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Impulse Volt-Time Characteristics of Oil and OIP Insulation

S. Venkatesan and S. Usa
Division of High Voltage Engineering, Anna University, Chennai, India

Abstract: Estimation of insulation strength of transformer oil and Oil Impregnated Paper (OIP) insulation, which constitutes major portion of insulation in power transformer, is an important task. Also, it is often necessary to evaluate the breakdown strength of oil and OIP under non-standard impulse voltages, since the oil and OIP insulation is subjected to non-standard waveshapes between inter-disc and inter-turn insulation. This necessitates for a generalized model to estimate the insulation strength of it. In this study impulse strength of transformer oil and OIP insulation have been extensively analysed for very small electrode gap distances ranging from 0.1 to 2.5 mm, which represents the inter-turn and inter-disc thickness of the insulation. The statistical mean volt-time characteristics for uniform and highly non-uniform electrode configurations are obtained experimentally for few gap distances. A Hyperbolic model is developed based on the Disruptive Effect (DE) model parameters, namely onset voltage (U_o) and Critical Disruptive Effect Area (DE^*) to predict the volt-time characteristics. The DE parameters are also utilised to predict the impulse breakdown characteristics of oil and OIP under non-standard impulse voltages of standard and unidirectional oscillatory impulse waveshapes for all the gap distances and the errors are found to be less than 10%.

Key words: Disruptive Effect, Volt-time Characteristics, Non-standard Impulse

INTRODUCTION

The major proportion of failures in transformers are due to the inter turn and inter disc failures, whose distance is of few millimeters. These parts of the windings are stressed with non-standard impulse voltages of both unidirectional and bi-directional oscillating voltage waves. Hence apart from the standard 1.2/50 μs waveshapes, it is essential to estimate the insulation strength for nonstandard waveshapes also. But it is impracticable to estimate the insulation strength for all possible waveshapes. For example, the use of the standard v-t characteristics is not adequate to determine the impulse strength with non-standard waves. The most convenient approach to the problem is to develop an analytical prediction procedure based on the sparkover data obtained with standard waves. Kind, made the first significant advance in the development of a suitable analytical method by proposing the equal area criterion using the generalized integration method. The Disruptive Effect (DE) method is a generalized integration method developed based on equal area criterion, used to estimate the instant of breakdown of insulation under non-standard lightning impulse. There exists a theoretical basis for the Disruptive Effect method for predicting the impulse strength of insulation subjected to non-standard impulse wave shape [1]. It has a reasonable success as far as waveforms close to lightning impulses (unidirectional) are concerned but does not fare well for bidirectionally oscillating impulse. Hence, a new method called "Unconditionally Sequential Approach" developed by Usa *et.al.*, [2] serves as a measure of insulation strength under bi-directionally oscillating impulse voltages. The co-authors have already reported this method in the reference cited. Thus the Disruptive Effect method shall be utilized to predict the insulation strength of any insulation. It will be of a significant contribution if we can define a mathematical model based on the Disruptive effect parameters, which will indirectly predict the volt-time curve for any given waveshape. Since the gap distance between the discs will be of few millimeters, a fundamental study on 1 to 6 mm gap distances for different dielectric media is essential for uniform electrode configurations. To comply with this requirement, an extensive analysis on oil and Oil Impregnated Paper (OIP) over the gap distances of 0.1 to 2.5mm has been reported here. Since the behavior of these insulating mediums will depend on so many factors, it is essential to know it during impulse breakdown. An extensive analysis about this fact and the suitability of the DE method is reported here.

Energy Balance Model For Impulse Breakdown: Although different breakdown mechanisms are involved in breakdown of oil and OIP insulation medium, it will be appropriate if a universal breakdown model applicable for all insulating medium (Gas, Liquid, Solid and Composite dielectric) is defined which is independent of the physical process involved. One such model is the Disruptive Effect model. The DE model, which is based on Energy Balance approach, states that, when the impulse applied across the insulation exceeds a threshold value (onset voltage – the voltage above which the breakdown process getting started), the energy required to make the breakdown process complete is constant. It is explained with the two impulse waves with different breakdown times as shown in Fig. 1. If the area above the onset voltage (U_o) of these two waveforms are equal then breakdown occurs.

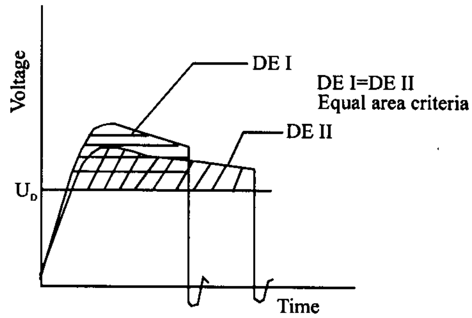

Fig. 1: Impulse Waves with Different Breakdown Times

The development of the process, which leads to breakdown, called disruptive effect DE of an applied surge depends on both magnitude and its duration [1]. DE is defined by

$$DE = \int_{to}^{ts} (U(t) - Ua)\,dt$$

Here:
U(t) is the time function of applied voltage.t_o – is the first time, when $U(t)>U_o$, and U_o is the onset voltage. It is assumed that there exists an optimum set of these parameters. In order to characterize a medium, the most useful standard test result is the volt-time characteristics.

Prediction of Volt-time Charateristics

Volt-time characteristics: Since the gap distance chosen for analysis is very small, it is necessary for the impulse generator to have fine voltage control. Also the test cell needs to have provision for minute gap adjustment. MWB (Messwandler-Bau), 100 kV, 250 kJ impulse generator with fine voltage control in steps of 125 V is utilised. The impulse generator is adjusted to generate standard 1.2/50 μs impulse voltages. Uniform plane electrodes in the test cell, are made of brass and are coated with tin to provide clean surface. The measuring system consists of a Tektronix TDS 420 oscilloscope, which is connected to the computer via GPIB (IEEE 488) interface, by which digitized waves can be acquired to the computer for further analysis.

In practical conditions there will always be some deviations in the time to breakdown and the statistical and formative time lag will play a significant role while plotting the experimental volt-time curve. Due to variations in the time to breakdown, it is essential to plot the mean statistical impulse volt-time curve. While performing constant voltage test, the time to breakdown of the impulse, where breakdown occurs in the tail follows Normal distribution. Hence, for each gap setting, constant voltage tests are performed at different voltage levels, so that the breakdown occurs in tail of the impulse. n_i number of impulses resulting in breakdown is applied at every voltage level and the time to breakdown t_b is measured every time. The mean value of time to breakdown (t_b) shall be expressed as:

$$t_{b,\,mean} = \frac{\sum_{n_i} t_{bi}}{n_i} \qquad (3)$$

and the standard deviation ($s(t_b)$) is given by:

$$s(t_b) = \sqrt{\frac{1}{n_i - 1}\sum_{n_i}(t_{bi} - t_{b,\,mean})} \qquad (4)$$

A schematic plot between impulse peak value and breakdown time gives the volt-time band. It yields the minimum and maximum breakdown times to be expected for a certain configuration at a given impulse voltage. For small oil and OIP insulation gaps from 0.1 to 2.5 mm, the impulse volt-time band is obtained experimentally for standard impulse waveshapes. Figure 2 shows the impulse volt-time band for 1.5 mm plane-cone oil gap.

A band rather than a single line represents the volt-time characteristics of any insulation like the volt-time characteristics shown in Fig. 2. The mean value of time to breakdown for each impulse crest voltage is obtained. And by joining the mean breakdown time of all crest voltages the statistical mean volt-time characteristics are obtained. The statistical mean volt-time characteristics also shown.

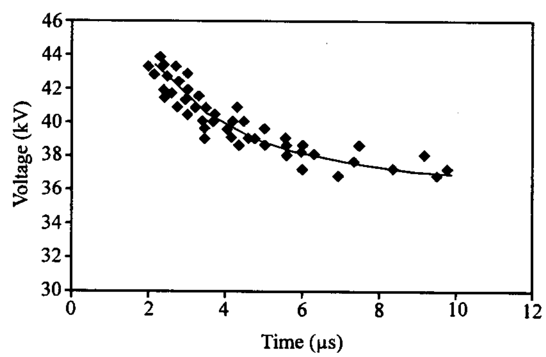

Fig. 2: Statistical Mean Volt-time Characteristics of 1.5 mm Plane-Cone Oil Gap

Similarly for an OIP insulation of 1 mm thickness the volt-time curve band will be as shown in the Fig. 3.

Hyperbolic model for v-t characteristics: From the statistical mean volt-time characteristics, a regression model is developed to predict the mean breakdown time of the oil for given configuration under the given crest voltage. That model is given by

$$V = A + B / t$$

Where:
v, crest value of the applied impulse voltage, t –time to breakdown in µs and A and B are constants.
The statistical mean volt-time characteristics of various gap distances for oil gaps of plane-plane configuration are shown in Fig. 4. and the variations of values of constants (A and B) with the distances are also shown in Fig. 5.

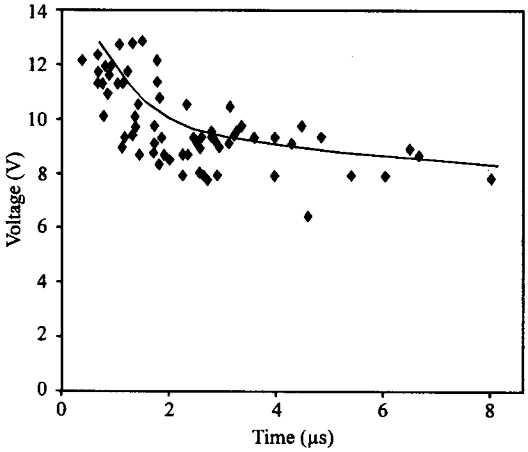

Fig. 3: v-t Characteristics for 0.12 mm OIP insulation

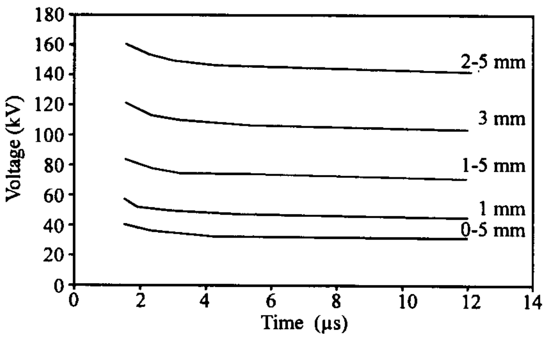

Fig. 4: Volt-time Characteristics for Plane-Plane Configuration of Oil

For plane-cone configurations the statistical mean volt-time characteristics of various gap distances and the variation of constant's values with distance are shown in the following Fig. 6 and Fig. 7.
The similar approach is dealt in OIP insulation with plane-plane electrode configuration and is shown in Fig. 8 and 9.

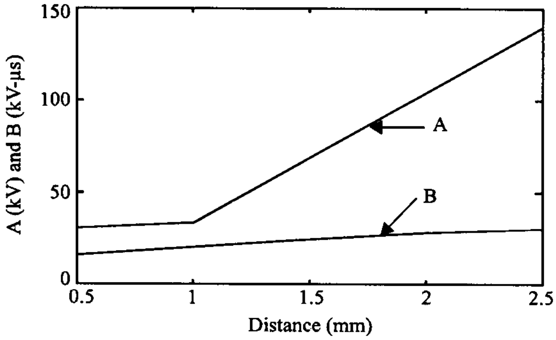

Fig. 5: A and B Values for Plane-Plane Configuration of Oil

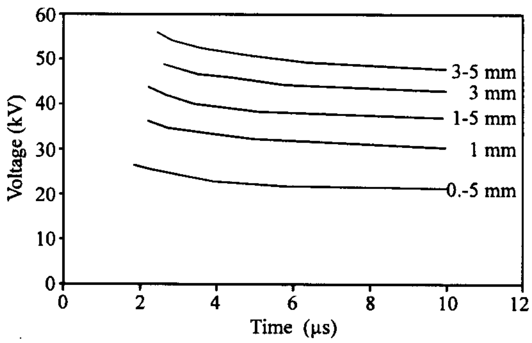

Fig. 6: Volt-time Characteristics for Plane-cone Configuration of Oil

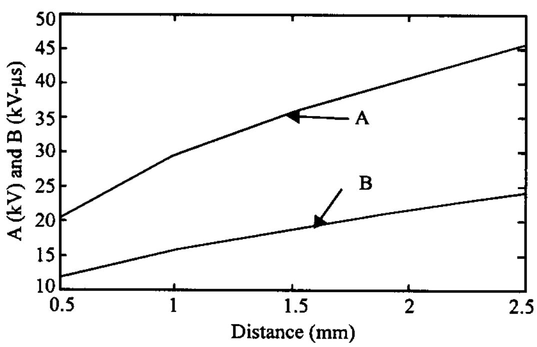

Fig. 7: A and B Values for Plane-cone Configuration of Oil

The DE model parameters, onset voltage (U_o) and critical disruptive area (DE^*) are extracted from the statistical mean volt-time characteristics.

Extraction of Parameters: The critical disruptive area (DE*) gives the area under the curve U(t) bounded by the onset voltage (Uo) between time t = 0 and t = t_b (breakdown time). Based on this logic an algorithm has been developed to calculate Uo and DE* from the impulse voltage waveforms corresponding to the points taken from the statistical mean volt-time characteristics.

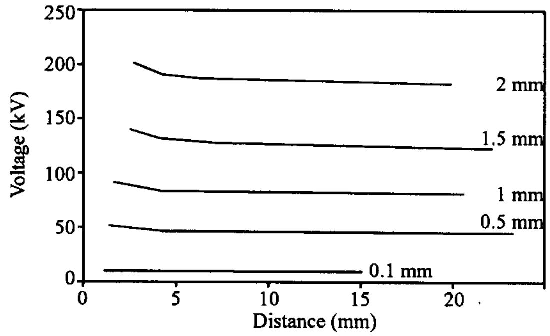

Fig. 8. Volt-time Characteristics for Plane-plane Configuration of OIP Insulation

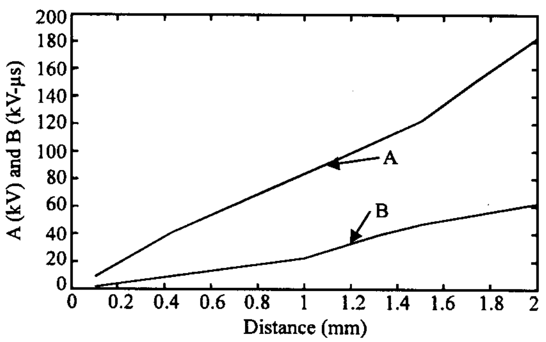

Fig. 9: A and B Values for Plane-plane Configuration of OIP

The better accuracy is achieved by selecting the data points having well separated time to breakdown.

The DE model parameters DE* and Uo of oil obtained experimentally for uniform electrode configuration (plane-plane) and for non-uniform configuration (plane-cone) the results are shown in Fig. 10 and 11.

The DE model parameters DE* and Uo of oil obtained experimentally for uniform electrode configuration (plane-plane) the results are shown in Fig. 12 and 13.

Prediction of Parameters using Hyperbolic Model: The statistical mean volt-time characteristics of the transformer oil under given configuration for the given distance is predicted by using the Hyperbolic model for v-t characteristics.

In that, the model constant 'A' represents the minimum breakdown voltage of the insulation for the given configuration. The onset voltage also represents the voltage level that is required to initiate the breakdown process. Thus, the onset voltage is linearly proportional with the model constant 'A'. So , a regression analysis is carried out to analyse the vatiation of Uo with 'A', which is given by:

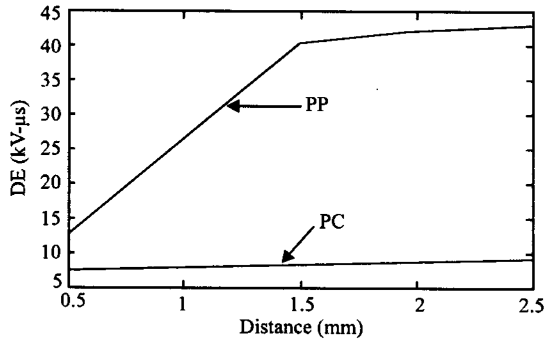

Fig. 10: Critical Disruptive Effect for Various Gap Distances in Oil

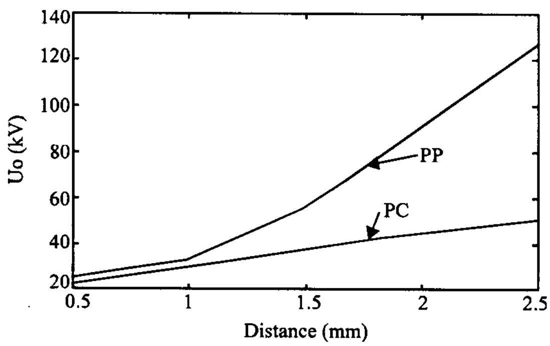

Fig. 11: Onset Voltage for Various Gap Distances in Oil

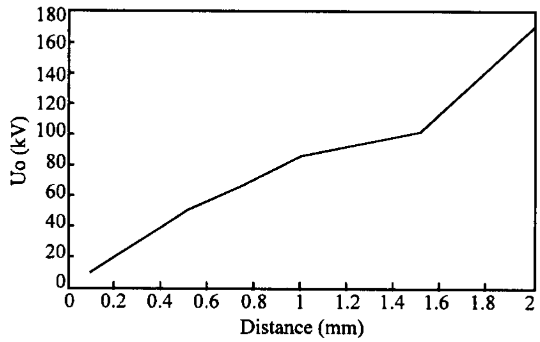

Fig. 12: Onset Voltage for Various Gap Distances in OIP

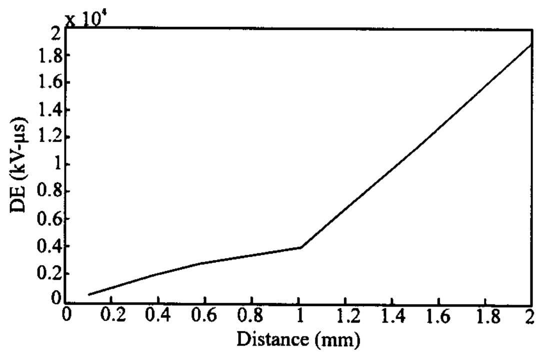

Fig. 13: Critical Disruptive Effect for Various Gap Distances in OIP

Table 1: Validation of DE Parameters for Plane-Plane (Oil) Configuration with Standard Impulse Voltages

Distance (mm)	Actual time to b/d (μs)	Predicted time to b/d (μs)	% Error
.5	3.72	3.60	3.20
	8.78	8.54	2.70
1	4.98	4.9	1.6
	8.42	8.22	2.3
1.5	3.7	3.46	6.4
	7.14	7.00	1.9
2	4.98	4.74	4.8
	7.74	7.58	2.0
2.5	3.58	3.36	6.1
	10.38	10.02	3.4

Table 2: Validation of DE Parameters for Plane-Plane (Oil) Configuration with Unidirectional Oscillating Impulse Voltages

Distance (mm)	Actual time to b/d (μs)	Predicted time to b/d (μs)	% Error
.5	3.88	3.60	7.77
	8.58	7.92	7.68
1	8.10	8.18	-1.0
	4.18	4.02	3.8
1.5	5.78	5.22	8.6
	10.88	10.24	5.8
2	4.56	4.44	2.6
	7.38	7.12	3.5
2.5	3.4	3.22	5.3
	9.98	9.24	7.4

$$U_o = f(A) = C1 * A + C2$$

where, 'U_o' is onset voltage in kV, and C1, C2 are constants.

In the regression model for volt-time characteristics, the value (B/t) represents the magnitude of applied voltage above the minimum breakdown voltage. That is breakdown voltage is proportional to (B/t). So, the model constant B is proportional to V*t (in kV- μs). In energy balance model, the critical disruptive effect (DE^*) is also represent by V*t (in kV- μs). So, the DE^* is proportional to the model constant 'B'. Here, a regression model developed for DE* as a function of 'B'.

$$DE^* = f(B) = C3 * B + C4$$

where, DE^* is Critical disruptive area, and C3, C4 are constants.

Validation of the Developed Model: The validation is done for all the gap distances including intermediate gap distances for standard impulse. Table 1 shows the error between the actual time to breakdown and the predicted time to breakdown.

By using the DE model, the time to breakdown of oil gaps is predicted for unidirectional oscillating impulses. Fig. 14 shows the example for prediction of time to breakdown for unidirectional oscillating impulses with the frequency of 512.5 KHz.

Similarly for all the distances the time to breakdown is predicted for unidirectional oscillating impulse wave using the DE parameters and the error in time prediction is given in Table-2.

Wave.I shows unidirectional oscillating impulse wave and Wave.II shows oscillating impulse when breakdown occur. Time to breakdown, t_b (Experiment) = 2.8 μs and t_b (predicted) = 2.72 μs. The percentage error is 2.857 %. Thus the energy balance model parameters DE* and Uo are calculated from the statistical mean volt-time characteristics by using integration method. The parameters are verified for all the gap distances. With the parameters obtained from the statistical mean volt-time characteristics the error in predicting the time to breakdown is found to be less than 10 %.

DISCUSSION AND CONCLUSION

The behavior of transformer oil and OIP under non-standard waves is analyzed by using the Disruptive Effect method. Analysis is carried out under both uniform and highly non-uniform configurations with different distances of 0.1to 2.5 mm.

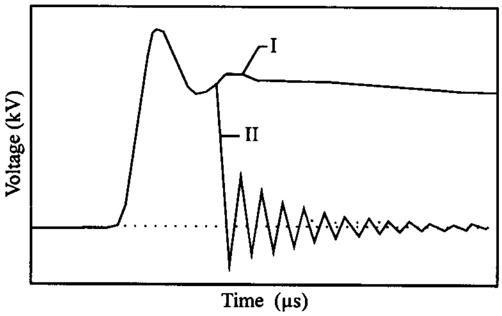

Fig. 14: Prediction of Time to Breakdown for Unidirectional Oscillating Impulses with the Frequency of 512.5 KHz

The volt-time characteristics for few gap distances are obtained experimentally using standard 1.2/ 50μs impulse wave shape. Statistical mean volt-time characteristics are obtained from the volt-time characteristics band. A Hyperbolic model is developed for predicting the volt-time characteristics with the help of constants 'A' and 'B'. By using these constants the volt-time characteristics for intermediate distances are predicted. The error in the prediction of the volt-time characteristics is less than 5%.

The DE model parameters DE^* and U_0 are extracted for different gap distances under both uniform and non-uniform electrode configurations using the information derived from the statistical volt-time characteristics.

The calculated parameters are verified for both standard and unidirectional oscillatory impulse waves for all distances. The percentage error between the actual time to breakdown and the predicted time to breakdown obtain using Disruptive Effect model is less than 10%. Thus, this approach gives a generalized methodology to predict the dielectric strength of transformer oil and OIP under non-standard impulses.

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