PREDICTION OF v-t CHARACTERISTICS OF TRANSFORMER INSULATION

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Abstract: Insulation coordination among the power system components plays a crucial role in reliable design of the power system. Usually the insulation coordination is effected through the volt-time characteristics of the components under overvoltages of standard waveshapes, like Lightning impulse 1.2/50 µs and switching impulses. In practice the system components might be stressed with the overvoltages of non-standard Lightning impulses and the advent of gas insulated substation necessitates the v-t characteristics under VFTO. To incorporate the above facts the CIGRE Working Group C4.302 has discussed the importance of the v-t characteristics for non standard lightning impulse waveforms. As transformers play an important role in power system detailed analysis on v-t characteristics of transformer insulation becomes necessary. In this paper an attempt has been made to analyse the degradation of Oil Impregnated Paper (OIP) for different impulse waveshapes with varying front times from 64 ns to 1.4 µs with same tail time of 50 µs and CIGRE representative waveforms. The v-t characteristics are mathematically modelled using hyperbolic model and the corresponding model parameters are extracted. 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.

1 Introduction

Power transformers play a very important role in the power system. Transformer insulations designed to meet the Basic Impulse Level (BIL) often fail due to switching operations in Gas Insulated Switchgear [1]. The insulation failure is due to increased dielectric stress on the insulation. Very Fast Transient Over voltages (VFTO) generated at the switching operation of a disconnector in Gas Insulated Substation (GIS) [2] comprises oscillatory waveforms of several MHz lasting for tens of µs. Front times and tail times may be shorter or longer than the standard ones, the wave shapes may be very different from the unipolar double exponentials used in laboratories, and they may even be bi-polar. These surges are often steeper and attenuates more quickly than standard Lightning impulse [7]. The High frequency oscillatory overvoltages are occurred due to resonance and reflections between over head lines and substations. The detailed classifications of overvoltages are given by CIGRE working group C4.302.

In this paper an attempt as been made to analyse the v-t characteristics for the Impulse voltages of varying front times, voltage waves with steep pulse shaped crest with flat tail, voltages with damped oscillations of frequency of 0.5MHz to 5MHz 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 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.

2 CRITERIA FOR THE SELECTION OF 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 a wide variety of waveshapes [6]. 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 and the different types of possible overvoltages, the standards of International Electro technical Commission (IEC 71-1) [4], has subdivided the transient overvoltages into three groups such as switching, lightning and very fast transient overvoltages (VFTO). The VFTO's have a rise time of about 3-10 ns with a peak magnitude of about 2.8 p.u (~1000 kV for a 420 kV substation) [5]. The CIGRE Working Group C4.302 has further classified oscillatory waveforms into B (pulse-in-wavefront), C (damped-oscillation) and D (rising-oscillation)

The B waveform "pulse-in-wavefront waveform" has a sharp peak in magnitude followed by a relatively flat wavetail. This waveform occurs when a pulse shaped high voltage comes in and later drops to the protection level of the lightning arrester. The shape of the waveform is dependent on the distance between the lightning arrester and the transformer terminal.

The C waveform "damped-oscillation waveform" has a steeper wavefront and oscillatory nature. This waveform occurs in substations with series and parallel resonance points.

The D waveform "rising-oscillation waveform" has its crest value not in the first peak but in the second or subsequent peaks. This waveform is derived form of the C-waveform and attenuates thereafter due to superposition of incoming surges delayed due to repeated reflections between the bushing and the transmission line flashover points outside the substations.

3 GENERATION OF OVERVOLTAGES

The impulse voltages of different waveshapes with varying front times and CIGRE representative waveshapes are generated using 140kV, MWB (Mess Wandler-Bau, Germany) Marx circuit test kit, available in the High Voltage Laboratory, College of Engineering, Anna University, Chennai. The Marx circuit is shown in Figure 1.

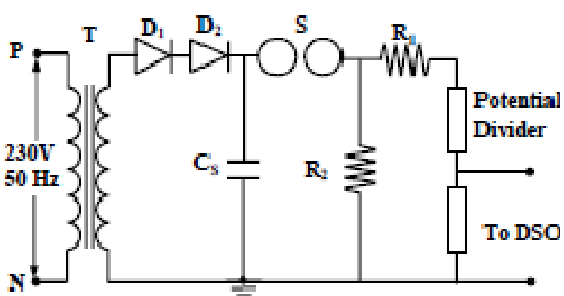
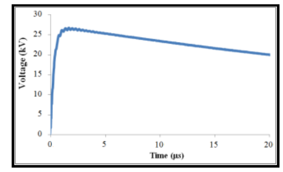
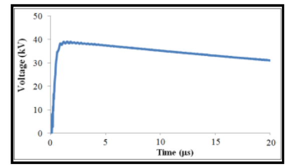
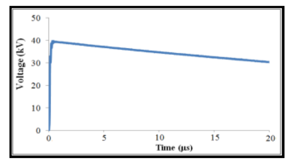
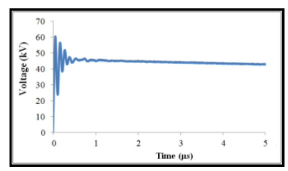


Figure 1: Marx Circuit for Impulse Generation

In Figure 1, R_1 and R_2 are waveshaping resistors, C_s is the charging capacitors, S is the sphere gap. The different waveshapes are generated by suitably selecting the waveshaping resistors and measured using capacitive and resistive dividers [8]. The resistive dividers are used to damp out the unnecessary oscillations in the high frequency waveshapes.

Table 1. Generated impulse waveshapes

Waveshapes		Generated Waveforms
Lightning Impulse (1.4/50 μs)		
Steep fronted	0.78/50 μs	
	0.38/50 μs	
VFTO (0.064/50 μs)		

4 TEST PROCEDURE

Calibration of the generator with the test specimen is carried out using the standard sphere gap arrangement with relevant atmospheric correction factors. The voltages are measured using Digital Storage Oscilloscope TDS 3054B at sampling rate of 250MSa/sec.

1. The minimum breakdown voltage of the dielectric medium with a single impulse (N=1) is considered as V_{BD} (100% breakdown).
2. The V_{BD} is increased in steps and the corresponding time taken to breakdown is noted.
3. The breakdown of sphere gap is controlled by the use of trigatron gap.

The above procedure is repeated for different waveshapes having different V_{BD}.

5 EXPERIMENTAL SETUP

Normally oil-impregnated Kraft (cellulose) paper (OIP) is used for the inter-turn and inter-disc insulation in oil filled 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. Five layers of Kraft paper of 0.25mm thickness (5x0.05mm) from a single manufacturer has been used in the entire study. Before impregnating the paper with oil it is heated to reduce the moisture content.

Electrode arrangement required for OIP insulation has been designed as per standard ASTM (D149-97a). The desired thickness of paper is obtained by stacking the required number of layers. The insulation is kept in between the electrodes and made tight by a holding arrangement. Figure 2 shows the Arrangement and photograph of the test cell.

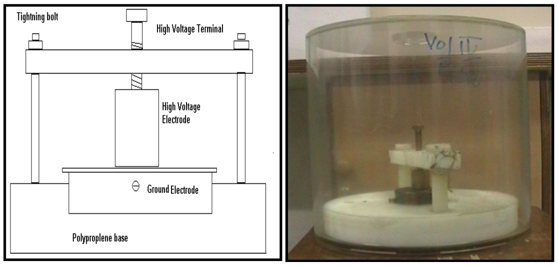


Figure 2: OIP Arrangement and Photograph of Test cell

6 MATHEMATICAL MODEL FOR v-t CHARACTERISTICS

- **Hyperbolic model**

The v-t characteristics is analysed using the hyperbolic model [8]. The expression for hyperbolic model is given as.,

$$V = A + B/t_b \qquad (1)$$

Where,

V is the breakdown voltage in kV.
t_b is the breakdown time in µs.
A and B are constants.

The parametric constants A and B are extracted from the v-t characteristics. The constant A is proportional to offset voltage (i.e. minimum voltage required to initiate the breakdown process, this voltage is dependent on gap distance, dielectric and also on electrode configuration) and constant B is proportional to breakdown time, which is inversely proportional to the peak of voltage applied.

7 v-t CHARACTERISTICS

The effect of overvoltages on the insulation strength can be analysed using the v-t characteristics. v-t characteristics for each type of waveforms considered are obtained as follows.

7.1 IMPULSES OF VARYING FRONT TIME

Using the test procedure mentioned in the section 4, V_{BD} and the time to breakown at different voltages above V_{BD} for 1.4/50 µs is obtained experimentally. Similar measurements are carried out for 0.78/50µs, 0.38/50µs and 0.064/50µs impulses and the corresponding v-t characteristics are shown in Figure.2.

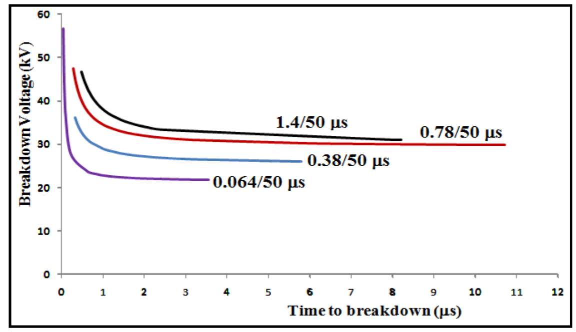


Figure 3. v-t characteristics for impulse waveshapes with varying front times

From the above figure, the breakdown voltages are 31kV, 30.45Kv, 29.5kV and 25kV for 1.4/50 µs, 0.78/50 µs, 0.38/50 µs and 0.064/50 µs respectively. V_{BDV} of OIP decreases by 1.8%, 3.8% and 19.2% for the decrease in the wavefront of 44%, 73% and 95% for 0.78/50 µs, 0.38/50 µs and 0.064/50 µs respectively with reference to the standard wave of 1.4/50 µs. It is evident that as the steepness of the wave increases breakdown voltge decreases. This is mainly due to the high displacement current produced as a result of high dv/dt [9].

The constants A and B are extracted from the v-t characteristics for the impulses for varying front times is tabulated in Table 2 and shown in Figure 4.

Table 2. Exponential constants for varying front times

Waveshapes	A (kV)	B
1.4/50 µs	30.09	7.99
0.38/50 µs	25.36	3.60
0.064/50 µs	21.47	1.41

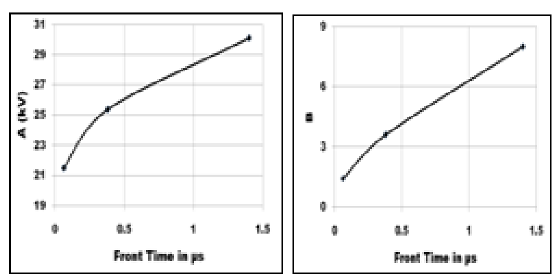


Figure 4: Variation of parametric constants (A and B) with Front time

The confidence interval is used to check the fitness of the exponential model. The percentage of confidence interval increases, the degree of uncertainty decreases with the increasing in percentage confidence level.

From the analysis it was found that more than 95% of obtained data for the considered waveforms lies within the error range of (0–5) % for hyperbolic model, given by the Confidence Interval.

8 PREDICTION OF v-t CHARACTERISTICS

In practice all the components in a power system are stressed with transient overvoltages of a wide variety of waveshapes [3]. An attempt has been made to predict the time to breakdown of transformer insulation for any waveshape.

The developed model is validated with the test waves of 0.78/50 µs. Using Figure 4, where the parametric constants are plotted against front time, the values of A and B are predicted for 0.78/50 µs waveshape and compared with experimental values and shown in Table 3.

Table 3. Comparison of Parametric constants for 0.78/50 µs

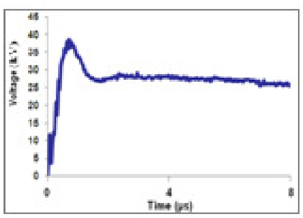
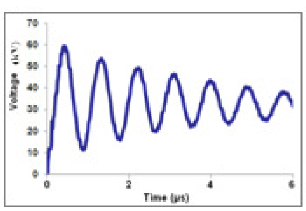
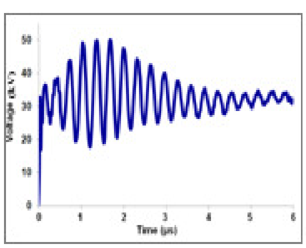
Test waveshape (0.78/50 µs)	Experimental Value	Predicted value	%Error
A	29.46	27.40	6.99
B	5.18	5.40	4.07

9 v-t CHARACTERISTICS OF OIP FOR OSCILLATORY WAVEFORMS

In this section, an attempt has been made to analyze the v-t characteristics for the B-waveform and oscillatory overvoltage waveforms (C and D) described in CIGRE Working Group C4. 302. The standard Marx generator has been altered to generate the B, C and D waveforms.

The specification of the generated waveshapes referred to the representative waveforms given by CIGRE are listed in Table 4.

Table 4: Reference and Generated Waveforms (CIGRE)

<table>
<tr><th>Generated Waveforms</th><th>Waveshape</th><th colspan="2">References</th><th colspan="2">Generated</th></tr>
<tr><td rowspan="2">B-waveform (Pulse-in-wavefront waveform)</td><td rowspan="2"></td><td>t_f (µs)</td><td>0.52 - 0.73</td><td colspan="2">0.72</td></tr>
<tr><td>Ratio of flat part to peak</td><td>0.71 - 0.385</td><td colspan="2">0.75</td></tr>
<tr><td rowspan="2">C-waveform (Damped-oscillation waveform)</td><td rowspan="2"></td><td>Frequency</td><td>0.40 - 1.0 MHz</td><td>0.55 MHz</td><td>0.29 MHz</td></tr>
<tr><td>Damping (Second peak/ First peak)</td><td>0.382 - 0.97</td><td>0.9</td><td>0.89</td></tr>
<tr><td rowspan="2">D-waveform (Rising-oscillation waveform)</td><td rowspan="2"></td><td>Frequency</td><td>0.40 - 1.0 MHz</td><td colspan="2">1 MHz</td></tr>
<tr><td>Magnitude of preceding wave (First peak/ Second peak)</td><td>0.71 - 1.0</td><td colspan="2">0.89</td></tr>
</table>

From the experiments carried out using the procedure shown in section 4, the breakdown voltages are found to be 20.63, 18.10, 17.6 and 14.32 kV for B-Waveform, C-Waveform of frequency 0.29MHz and 0.55MHz, and D-Waveforms respectively.

9 COMPARISION OF CIGRE REPRESENTATIVE WAVEFORMS WITH LIGHTNING IMPULSES

The v-t characteristics for CIGRE representative waveforms are compared with the impulses of corresponding wavefronts. The hyperbolic parametric constants are predicted from the Figure 4 for the corresponding wavefronts. The hyperbolic parametric constants for different waveforms are extracted and compared with the predicted parametric constants for corresponding wavefronts from Figure 4. The above mentioned comparison is tabulated in Table 5.

The comparison v-t characteristics of B-wave and oscillatory wave with that of the impulses of corresponding wavefronts are shown in Figure 7.

Table 6. Comparison of predicted and experimental parameters for the CIGRE representative waveforms

Waveshapes		t_f (µs)	A (kV)		B	
			Experimental value for B-wave and oscillatory type	Predicted value for impulse waveform (t_f/50 µs)	Experimental value for B-wave and oscillatory type	Predicted value for impulse waveform (t_f/50 µs)
B		0.72	24.64	27.1 (0.72/50 µs)	3.64	5.1
C	0.55 MHz	0.44*	19.47	25.7 (0.84/50 µs)	1.53	3.9
	0.29 MHz	0.84*	20.23	27.6 (0.44/50 µs)	3.39	5.35
D		0.16*	18.17	23.0 (0. 16/50 µs)	0.95	2.2

*Time to initial peak

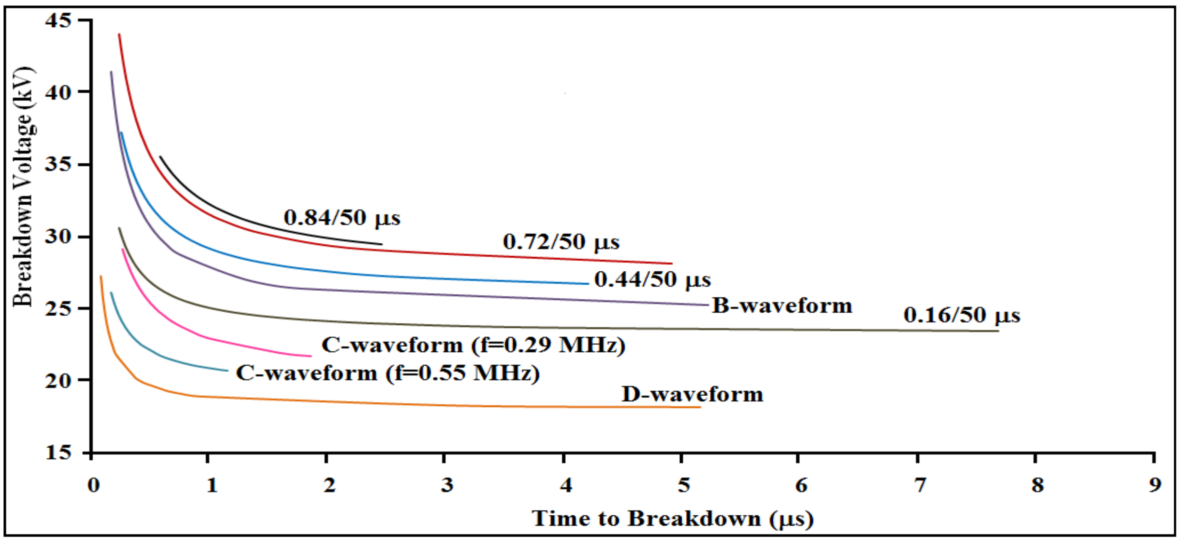


Figure 5: Comparison of CIGRE representative waveforms with impulses

From the above Figure 5, the breakdown voltage of B-waveform is lower than that of the 0.72/50 µs impulse waveform.

Likewise other CIGRE representative waveforms are compared with the impulses of corresponding wavefronts. From the comparison it is proved that the B-Waveform and oscillatory waveforms are severe than impulses of same wavefronts.

In general, the V_{BD} greatly depends on higher dv/dt and also on the frequency of oscillations which can be observed from the Table 6.

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 breakdown voltage of the insulation subjected to it decreases. The comparison also shows that the severity of D-waveform is higher than impulse and other oscillatory waveforms.

10 CONCLUSIONS

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

- For varying front times from 0.064 µs to 1.4 µs (VFTO to Lightning), the breakdown voltage (V_{BD}) decreases with decreasing wavefronts due to higher rate of change of voltage (dv/dt).
- The breakdown voltage is 1.8% less for 0.78/50 µs, 4.8% less for 0.38/50 µs impulse and 19.2% less for VFTO compared to that of standard lightning impulse with oil impregnated paper as dielectric medium.
- The breakdown voltage of OIP is 33.4% less for B-waveform, 41.6% less for C-waveform of 0.29 MHz frequency, 43.23% less for C-waveform of 0.55 MHz frequency and 53.81% less for D-waveform compared to that of standard lightning impulse.
- For oscillatory waveforms the breakdown voltage decreases as compared with the impulse overvoltage of same front time.
- Also, the breakdown voltage of the insulation decreases when the frequency of oscillation increases due to higher (dv/dt).
- An average of 95% of data lies within the confidence limit of 95% for the v-t characteristics of OIP for all the considered waveshapes.

The developed mathematical models are validated for test waveforms. The methodology developed can be used for predicting the withstand capability of insulation for any type of waveforms.

8 REFERENCES

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