Investigations of Accelerated Aged Polymeric Insulators Using Partial Discharge Signal Measurement and Analysis

K. Mekala*, S. Chandrasekar† and R. Samson Ravindran**

Abstract – Reduction in pollution performance of polymeric insulators, aged due to water absorption stress and thermal stress, is a major threat to the reliable operation of power transmission and distribution system. Formation of partial discharges on the surface of wet polluted insulator plays a major role in determining the life time and pollution performance of outdoor polymeric insulators. However, reports on partial discharge characteristics of water absorption stress aged and thermal aged polymeric insulators are scanty. This paper discusses the pollution performance characteristics of accelerated aged polymeric insulators using the advanced ultra wide band PD signal measurement and analysis. Laboratory experiments on accelerated aged polymeric insulators were carried out as per IEC 60507 under AC voltage, at different humidity and contamination levels using NaCl as a contaminant. PRPD pattern and Time-Frequency map analysis of PD signals were carried out. From the results, it can be speculated that PD analysis is a well suited technique to understand the pollution performance of aged polymeric insulators.

Keywords: Polymeric insulator, Silicone rubber, Pollution, Accelerated aging, Partial discharge, Time-frequency map

1. Introduction

In recent times, polymeric insulators have replaced ceramic insulators in power transmission and distribution systems [1]. In service, since polymeric insulators are organic in nature, environmental stresses lead to aging of the material and causes increase in surface roughness. Usually polymeric insulators are made of silicone rubber which offers good hydrophobicity (high resistance to wetting of surface) and hence provides high electrical surface resistance. However, hydrophobicity of polymeric insulators is reduced by long term aging of material due to environmental stresses. Surface wettability increases with increase in surface roughness due to aging, which in turn reduces the hydrophobicity. Many researchers reported the role of ambient stresses in the outdoor performance of polymeric insulators [2-10]. Among the environmental stresses, the surface degradation effect of water absorption stress and long term thermal stress on energized outdoor insulators is considered to be more severe. Water absorption stress is due to highly humid, rainy and foggy conditions and thermal stress is due to ambient temperature variations experienced by the insulators in service.

In coastal areas, accumulation of pollution layer (such as salt and airborne particles) on the polymeric insulator surface causes the flow of leakage current (LC) under wet weather conditions. The density of LC is non-uniform over the surface of the insulator and due to flow of LC sufficient heat is developed leading to formation of dry bands in the surface. Strong electric field intensity across the dry bands creates partial discharges (PD) across the dry bands which lead to erosion and surface degradation of polymeric insulating material. When the surface resistance is low enough due to aging of the material, these dry band arcs will grow along the insulator profile fastly and may eventually cause insulator flashover. In addition, dry band arcing due to wet pollution increases the local surface temperature, which accelerates the thermal aging process and surface degradation. Hence pollution performance studies considering the aging effects of polymeric insulators have created lot of interest among researchers.

In many earlier papers, pollution performance studies have been carried out using LC measurement [11-15]. In recent times, PD detection and analysis is a well recognized insulation condition monitoring method in determining the quality of insulation. Since the dry band partial arcs due to wet pollution are a precursor of flashover, the PD measurement and analysis will provide better mechanism to effectively understand the pollution performance of the aged polymeric insulators [16-18]. However, the pollution performance of aged polymeric insulators considering the effects of water absorption stress and thermal stress using the advanced PD signal measurement and analysis has not been reported so far. Hence it is necessary to collect a data base of PD signal
characteristics of thermal aged and water aged polymeric insulators in the laboratory, which will be useful for electrical utilities in the development of effective condition monitoring techniques.

Considering these facts, major aim of the present work is to collect the typical PD patterns of accelerated thermal and water aged polymeric insulators in order to understand the effects of conductive pollution on PD activity. Laboratory experiments are conducted at different pollution levels and relative humidity (RH) conditions and PD signals along with PD patterns have been collected through an innovative PD detection system. Time-Frequency characteristics of PD pulses are evaluated to understand the pollution performance of aged polymeric insulators.

2. Test Specimen Preparation

Commercially available 11 kV polymeric insulators with specifications as listed in Table 1 were used for laboratory experiments. Fig. 1 shows the sketch of the polymeric insulator used in this study.

Accelerated aging of insulators in the laboratory will simulate the real time surface conditions experienced by the insulators after a long period of service. In the present work, accelerated thermal aging was carried out by keeping the insulator specimen inside the temperature controlled hot air oven at 150°C for a period of 1440 hrs. Water aging of insulator was carried out by immersing the specimen in a distilled water bath (1 μS/cm) maintained at room temperature for 240 hrs. Water aging was also carried out for a different set of samples by maintaining the temperature of water bath at 60°C and 90°C, which will accelerate the water absorption process and help in the reduction of hydrophobicity. This water aging process simulates the effect of water absorption due to moisture, dense fog and rain faced in outdoor applications. After the completion of accelerated aging process, insulator samples were used for pollution performance studies. Table 2 shows the details of test specimens used in the present work.

### Table 1. Insulator specifications

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Creepage distance</td>
<td>307 mm</td>
</tr>
<tr>
<td>Shed diameter</td>
<td>90 mm</td>
</tr>
<tr>
<td>Wet power frequency withstand voltage</td>
<td>35 kV</td>
</tr>
<tr>
<td>Dry lightning impulse withstand voltage</td>
<td>75 kV</td>
</tr>
<tr>
<td>Tensile load capacity</td>
<td>45 kN</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-100 to 300°C</td>
</tr>
</tbody>
</table>

### Table 2. Details of test specimens

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Virgin specimen</td>
</tr>
<tr>
<td>S2</td>
<td>Thermal aged</td>
</tr>
<tr>
<td>S3</td>
<td>Water aged at Room Temperature</td>
</tr>
<tr>
<td>S4</td>
<td>Water aged at 60°C</td>
</tr>
<tr>
<td>S5</td>
<td>Water aged at 90°C</td>
</tr>
</tbody>
</table>

Fig. 2 reports the schematic diagram of the PD measuring experimental set up used in the laboratory. The silicone rubber insulator was suspended vertically inside the fog chamber (1.5×1.5×1.5 m). Test voltage applied was 11 kV rms, 50Hz. Tests were conducted as per IEC 60507 clean fog test procedure. Before test, the insulator surface was cleaned by washing with isopropyl 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 [19].

Concentration of NaCl salt was varied to give Equivalent Salt Deposit Density (ESDD) in mg/cm² to 0.06 (lightly polluted), 0.08 (moderately polluted), and 0.12 (heavily polluted). Contaminated insulators were allowed to dry naturally and deionized water droplet of conductivity 5 μS/cm was placed on the surface of contaminated insulator in a discrete area ≈ 2 cm². It was sucked into a syringe after 5 minutes and the new conductivity was measured (Horiba Scientific, B-173 compact conductivity meter) and used for ESDD calculation as per ref [19]. Four Omron ultrasonic nebulizers (NE-U17), which generate particle size of 2-5 μm, were used to maintain the required relative humidity inside the fog chamber within a limit of ±5% of required
value [20-21]. Relative humidity was measured using the wall-mount Hygrometer (HTC-1) instrument which was kept inside the fog chamber and readings were noted through a glass window fixed on the chamber.

PD signals were picked by connecting a high frequency current transformer (HFCT) around the ground lead. 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 measurement of insulators. Output of the HFCT is connected to the large bandwidth PD detecting instrument, PDBASE II (TechIMP, Italy), which is able to sample the complete PD waveforms at a sampling rate of upto 100 MSa/s and bandwidth of 0-50 MHz. Sensitivity of PDBASE II instrument lies in the range of 2 mV/div to 5 V/div. It also provides large number of digitized PD pulse waveforms and able to separate them according to the PD waveform shape characteristics [22-23]. PD pulses were sent to a remote PC for further processing.

4. Results and Discussion

4.1 Analysis of PDIV

Initially, the partial discharge inception voltage (PDIV) was evaluated for each test object at various pollution levels. PDIV is the lowest voltage at which observable PD pulses appear on the PD detector. PD signals were measured in stable condition after voltage application and a set of 5 PD measurements were carried out at each pollution level in order to extract the 95 % of confidence level. Fig. 3 shows the PDIV of insulator samples measured at a constant 85% relative humidity. As expected, unaged insulator showed higher PDIV when compared with aged specimens irrespective of the pollution level. It is noted that difference in PDIV of unaged and aged insulators at each pollution level is within a narrow range of 2 kV. It is also clear that water absorption stress significantly reduced the PDIV when compared with thermal stress. In particular, water aged sample at 90°C showed less PDIV than other samples. It is also observed that increase in saline pollution level is able to reduce remarkably PDIV from 9 kV for the lightly polluted insulator to about 5 kV for the highly polluted insulator.

4.2 Separation of noise signal from PD signal

In the case of laboratory PD measurements on insulators, presence of significant noise and/or pulses coming from various sources active at the same time will make the diagnosis of insulator PD extremely difficult. Therefore spectral analysis of HFCT measured signals was performed to make an effective noise/disturbance separation from the
original insulator PD signals.

In the present work, initially the PD test is conducted on lightly polluted insulator to verify the presence of any noise/disturbance signals. Fig. 4 shows the typical original PRPD pattern and the steps involved in the separation of noise signals. In step 1, Time-Frequency map of the PRPD pattern is evaluated using the equivalent timelength and equivalent bandwidth concept [24-25]. In particular, let \( s(t) \) be the time domain representation of PD pulse, then equivalent time length and equivalent bandwidth are obtained using,

\[
\sigma_T = \sqrt{\int_0^1 (t-t_0)^2 \tilde{s}(t)^2 \, dt}
\]

(1)

\[
\sigma_F = \sqrt{\int_0^1 \left| \tilde{S}(f) \right|^2 \, df}
\]

(2)

where \( f \) is the frequency, \( \tilde{S}(f) \) is the Fourier transform of the normalized pulse \( \tilde{s}(t) \). PD pulses are reduced to two real numbers by (1) and (2) and represented as a dot in the T-F map. In Fig. 4, T-F map shows the typical equivalent timelength-equivalent bandwidth map of original PRPD pattern, in which equivalent time length is represented in ns and equivalent bandwidth is represented in MHz. It is observed that T-F map contains two clusters, one corresponds to PD signals and another one corresponds to high frequency noise signals. Typical PD signal and noise signal of each cluster are also shown in the figure. It is observed that PD signal lies in the frequency band of 5 MHz to 8.5 MHz and noise signal lies above 10 MHz. In step 2 and 3, PRPD pattern corresponding to PD signal cluster and noise signal cluster are separated as shown in the figure. From this analysis, it is noted that the noise signal peak magnitude lies in the range of 1 mV to 4 mV (which is also significantly less when compared with insulator PD signal magnitude). Therefore threshold value of PD measuring system is set above 4 mV in order to avoid the noise signals completely during the insulator PD measurement.

4.3 Analysis of PRPD pattern
In the case of PRPD pattern analysis, peak discharge magnitude for each phase position window is plotted against the phase position. It investigates the PD patterns in relation to the 50 Hz AC cycle. PD pulse magnitude as well as their PRPD pattern can give useful information about the state of deterioration of solid insulation. Environmental stresses such as water absorption stress and thermal stress may lead to increased surface degradation and which may result in earlier flashover of insulators under wet and contaminated conditions. Hence it is necessary to understand the PRPD characteristics of water aged and thermal aged insulators at different pollution levels. Therefore, PD measurement is carried out on both unaged and accelerated aged insulator specimens, by keeping the sample inside the fog chamber under different pollution level at a constant relative humidity. Typical PRPD pattern

<table>
<thead>
<tr>
<th>S 1</th>
<th>0.06 ESDD</th>
<th>0.08 ESDD</th>
<th>0.12 ESDD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FS = 30 mV</td>
<td>FS = 50 mV</td>
<td>FS = 50 mV</td>
</tr>
<tr>
<td>S 2</td>
<td>FS = 35 mV</td>
<td>FS = 100 mV</td>
<td>FS = 130 mV</td>
</tr>
<tr>
<td></td>
<td>FS = 40 mV</td>
<td>FS = 150 mV</td>
<td>FS = 150 mV</td>
</tr>
<tr>
<td>S 4</td>
<td>FS = 50 mV</td>
<td>FS = 150 mV</td>
<td>FS = 250 mV</td>
</tr>
<tr>
<td>S 5</td>
<td>FS = 100 mV</td>
<td>FS = 100 mV</td>
<td>FS = 250 mV</td>
</tr>
</tbody>
</table>

Fig. 5. Typical PRPD pattern of 11 kV insulators obtained at different pollution levels. RH=90%. FS stands for full scale.
obtained at rated voltage and 90% relative humidity is shown in Fig. 5. The contamination level is varied from 0.06 ESDD to 0.12 ESDD in this set of experiments. The sine waveform used in the PRPD pattern is used as a phase reference signal and its amplitude is not given in vertical scale. Occurrence of PD pulses in both positive and negative half cycles is noticed.

From Fig. 5, irrespective of the type of specimen, it can be inferred that the magnitude of PD and dispersion of PD amplitude in the pattern increases with respect to increase in pollution level. Water aged specimens show higher PD magnitude and increase in spreading of PD amplitude pattern when compared with unaged and thermal aged specimens. Significant reduction in PD inception phase delay is noticed with increasing pollution level. PD magnitude of water aged material (specimen S4 and S5) is considerably higher when compared with water aged material at room temperature (specimen S3). At heavily polluted conditions, water aged specimens display a reduction in the occurrence of total number of PD pulses in the specified capturing time when compared with unaged and thermal aged specimens. It is also noticed that large PD pulses occur in both positive and negative cycles.

S.Kumagai et al., [9] reported that when water is absorbed into the bulk volume of silicone rubber insulator, ions or electrons in the contamination layer can migrate into the interior via absorbed water and develops leakage current through the bulk volume. Development of more leakage current promotes erosion and degradation of material. In addition, increased temperature of water bath in specimen S4 and S5 allows more water absorption by the material, which accelerates the above process of degradation and leads to more partial arcs in the surface of insulator. S.Kumagai et al., [9] also reported that reduction in surface resistance and hydrophobicity is associated with the degree of water penetration in to the bulk volume. In addition, increased surface roughness due to aging gives way for water particles to be held in the pits and cavities on the surface and leads to increase in leakage current and dry band arcing. Therefore, in the case of water aged specimens, occurrence of large number of high magnitude PD on the surface is noticed, which causes faster surface degradation and erosion of the material and leads to reduction in electrical insulation strength. Photograph of short duration PD, long arc and multiple PD observed at 100% RH of water aged specimen are shown in Fig. 6.

Fig. 6. Photograph of water aged polymeric insulator at 100% RH: (a) Short duration PD observed at 0.08 ESDD; (b) Long arc and (c) Multiple PD observed at 0.12 ESDD

Fig. 7. PD repetition rate of insulator specimens at different pollution levels. RH = 100 %

Fig. 8. Typical plot of variations in number of PD pulses with respect to PD amplitude of water aged specimen (a) 0.06 ESDD (b) 0.08 ESDD (c) 0.12 ESDD
In the case of outdoor polymeric insulators, the PD appear in pulse bursts and their repetition rate is irregular. Fig. 7 shows the PD repetition rate with respect to pollution level of polymeric insulators at 100% RH conditions. At lightly polluted conditions, there is no significant difference in repetition rate of insulator specimens, whereas at moderately polluted conditions (0.08 ESDD) considerable increase in repetition rate of aged specimens is noted. R.S.Gorur et al., [10] reported that aging of silicone rubber material increases the surface roughness which provides an increase in surface wetting area and enhances leakage current in the insulator. It leads to formation of more PD activity with high repetition rate in the aged insulator specimens. However, at highly polluted conditions, a sudden decrease in repetition rate is observed, which may be due to the formation of repetitive arcs and long arcs along the surface which heats and dries the surface quickly and causes a time lag for the initiation of another discharge. Fig. 8 shows the variations in the number of PD pulses with respect to PD magnitude of water aged specimen at different pollution levels. It is clear that number of high amplitude PD pulses significantly increases with increase in pollution level.

4.4 PD Magnitude as a function of Relative humidity

Hydrophobic polymers are characterized by high electrical surface resistance which however reduces due to water absorption during outdoor applications. Relative humidity is a major factor which influences the wetting of insulator surface and initiates partial arcs along the surface of the polluted insulator. Hence it is necessary to understand the effect of increase in RH level on the PD activities of the aged polymeric insulators. Therefore, accelerated aged polymeric insulators were tested at constant pollution level of 0.06 ESDD and 0.12 ESDD and the relative humidity inside the fog chamber was varied from 50% to 100%. Fig. 9 shows the variations of peak PD magnitude at different relative humidity levels of tested insulator specimens.

From the PRPD patterns, it can be identified that the PD peak magnitude increases with increasing relative humidity. At lower RH level (50 %), there is no significant PD activities observed in all the tested specimens and low magnitude noise signals are only present during this measurement. When the RH level rises above 60%, then the PD activity slowly increases on the surface of insulator. In general, water aged specimens show high PD magnitude when compared with other specimens.

In particular, water aged specimens S4 and S5 show high PD magnitude which may be attributed to the reduction in hydrophobicity due to more water absorption at high temperature of water bath. At high relative humidity, significant increase in PD peak is observed for water aged samples compared with thermal aged specimens. This is mainly due to the collection of more water droplets along the surface of the polymeric insulator 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 and surface degradation due to accelerated water aging, more number of PD pulse occurs in higher magnitude.

4.5 PD signal and T-F map analysis

Understanding the time and frequency domain characteristics of PD signal is important in order to extract important features and develop a better diagnostic system for the flashover prediction of 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 T-F map analysis. Typical PD pulses and T-F map of water aged insulators obtained at different pollution conditions are shown in Fig. 10. Short duration discharges (Fig. 10 a(i)) are mostly observed at lightly polluted conditions, whereas long arcs are observed at heavily polluted conditions (Fig. 10 c(i)). Time length and rise time of PD pulses increases considerably with respect to increase in pollution level.
Energy content of the PD signal considerably increases at repetitive PD (Fig. 10 b(i)) and long arcs and this will increase the local surface temperature of the aged specimens, which will lead to faster erosion and degradation of the polymeric material.

From the T-F map, it is noted that during lightly polluted conditions (Fig. 10 a(ii)), most of the PD signals lies in the frequency band of 6-10 MHz and its timelength varies from 100 to 300 ns, which clearly shows the presence of majority of short duration discharges. Once the pollution level increases to 0.08 ESDD (Fig. 10 b(ii)), then equivalent timelength of PD pulse increases upto 700 ns and its equivalent bandwidth range shifts to 4.5-8 MHz. Increase in equivalent timelength is due to the presence of multiple repetitive PD pulses and decrease in frequency bandwidth to 4.5 MHz is mainly due to initiation of long arcs. Under highly polluted conditions (Fig.10 c(ii)), both repetitive PD and long arcs are present and it is noted that a separate long arc cluster is formed in the frequency bandwidth of 1-4 MHz. This clearly shows increase in number of long arcs due to highly polluted surface.

In general, from the T-F map observations, it is clear that there is an increase in mean equivalent time length and reduction in mean equivalent bandwidth with respect to increase in pollution level of aged specimen. In addition, this analysis clearly indicates that increase in long arc cluster density due to pollution will lead to earlier flashover of the insulator. The reported PD characteristics such as PRPD pattern, PD pulse T-F map, PD peak magnitude and repetition rate analysis show that pollution performance of aged 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 unaged insulators under similar experimental conditions, it is noticed that water aged and thermal aged insulators show increased PD activity, which will certainly lead to surface erosion and degradation.

5. Conclusion

Laboratory measurement and analysis of PD signals and PRPD pattern of water aged and thermal aged silicone rubber insulators has been presented in this paper. Laboratory tests are performed at different pollution levels and at different relative humidity conditions as per IEC 60507 test procedure. When compared with PD test results of unaged insulators, it is noticed that water aged and thermal aged silicone rubber insulators show increased PD activity. It is shown that variations in PRPD pattern, PD peak magnitude, repetition rate and T-F map of PD pulses are closely related to the surface pollution condition of the polymeric insulator and it can be used as a diagnostic tool to predict the pollution severity of insulator. These lab results on water aged and thermal aged polymeric insulators show 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 and erosion of the material under severe pollution conditions, which may lead to reduced insulation strength and possibility of surface flashover.
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