Estimation of Partial Discharge Inception Voltages Due to Voids in Solid Sheet Insulation

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Abstract—Defects like formation of voids, cavities, and cracks or inclusion of dust particles/small metallic turnings in the solid insulation of modern power cables may not be completely avoided even under the most stringent manufacturing conditions. These defects or weak points are the vulnerable sites of occurrence of Partial Discharges (PD). A continuous dissipation of energy due to discharges at afore-mentioned sites causes a gradual but definite damage to insulation and brings about its premature failure. Since PD adversely affects the insulation life, knowledge of the voltage at which PD start, Partial Discharge Inception Voltage (PDIV) is very important for proper and safe stress for design as well as reliable operation of the equipment.

In this paper we report a technique for estimating the PDIV in case of discharges occurring in voids in solid sheet insulation in the ambient medium of air. Since occurrence of PD is a phenomenon dependent on upon many factors such as the type of gas in the void, the gas pressure, surface properties of the void, size and shape of the void, location of the void, dielectric constant of the surrounding medium etc; these parameters have to be taken into account. The computed values are valid in the pressure range of 0.067 kPa to 101.333 kPa. The results obtained have been compared with experimentally obtained values of PDIV for artificial voids of known dimensions in solid sheet insulation.

Index Terms—Partial Discharges, Inception Voltage, Electrical Insulation

I. INTRODUCTION

Quality of insulation is essential for successful and reliable operation of any power apparatus. Minor flaws and irregularities such as voids, surface imperfections in the insulation are however inevitable and lead to partial discharges which are characterized by an electrical breakdown at localized regions of the electrical insulation. [1]-[3]. The localization of the discharge may be the consequence of an electric field enhancement restricted to region that is relatively small compared with the dimensions of the space or gap between the conductors. The field enhancement can be associated with abrupt changes in the nature of the insulating medium that may be caused by voids in solid dielectrics or gas filled spaces at dielectric or gas filled spaces at dielectric-conductor or dielectric-dielectric interface.

Discharges within cavities (voids) in solid insulating system [4] have long been associated with gradual degradation and dielectric failure. The correlation between cavity discharge and degradation has been established for rotating machines [5], power cables [6] encapsulated transformers and many other solid dielectric systems so that the correlation between cavity discharge and degradation is now well established. Gas filled cavities can originate in a wide range of solid dielectric systems through many mechanism including differential thermal expansion(composite systems) incomplete impregnation or excessive mechanical stress(fiber reinforced systems) or improper process control (epoxy castings).Cavities can also originate over a lifetime of operation as a result of environmental stresses.

For PD tests, some existing standards have already evolved from the ‘representation of the worst working conditions’ to the requirement of a ‘quality of the insulation system’. This procedure requires a high quality for the design and construction of the insulating structures by controlling their electric field strength at any point. However, in most of the cases it is in fact impossible to estimate the real dimensions of the PD source and of the cavity where it has been produced. Even more difficult is the evaluation of the chemical or physical deterioration that it will produce during long operating times. Since it has not been possible to establish a definite relationship between the discharge intensity and the in-service life of electrical insulating systems employed in cables and power apparatus, the conventional wisdom has always been to insist on the total absence of PD under operating conditions, which in turn favored the establishment and universal acceptance of standardized go/no-go PD tests. In an attempt to quantify the use of partial discharges in evaluating the quality of any insulation system, the lowest voltage at which such events is detected, the partial discharge inception voltage (PDIV) is proposed in [7].

The partial discharge (PD) process in embedded voids in solid dielectrics depends upon many factors such as the type of gas in the void, the gas pressure, surface properties of the void, trapped charge on the cavity walls, size and shape of the void, statistical time lag, and dielectric constant of the surrounding medium.

Numerous papers discuss the mechanisms and PD patterns observed (for example [8-10]). Various models of partial discharge activity in solid dielectrics have been developed [11-14].

During aging studies PD patterns are often found to change with time. A reduction in gas pressure is considered one of the possible causes for the change in PD activity [8]. The question
arises as to how the PDIV depends on pressure as the pressure in the void decreases to near the Paschen minimum or below. This situation may be important for low pressure applications such as space or for superconductors when insulation is subjected to cryogenic temperatures where oxygen or nitrogen in air condense out or freeze [15].

In the present work a technique has been developed to evaluate the partial discharge inception voltages in case of discharges occurring at the interface as well as in voids in the ambient medium of air. The estimation of partial discharge voltages is based on the analysis of Townsend breakdown criterion and is valid for the whole range of Paschen’s curve available. These formulations can be applied for estimating the PD inception voltages in case of discharges occurring in voids for various sample thickness and pressures.

The formulations so obtained are subsequently tested for their accuracy by comparing the results obtained with actual observations obtained for partial discharge inception voltages in artificial cavities in the ambient medium of air.

II. PRESENT APPROACH

On the basis of the Townsend breakdown criterion $$\gamma = \exp (\alpha t' - 1) = 1$$, breakdown voltage $$V_b$$ is given as:

$$V_b = \frac{Bp}{\ln(Apt' / \ln(1 + 1/\gamma))}$$  \hspace{1cm} (1)

where $$p$$ is pressure, $$t'$$ is gap spacing and $$\gamma$$ is the secondary ionization coefficient. The constants $$A$$ and $$B$$ can be evaluated from the Townsend equation [16], [17] for the primary ionization coefficient, $$\alpha = Ap \exp [-Bp/E]$$  \hspace{1cm} (2)

where $$A$$ is the saturation ionization in the gas at a particular $$E/p$$ (electric stress/pressure) and $$B$$ is related to the excitation and ionization energies [17], [18].

In the absence of secondary ionization coefficient, for the whole range of $$E/p$$, equation (1) is of little use for the evaluation of sparking potentials for the whole $$pt'$$ range. It is this drawback in Townsend’s equation which prevents the use of equation (1) for practical applications.

Since, reasonably accurate breakdown voltages for the gas under consideration in our case are available [19] for a wide range of $$pt'$$ values, it is possible to use these values.

Equation (1) can be written as:

$$V_b = \frac{Bp}{\ln(pt' + k)}$$  \hspace{1cm} (3)

where

$$k = \ln[A/ \ln(1 + 1/\gamma)]$$  \hspace{1cm} (4)

The values of $$A$$ and $$B$$ in equation (2) for air [16], [17] are given in Table I.

<table>
<thead>
<tr>
<th>Gas</th>
<th>$$A$$ Ionisation /kPa-cm</th>
<th>$$B$$ V /kPa-cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>112.50</td>
<td>2737.50</td>
</tr>
</tbody>
</table>

Using breakdown voltages $$V_b$$ from [19] and the values of $$A$$ and $$B$$ from Table I, $$k$$ is computed and obtained [20] as a function of $$pt'$$ as shown in Table II.

<table>
<thead>
<tr>
<th>Gas</th>
<th>$$pt'$$ kPa-cm</th>
<th>$$K$$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.0133 -0.2</td>
<td>2.0583$(pt')^{2.1724}$</td>
</tr>
<tr>
<td></td>
<td>0.2 - 100</td>
<td>3.5134$(pt')^{0.0599}$</td>
</tr>
<tr>
<td></td>
<td>100 - 1400</td>
<td>4.6295[corresponding to $$pt'$$ = 100 kPa-cm in $$k=3.5134$$ $(pt')^{0.0599}$]</td>
</tr>
</tbody>
</table>

Equation (3) is re-written as:

$$E_g = \frac{V_b}{t'} = \frac{Bp}{\ln(pt' + k)}$$  \hspace{1cm} (5)

III. ESTIMATION OF PARTIAL DISCHARGE INCEPTION VOLTAGES IN VOIDS

On the basis of capacitance voltage distribution law [21] and Fig. 1, the PD inception voltage ($$V_i$$) for discharges occurring in voids is given as:

$$V_i = E_g \left[t + t (\varepsilon_r - 1)\right] \varepsilon_r$$  \hspace{1cm} (6)

In the above equations $$E_g$$ is the electric strength of the gap at pressure $$p$$ and $$t'$$ denotes the thickness of the discharge gap included within the thickness $$t$$ of insulation (Fig. 1) and $$\varepsilon_r$$ denotes the relative permittivity of the dielectric sample.

Substituting $$E_g$$ from equation (5) into equation (6), $$V_i$$ is written as:

$$V_i = \frac{Bp}{\ln(pt' + k)} \left[t + t (\varepsilon_r - 1)\right] \varepsilon_r$$  \hspace{1cm} (7)

where $$k = M (pt')^N$$, $$M$$ and $$N$$ are constants as given in Table II for different $$pt'$$ ranges.
IV. EXPERIMENTAL

A. Test Samples and their preparation

The samples were prepared from commercially available insulation sheets of PMMA of various thicknesses. The insulation sheets were cut as circular pieces of 110 mm diameter. Cylindrical hole of various known diameters was drilled at the centre of the insulation sheets, using a high speed drilling machine. The surface of the sheets was cleaned and kept dry, since moisture or contamination on the test sample may affect the breakdown voltage and a thin film of impregnating oil was manually pasted on each layer to form the impregnated sample. An insulation sheet with drilled hole was kept between two single plane sheets to form a dielectric bounded artificial cavity. Silicone grease was used at the edges to completely seal the cavity. The cavity so created contained air at local atmospheric pressure, temperature and humidity. Apart from noting the atmospheric conditions, no attempt was made to control them.

B. Electrodes and the Test Cell

Electrodes were made of good quality brass having $2\pi/3$ Rogowski profile uniform-field configuration of 5.8 cm overall diameter and 1.9 cm radius of curvature with the flat portion of the electrode surface in contact with the test samples (exposed effective diameter of the electrode being 4.8 cm). The electrodes were polished, buffed and cleaned with ethanol. Sufficient care was taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The test sample was then sandwiched between the electrodes as shown in Figure 2. The pressurizing arrangement, after putting in the test samples, was provided by two acrylic plates with polycarbonate nut and bolt arrangement.

The test chamber was a cubical of size 200 mm x 250 mm x 300 mm and was made of PMMA and filled with transformer oil. The electrode-sample assembly was completely immersed in oil. The presence of oil in the test cell was essential to avoid any surface discharges at the electrode edges.

The lower electrode of the assembly was earthed through the cell. The other electrode was extended to the outside of the tank by means of a brass rod and connected to the high voltage source. Any corona discharge at the high voltage electrode terminal was prevented by providing a suitable corona shield.

The applied voltage was 50 Hz. ac obtained from 150 kV, 30 kVA testing transformer that is discharge free up to 100 kV. The voltages were measured with an accuracy of ± 3%.

C. Experimental Technique

I. Sample Thickness

The sample thickness was measured at some randomly distributed 20 points, spread all over the sheet area with a micrometer having a least count of 0.01 mm. The average of the 20 measurements was taken as the thickness of the sample.

II. Relative Permittivity

Figure 3 shows the schematic of three-electrode system to measure the relative permittivity of various dielectrics using a LCR data bridge (Forbes Tinsley Co. Ltd) with an accuracy of ± 0.1%. Measurements of relative permittivity were carried out on different samples of insulating sheets. The average of the 5 measurements was taken as the average relative permittivity of the sample.

III. Partial Discharge Inception Voltage

In order to determine $V_i$, a voltage equivalent to 50% of the expected $V_i$ was applied first and maintained for 20 seconds. If no discharges appeared, the voltage was raised in steps of 5% of the 50% voltage at 20 seconds interval until inception occurred. The voltage was maintained for one minute at $V_i$ when the discharges occurred continuously. Afterwards the voltage was reduced slowly and the voltage at which the discharges disappeared was recorded as the Partial Discharge Extinction Voltage, $V_e$. The voltage was then reduced to zero and a time interval of five minutes was allowed before next observation was taken. The values reported are the average of ten such observations.

The PD measurements were made using a Mtronix MPD540 Partial Discharge Analysis System which is a high-precision, modular acquisition and analysis toolkit for detecting, recording, and analyzing partial discharge events in full accordance with international standards as well as relevant standards i.e. IEC 60044, 60076, 60270 and 60885.
TABLE III.  PARTIAL DISCHARGE INCEPTION VOLTAGE FOR PMMA SAMPLES (ε_R: 3.5) AT ATMOSPHERIC PRESSURE OF 98.658 KPA

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Sample Thickness, t (cm)</th>
<th>Depth of Void, t' (cm)</th>
<th>Diameter of Void, d (cm)</th>
<th>Inception Voltage, V_i (k)</th>
<th>Extinction Voltage, V_e (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.334</td>
<td>0.084</td>
<td>0.236</td>
<td>6.04</td>
<td>5.06</td>
</tr>
<tr>
<td>2</td>
<td>0.368</td>
<td>0.090</td>
<td>0.314</td>
<td>4.99</td>
<td>4.20</td>
</tr>
<tr>
<td>3</td>
<td>0.372</td>
<td>0.124</td>
<td>0.150</td>
<td>7.92</td>
<td>7.04</td>
</tr>
<tr>
<td>4</td>
<td>0.383</td>
<td>0.091</td>
<td>0.157</td>
<td>7.52</td>
<td>6.10</td>
</tr>
<tr>
<td>5</td>
<td>0.390</td>
<td>0.127</td>
<td>0.236</td>
<td>7.80</td>
<td>6.63</td>
</tr>
<tr>
<td>6</td>
<td>0.416</td>
<td>0.101</td>
<td>0.157</td>
<td>6.52</td>
<td>5.60</td>
</tr>
<tr>
<td>7</td>
<td>0.418</td>
<td>0.089</td>
<td>0.236</td>
<td>5.20</td>
<td>4.31</td>
</tr>
<tr>
<td>8</td>
<td>0.426</td>
<td>0.094</td>
<td>0.314</td>
<td>4.54</td>
<td>3.97</td>
</tr>
<tr>
<td>9</td>
<td>0.427</td>
<td>0.133</td>
<td>0.157</td>
<td>7.98</td>
<td>6.49</td>
</tr>
<tr>
<td>10</td>
<td>0.427</td>
<td>0.153</td>
<td>0.314</td>
<td>7.08</td>
<td>6.02</td>
</tr>
<tr>
<td>11</td>
<td>0.430</td>
<td>0.149</td>
<td>0.157</td>
<td>7.10</td>
<td>5.92</td>
</tr>
<tr>
<td>12</td>
<td>0.468</td>
<td>0.151</td>
<td>0.236</td>
<td>6.81</td>
<td>5.68</td>
</tr>
<tr>
<td>13</td>
<td>0.493</td>
<td>0.245</td>
<td>0.150</td>
<td>10.78</td>
<td>9.25</td>
</tr>
<tr>
<td>14</td>
<td>0.498</td>
<td>0.154</td>
<td>0.314</td>
<td>6.04</td>
<td>5.30</td>
</tr>
<tr>
<td>15</td>
<td>0.519</td>
<td>0.260</td>
<td>0.157</td>
<td>8.96</td>
<td>7.75</td>
</tr>
<tr>
<td>16</td>
<td>0.536</td>
<td>0.259</td>
<td>0.236</td>
<td>7.97</td>
<td>6.90</td>
</tr>
<tr>
<td>17</td>
<td>0.556</td>
<td>0.232</td>
<td>0.314</td>
<td>6.99</td>
<td>6.15</td>
</tr>
<tr>
<td>18</td>
<td>0.570</td>
<td>0.254</td>
<td>0.157</td>
<td>11.04</td>
<td>9.22</td>
</tr>
<tr>
<td>19</td>
<td>0.574</td>
<td>0.260</td>
<td>0.236</td>
<td>10.06</td>
<td>8.50</td>
</tr>
<tr>
<td>20</td>
<td>0.608</td>
<td>0.282</td>
<td>0.314</td>
<td>9.02</td>
<td>7.80</td>
</tr>
<tr>
<td>21</td>
<td>0.770</td>
<td>0.463</td>
<td>0.236</td>
<td>13.08</td>
<td>11.21</td>
</tr>
<tr>
<td>22</td>
<td>0.778</td>
<td>0.476</td>
<td>0.314</td>
<td>11.95</td>
<td>9.96</td>
</tr>
<tr>
<td>23</td>
<td>0.788</td>
<td>0.482</td>
<td>0.236</td>
<td>10.95</td>
<td>9.51</td>
</tr>
<tr>
<td>24</td>
<td>0.817</td>
<td>0.489</td>
<td>0.314</td>
<td>9.97</td>
<td>8.81</td>
</tr>
<tr>
<td>25</td>
<td>0.859</td>
<td>0.499</td>
<td>0.157</td>
<td>12.09</td>
<td>11.02</td>
</tr>
</tbody>
</table>

V. DISCUSSION

On the basis of Paschen’s curve and analysis of Townsend breakdown equation it is possible to compute PD inception voltage for discharges occurring in voids at different pressure and thickness of insulation. This approach is of great use to researchers in deciding their experimental parameters and help in deciding safe working stress for longer life.

The observed values of $V_i$ against $p t'$ are plotted for discharges in voids in Figure 4. The observed values of PDIV are compared with the corresponding calculated values of $V_i$ using equation (7). It is seen that the observed PDIV values are lower as compared to the computed values. Furthermore, the error in the computed values shows a positive divergence as the value of $p t'$ increases. This suggests that for a given void size, the computed value of PDIV will give a sufficiently accurate result for low pressures.

However, at higher pressures the partial discharges will incept at 20-30% lower voltages as predicted by the Paschen’s curve. This is quite in agreement with the earlier reported results [14, 22].

This may be on account of the fact that in actual insulation, a number of voids of different shape and dimension are present at random and the critical discharges start at the most favorable site i.e. where stress concentration is maximum.

Furthermore, the analysis presented does not address the surface roughness condition, trapped charge on the cavity walls etc which may exist in voids. Additionally, any variation in PDIV due to change in void diameter for same void depth has also not been accounted for. Also deviations may exist because the values of breakdown voltages obtained from Paschen’s curve are valid for stress between metal-metal surfaces, whereas in case of partial discharge occurrence the electric stress is between metal-dielectric surface (interface) and dielectric-dielectric surface.
This method of estimation may be used for predicting PD inception voltage in case of discharges occurring at interface with sufficient accuracy and has been utilized for predicting PDIV in the ambient medium of air [23], N₂ [24] and SF₆ [25].

VI. REFERENCES


Fig. 4. Observed and computed values of inception voltage $V_i$ for discharges in cavities at atmospheric pressure