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VOLT-TIME CHARACTERISTICS OF SHORT AIR GAPS UNDER NONSTANDARD LIGHTNING VOLTAGE WAVES

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Abstract - The volt-time characteristics of 5-cm long rod-plane and rod-rod air gaps were experimentally determined with five different waveshapes of the applied impulse voltage. The front time of the waves was varied from 25 ns to 10 μs, and the time to half value was varied from 0.5 μs to 100 μs. The volt-time characteristics were also checked analytically using the concept of disruptive effect. The parameters for the disruptive effect were experimentally determined.

INTRODUCTION

The breakdown voltage level of a dielectric system under a transient voltage of a given waveshape is not a constant parameter. When transient voltages of the same waveshape but of increasing amplitude are applied to a dielectric system, the dielectric breaks down at higher voltage levels at shorter time delays for the higher applied voltages. This characteristic, known as the volt-time or time-lag characteristic, significantly influences the insulation coordination of an electric power system. The volt-time characteristic is different for the same dielectric system under transient voltages of different waveshapes. The volt-time characteristic of a dielectric system for the standard 1.2/50-μs lightning voltage is generally available. However, a large number of tests are required to determine such a volt-time characteristic.

The volt-time characteristics under nonstandard lightning voltages are seldom available, even though a dielectric system is mostly stressed by such lightning voltages in practice. Many attempts have been made in the past to analytically derive the volt-time characteristics under nonstandard lightning voltages from the known standard volt-time characteristic.

In dealing with the time-lag characteristics of transformers under nonstandard lightning voltages, Witzke and Bliss introduced the term "disruptive effect", DE [1,2]. Disruptive effect has since then been used to define the volt-time characteristics of dielectric systems in general. The general form of the equation defining the disruptive effect is:

$$DE=\int_{t_o}^{t_b}[V(t)-K_1]^{K_2}\cdot dt \ , \qquad (1)$$

where V(t) is the applied impulse voltage, DE, K_1 and K_2 are constants for a dielectric system, t_b is the time lag of breakdown, and t_o is the time when $V(t_o)=K_1$. With the assumption that DE is constant, it can be evaluated from tests with the standard 1.2/50-μs impulse voltage. However, difficulties have been encountered in the determination of K_1, K_2 and t_o. K_1 has been varied from zero to the static withstand voltage level of the insulation system; K_2 has been assumed to be 1 or 2; and, t_o has been assumed to be zero for simplicity. As a result, it has not been possible to apply (1) universally, and no acceptable method exists today. A comprehensive review of the volt-time characteristics has been published previously [3,4].

The goal of the present study was to perform a series of statistically designed tests on several types of short air gaps under lightning voltages of front times varying from the nanoseconds regime to the microseconds regime. The objective was to compare the critical breakdown voltage levels, V_{50}, and the volt-time characteristics of these short air gaps under lightning voltages of various waveshapes. The results of the critical breakdown voltages were presented previously [5]. The results of the volt-time characteristics of these air gaps are presented in this paper.

EXPERIMENTS

Two vertically mounted 5-cm long air gaps were selected for the tests: (i) rod-plane gap, and (ii) rod-rod gap. The rods were 1.25-cm square, square-cut aluminum rods; and the plane was a 1-m square aluminum plate. The test gaps were mounted in direct line of sight of the spark gaps of the impulse generator, located a few meters away, thus being exposed to the UV light emitted by these spark gaps.

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Eight voltage waveshapes of both polarities were selected for the evaluation of V_{50}, [5], of which five waveshapes were used to determine the volt-time characteristics of the air gaps. The wavefronts were varied from 25 ns to 10 μs, and the wavetails to half value were varied from 0.5 μs to 100 μs. The individual waveshapes used for the determination of the volt-time characteristics are shown in Table I.

TABLE I: TEST IMPULSE WAVESHAPES

	Wave Number				
	1	2	3	4	5
Front, μs	0.025	0.025	0.12	1.2	10
Tail, μs	0.5	25	25	50	100

Tests were started at a charging voltage level of the impulse generator where the test gap broke down on the tail of the applied voltage wave. The charging voltage level was progressively increased until the test gap broke down on the front of the applied voltage with very short time lag. Ten shots were applied at each charging voltage level. The mean of the 10 time lags of breakdown at each charging voltage level was then plotted against the peak of the applied voltage when the breakdown occurred on the tail of the applied voltage, and against the actual voltage at breakdown for breakdown on the front of the applied voltage.

ANALYSIS

The volt-time characteristic of each of the test gaps was also analytically determined from two breakdown tests at two different applied voltage levels by the following empirical equation:

$$DE=\int_{t_o}^{t_b}[V(t)-V_o]^{\alpha\frac{V(t)}{V_o}}\cdot dt \ , \qquad (2)$$

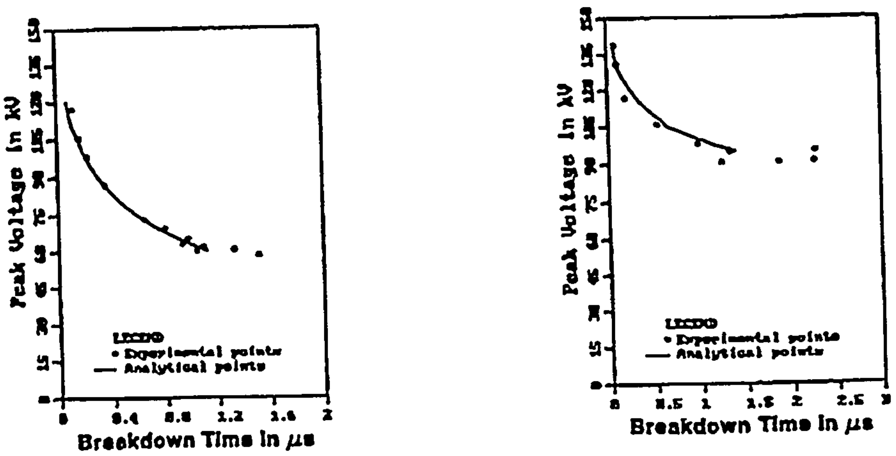
where α and V_o are two constants to be determined from two experimental points; t_o is the time (from start) when the instantaneous applied voltage exceeds V_o, and t_b is the time when the applied voltage collapses due to breakdown. DE (disruptive effect) is a parameter which is constant for a particular gap under a specified voltage waveshape. Equation 2 is similar to (1) thus assuming that the breakdown process is a cumulative process in voltage and time. However, (2) is different in interpreting the breakdown mechanism. It quantifies the breakdown process by assuming that DE is a constant parameter of a particular gap under a specified voltage waveshape, irrespective of the magnitude of the voltage. DE will assume different values for different gaps, and for different voltage waveshapes even for the same gap. V_o has been assumed by various researchers as the dc withstand voltage, power-frequency withstand voltage or even zero. Equation 2 proposes that V_o is a parameter which is constant for a particular gap under a specified voltage waveshape, and that it needs to be determined by statistical analysis. The exponent of the voltage in the expression for DE has been assumed by others as constant. In contrast, (2) proposes that this exponent is a function of the overvoltage factor ($=V(t)/V_o$). This assumption stems from the fact that the velocity of the propagating streamer (leader) in the air gap is higher the higher the electric field (i.e., the applied instantaneous voltage) is. The parameter, α, will vary with the type of the air gap and the waveshape of the applied voltage. Therefore, both V_o and α need to be determined for each setup. As no theoretical basis has been arrived as yet, V_o and α were experimentally derived.

V_o is defined as the voltage of a specified waveshape which a particular air gap will withstand under repeated applications with very low probability of breakdown. If the estimates of the critical breakdown voltage, V_{50}, and the standard deviation, s, are known, based on n observations of a normal distribution, then it can be stated that at least a portion, P, of the population is greater than V_o with confidence, γ, where V_o is given by:

$$V_o = V_{50} - k\times s \ . \qquad (3)$$

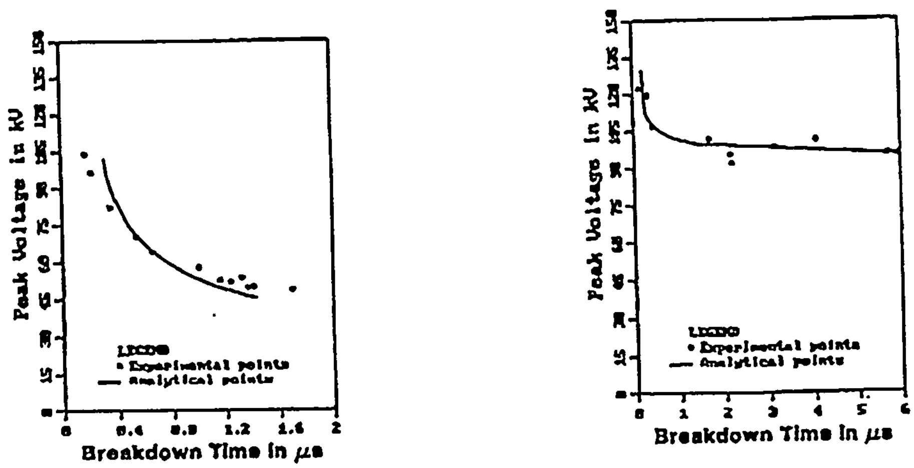
The parameter, k, which is a function of n, P and γ, can be found from statistical tables [6]. P was assumed to be 0.999, and $\gamma=0.95$.

Once V_o is computed, there still remain two unknowns in (2): DE and α. These two parameters were computed from two breakdown voltage levels at two different breakdown times, the voltage profiles (V(t) *vs.* t) of which were already stored in the computer. The integral in (2) was evaluated for each of the two breakdown voltages for various values of α. The correct value of α would produce equal DE for the two V(t). Once DE, V_o and α are determined for a particular gap under a specified voltage waveshape, the volt-time characteristic of the air gap under the specified voltage wave is determined as follows. The full-wave voltage profile which is stored in the computer is multiplied by a factor greater than 1. Using this V(t), the integration in (2) is performed up to a time, t_b, when the numerical value of (2) is equal to the specifed DE. The peak value of the voltage and t_b provide one point on the volt-time curve. This step is repeated with increasing values of the miltiplying factor to compute other points on the volt-time characteristic. The analysis was performed with the ASYSTANT software, installed in the HP Vectra personal computer. This software can perform mathematical operations on data arrays. Some of the experimental and analytical volt-time characteristics are shown in Figs. 1 - 6.



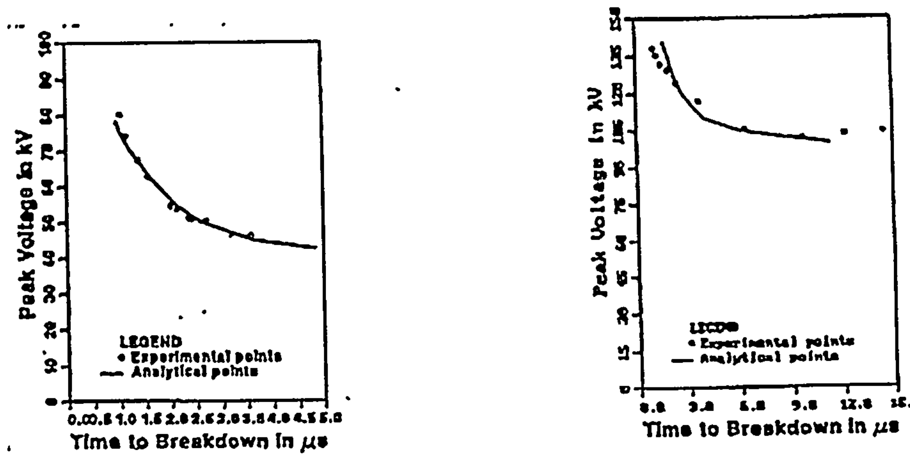
(a) (b)

Fig. 1 Volt-time characteristics of 5-cm rod-plane air gap under 0.025/25-μs impulse voltage.
(a) positive polarity; (b) negative polarity



(a) (b)

Fig. 2 Volt-time characteristics of 5-cm rod-plane air gap under 0.12/25-μs impulse voltage.
(a) positive polarity; (b) negative polarity



(a) (b)

Fig. 3 Volt-time characteristics of 5-cm rod-plane air gap under 1.2/50-μs impulse voltage.
(a) positive polarity; (b) negative polarity

DISCUSSION

According to the proposed analytical method, DE, V_o and the exponent, $\alpha V(t)/V_o$, are functions of the air gap (type and length) and the applied voltage waveshape. These differences are shown in Tables II and III. There is no similarity in V_o, α and DE between the rod-plane and the rod-rod gaps when stressed by voltages of the same waveshape. For the rod-plane gap where the critical breakdown voltage levels, V_{50}, are significantly different between the two polarities [5], the three volt-time parameters are also significantly different.

TABLE II: VOLT-TIME PARAMETERS FOR 5-cm ROD-PLANE AIR GAP

Waveshape (µs)	Polarity	V_{50} (kV)	V_o (kV)	α	DE
0.025/0.5	+	88.3	63.30	0.10	0.97
	-	119.0	75.09	0.23	5.19
0.025/25	+	61.3	27.76	0.11	9.13
	-	92.0	70.47	0.35	82.36
0.12/25	+	50.3	38.80	0.15	6.45
	-	93.4	72.57	1.00	1.5e6
1.2/50	+	49.2	40.30	0.24	21.80
	-	101.9	83.98	0.50	2.4e3

TABLE III: VOLT-TIME PARAMETERS FOR 5-cm ROD-ROD AIR GAP

Waveshape (µs)	Polarity	V_{50} (kV)	V_o (kV)	α	DE
0.025/25	+	70.0	43.34	0.18	14.36
	-	68.4	46.95	0.18	10.31
0.12/25	+	54.6	40.33	0.18	11.45
	-	56.9	44.23	0.22	22.95
1.2/50	+	56.6	31.18	0.13	18.25
	-	59.0	30.62	0.16	52.50

The volt-time characteristics of the rod-rod gap with the 0.025/0.5-µs wave could not be analytically drawn because of the large scatter in the breakdown times. Similarly, the analytical volt-time curves for the rod-plane gap (under positive-polarity voltage) and the rod-rod gap (under voltages of both polarities) with the 10/100-µs wave could not be drawn because of the breakdown on the wavefront at low amplitudes. The relatively long breakdown time lag under the 0.025/0.5-µs wave and the breakdown on the wavefront at low amplitude of the applied voltage under the 10/100-µs wave were discussed in [5].

Three shots of the 10/100-µs applied voltage across the rod-plane gap for the same charging voltage of the impulse generator are shown in Fig.7. The gap broke down during the first shot (bottom) after a long time delay, withstood the second shot (middle), but broke down at a low amplitude on the front (upper) during the third shot. Figure 8 shows the experimental and the analytical volt-time characteristics of the rod-plane gap under the negative-polarity 10/100-µs wave, where low voltage level for front-of-wave breakdown was not observed. The anomalous breakdown phenomenon of the rod-rod gap under the 10/100-µs wave for both polarities is shown in Fig.9.

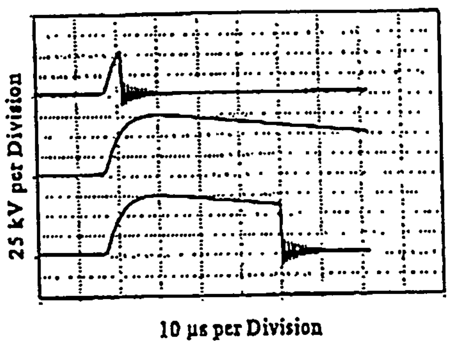


Fig.7 Three shots of applied voltage across 5-cm rod-plane gap with positive-polarity 10/100-µs wave at the same charging voltage level of impulse generator.

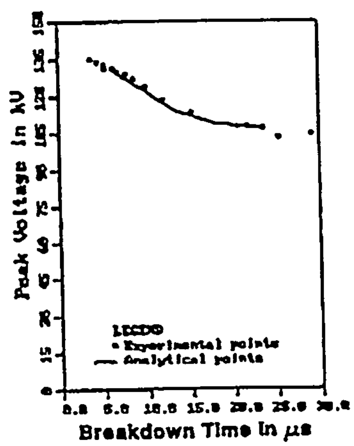
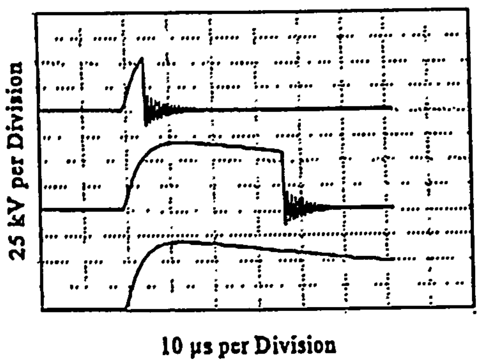
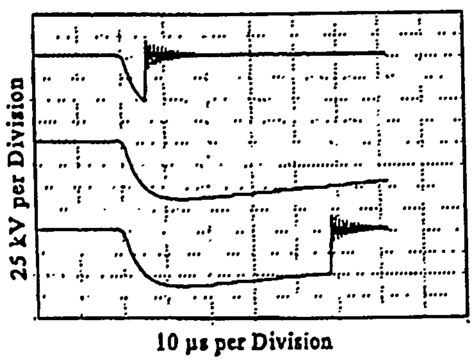


Fig.8 Volt-time characteristic of 5-cm rod-plane air gap under negative-polarity 10/100-µs wave.



(a)



(b)

Fig.9 Three shots of applied voltage across 5-cm rod-rod air gap with 10/100-µs voltage wave at the same charging voltage level of impulse generator.
(a) positive polarity; (b) negative polarity

CONCLUSIONS

The concept of the disruptive effect (DE), as originally proposed by Witzke and Bliss, is very effective in the determination of the time lag characteristics of an air gap. However, DE, the withstand voltage (K_1) and the exponent of the voltage (K_2) are not constants for a particular gap, as generally assumed. These parameters are functions of the applied voltage waveshape. K_2, in addition, is a function of time; it varies with time during the application of the voltage. These parameters can be experimentally determined.

To be of practical value to the design engineer, the parameters for the disruptive effect must be determined analytically. Quantitative knowledge of the physics of progression of ionization across the gap will be needed to accomplish that.

The breakdown on the front of the applied 10/100-µs voltage at relatively low amplitude will make insulation coordination difficult. This observation, made here and in [5], should be independently verified by other researchers.

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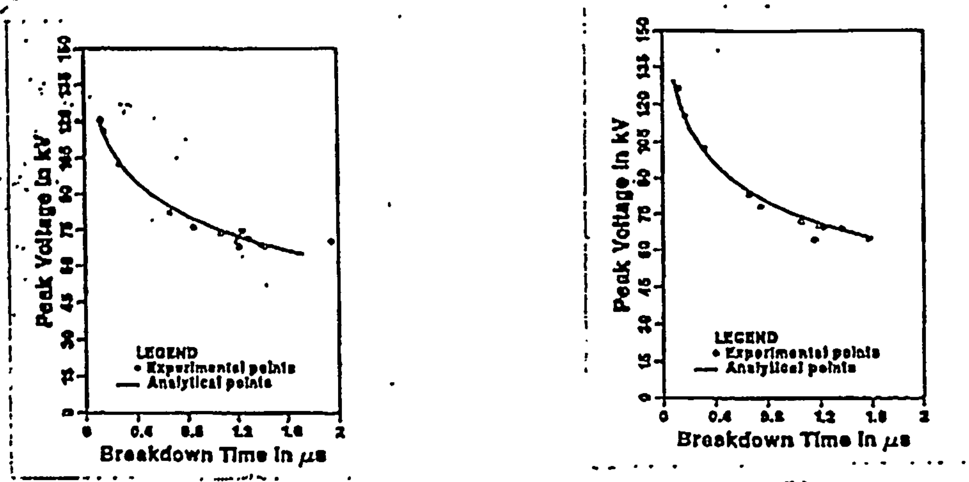
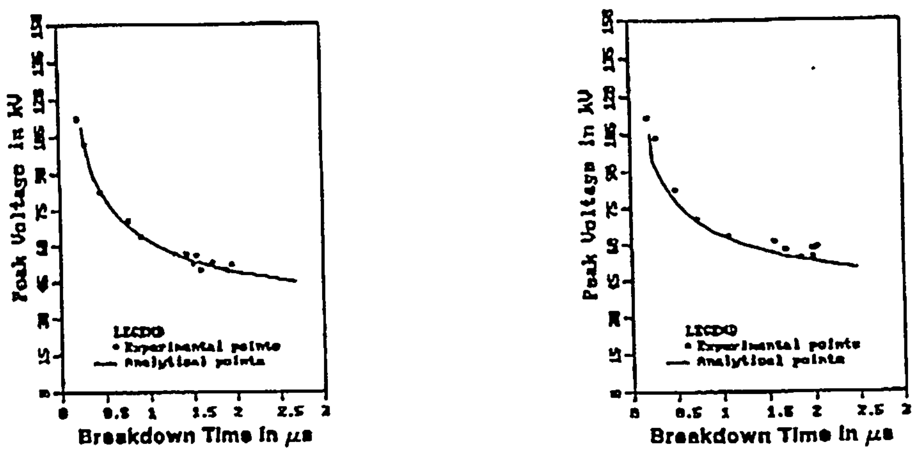


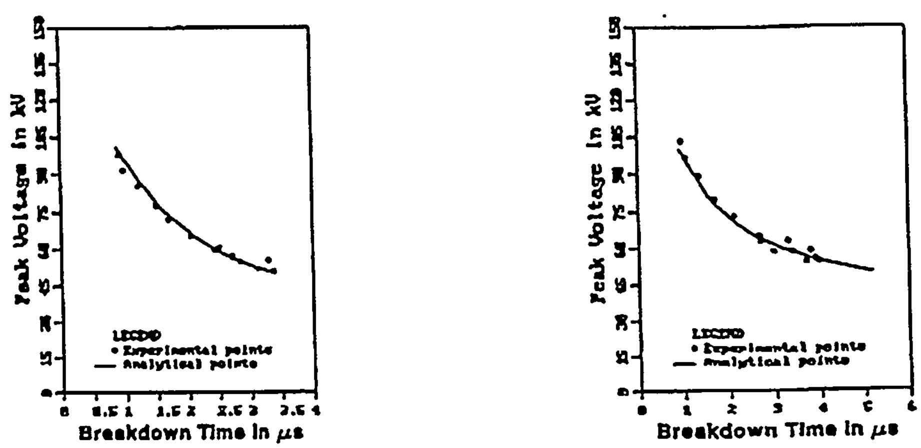
(a) (b)

Fig. 4 Volt-time characteristics of 5-cm rod-rod air gap under 0.025/25-µs impulse voltage. (a) positive polarity; (b) negative polarity



(a) (b)

Fig. 5 Volt-time characteristics of 5-cm rod-rod air gap under 0.12/25-µs impulse voltage. (a) positive polarity; (b) negative polarity



(a) (b)

Fig. 6 Volt-time characteristics of 5-cm rod-rod air gap under 1.2/50-µs impulse voltage. (a) positive polarity; (b) negative polarity