Conf-
CONF-920202--2
DE92 003530

THE EFFECTS OF NONSTANDARD LIGHTNING VOLTAGE WAVESHAPES ON THE IMPULSE STRENGTH OF AIR GAPS

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Abstract - Sphere-sphere, rod-rod and rod-plane air gaps, each 5-cm long, were tested with lightning surges of eight voltage waveshapes of both polarities. The critical breakdown voltage of the tested air gaps showed a minima at a certain voltage wavefront. Long time delays of breakdown for the fast-front and short time delays for the slow-front waves were observed. These phenomena would significantly affect the insulation coordination of the power apparatus and systems.

Key Words: air gaps, impulse strength, lightning

INTRODUCTION

Transient overvoltages caused by lightning are the most frequent causes of failure of electrical insulation and the subsequent damages and outages in electrical power systems. Insulation coordination is universally based on the impulse characteristics of dielectric systems determined with a standard waveshape of the transient voltage. This internationally agreed upon voltage waveshape is designated as the 1.2x50-μs wave, defining the time to crest as 1.2 μs and the time of the subsequent decay to half value of the crest as 50 μs.This specific waveshape has helped in standardizing insulation levels of power apparatus and systems. In practice, however, a dielectric system is stressed by transient voltages of wide varieties of waveshapes, caused by lightning as well as by switching. The rise (front) time of a lightning-caused transient voltage varies from submicrosecond regime to about 10 μs [1]. The rise time of a switching surge is generally believed to be several hundred microseconds. However, it is known that certain types of circuit breakers (e.g., SF_6 and vacuum) can generate switching surges with rise times in the nanosecond regime.

Considerable worldwide interest has been focused on the breakdown characteristics of long air gaps under the slow-rising (several hundred microseconds) switching surges. This is understandable; because the switching-surge breakdown voltage level of a long air gap under certain conditions can be dangerously close to the power-frequency operating voltage of an UHV power transmission line. However, the outages of the bulk of the transmission and distribution systems of lower voltage levels are caused by the lightning surges. In the earlier years of the electric power industry, the influence of the nonstandard lightning voltage waves was compensated by overdesign of the dielectric systems. As the demands for cost effectiveness and reliability of electric power are simultaneously rising, the design safety margins are diminishing, and the need to reliably predict the performance of a dielectric system under nonstandard lightning voltages is increasing.

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REVIEW OF PAST RESEARCH

In earlier research, sphere-sphere, rod-rod and rod-plane gaps, and insulator strings were tested under 1x5-, 1x50-, 1.5x40- and 1x580-μs voltage waves [2-6]. The earlier research showed that shorter wavetails would increase the breakdown voltage level of a given air gap.

Hagenguth generated front times of 0.5, 2.4 and 9.6 μs to study the breakdown characteristics of rod-rod gaps, sphere-sphere gaps, insulator strings, apparatus insulators and bushings [7]. He showed that longer front time of the voltage wave would significantly increase the breakdown voltage level (under both polarities) of a 20-inch rod-rod air gap. Unfortunately, Hagenguth did not state the time to half value of the test voltage waves.

Linck, on the other hand, observed that the sparkover voltage of a 20-inch rod-rod gap decreased on positive polarity and increased on negative polarity as the front time of the applied voltage wave was increased from 1 to 10 μs [8]. Kuffel and Abdullah reported an increase in the sparkover voltages of 10-30 cm rod-rod gaps on the positive polarity as the front time was increased from 2 to 17 μs, after which the sparkover voltage decreased. The results with the negative-polarity voltage, although more complicated, also showed an initial rise in the breakdown voltage and a later decline with increase in the front time of the applied voltage [9]. Allibone and Dring studied the breakdown voltages of rod-rod and rod-plane gaps by varying the front time of the applied voltage from 2 to 120 μs, keeping the wavetail constant at 1000 μs [10]. They observed that the sparkover voltage for different rod gaps changes in a complex manner; for small rod-rod gaps, the critical breakdown voltage, V_{50}, first rises and then falls as the front time of the applied voltage is increased; for larger gaps, and for the rod-plane gaps, V_{50} falls slightly and then rises. On negative polarity, Allibone and Dring found that there is very small initial fall in V_{50}; however, in general, it increases as the front time is increased.

From observation of glaze burns on insulators of high voltage transmission lines, and corroborated by laboratory tests, Miller concluded that many of the anomalous outages of the high voltage transmission lines were caused by lightning voltages of extremely steep fronts, which resulted in insulator flashovers in the submicrosecond regime [11]. Since then, the importance of very fast rise times of transient voltages has gained attention [12-24]. Such short front times of transient voltages can be caused by lightning as well as by certain types of switching surges.

Wiesinger tested rod-rod, rod-plane, rod-sphere and sphere-sphere air gaps in the range of 3 to 10 cm long with voltages of rise times from 5 ns to 2.7 μs, and time to half value of 550 μs [12]. He observed that the impulse withstand voltages of the sphere

gaps were insensitive to the front time and also to the polarity of the applied voltage wave. However, for the other gaps having nonuniform electric field, the impulse withstand voltages of positive polarity were lower than those of negative polarity; the negative-polarity withstand voltage increased with the front time, although the positive-polarity withstand voltages were insensitive to the front time.

Miller, et al., have used 60x300-ns positive-polarity voltage waves to perform tests on various power distribution components, such as cable potheads, insulators, lightning arresters and cables [22]. Grzybowski and Jacob generated a 65x5000-ns voltage wave to test distribution-class insulators, wood crossarms and combinations of insulators plus wood crossarms under dry and wet conditions with both positive and negative polarities [23].

EXPERIMENTS [25]

The goal of the present project was to compare in a consistent manner the critical breakdown voltage levels, V_{50}, of several types of short air gaps under lightning voltages of various waveshapes. In particular, three five-centimeter long air gaps were selected for the tests: 1. sphere-to-sphere gap; 2. rod-to-rod gap; and 3. rod-to plane gap. The spheres were of 25-cm diameter; the rods were 1.25-cm square, square-cut aluminum rods; and the plane was a 1-m square aluminum plate. All three gaps were vertically mounted. The test gaps were installed in direct line of ultraviolet radiation from the spark gaps of the impulse generator to minimize their statistical time lag of breakdown.

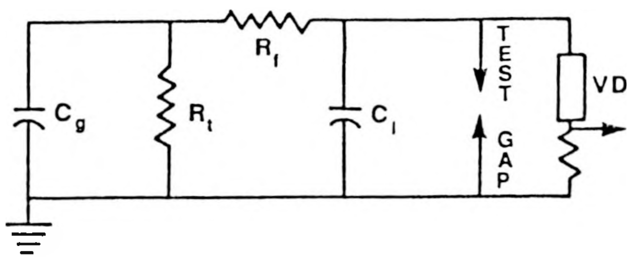
Eight voltage waves of both positive and negative polarities were selected. The wavefronts were varied from 25 ns to 10 μs, and the wavetails to half value were varied from 0.5 μs to 100 μs. The test program was statistically designed, based on the results of preliminary tests. The test series consisted of three replications. Tests with each type of air gap were performed consecutively in each replication, although the order of tests with each type of air gap was varied from one replication to the other. The order of tests with the eight waveshapes with each of the three test gaps was also varied in each replication. The eight voltage waveshapes were identified by a numeral, as shown in Table I.

Table I: Identification of Eight Impulse Voltage Waveshapes

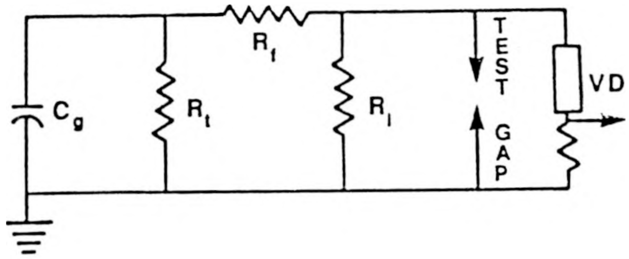
Front/Tail	500 ns	25 μs	50 μs	100 μs
25 ns	1	2		
0.12 μs		3	4	
1.2 μs		5	6	
10 μs			7	8

Generation of Impulse Voltages

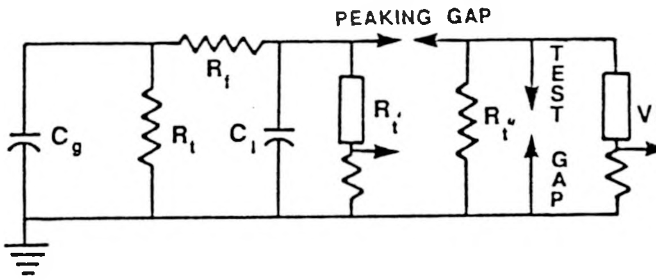
The various impulse voltages were generated by a four-stage, 400-kV impulse (Marx) generator. The 1.2- and 10-μs front voltage waves were produced by the usual front (R_f) and tail (R_t) resistors and a 5-nF preload capacitor, C_l (Fig.1a). C_l was replaced by a 7.5-kΩ resistor, R_l, to generate the 0.12-μs front voltage waves (Fig.1b). A peaking gap of adjustable length was connected between the output of the impulse generator and the test gap to generate the 25-ns front waves (Fig.1c). A 50-Ω auxiliary tail resistor, R_t'', was connected between the load-end (test gap) of the peaking gap and ground to generate the short tail of the 25x500-ns voltage wave.



(a) circuit for wave nos.5-8



(b) circuit for wave nos.3,4



(c) circuit for wave nos.1,2

Fig.1 Schematics for the generation of impulse voltage waves. C_g=impulse generator capacitor; R_f=front resistor; R_t=tail resistor; C_l=preload capacitor; VD=voltage divider; R_l=load resistor; R_t'=auxiliary voltage divider; R_t''=auxiliary tail resistor.

A needle-type peaking gap was found to be suitable for generating the desired 25-ns front time.The instant of breakdown of the peaking gap determines the peak of the output voltage. Deviations in the breakdown of the peaking gap would result in fluctuations in the output voltage for the same charging voltage of the impulse generator. For minimum fluctuations in the output voltage, the peaking gap should be set such that it breaks down after the peak of the voltage generated by the impulse generator. The tail of the generated voltage should also be long to minimize the effects of the time lag of breakdown of the peaking gap on the output voltage. Therefore, it is advantageous to keep R_t as high as possible, and adjust the wavetail of the output voltage by R_t''. A mercury-vapor lamp was used to illuminate the peaking gap to minimize the fluctuations in its breakdown level. The peaking gap was adjusted so that it would fire after the peak of the generated voltage at the flat part on the wavetail. The firing of the peaking gap was monitored by a 800-Ω liquid resistor voltage divider, R_t', connected at the generator side of the peaking gap. The upper curve of Fig.2 shows the 25x500-ns voltage wave across the test gap; the lower curve shows the voltage across R_t', where the instant of breakdown of the peaking gap is encircled.

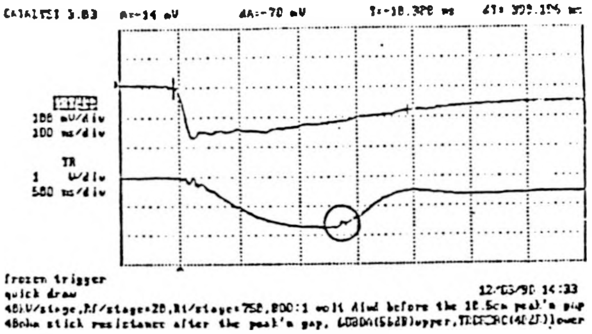


Fig.2 25x500-ns negative-polarity test voltage wave.
upper curve: voltage across test gap
100 mV/div; 100 ns/div
voltage attenuation factor=6.31×10^5
lower curve: voltage across R_t'
1 V/div; 500 ns/div
voltage attenuation factor=8×10^4

Note: instant of breakdown of peaking gap encircled

Measurement of Impulse Voltages

The voltage across the test air gap had to be reduced by almost one million to one for input to the digital data acquisition system which can handle only ± 250 mV. For the measurement of the 1.2- and 10-μs front voltage waves, a high-voltage 7.5-kΩ resistive voltage divider was connected across the test gap. The step response of this divider was 100 ns. The signal across the low-voltage arm of the divider was further attenuated by a specially built 20-dB, 50-Ω attenuator (step response (5 ns) before transmitting it via a coaxial cable to the data acquisition system. The signal was further attenuated at the receiving end of the coaxial cable by several low-voltage 1-GHz attenuators before inputting to the digitizer. Ground currents through the sheath of the coaxial cable was suppressed by a ferrite-cored toroid which was connected between the receiving end of the coaxial cable and the low-voltage attenuators.

A 1000:1, 1-kΩ voltage divider was built with liquid resistor as the high-voltage arm of the divider for the measurement of the 0.12-μs and the 25-ns front voltage waves. It was made up of copper sulfate solution in deionized distilled water, contained in a 6.35-cm diameter 65-cm long plexiglas tube. Its two electrodes were made of type 316L stainless steel to minimize corrosion. The position of the upper electrode was adjustable for accurate calibration of the resistance. The one-ohm low-voltage arm of the divider was made up of ten 10-Ω carbon resistors connected in parallel in a sunburst pattern to minimize inductance, and encased in a copper cup to suppress electromagnetic interference. The step response of this voltage divider was less than 5 ns.

The digital data acquisition system included a LeCroy Century Series 2000 waveform recorder, monitor, an IBM proprinter and a Hewlett-Packard Vectra personal computer. The waveform recorder, in turn, consisted of two 400-MHz digitizers, LeCroy type 6880A, and one 100-MHz digitizer, LeCroy type TR8828C. The data acquisition system also contained a signal-processing software package ASYST. The software package, Statistical Analysis of Systems (SAS) installed in the VAX computers of the university was used for statistical analysis of the data.

Experimental Procedures

The critical sparkover voltage, V_{50}, for a test gap under a given test voltage wave was determined by the multiple-level method [26]. For a particular test setup, the charging voltage level of the impulse generator was selected on the basis of the previous preliminary tests, which would produce less than 100 percent sparkover of the test gap when it was subjected to 10 applications of the voltage at the same charging voltage level. If this level of the charging voltage produced more than 50 percent sparkover for the 10 shots, then the charging voltage was reduced by 1 kV and the procedure was repeated until a charging voltage was reached where the sparkover was less than 50 percent. V_{50} was then estimated from statistical analysis.

The temperature, atmospheric pressure and the relative humidity were measured before, after and during the tests. When the liquid-resistor voltage divider was used, its resistance was checked before and after each set of experiments. The breakdown voltages were corrected for 20°C temperature and 760 mmHg of pressure. No corrections were made for the humidity.

Analysis of Experimental Data

Assuming the breakdown voltage of an air gap to follow a Gaussian (normal) probability distribution, the standardized cumulative distribution function, $\Phi(u)$ is defined as [27]

$$\phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{\frac{-u^2}{2}} du, \qquad (1)$$

$$u = \frac{x - \mu}{\sigma}, \qquad (2)$$

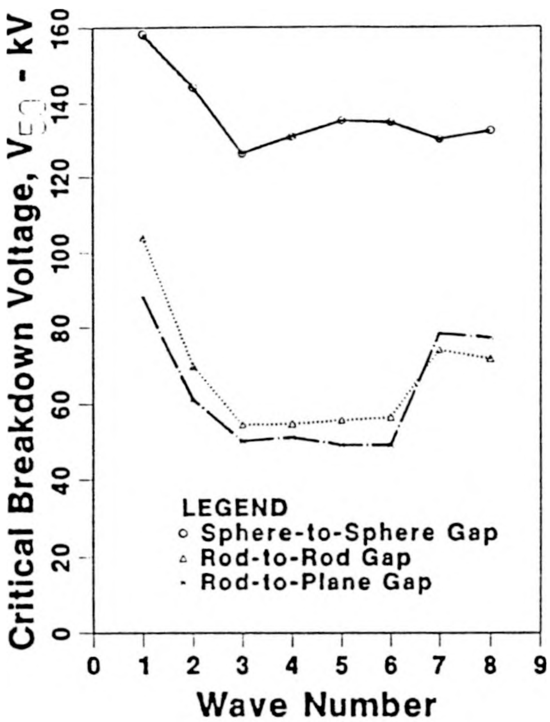
where, x = variable, and μ, σ = mean and standard deviation of the variable.

The quantities to be determined are μ (=V_{50}) and σ. x (=V_p) is the breakdown voltage of the test gap with the probability of breakdown p. If V_{p1} and V_{p2} are experimentally determined at two p's, e.g., V_{40} and V_{60}, then u_{p1} and u_{p2} can be found from the statistical tables for the given p1 and p2. V_{50} and σ can be found from eq.(2) with two unknowns and two equations. V_{50} as a function of the wave number (Table I) is shown in Fig.3. V_{50} from each test configuration, averaged over the three replications, are shown in Table II.

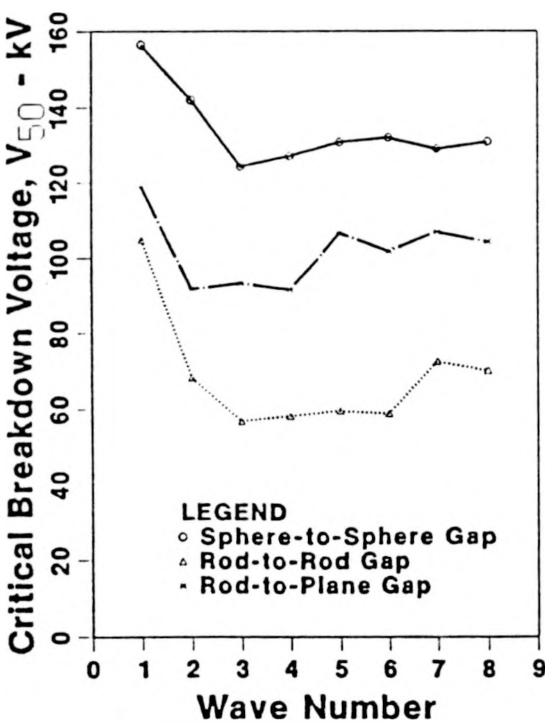
DISCUSSION

Influence of Wavefront

It is evident from Fig.3 and Table II that the breakdown voltage at first decreases with increasing wavefront until a critical wavefront is reached before rising with the increase of the wavefront. The breakdown voltages of all three test gaps are the lowest under the 0.12-μs front voltage wave. This is more pronounced with the air gaps with nonuniform electric fields, i.e., rod-rod and rod-plane gaps. This observation appears to contradict the conclusions made by Hagenguth [7] and Wiesinger [12]. However, Hagenguth's shortest wavefront was 0.5 μs. In our case, V_{50} also rises with increasing wavefront after it has reached its minima at 0.12 μs. Wiesinger's shortest and longest wavefronts were 5 ns and 2.7 μs. It is not known how many wavefronts were used between these two limits. Moreover, the bandwidth of Wiesinger's measurement system was only 60 MHz, which may have caused some errors in the nanoseconds regime. The short wavetail of the 25x500-ns wave (wave no.1) must also have contributed significantly to the higher breakdown voltage. However, there is a distinct minima in the breakdown voltage at a critical wavefront.



(a) positive polarity



(b) negative polarity

Fig.3 Critical breakdown voltage vs. wave number (Table I).

Table II: Critical Breakdown Voltage, V_{50}, in kV
Corrected for Temperature and Pressure at 20°C and 760 mmHg
Not Corrected for Humidity
Gap Length = 5.0 cm

Waveshape		Sphere-Sphere[1)]	Rod-Rod[2)]	Rod-Plane[3)]
0.025x0.5-μs	+	158.3	104.2	88.3
	-	156.5	104.9	119.0
0.025x25-μs	+	144.4	70.0	61.3
	-	142.1	68.4	92.0
0.12x25-μs	+	126.5	54.6	50.3
	-	124.5	56.9	93.4
0.12x50-μs	+	131.0	54.8	51.2
	-	127.3	58.3	91.7
1.2x25-μs	+	135.4	55.8	49.3
	-	131.0	59.7	106.7
1.2x50-μs	+	135.0	56.6	49.2
	-	132.2	59.0	101.9
10x50-μs	+	130.3	74.2	78.4
	-	129.2	72.5	107.0
10x100-μs	+	132.6	72.0	77.5
	-	131.1	70.2	104.3

1) sphere diameter = 25 cm
2) 0.5-inch square aluminum rods square cut
3) 0.5-inch square aluminum rod square cut, and 1x1 m^2 aluminum plate

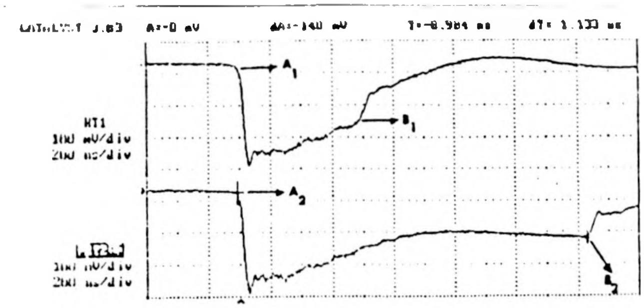
The occurrence of the minima in the breakdown voltage across a long air gap under slow-front switching surges has been reported before [28]. It is well known that the space charges associated with impulse corona play a significant role in the breakdown of air gaps with nonuniform electric field. Positive ions shroud the positive rod electrode, these ions moving relatively slowly towards the cathode. The ion density grows as the voltage rises. At the same time, some ions drift away from the electrode space, thus tending to decrease the ion density. If the net ion density grows, then a channel (or leader) develops from the positive electrode at a critical ion density, moving towards the cathode. The voltage gradient of the leader being very small, the leader virtually extends the positive electrode into the interelectrode space, increasing the elctric field in this space further, and facilitating breakdown of the air gap. If the wavefront is short, then the voltage may attain relatively high value before the critical space charge density develops; in that case, the breakdown voltage will be high. As the rate of rise of the voltage decreases (i.e., longer wavefront), the space charge density increases at a faster rate. Therefore, the breakdown voltage of the air gap will decrease as the wavefront increases. However, if the wavefront is slow enough that some of the ions drift away from the interelectrode space, then higher voltage will be required to break down the air gap. The critical wavefront at which the breakdown voltage is minimum will depend upon the gap length. If the critical wavefront is several hundred microseconds for an air gap of several meters, then the crtical wavefront for a gap of a few centimeters might be in the submicrosecond regime.

Time Lag of Breakdown

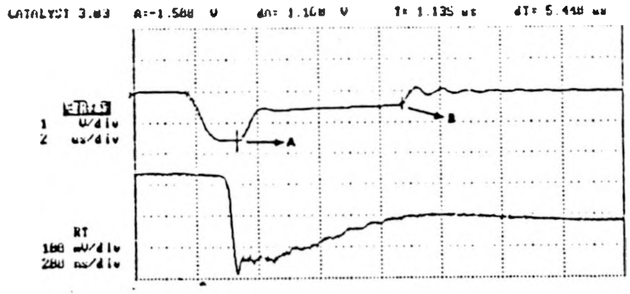
Several interesting phenomena were observed in the time lag of breakdown of the rod-rod and rod-plane air gaps. These phenomena were observed only under the 25x500-ns-front and the two 10-μs-front voltage waves.

The time lag of breakdown of the rod-rod gap under the 25x500-ns voltage wave was occasionally beyond the time range (10 k sample points) of the 400-MHz LeCroy 6880A digitizer. An example is shown in Fig.4, where voltage was applied to the rod-rod gap three times at the same charging voltage level of the impulse generator. In Fig.4a (upper curve), once the gap broke down at B_1, which is about 0.3 μs after the application of the voltage (point A_1), while the gap broke down at B_2 (lower curve), which is 1.13 μs after the application of the voltage at A_2 during another application of the voltage. During yet another application of the voltage (Fig.4b), the gap broke down 5.44 μs (point B of the upper curve) after the application of the voltage at point A. This time period was beyond the range of the 6880A digitizer (lower curve). The upper curve is the output voltage of the impulse generator before the peaking gap (Fig.1c), simultaneously recorded with the TR8828C digitizer. This phenomenon has been observed only with the rod-rod gap. It should be observed in Fig.4 that the tail of the applied voltage has two slopes; after the rapid fall on the first part of the tail, the voltage rises slightly before declining at a much slower rate.

The rod-rod and the rod-plane gaps frequently broke down on the wavefront under the two 10-μs-front voltage waves. Figure 5 shows three shots during a 10-shot series of tests, where the rod-rod gap broke down once at 36.7 μs on the wavetail (upper curve), it withstood a second shot (middle curve), but broke down during a third shot on the wavefront at about 5 μs (lower curve) at a much lower voltage level than its previous withstand level, all at the same charging voltage level of the impulse generator. In the measurement of the breakdown voltage level, the highest point of the voltage wave is taken as the breakdown level [26]. If breakdown occurs on the tail of the voltage wave, then the peak (not the voltage at the instant of breakdown) of the voltage wave is taken as the breakdown level; if breakdown occurs on the wavefront, the voltage at the instant of breakdown is taken as the breakdown level. If this rule is followed for the 10-μs-front voltage waves, then the 60 percent breakdown level (for example) could be



(a)



(b)

Fig.4 Breakdown of rod-rod gap with 25x500-ns voltage wave.
(a) 100 mV/div; 200 ns/div
voltage attenuation factor=3.16×10^5
(b) upper curve: 1 V/div; 2 μs/div
voltage attenuation factor=8×10^4
lower curve: 100 mV/div; 200 ns/div
voltage attenuation factor=3.16×10^5

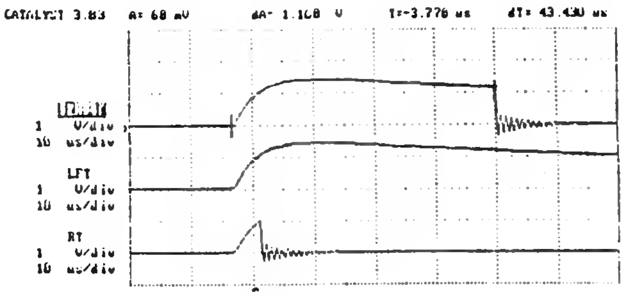


Fig.5 Breakdown of rod-rod gap with 10x100-μs voltage wave.
1 V/div; 10 μs/div
voltage attenuation factor=5.12×10^4

lower than the 40 percent level. The 'prospective' peak was taken as the breakdown level for the 10-μs-front voltage waves to avoid the problem of dealing with lower breakdown voltage level at higher percent breakdown. This is also the practice in the switching surge tests.

Although the breakdown of air gaps on the front of voltage waves have been reported in the literature [10,29-31], the exact mechanism of such phenomenon is not known. In explaining large scatter in the breakdown voltage levels of air gaps, Feser has shown that two different types of predischarges may occur across an air gap at the same voltage level but in two separate applications [32]. These are streamer corona and leader corona. Lower breakdown voltage level will occur under a leader corona, whereas the streamer corona will produce a higher level of breakdown level. Such statistical scatter in the breakdown voltage due to two predischarge phenomena would also result in a scatter in the breakdown time lag. Although Feser's observation was directed to switching surge flashovers for long air gaps, it may still apply to small air gaps under lightning surges.

The breakdown of the sphere-sphere gap under the 10-μs-front waves always occurred near the peak of the voltage wave. Breakdown of the rod-plane gap occurred on the wavetail of the 10-μs-front waves only with the negative-polarity voltage.

CONCLUSIONS

The critical breakdown voltage level attains a minima at a specific wavefront of the lightning surges, at least for the gap types and the gap length used in this study. The long breakdown time lag for fast-front waves and the breakdown on the front of slow-front waves need further study. The minima in the critical breakdown voltage and the time lag of breakdown for the nonstandard voltage waves should be taken into consideration in the insulation coordination of power apparatus and systems.

ACKNOWLEDGMENT

This project was sponsored by the Office of Energy Management of the U.S. Department of Energy (DOE) under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. through the Power Systems Technology Program of the Oak Ridge National Laboratory. It was also co-sponsored by the Center for Electric Power at the Tennessee Technological University. The statistical design of experiments was performed by R.L. Schmoyer, Oak Ridge National Laboratory.

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