Quality Analysis of Ceramic Insulators Under Steep Front Impulse Voltage

K. Marimuthu, S. Vynatheya and Dr. N. Vasudev
Central Power Research Institute
Bangalore, India
marimuthuk@cpri.in, vyn@cpri.in and vasu@cpri.in

Abstract — The insulators used in power transmission and distribution networks are meant to provide electrical isolation and mechanical support to the power lines. Hence, the insulators are exposed to continuous electromechanical stresses. These insulators are also expected to withstand abnormal electrical stresses like system generated switching impulses and natural lightning impulses. Failure of ceramic insulators in the field due to puncturing is often reported. The methodology to analyse the impulse puncture strength of the ceramic insulator is stipulated in IEC 61211/2004-11. In the present work, cap-and-pin type insulators from five different manufacturers are subjected to standard stipulated steep front impulse voltage test. After the test, one sample of healthy insulator from each manufacturer and samples of failed insulator are subjected to Scanning Electron Microscopy and Energy Dispersive Spectroscopy. It is observed that the presence of impurities reduces the dielectric strength of the ceramic insulator resulting in its puncture.

Keywords — Ceramic Insulators, Impulse Voltage, Steep Front Impulse, Scanning Electron Microscopy and Energy Dispersive Spectroscopy.

1. INTRODUCTION

Insulators in the power transmission and distribution lines play a vital role by providing required air clearance and mechanical support [1]. Though the insulators are about 5% of the direct capital cost of the line, they are accountable for around 70% of the line outages and more than 50% of the line maintenance costs [2]. Thus, the quality of the insulators is crucial for system reliability and reduction in the maintenance cost of the power lines.

It is necessary that the insulators in the field should withstand severe electrical stresses caused by lightning and switching surges. These impulse surge voltages are high in magnitude and short in duration. The premature failures of the insulators were reported due to such surges. The stresses due to impulse surge voltages cause puncturing in solid insulation (of about 20-25mm) between cap-and-pin [3]. The phenomena lead to detachment of hardware on the insulator unit resulting in the physical dropping of power line.

Hence, it is necessary to evaluate the puncture strength of the insulator by steep front impulse voltage test (SFW Test) followed by power frequency flashover voltage test. Further, the samples of failed and healthy insulator were investigated by Scanning Electron Microscopy, Energy Dispersive Spectroscopy analysis and the results are discussed.

2. SAMPLE DETAILS

The units were sampled from insulator lots belonging to five different manufacturers (A, B, C, D & E). The profile parameters of sample insulators for the present study are given in Table I.

<table>
<thead>
<tr>
<th>Insulator Series</th>
<th>No of Insulator units</th>
<th>Diameter in mm</th>
<th>Spacing in mm</th>
<th>Arcing Distance in mm</th>
<th>Creepage Distance in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>260</td>
<td>145</td>
<td>210</td>
<td>345</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>255</td>
<td>145</td>
<td>210</td>
<td>312</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>255</td>
<td>145</td>
<td>205</td>
<td>340</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>255</td>
<td>145</td>
<td>210</td>
<td>370</td>
</tr>
<tr>
<td>E</td>
<td>5</td>
<td>275</td>
<td>145</td>
<td>235</td>
<td>410</td>
</tr>
</tbody>
</table>

2.1 MEASUREMENT OF INSULATION RESISTANCE

The insulator samples insulation resistance (IR) values are measured by megger at 5kV and the values are shown in Fig.1. All the insulators are meeting the standard insulation resistance (2GΩ) requirement.

Figure 1. Bar chart of insulation resistance of insulators

Figure 2. Average and standard deviation of IR values of insulators
The average, standard deviation and variance of insulation resistance of each insulator manufacturer (each series of insulators) are shown in Fig. 2 & 3. Though the insulation resistance of all samples meeting the requirement, the higher variance of IR values of D series insulators may be due to inconsistency in insulator manufacturing process.

3. STEEP FRONT IMPULSE VOLTAGE TEST

The steep front impulse voltage wave stipulates high dv/dt and different from 1.2/50μs standard lightning impulse wave. The rate of voltage rise is ≥ 2500kV/μs. The standard stipulated test procedure for this test is adopted as follows [4].

3.1 Determination of Critical Flashover Voltage (U50) for p.u voltage specification

The 50% flashover voltage (U50ss) of a short standard string comprising of five number of same make insulators is determined using up and down method with standard lightning impulse (1.2/50μs) [5][6]. The U50ss values of insulator strings are mentioned in Table II and the experimental setup is shown in Fig.4.

### TABLE II

<table>
<thead>
<tr>
<th>Insulator Series</th>
<th>+ve Polarity</th>
<th>-ve Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>468</td>
<td>481</td>
</tr>
<tr>
<td>B</td>
<td>472</td>
<td>451</td>
</tr>
<tr>
<td>C</td>
<td>427</td>
<td>438</td>
</tr>
<tr>
<td>D</td>
<td>473</td>
<td>463</td>
</tr>
<tr>
<td>E</td>
<td>453</td>
<td>453</td>
</tr>
</tbody>
</table>

3.2 Determination of Test voltage level (Ut)

The U50 value of each unit is arrived by dividing the value of flashover voltage (U50ss) of short standard insulator string by the number of units (five) in the given string. For disc insulators, the test voltage (Ut) is 2.8 p.u of U50 value of each unit. The lowest value is taken as base value of Ut for practical reasons irrespective of polarity and mentioned in Table III.

### TABLE III

<table>
<thead>
<tr>
<th>Insulator Series</th>
<th>+ve Polarity</th>
<th>-ve Polarity</th>
<th>Base Value of Ut</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>271</td>
<td>277</td>
<td>271</td>
</tr>
<tr>
<td>B</td>
<td>272</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>C</td>
<td>250</td>
<td>257</td>
<td>250</td>
</tr>
<tr>
<td>D</td>
<td>275</td>
<td>269</td>
<td>269</td>
</tr>
<tr>
<td>E</td>
<td>263</td>
<td>264</td>
<td>263</td>
</tr>
</tbody>
</table>

3.3 Test procedure

Steep front impulses with magnitude Ut (with 0 to 10% tolerance) in a series of five +ve, five -ve, five +ve and five -ve are applied with a time gap of 1 min between each impulse applications. For each impulse voltage application, value of test voltage and steepness were recorded.

During the test, if puncture occurs, external flashover will not take place further and the failure of insulator is observed from the recorded oscillograms. Further, the failure can be confirmed by doing two flashovers at standard lightning impulse (1.2/50μs) or at power frequency voltage.

3.4 Test Setup

The test circuit diagram and experimental setup are shown in Fig. 5 & 6. This diagrams show the apparatus involved in the experiment.

![Figure 4. Experimental Setup for short string flashover test](image-url)
To achieve smooth and steep front impulses with high \( \frac{dv}{dt} \), the external sphere gap in series with test specimen and parallel capacitance as shown in Fig.6 are used. The generated steep front impulses are measured by using 500kV resistive voltage divider.

### 3.5 Test Results

All the samples were withstood the steep front impulse voltages except one insulator of A series (porcelain) and one insulator of E series (glass). Fig.7 (a) & (b) shows the failed insulators.

The oscillograms pertaining to failed insulator (porcelain) are shown in Fig.8 & 9. There is considerable reduction in magnitude of test voltage from \( \sim 278kV \) to \( \sim 183kV \). The oscillogram shown in Figure.8 results the peak voltage of 278kV during the test. Further, the failure of porcelain insulator is confirmed by null voltage across the insulator and high test current under power frequency voltage test.

The oscillogram pertaining to failed insulator (glass) is shown in Fig.10. After the application of test voltage, the insulator was shattered as shown in Fig.7 (b).

Though the failed samples have good IR value and power frequency flashover voltage, they have failed in steep front impulse voltage test. The other insulators in the same series withstood SFW test. Further the material characterization is carried out on one sample from the healthy insulator of A, B, C, D (porcelain) series and samples of failed insulator. The glass insulator results are mentioned as additional information.

### 4. CERAMIC MATERIAL QUALITY ANALYSIS

Porcelain is an extremely heterogeneous material with numerous interfaces and different coexisting structural phases (amorphous and crystalline). Defects can propagate more easily at these interfaces. Pores are to be expected due to the wet process employed and material impurities which reduces the puncture strength. Therefore it is necessary to investigate material characteristics to find the root cause for failure.
In the failed insulator (A1), two separate specimens were prepared from the punctured region and good region. Also, another four specimens prepared from the healthy insulators (A2, B1, C1 & D1) are analyzed using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDAX). The material characterization results are discussed in the following sections.

4.1 Scanning Electron Microscopy (SEM)

The scanning electron microscopy reveals information about the sample’s surface morphology (texture), chemical composition, crystalline structure and orientation of materials making up the sample.

The microstructure views from SEM are shown in Fig.12. The defective region has high surface porosity and mullite content as compared to good region of failed insulator. Also, the defective region of failed insulator (Fig.12-b) has high surface porosity and mullite content compared to healthy insulators (Fig.12-c to 12-f).

4.2 Energy Dispersive Spectroscopy (EDAX)

Energy Dispersive Spectroscopy is an analytical technique used for the elemental analysis or chemical characterization of a sample. The chemical composition of samples of failed and healthy insulators are given in Table. IV.

![Figure 12](a) & (b) Good and defective regions of failed insulator (A1). (c) to (f) Healthy insulator of A2,B1,C1 & D1.

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Failed insulator</th>
<th>Good Insulator (A2)</th>
<th>Good Insulator (B1)</th>
<th>Good Insulator (C1)</th>
<th>Good Insulator (D1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Defective Region (A1)</td>
<td>Good Region (A1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na2O</td>
<td>1.18</td>
<td>1.14</td>
<td>0.54</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Al2O3</td>
<td>33.12</td>
<td>33.12</td>
<td>22.96</td>
<td>22.61</td>
<td>17.05</td>
</tr>
<tr>
<td>SiO2</td>
<td>61.09</td>
<td>60.98</td>
<td>73.15</td>
<td>75.19</td>
<td>80.56</td>
</tr>
<tr>
<td>K2O</td>
<td>1.80</td>
<td>1.86</td>
<td>0.81</td>
<td>1.31</td>
<td>2.40</td>
</tr>
<tr>
<td>MgO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>UO3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.90</td>
<td>0.00</td>
</tr>
<tr>
<td>CaO</td>
<td>0.46</td>
<td>0.38</td>
<td>0.74</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.85</td>
<td>0.94</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>1.50</td>
<td>1.58</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

5. CONCLUSION

Laboratory studies of Steep front impulse test for ceramic insulators were conducted. Scanning Electron Microscopy and Energy Dispersive Spectroscopy analysis indicated that the presence of impurities in the insulator reduces its dielectric strength and leads to puncture under steep front impulses. The difference in microstructural details and quantity of various constituents shows that the poor quality of manufacturing or manufacturing defects leads to failure.

From the microstructures in Fig.12 and chemical compositions in Table IV, it can be observed that the content of impurities (CaO, TiO2 and Fe2O3) in failed insulator (A1) is 2.86% (sum of average value of both defective and good region) and healthy insulator (A2) is 0.74%. The average value of CaO, TiO2 and Fe2O3 content
of healthy insulators (A2, B1, C1 and D1) are 0.3675%, 0.165% and zero respectively. It is evident that the sum of average impurities content of healthy insulators is meager 0.53%. The material analysis shows that there is a wide difference in material quality between failed and passed insulators in steep front impulse voltage test. Hence, the steep front impulse voltage test is very effective to eliminate the poor quality insulators.

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