged specimens at different relative humidity conditions. In general, the repetition rate of the PD pulses increases with increase in pollution level and relative humidity level. Once the partial discharge inception starts, the repetition rate rises gradually with respect to increase in pollution and when the pollution level reaches the maximum to 0.12 ESDD, it shows a reduction in repetition rate. Similar trend is obtained for both virgin and thermal aged specimens; however the magnitude of repetition rate is considerably higher for thermal aged specimens when compared with virgin specimens. Rate of rise of repetition rate is higher for 100 % relative humidity level when compared with 80 % relative humidity level. The reason for sudden decrease in repetition rate at high pollution may be due to the formation of long partial arcs along the surface which heats the surface and causes a time lag for the formation of next partial arc. This clearly shows that PD repetition rate can be used as additional information to diagnose the surface pollution severity of the outdoor polymeric insulators.

Analysis of PRPD pattern equivalent timelength-equivalent bandwidth : In the case of on-line outdoor PD measurements on transmission tower insulators, the presence of significant noise and/or pulses coming from various PD sources active at the same time will make the diagnosis of pollution severity of insulators extremely difficult even for skilled operators. Accurate diagnosis based on PD analysis depends on effective noise/disturbance rejection and on the collection of large amount information on PD signals. Hence it is necessary to classify the large collection of PD signals based on the equivalent timelength and equivalent bandwidth, i.e. the two real numbers used to localize the PD signal in time/frequency plane [13,14]. PDBASE II system classifies each of the PD pulse having similar shapes in the time-frequency plane. This representation will be useful to cluster the PD pulses into different groups and to understand the pollution severity of the insulator.

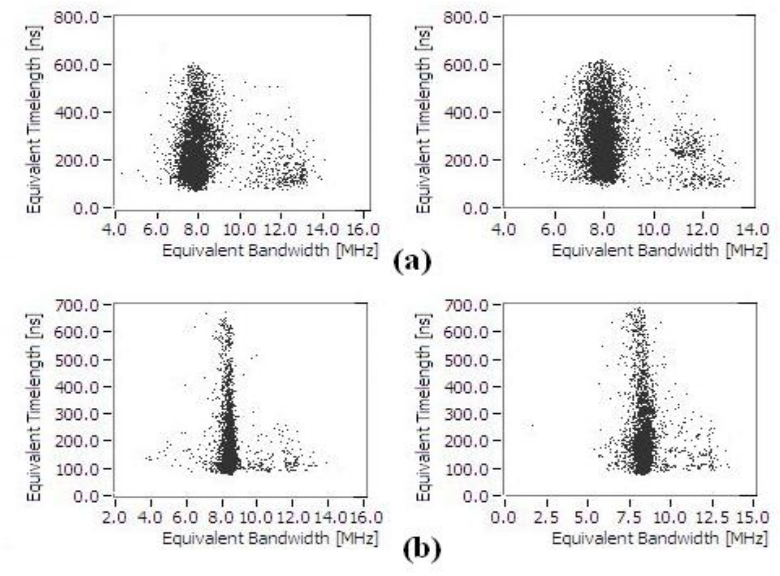


Figure 11. Typical equivalent timelength-bandwidth plot of virgin (left) and thermal aged (right) specimen at 100 % RH (a) 0.06 ESDD and (b) 0.12 ESDD

Figure 11 shows the time/frequency plane representation of PRPD pattern obtained at 100 % RH of virgin and thermal aged specimen at different pollution level. Since the PD measurements were carried out above noise level in the laboratory, presence of high frequency noise signals above 20 MHz is completely absent in this represenation. It is observed that PD signals lies in the frequency band of 6 MHz to 12 MHz. However, most of the PD signals lies in the frequency band of 7-9 MHz. It is also noticed that PD signals lying in the 7-9 MHz bandwidth has varying timelength from 100 ns to 700 ns. Increase in equivalent timelength above 600 ns of the PD signal clearly related with long arcs obtained at high pollution (0.12 ESDD). In the case of thermal aged specimens at high pollutions (Figure 11 b), the presence of long arcs above 600 ns is higher when compared with virgin specimens. With respect to increase in pollution, it is also observed that the frequency content in the range of 10-13 MHz reduces.

This time/frequency plane analysis clearly indicates the increase in pollution level on the surface of the insulator and at the same time, significant difference between virgin and thermal aged specimen are also noticed. The above-reported partial discharge characteristics such as PRPD pattern, PD pulse-frequency spectrum, repetition rate and equivalent time length-equivalent bandwidth analysis show that pollution severity of polymeric insulators can be assessed by looking at the evolution of PD- related quantities in the course of time. When compared with PD test results of virgin insulators under similar experimental conditions, it is noticed that thermal aged silicone rubber insulator shows increased PD activity, which will certainly lead to surface erosion and degradation. When the polymeric insulating materials are used for outdoor applications, they are exposed to electric, mechanical, thermal and ambient stresses, which will accelerate the multi-stress aging and surface degradation of the material. Therefore, further research activities are being carried out in order to understand the influence of multiple stresses and aging phenomena on the PD characteristics of the silicone rubber insulators.

V. CONCLUSION

Laboratory measurement and analysis of partial discharge pattern and PD pulses of virgin and thermal aged silicone rubber insulators has been presented in this paper. The laboratory tests are performed at different relative humidity and pollution levels as per IEC 60507 test procedure. It is shown that variations in time and frequency domain characteristics of PD pulses are closely related to the surface pollution condition of the polymeric insulator. When compared with PD test results of virgin insulators, it is noticed that thermal aged silicone rubber insulator shows increased PD activity, which will certainly lead to surface erosion and degradation. Equivalent timelength-equivalent bandwidth plane clearly shows the increase in pollution level on the surface of insulator and it can be used as a diagnostic tool to identify the pollution severity of insulator. These preliminary lab results on thermal aged polymeric insulator shows that, when these insulators are used in tropical regions, they are exposed to large thermal and ambient stress variations for the entire life span which will accelerate the surface degradation of the material under severe pollution conditions.

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