CHAPTER 2

v-t CHARACTERISTICS FOR STANDARD IMPULSE VOLTAGES

2.1 INTRODUCTION

For reliable design of power system, proper insulation coordination among the power system equipment is necessary. Insulation of any power system equipment is stressed by internal and external overvoltages of various origins. Usually, behavior of insulating materials for standard lightning and switching impulses are studied for the design of insulation. In addition to standard lightning and switching impulses, the effect of Very Fast Transient Overvoltages (VFTO) need to be considered with increasing number of Gas insulated substations (GIS). As the equipment are stressed with overvoltages of varying waveshapes of \( t_f \) from tens of nanoseconds to few microseconds and \( t_t \) from tens of microseconds to few milliseconds in practice, a study on the behavior of insulating materials under impulses of varying \( t_f \) and \( t_t \) becomes necessary. In general, the breakdown characteristics of any insulation under transient overvoltages are analyzed using v-t characteristics.

In transformers more than 19% of failures occur in windings and the failures are mainly due to mechanical deformation and insulation failure (Bhide RS et al 2010). Oil Impregnated Paper (OIP) is the commonly used insulation in windings and hence a study on breakdown characteristics of OIP is essential.
for winding design. The effect of impulse waveshape, polarity, electrode configurations on OIP are already reported in literature. The v-t characteristics of oil and OIP for different thicknesses are analyzed under standard lightning impulse of both positive and negative polarity (Venkatesan S & Usa S 2007). The v-t characteristics of air and oil under both uniform and non-uniform fields are analyzed and is predicted using Hyperbolic Model (Sharath B & Usa S 2009). The effect of tail time is found to be not critical in determining the breakdown voltage (Vandermaar AJ 1994).

An attempt is made to analyze the breakdown characteristics of air and OIP for impulse voltage waveforms from lightning to VFTO of $t_f$ 90 ns to 1.2 $\mu$s and model the characteristics using Hyperbolic model.

2.2 INSULATION COORDINATION

2.2.1 Definitions as per IEC 60071-1

Insulation coordination is the selection of dielectric strength of equipment in relation to the voltages that can appear on the system for which the system is intended and taking into account the service environment and characteristics of the available protective devices (IEC-60071-1 1993).

Proper insulation coordination ensures the effective protection of the power system equipment from overvoltages. The correlation between the insulation levels of protecting equipment and the equipment to be protected with the safety margin is shown in Figure 2.1. Generally, insulation strength is tested with standard lightning impulse at Basic Lightning Impulse Insulation Level (BIL) and standard switching impulse at Basic Switching Impulse Insulation Level (BSL) where BIL and BSL are defined as,
**BIL:** The electrical strength of insulation is expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions.

**BSL:** The electrical strength of insulation is expressed in terms of the crest value of a standard switching impulse.

The equipment are subjected continuously to operating voltages and occasionally to overvoltages. The operating voltage decides on the working voltage stress and overvoltage decides on the maximum withstand stress on the equipment insulation. All transformer insulations are designed with a safety margin between the electric field strength and electric field stress that is expected to be minimum to reduce unnecessary increase in insulation cost (CIGRE 2013).

![Figure 2.1 Insulation coordination (Wadhwa CL 2007)](image)

The maintenance of the insulation system of major equipment like transformer is critical as it leads to outages of the power system for a longer duration. Hence, the transformer insulation is required to pass the long duration (one hour) induced overvoltage test without partial discharges and also the impulse voltage withstand test (Kulkarni SV 2005). The permissible working
stress is fixed based on static, voltage-time and statistical characteristics of insulations (Ushakov VY 2004).

2.2.2 Voltage-Time Characteristics

Characterization of any insulating material based on the applied voltage is the basis for insulation coordination. If an overvoltage of particular waveshape with different magnitudes (above the maximum withstand level) are applied on the insulation, the time to breakdown changes. The characterizing curve drawn with the maximum voltage withstood by the insulation and the time to breakdown \( t_b \) is called the v-t characteristics of the insulation. The typical v-t characteristic is shown in Figure 2.2.

![Figure 2.2 Typical v-t characteristics (Kuffel E 2000)](image_url)

2.3 STANDARD OVERVOLTAGES AS PER IEC-60071-1

Generally, high voltage power transformers are subjected to standard lightning and switching impulse tests, as one of the important criteria after manufacture. However, in practice transformers are stressed with transient overvoltages of wide varieties of waveshapes. Among the steep wavefronts the
The most severe one is the Very Fast Transient Overvoltage (VFTO) which occurs in the Gas Insulated Substations (GIS) due to switching operation or earth faults. VFTO also occurs due to switching of vacuum circuit breakers and at certain conditions due to lightning. The VFTO has a rise time of about 3-10 ns with a peak magnitude of about 2.8 p.u (approximately 1000 kV for a 420 kV substation) (Mohana Rao 2007).

To consider the different types of possible overvoltages, IEC-60071-1 has defined the waveshapes under standard overvoltages as given in Table 2.1. In the present study, fast and very fast front transients are considered for characterizing the insulation.

**Table 2.1 Standard Overvoltages as per IEC-60071-1**

<table>
<thead>
<tr>
<th>Waveshape</th>
<th>Specification</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Front Transient</td>
<td>$5000 \mu s \geq t_f &gt; 20 \mu s$</td>
<td>Switching or fault</td>
</tr>
<tr>
<td></td>
<td>$t_i \leq 20000 \mu s$</td>
<td></td>
</tr>
<tr>
<td>Fast Front Transient</td>
<td>$20 \mu s \geq t_f &gt; 0.1 \mu s$</td>
<td>Lightning</td>
</tr>
<tr>
<td></td>
<td>$t_i \leq 300 \mu s$</td>
<td></td>
</tr>
</tbody>
</table>
2.4 GENERATION OF OVERVOLTAGES

A 140 kV, 980 J MWB (Mess Wandler-Bau, Germany) single stage Marx circuit in the High Voltage Laboratory of Anna University is suitably modified to generate the fast and very fast front transients overvoltages (Figure 2.3). Capacitive divider is used for measuring fast front transients and resistive divider is used for very fast front transients.

Where, $C_1$ – Charging capacitor; $C_{hv}, C_{lv}$ – Potential divider;
$R_1$ – Front resistor; $R_2$ – Tail resistor;
$G$ – Sphere gap; $D_1, D_2$ - Diodes

Figure 2.3 (a) Circuit diagram of the impulse voltage generator
As the effect of the tail time is not appreciable on the breakdown voltage of insulation, the effect of front time alone is considered. To characterize the insulation under standard overvoltages as per IEC-60071-1, 1.2/50 µs and 0.58/50 µs under fast front transients and 0.09/50 µs under very fast transients are generated and are shown in Figures 2.4 (a) & (b).

![Figure 2.3 (b) Photograph of impulse generator setup](image)

**Figure 2.3 (b) Photograph of impulse generator setup**

**Figure 2.4 (a) Fast front transients (generated)**

![Graph 1](image)

**1.2/50 µs**

![Graph 2](image)

**0.58/50 µs**
2.5 TEST CELLS AND SAMPLES UNDER STUDY

In oil filled transformer windings, OIP is used as the inter-turn and inter-disc insulations. As the thickness of OIP between turns is around 0.2 to 1.5 mm and between the discs is around 4 to 12 mm (Karsai K 1987), 0.25mm (0.05mm thick x 5 layers) thickness of OIP is considered for the analysis. Before impregnating with oil, the paper is heated at 60 °C for 72 hours to reduce the moisture content. To ensure proper impregnation, the paper is impregnated in oil for a minimum duration of 240 hours.

Brass electrodes as per the standard ASTM D149-97a (2004) are designed without any sharp edges to avoid corona. The diameter of high voltage electrode is 25 mm and ground electrode is 75 mm. Figure 2.5 shows the electrode designed for the experimental study on solid insulations. To avoid surface flashover the electrode arrangement is placed inside the oil cell and the test cell is shown in Figure 2.5.
The presence of voids in any insulation reduces the electrical strength of the power equipment as the void (air) has lesser dielectric strength compared to other insulation materials. The ionization of air during the normal operating condition leads to serious effects on the transformer performance like partial discharges. The electrode arrangement in the test cell for testing gaseous and liquid insulation is shown in Figure 2.6.

The stainless steel hemispherical electrodes are designed as per IEC-60156 (1995) (Figure 2.6). The test cell is made of Methyle Methacrylate.
(Acrylic) having effective volume between 300 to 500 ml with adjustable and removable electrodes.

2.6 v-t CHARACTERISTICS OF AIR AND OIP

2.6.1 Test Procedure

The effect of transient overvoltages on the insulation can be analyzed using the v-t characteristics. The v-t characteristics are experimentally obtained as per IEC 60060-1 & 2. The impulse generator is calibrated with the test specimen using the standard sphere gap arrangement and appropriate atmospheric correction factors are incorporated. The impulses are recorded using 1.0 GHz, 5.0 GS/s Digital Storage Oscilloscope of Lecroy make.

The minimum voltage at which the insulation breaks down with a single impulse is considered as minimum breakdown voltage ($V_{BD}$). The test voltage is increased above $V_{BD}$ in steps and the corresponding time taken to breakdown ($t_b$) is noted. The test voltage is increased till the breakdown occurs in the wave front. At each voltage level, a minimum of six samples are used. For each case, the maximum withstood voltage and the corresponding time to breakdown are noted. In case of OIP, sample is changed after each breakdown and ensured that there is no air gap between the layers and oil in the test cell is changed frequently.

2.6.2 v-t Characteristics of Air for 1.2/50 μs Impulse

To analyze the v-t characteristics of air, an air gap of 1.0 cm is maintained between the hemispherical electrodes of the test cell. Using the procedure mentioned in section 2.6.1, the minimum breakdown voltage (35.03kV) and the corresponding time to breakdown of air for 1.2/50 μs for different voltage levels are experimentally obtained and shown in Figure 2.7.
Figure 2.7 Breakdown time dispersion of air for 1.2/50 μs impulse

The experimentally obtained data are highly statistical due to the impact of formative time lag of insulation breakdown. The mean curve of the data is obtained by statistical analysis. The mean and standard deviations are obtained using Equations 2.4 and 2.5 respectively.

Let ‘n_i’ be the number of impulses resulting in breakdown at each voltage level and ‘t_{bi}’ be the corresponding breakdown times (at i\textsuperscript{th} instant).

Mean breakdown time (μ) = \[ \frac{\sum t_{bi}}{n_i} \] (2.4)

Standard deviation (σ (t_b)) = \[ \sqrt{\frac{1}{n_i - 1} \sum (t_{bi} - t_b) \sqrt{n_i}} \] (2.5)
As the breakdown time is Normal Distributed, the probability of a voltage to breakdown at time $t_b$ can be expressed as

$$f(t_b) = \frac{1}{\sigma \sqrt{2\pi}} \left[ -\frac{(t_b - \mu)^2}{2\sigma^2} \right]$$

(2.6)

Equation 2.6 gives the relation between the probability of breakdown and $t_b$. Using this equation the 5% and 95% probability of breakdown curves are calculated to provide the confidence interval. The fitness of the curve is verified by the confidence interval, where for all the curves more than 95% of the data are ensured to lie within a confidence interval of 5%.

![Figure 2.8 v-t characteristics of air for 1.2/50 µs impulse](image)

From Figure 2.8, it is observed for $t_b$ less than 2 µs, the characteristic is very steep which may attribute to a minimum time delay required for initiation of breakdown process.
2.6.3 v-t Characteristics of Air for Varying Front Times

The minimum breakdown voltage ($V_{BD}$) of air for 0.58/50 μs and 0.09/50 μs are measured to be 29.12 kV and 21.20 kV respectively. The maximum withstand voltage of air decreases as the $t_f$ of the impulses decreases (Li Z 1986). The breakdown strength of air decreases by 16.67% and 40% for 0.58/50 μs and 0.09/50 μs respectively.

The v-t characteristics for 0.58/50 μs and 0.09/50 μs are experimentally obtained and the same are plotted and shown in Figure 2.9.

![Figure 2.9 v-t characteristics of air for impulse voltages with varying $t_f$](image)

- The v-t characteristics for all $t_f$ follow the same pattern and the characteristics are steeper for $t_b$ less than 2 μs.
- The percentage shift (down) with reference to 1.2/50 μs is not uniform for the entire region and increases with decreasing $t_b$, (for $t_b$ less than 2 μs).
Table 2.2 Comparison of v-t characteristics of air for different $t_f$

<table>
<thead>
<tr>
<th>Waveshape</th>
<th>$V_{BD}$ (kV)</th>
<th>% decrease in $V_{BD}$</th>
<th>$t_b=1.0$ $\mu$s</th>
<th>$t_b=8.0$ $\mu$s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V (kV)</td>
<td>% decrease</td>
<td>V (kV)</td>
<td>% decrease</td>
</tr>
<tr>
<td>1.2/50$\mu$s</td>
<td>35.03</td>
<td>-</td>
<td>59.36</td>
<td>-</td>
</tr>
<tr>
<td>0.58/50$\mu$s</td>
<td>29.12</td>
<td>16.87</td>
<td>43.07</td>
<td>27.44</td>
</tr>
<tr>
<td>0.09/50$\mu$s</td>
<td>21.02</td>
<td>39.99</td>
<td>30.10</td>
<td>49.29</td>
</tr>
</tbody>
</table>

- From Table 2.2, it is observed that, the percentage shift is almost equal for $V_{BD}$ and after 2 $\mu$s (17% and 40% for 0.58/50 $\mu$s and 0.09/50 $\mu$s respectively) and is more (30% and 49% for 0.58/50 $\mu$s and 0.09/50 $\mu$s respectively) around the knee point of the characteristics (here for less than 2 $\mu$s).

From the above discussion, it is evident that the $V_{BD}$ is 40% lesser and withstand capability over the entire region of $t_b$ is almost 40-50% lesser for air under VFTO than the standard lightning impulse voltage.

2.6.4 v-t Characteristics of OIP for Varying Front Times

The v-t characteristics of OIP of 0.25 mm thickness under considered overvoltages are experimentally obtained. The maximum withstand voltages of OIP are 31.02 kV, 26.25 kV and 20.78 kV for $t_f$ of 1.2 $\mu$s, 0.58 $\mu$s and 90 ns respectively. Since uniform field configuration is used for the analysis on OIP, the electrical breakdown strength ($E_{BD}$) is calculated from the maximum withstand voltage. The $E_{BD}$ for OIP under varying $t_f$ are calculated (Table 2.3) and $E_{BD}$ is lesser by 15.4% and 33.0% for 0.58/50 $\mu$s and 0.09/50 $\mu$s when compared to 1.2/50 $\mu$s.
Table 2.3 Impulse Breakdown strength of OIP

<table>
<thead>
<tr>
<th>Waveshape</th>
<th>$E_{BD}$ (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2/50 μs</td>
<td>1241</td>
</tr>
<tr>
<td>0.58/50 μs</td>
<td>1050</td>
</tr>
<tr>
<td>0.09/50 μs</td>
<td>831</td>
</tr>
</tbody>
</table>

The v-t characteristics of OIP for varying $t_r$ are experimentally obtained and shown in Figure 2.10.

Figure 2.10 v-t characteristics of OIP for impulse voltages with varying $t_r$

- The v-t characteristics for OIP under standard overvoltages of varying $t_r$ follow the same pattern as that of air.
- The lower time regions (for $t_b$ less than 2 μs) of v-t characteristics are steeper and the steepness increases with decreasing $t_r$. 
Table 2.4 gives the percentage shift in $V_{BD}$ and v-t characteristics of OIP for decreasing $t_f$.

Table 2.4 Comparison of v-t characteristics of OIP for different $t_f$

<table>
<thead>
<tr>
<th>Waveshape</th>
<th>$V_{BD}$ (kV)</th>
<th>$%$ decrease in $V_{BD}$</th>
<th>$t_b=1.0$ $\mu$s</th>
<th>$V$ (kV)</th>
<th>$%$ decrease</th>
<th>$t_b=8.0$ $\mu$s</th>
<th>$V$ (kV)</th>
<th>$%$ decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2/50$\mu$s</td>
<td>31.02</td>
<td>-</td>
<td>46.07</td>
<td>-</td>
<td>31.44</td>
<td>-</td>
<td>31.44</td>
<td>-</td>
</tr>
<tr>
<td>0.58/50$\mu$s</td>
<td>26.25</td>
<td>15.38</td>
<td>35.68</td>
<td>22.55</td>
<td>26.50</td>
<td>15.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.09/50$\mu$s</td>
<td>20.78</td>
<td>33.01</td>
<td>22.95</td>
<td>50.18</td>
<td>20.84</td>
<td>33.71</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is observed from the table, that, the percentage shift is almost equal for $V_{BD}$ and after 2 $\mu$s (15% and 33% for 0.58/50 $\mu$s and 0.09/50 $\mu$s respectively) and is more around the knee point of the characteristics as in the case of air (here for less than 2 $\mu$s).

From the above results, it is found that the $V_{BD}$ is 33% lesser and withstand capability is almost 33-50% lesser for OIP under VFTO than the standard lightning impulse voltage.

2.7 HYPERBOLIC MODEL

Regression analysis is a statistical approach to obtain relation among variables and is used to model the v-t characteristics. Any insulation requires a minimum voltage to start the process of breakdown. The voltage varies with electrode configuration, thickness of insulation, electrode configurations like dimension, material etc.
The relation between maximum voltage withstood by the insulation and the corresponding time to breakdown ($t_b$) is given by the Hyperbolic model and is shown in Equation 2.7 (Venkatesan S & Usa S 2010).

$$V = A + \frac{B}{t_b} \quad \text{(2.7)}$$

where,  

- $A$ – constant proportional to the applied voltage (kV)
- $B$ – constant proportional to both applied voltage and $t_b$ (kV-$\mu$s)

### 2.7.1 Hyperbolic Model for Air

The Hyperbolic model parameters ($A$ and $B$) are extracted from the mean v-t characteristics of air under standard impulse voltages of varying $t_f$ and are given in Table 2.5.

<table>
<thead>
<tr>
<th>Waveform</th>
<th>$V_{BD}$ (kV)</th>
<th>$A$ (kV)</th>
<th>$B$ (kV-$\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2/50 $\mu$s</td>
<td>35.03</td>
<td>32.389</td>
<td>26.968</td>
</tr>
<tr>
<td>0.58/50 $\mu$s</td>
<td>29.12</td>
<td>27.534</td>
<td>15.533</td>
</tr>
<tr>
<td>0.09/50 $\mu$s</td>
<td>21.20</td>
<td>20.273</td>
<td>9.824</td>
</tr>
</tbody>
</table>

The $V_{BD}$ and the Hyperbolic parameters for air are plotted against $t_f$ and are shown in Figure 2.11.
The Table 2.5 and Figure 2.11 show that the Hyperbolic model parameters which are proportional to maximum voltage withstood by the insulation and are increasing with increasing $t_f$. With reference to 1.2/50 $\mu$s, $A$ reduces by 15% and 37% and $B$ reduces by 42% and 64% for 0.58/50 $\mu$s and 0.09/50 $\mu$s respectively.

### 2.7.2 Hyperbolic Model for OIP

Similarly, the model parameters are extracted from the $v$-$t$ characteristics of OIP under varying $t_f$ (Figure 2.10) and are tabulated.

**Table 2.6 Hyperbolic model parameters for OIP**

<table>
<thead>
<tr>
<th>Waveform</th>
<th>$V_{BD}$ (kV)</th>
<th>$A$ (kV)</th>
<th>$B$ (kV-$\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2/50\mu s</td>
<td>31.02</td>
<td>29.355</td>
<td>16.719</td>
</tr>
<tr>
<td>0.58/50\mu s</td>
<td>26.25</td>
<td>25.188</td>
<td>10.488</td>
</tr>
<tr>
<td>0.09/50\mu s</td>
<td>20.78</td>
<td>20.54</td>
<td>2.415</td>
</tr>
</tbody>
</table>

The values of $V_{BD}$ and the Hyperbolic model parameters for OIP are plotted with respect to $t_f$ and are shown in Figure 2.12.
Figure 2.12 Hyperbolic model parameters for OIP with \( t_f \)

Similar increasing trend of Hyperbolic model parameters is observed for OIP with respect to \( t_f \). With reference to 1.2/50 \( \mu \text{s} \), \( A \) reduces by 14% and 30% and \( B \) reduces by 37% and 86% for 0.58/50 \( \mu \text{s} \) and 0.09/50 \( \mu \text{s} \) respectively.

2.7.3 Prediction

The efficacy of the Hyperbolic model is checked by predicting the Hyperbolic model parameters and \( t_b \) with two test waveforms. The test waveforms considered are,

- Waveform without oscillations (0.8/50 \( \mu \text{s} \))
- Waveform with oscillations (\( t_f = 0.46 \mu \text{s} \))

2.7.3.1 Waveform without oscillations

In order to validate the Hyperbolic model for both the insulations (air and OIP), a non-oscillatory test waveform of 0.8/50 \( \mu \text{s} \) is considered. The parameters are taken (predicted) for \( t_f \) of 0.8 \( \mu \text{s} \) from Figures 2.11 and 2.12 for air and OIP respectively.
The test waveform of 0.8/50 µs is generated using modified Marx circuit and shown in Figure 2.13.

Figure 2.13 Test Waveform without oscillation (t_f = 0.8 µs)

The v-t characteristics are experimentally obtained for air with an air gap of 1.0 cm and OIP of thickness 0.25 mm with the same electrode configurations and the hyperbolic model parameters are extracted. Thus extracted parameters are compared with the predicted parameters (obtained from Figure 2.11 and Figure 2.12) and the percentage errors are shown in Table 2.7.

Table 2.7 Hyperbolic model parameters for 0.8/50µs impulse

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Hyperbolic model parameters</th>
<th>Predicted</th>
<th>Experimental</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>A (kV)</td>
<td>29.5</td>
<td>28.954</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>B (kV- µs)</td>
<td>19.3</td>
<td>18.747</td>
<td>2.86</td>
</tr>
<tr>
<td>OIP</td>
<td>A (kV)</td>
<td>26.75</td>
<td>25.91</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>B (kV- µs)</td>
<td>12.90</td>
<td>12.96</td>
<td>0.46</td>
</tr>
</tbody>
</table>

The Table 2.7 shows that the percentage errors between the predicted and experimental parameters are less than 4%. This shows that the prediction of
v-t characteristics for the given insulation under standard overvoltages (without oscillation) is possible with Hyperbolic model.

### 2.7.3.2 Waveform with oscillations

A non-standard impulse voltage of 0.46 µs $t_f$ with oscillations around the front is considered. The time taken to attain first peak is considered as $t_f$ which is 0.46 µs. The frequency of oscillation in the front is 1.56 MHz and the ratio of second peak to first peak is 1.07.

The Hyperbolic model parameters are taken for $t_f$ of 0.46 µs for air ($A=26$ kV & $B=14$ kV-µs) and OIP ($A=24.1$ kV & $B=8.8$ kV-µs) from Figures 2.11 and 2.12 respectively. Using these parameters, $t_b$ is predicted for a set of voltage magnitudes. The generated overvoltage as shown in Figure 2.14 is applied on air and OIP for the same set of voltage magnitudes and the corresponding $t_b$ are experimentally obtained.

![Figure 2.14 Test Waveform with oscillations ($t_f = 0.46$ µs)](image)

The predicted and experimental values of $t_b$ for the same set of voltage magnitudes are compared and the error in percentage is given in Table 2.8.
Table 2.8 $t_b$ for waveform with oscillations

<table>
<thead>
<tr>
<th>Insulation</th>
<th>V (kV)</th>
<th>$t_b$ (ȝs)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>Experimental</td>
</tr>
<tr>
<td>Air</td>
<td>25.30</td>
<td>13.50</td>
<td>7.80</td>
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<tr>
<td></td>
<td>28.95</td>
<td>4.69</td>
<td>3.30</td>
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<tr>
<td></td>
<td>37.63</td>
<td>1.18</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>40.06</td>
<td>0.97</td>
<td>1.04</td>
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<tr>
<td></td>
<td>39.87</td>
<td>0.986</td>
<td>0.985</td>
</tr>
<tr>
<td>OIP</td>
<td>22.92</td>
<td>7.08</td>
<td>6.27</td>
</tr>
<tr>
<td></td>
<td>26.80</td>
<td>3.32</td>
<td>3.09</td>
</tr>
<tr>
<td></td>
<td>29.72</td>
<td>1.58</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td>31.89</td>
<td>1.14</td>
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<td></td>
<td>32.42</td>
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<td></td>
<td>33.86</td>
<td>0.905</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>36.50</td>
<td>0.72</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>37.32</td>
<td>0.66</td>
<td>0.63</td>
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</tbody>
</table>

The percentage error between experimental and predicted $V_{BD}$ for both air and OIP are very high because of the presence of oscillations in the front. The error varies a lot depending on the instant of breakdown (trough or crest). This shows that the prediction of $v$-$t$ characteristics for waveform with oscillations is not successful with the Hyperbolic model.
2.8 CONCLUSION

Study on the effect of standard overvoltages of varying $t_f$ on air and OIP are carried out. Based on the standard overvoltages categorized in IEC-60071-1, transients of fast front (1.2/50 μs and 0.58/50 μs) and very fast front (0.09/50 μs) are considered for analysis. The v-t characteristics are experimentally obtained for air and OIP under all the considered waveforms and are modelled using Hyperbolic model.

The following conclusions are derived from the above mentioned analysis:

- $V_{BD}$ decreases with decreasing $t_f$ and the decrease of $V_{BD}$ is not linear with respect to $t_f$.
- The v-t characteristics shift down with decreasing $t_f$ and the shift is maximum for $t_b$ less than 2 μs and almost same for $t_b$ greater than 2 μs.
- $V_{BD}$ is decreased by 40% and withstand capability is almost 40-50% lesser for air under VFTO compared to the standard lightning impulse voltage.
- $V_{BD}$ is decreased by 33% and withstand capability is almost 33-50% lesser for OIP under VFTO compared to the standard lightning impulse voltage.

- **Hyperbolic Model**
  - v-t characteristics are modeled using Hyperbolic model. From the model parameters, the v-t characteristic for any intermediate $t_f$ can be predicted and verified experimentally.
  - The model is not successful for standard impulses with oscillations.

To predict the v-t characteristics for waveshapes with oscillations, already existing Disruptive Energy approach is discussed in detail in the forthcoming chapter.