Volt-Time Characteristics of OIP Under Non-Standard Impulses

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Abstract - The insulation of the power system equipment is stressed by internal and external overvoltages. For a reliable design of power system the proper insulation coordination among the power system components must be achieved. Insulation coordination is generally done by considering the behavior of insulation under standard lightning and switching impulses. In practice the system components might be stressed with the overvoltages of non-standard impulses like VFTO and oscillatory impulses. This necessitates the study of non-standard impulses on insulating materials. Transformers are considered as the major equipment in power system, which requires the detailed analysis on v-t characteristics of its insulation. In this paper an attempt has been made to analyze the breakdown characteristics of Oil Impregnated Paper (OIP) for different impulse waveshapes with varying front times from tens of nanoseconds to few microseconds and CIGRE representative waveforms. The v-t characteristics are mathematically modelled using Hyperbolic model. Thus developed models are used for predicting the v-t characteristics for any type of overvoltages of the above mentioned categories and compared with the experimental results.

Keywords - v-t characteristics, varying wavefronts, Oscillatory voltages, Hyperbolic model.

I. INTRODUCTION

Power transformers play a very important role in a power system. Transformer insulations designed to withstand the Basic Impulse Level (BIL) often fail due to switching operations in Gas Insulated Switchgear due to increased dielectric stress on the insulation [1]. Very Fast Transient Over voltages (VFTO) generated due to the switching operation of a disconnector in Gas Insulated Substation (GIS) comprises oscillatory waveforms of several MHz lasting for tens of μs [2]. The high frequency oscillatory overvoltages occur due to resonance and reflections between overhead lines and substations. The detailed classifications of overvoltages occurring in UHV substations of 1000 kV and 500 kV are given by CIGRE working group C4.302 [3].

In this paper an attempt has been made to analyze the v-t characteristics for the impulse voltages of varying front times (τ), voltage waves with steep pulse shaped crest with flat tail, voltages with damped oscillations of frequency of 0.5 MHz to 5 MHz and voltages with raising oscillations of frequency ranging from 0.4 to 1 MHz [3]. The v-t characteristics are modelled using Hyperbolic model and the corresponding model parameters are extracted. Thus developed model is used for predicting the v-t characteristics for any type of overvoltages of the above mentioned categories and compared with the experimental results.

II. TEST WAVESHAPES

The insulation design is generally based on the breakdown strength under standard lightning and switching impulse voltages. However, in practice all the components in a power system are stressed with transient overvoltages of wide variety of waveshapes [4]. To evaluate the insulation characteristics, it is necessary to consider the severity of actual waveforms occurred in the substations. Taking into account of the above mentioned facts, the different types of possible overvoltages considered are:

- Lightning, steep fronted and very fast transient overvoltages (VFTO) given by IEC 71-1 [5]
- Oscillatory waveforms: B (pulse-in-wavefront), C (damped-oscillation) and D (rising-oscillation) proposed by CIGRE Working Group C4.302 [3]

By suitably modifying the existing 140kV, MWB (Mess Wandler-Bau, Germany) Marx circuit test kit, the above mentioned waveshapes are generated and shown in Table I and Table II [6].

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>IMPULSE WAVESHAPES AS PER IEC 71-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning impulse</td>
<td>Steep fronted</td>
</tr>
<tr>
<td><img src="image" alt="Lightning impulse" /></td>
<td><img src="image" alt="Steep fronted" /></td>
</tr>
</tbody>
</table>

C A T C O N 2 0 1 3
III. INSULATION UNDER ANALYSIS

In oil filled transformers, Oil-Impregnated kraft (cellulose) Paper (OIP) is used as the inter-turn and inter-disc insulation in transformer windings. The thickness of OIP between turns is around 0.2 to 1.5mm and between the discs is around 4 to 12 mm. The thickness of the insulation considered for analysis is 0.25mm consist of five layers OIP (each of 0.05mm thick).

Before impregnating the paper with oil it is heated to reduce the moisture content. The electrodes are designed as per the standard ASTM (D149-97a). Fig 1 shows the test cell used for the analysis of solid insulations.

IV. V-T CHARACTERISTICS FOR IMPULSES OF VARYING FRONT TIMES

A. v-t characteristics – measurement

The effect of overvoltages on the insulation can be analyzed using the v-t characteristics. The v-t characteristics for the \( t_f \) of 1.4 \( \mu \)s, 0.38\( \mu \)s and 64 ns with same tail time (\( t_d \)) of 50 \( \mu \)s are experimentally measured as per IEC 60060 [7,8]. Fig 2 shows the v-t characteristics of 1.4/50 \( \mu \)s and Fig 3 shows the same for all the \( t_f \) for comparison.

B. Hyperbolic model

The v-t characteristics can be mathematically modelled using the Hyperbolic model [4,10], given by equation (1)

\[
V = A + \frac{B}{t_b}
\]

Where,

- \( V \) - peak voltage withstood by the insulation in kV
- \( t_b \) - breakdown time in \( \mu \)s
- ‘A’ and ‘B’ - constants

The parametric constants ‘A’ and ‘B’ are extracted from the v-t characteristics. The constant ‘A’ (kV) is proportional to maximum withstand voltage and constant ‘B’ (kV-\( \mu \)s) is inverse proportionality constant as breakdown time is inversely proportional to the peak of voltage applied.

The confidence interval is used to check the fitness of the Hyperbolic model. From the analysis it was found that more than 95% of obtained data for the considered waveforms lie within the error range of (0–5) % for Hyperbolic model.
The extracted values of ‘A’ and ‘B’ for different $t_f$ are given in Table III and Figs 4 and 5 and it is observed that both ‘A’ and ‘B’ decrease as $t_f$ decreases.

### Table III: Hyperbolic Constants for Varying Front Time

<table>
<thead>
<tr>
<th>Waveshapes</th>
<th>‘A’ (kV)</th>
<th>‘B’ (kV-µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4/50 µs</td>
<td>30.09</td>
<td>7.99</td>
</tr>
<tr>
<td>0.38/50 µs</td>
<td>25.36</td>
<td>3.60</td>
</tr>
<tr>
<td>0.064/50 µs</td>
<td>21.47</td>
<td>1.41</td>
</tr>
</tbody>
</table>

The value ‘A’ is 15.72% and 28.65% lesser for 0.38/50 µs and 0.064/50 µs (for the decrease in $t_f$ of 72.86% and 95.43% respectively) compared to 1.4/50 µs indicating clearly the effect of $t_f$ on breakdown characteristics.

### Validation of the Hyperbolic model

As the insulation is stressed with voltages of different $t_f$, an attempt has been made to predict the v-t characteristics using the Hyperbolic model.

v-t characteristics for 0.78/50 µs is experimentally obtained and the corresponding ‘A’ and ‘B’ values are extracted using curve fitting technique and compared with predicted values obtained from the Figs 4 and 5.

The error between the experimental and predicted v-t characteristics is less than 5%. Thus the v-t characteristics of any waveform with $t_f$ from tens of ns to 1.4 µs with a constant $t_i$ of 50 µs can be predicted using Figs 4 and 5.

### V. v-t Characteristics for Oscillatory Waveforms

v-t characteristics for the B-waveform and oscillatory overvoltage waveforms (C and D) described by CIGRE Working Group C4. 302 are obtained and shown in Fig 7.

C. Validation of the Hyperbolic model

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The error between the experimental and predicted v-t characteristics is less than 5%. Thus the v-t characteristics of any waveform with $t_i$ from tens of ns to 1.4 µs with a constant $t_f$ of 50 µs can be predicted using Figs 4 and 5.

#### Fig. 4.
Variation of ‘A’ with $t_i$

#### Fig. 5.
Variation of ‘B’ with $t_i$

### Fig. 6.
Comparison of experimental and predicted v-t characteristics for 0.78/50 µs

### Fig. 7.
v-t characteristics for oscillatory overvoltages

It is evident from the Fig 7, as the frequency of oscillation increases, the characteristics are shifted downwards and becoming steeper. The ‘A’ and ‘B’ values are computed for oscillatory waves using Hyperbolic model. To compare the effect of oscillatory waveforms, the initial time to rise of each oscillatory wave ($t_{fo}$) is noted and compared with the lightning impulse of $t_f$ equal to $t_{fo}$. The ‘A’ and ‘B’ values for lightning impulses of $t_f$ ($=t_{fo}$) are taken from Figs 4 and 5.

#### B-waveform

The Fig 8 shows the v-t characteristics of B-waveform whose $t_{fo} = 0.72$ µs and the predicted characteristics for 0.72/50 µs and the corresponding parameters are tabulated in Table IV.

### Fig. 8.
v-t characteristics of B-wave and 0.72/50 µs
The characteristics of C4/50, the methodology developed can be used for higher dv/dt and also on the frequency of oscillations which decreases. The frequency of oscillation increases (0.29 MHz and 0.55 MHz) are compared and it is found that as the frequency of oscillation is very high (1 MHz) D-waveform is severe than any other oscillatory waves as shown in Fig 7.

VI. CONCLUSIONS

To study the effect of overvoltages on the breakdown strength of transformer insulation (OIP), v-t characteristics for different waves from lightning to VFTO, B-waveform and different oscillatory waveforms are considered.

Impulse of varying \( t_0 \):
- As the \( t_0 \) decreases, the v-t characteristics shifts down and becomes steeper, inferring the effect of \( t_0 \) on breakdown strength of OIP which can be mainly attributed to higher rate of change of voltage (dv/dt).
- Using the Hyperbolic model the v-t characteristics can be predicted for any \( t_0 \) from tens of nanoseconds to few microseconds. The characteristics can be quantified using Hyperbolic model parameters.

Oscillatory waves
- The effect of oscillatory waves is more compared to their equivalent lightning impulses.
- As the frequency of oscillation increases, the breakdown strength decreases.

As the developed mathematical model is validated for test waveforms, the methodology developed can be used for predicting the withstand capability of insulation for any type of waveform.

\[ \text{TABLE IV. HYPERBOLIC CONSTANTS FOR B-WAVE AND 0.72/50 \mu s} \]

<table>
<thead>
<tr>
<th>Waveshape</th>
<th>‘A’ (kV)</th>
<th>‘B’ (kV-( \mu \text{s} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-waveform</td>
<td>24.64</td>
<td>3.64</td>
</tr>
<tr>
<td>0.72/50 ( \mu \text{s} )</td>
<td>27.10</td>
<td>5.10</td>
</tr>
</tbody>
</table>

For the given time to breakdown, the breakdown voltage is lower for B wave. The stress created on insulation by B-waveform is higher due to the pulse in its \( t_0 \), i.e. higher rate of change of voltage at the crest.

- **C-waveforms**

The v-t characteristics of C-waveforms of two different frequencies are compared. The comparisons of C-waveforms with their corresponding impulses are shown in Fig 9 and Table V.

\[ \text{Fig. 9. v-t characteristics of C-waves (0.55 MHz & 0.29 MHz), 0.44/50 \mu s and 0.84/50 \mu s} \]

\[ \text{TABLE V. HYPERBOLIC CONSTANTS FOR C-WAVES AND IMPULSES OF CORRESPONDING WAVEFRONTS} \]

<table>
<thead>
<tr>
<th>Waveshape</th>
<th>‘A’ (kV)</th>
<th>‘B’ (kV-( \mu \text{s} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C ( f=0.55 \text{ MHz} ) ( t_0=0.44 \mu \text{s} )</td>
<td>19.47</td>
<td>1.53</td>
</tr>
<tr>
<td>C ( f=0.29 \text{ MHz} ) ( t_0=0.84 \mu \text{s} )</td>
<td>20.23</td>
<td>3.39</td>
</tr>
<tr>
<td>0.44/50 ( \mu \text{s} )</td>
<td>25.7</td>
<td>3.9</td>
</tr>
<tr>
<td>0.84/50 ( \mu \text{s} )</td>
<td>27.6</td>
<td>5.35</td>
</tr>
</tbody>
</table>

The v-t characteristics of C-waveforms of two frequencies (0.29 MHz and 0.55 MHz) are compared and it is found that as the frequency of oscillation increases, the value of ‘A’ decreases. The effect of waveform of higher frequency is severe on the insulation.

The v-t characteristics of C-waveforms are compared with their corresponding \( t_0 \). That is 0.44/50 \( \mu \text{s} \) with C-waveform with a frequency of 0.55 MHz and 0.84/50 \( \mu \text{s} \) with C-waveform with a frequency of 0.29 MHz. From Fig 8, due to the oscillation present in the C-waveforms the stress on the insulation increases, in turn decreases the value of ‘A’.

In general, the breakdown voltage greatly depends on higher dv/dt and also on the frequency of oscillations which can be inferred from the comparison of the v-t characteristics.
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REFERENCES


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