INVESTIGATION INTO THE DISTRIBUTION OF TIME-TO-BREAKDOWN VALUES FOR A RANGE OF ROD-ROD GAP SIZES UNDER IMPULSE CONDITIONS

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Abstract: Voltage-time curves show the relationship between the average time-to-breakdown and the peak voltage of an impulse. A previous investigation revealed that the time-to-breakdown distributions for a rod-rod geometry were unevenly distributed and the average of the distribution does not truly reflect the time-to-breakdown. In this paper, the relationship between the distribution of time-to-breakdown values and peak impulse voltage is investigated for a range of gap geometries. It is seen that, for larger gap geometries, the time-to-breakdown distributions are evenly distributed and the relationship to voltage is as expected. As the gap size decreases, however, the time-to-breakdown distributions are seen to become increasingly less predictable for the peak voltage of the applied impulse.

1 INTRODUCTION

The process of electrical breakdown in an air gap due to an overvoltage is not always a predictable event. The time it takes when breakdown does occur is also unpredictable. It has, however, been shown that the peak voltage of an applied impulse and the time-to-breakdown have an inverse relationship – the greater the peak voltage, the quicker it takes for breakdown to occur [1].

Voltage-time curves are often used to show the relationship between the time-to-breakdown and the voltage for specific gap geometries [1, 2]. These curves show how the average of the time-to-breakdown values changes as the peak of the impulse voltage increases.

In a previous investigation, it was seen that the time-to-breakdown values obtained from a rod-rod gap geometry were not always predictable [5]. Consequently, plotting the average of the time-to-breakdown results against voltage would not provide an accurate description of the relationship.

The aim of this paper is to investigate the distribution of time-to-breakdown values against peak voltage for a range of rod-rod gap sizes.

2 BACKGROUND

2.1 Time-to-breakdown under impulse conditions

The time-to-breakdown associated with the breakdown process has been well investigated under many different conditions. While the overall event time can be described by the sum of the times for the many different mechanisms involved in the breakdown process, under impulse conditions it is often simplified to the sum of two time delays – the statistical time delay and the formative time delay as given by equation (1).

$$T_{TOTAL} = T_S + T_F \qquad (1)$$

The statistical time delay describes the time taken for a seed electron to become available and begin the discharge process. The formative time delay describes the time it takes for breakdown mechanism to occur once it has been initiated [3, 4]. In this way, the unpredictable nature of breakdown under impulse conditions is described.

2.2 Previous Investigation

A previous investigation into the relationship between the time-to-breakdown and the applied peak impulse voltage under impulse conditions revealed that the distribution of time-to-breakdown values for a rod-rod geometry did not follow an even distribution [5].

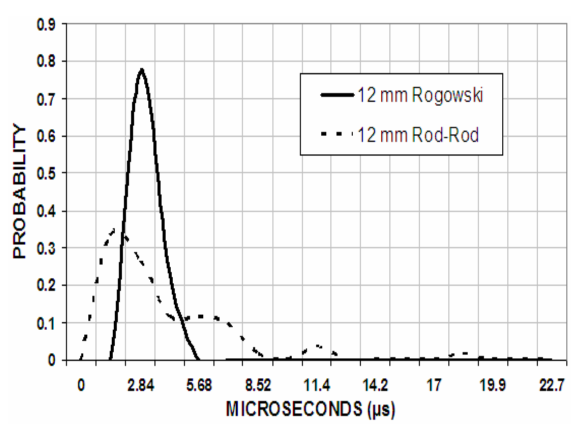

Figure 2: Distributions of time-to-breakdown for 12 mm gaps at mean probability of breakdown [5].

The investigation was performed on two different gap geometries – Rogowski profile geometry and a rod-rod geometry both at a gap size of 12 mm. The Rogowski profile was used to simulate uniform electric field conditions while the rod-rod geometry provided a non-uniform electric field.

Figure 2 shows the distribution of time-to-breakdown values for both the 12 mm Rogowski profile as well as the 12 mm rod-rod geometry. The time-to-breakdown values are fairly evenly distributed for the uniform geometry while the time-to-breakdown results on the rod-rod gap geometry have a range from 2 µs to 20 µs.

This observation was attributed to the difference in the uniformity of the electric field given that this is the major difference between the two geometries. However, the investigation was only performed at gap sizes of 12 mm and it was not seen whether this same observation could be made for larger gaps.

3 EXPERIMENTAL SETUP

Figure 3 shows the Marx generator circuit used to apply lightning impulses to a rod-rod geometry.

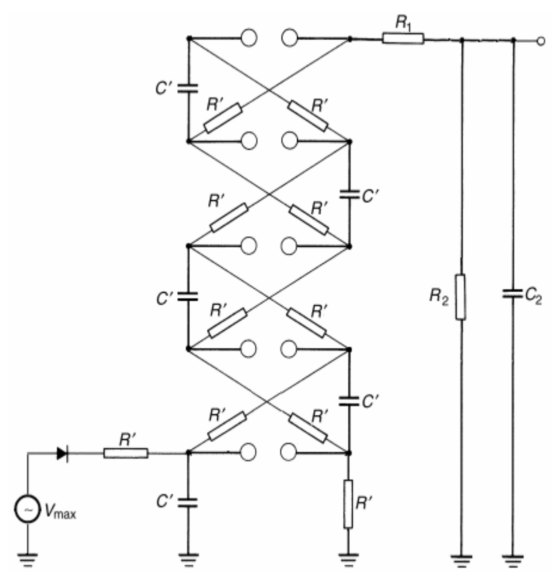

Figure 3: Multistage Marx Generator circuit used in the experiment. Adapted from Kuffel et al. [3].

The generator is powered by a 230:140 kV transformer with a supply of 230 V at 50 Hz. The supply is then rectified and charges the first stage of the generator.

The magnitude of the peak voltage is controlled by the size of the first stage gap – this determines at what voltage the generator will fire and, consequently, the peak voltage of the impulse. Resistors R_1 and R_2, along with capacitor C_2 control the rise and fall time of the impulse waveform.

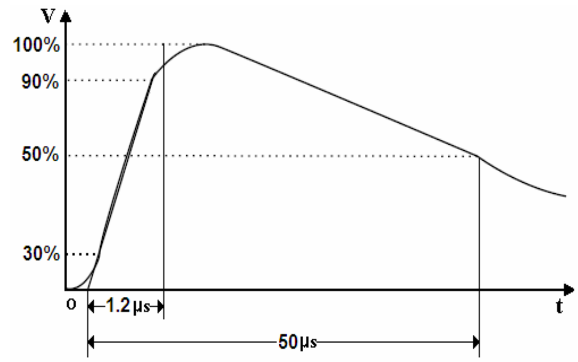

Figure 4: Illustration of a 1.2/50 µs lightning impulse waveform as defined in the IEC60060-1: *High Voltage Test Techniques* [6].

These waveforms are such that the standard 1.2/50 µs lightning impulse as defined in the IEC60060-1 *High Voltage Test Techniques* standard is applied to the test gap. Figure 4 shows this waveform [6].

This voltage is applied to the test gap in order to cause breakdown and measure the time it takes for this to occur. A Tektronix® TDS 320 oscilloscope is used to view the voltage waveform occurring across the gap geometry. To step down the voltage so that it may be measured on the scope, a resistive divider with a ratio of 150355:1 was used.

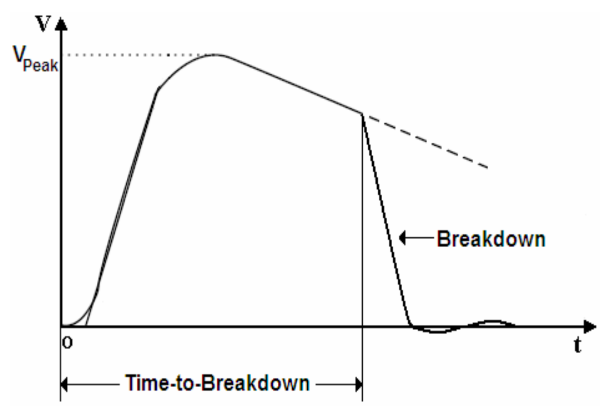

Figure 5: Illustration of voltage waveform when breakdown across the gap occurs.

If an impulse is applied to the gap, and the gap withstands, then the waveform shown in figure 4 is viewed on the oscilloscope. However, if breakdown occurs across the gap, the tail of the impulse will suddenly drop to ground potential as shown in figure 5.

The time-to-breakdown measurement for the following experiments is performed as shown in the figure. It is defined, for the purposes of this work, as the difference in time between the initial application of the impulse and the time at which the breakdown event begins.

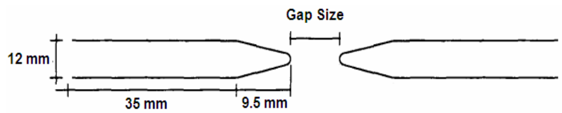

Figure 6: Dimensions of rod-rod gap geometry.

Figure 6 shows a diagram of the rod-rod gap geometry and the dimensions of the rods. The rods are both 12 mm in diameter and 35 mm in length. The ends of both the rods are tapered to a spherical point. The distance between the rods is adjusted for the different ranges of gap lengths that are investigated.

4 EXPERIMENTAL METHOD

The behaviour of the time-to-breakdown of the rod-rod gap geometry was investigated by applying high voltage lightning impulses to varying gap distances for comparison with the original time-to-breakdown results obtained on the 12 mm rod-rod gap geometry. Gap sizes of 75 mm, 100 mm, 125 mm and 150 mm were investigated. For each gap distance, a range of peak impulse voltages were applied to the gap. Each of these impulse voltages correspond to a probability of breakdown for the given gap size. A total of 30 shots were performed at each specified peak impulse voltage which allowed the probability of breakdown for that voltage (given the gap size) to be calculated. Probability of breakdown at a given voltage is determined by the number of breakdowns that occurred as a percentage of the total number of shots applied at that voltage.

For peak voltages yielding high probabilities of breakdown, almost all of the 30 shots applied will result in a breakdown, providing a time-to-breakdown result. If breakdown does not occur, and the gap geometry withstands the impulse, no time-to-breakdown data is obtained. For low probabilities of breakdown, the majority of the 30 applied impulses will not breakdown and the amount of time-to-breakdown results for low probabilities of breakdown will be less than 30 values.

5 EXPERIMENTAL RESULTS

Figure 7 shows the peak voltage against time plots for each of the different rod-rod gap sizes. Unlike voltage-time curves, the time-to-breakdown values are not shown as an average but rather as a distribution. Since time-to-breakdown values are obtained over a range of breakdown probabilities, the behaviour of distribution of time-to-breakdown values over a range of breakdown probabilities is observed.

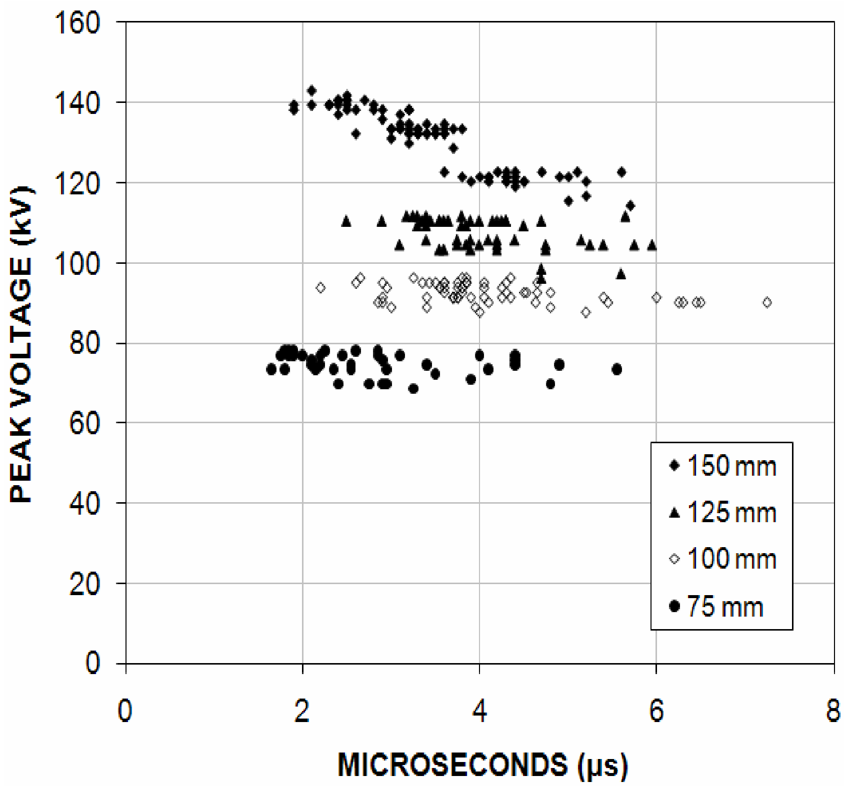

Figure 7: Peak Impulse Voltage (kV) against Time-to-Breakdown (μs) values for four gap sizes.

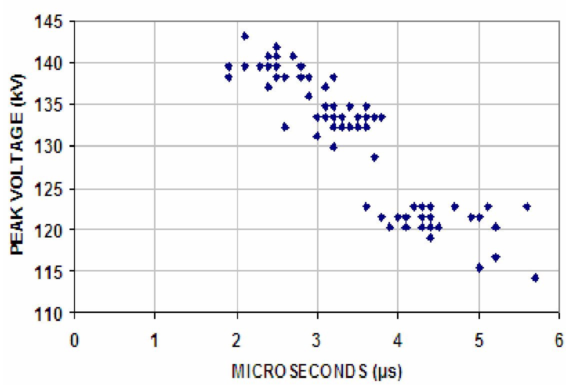

Figure 8: Peak Impulse Voltage (kV) against Time-to-Breakdown (µs) for 150 mm Rod-Rod gap geometry.

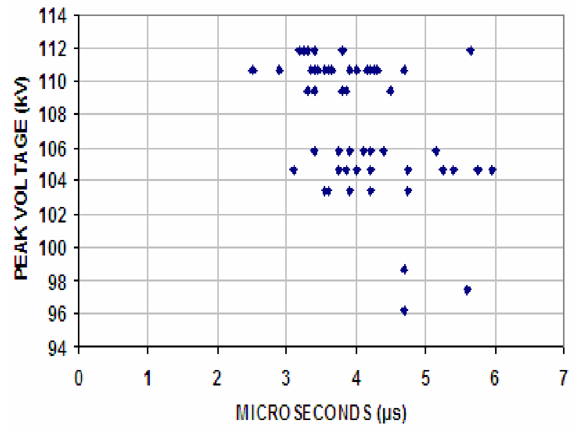

Figure 9: Peak Impulse Voltage (kV) against Time-to-Breakdown (µs) for 125 mm Rod-Rod gap geometry.

In all cases, it is seen that the time-to-breakdown values range between approximately 2 and 7 µs. However, it is noted that, for a gap size of 150 mm, the peak voltage greatly influences the distribution of these time-to-breakdown values and is quite predictable. Peak voltages yielding high probabilities of breakdown tend to cause breakdown within 2 to 3 µs. Peak voltages around the 50% breakdown voltage seem to cause breakdown within 3 to 4 µs. For lower voltages, breakdown occurs within approximately 5 to 6 µs. It is clear that the greater the voltage peak and the greater the probability of breakdown, the quicker it will take for breakdown to occur.

Figure 8 shows the distribution of time-to-breakdown values for a range of peak impulse voltages on a rod-rod gap of 150 mm gap distance. The voltage peaks range from 113 to 143 kV and encompass breakdown probabilities of approximately 10% to 100%. The relationship between peak voltage and time-to-breakdown is also fairly distinguishable with the time-to-breakdown clearly increasing as the peak voltage increases. The time-to-breakdown values range from 1.9 to 5.7 µs.

Figure 9 shows the same relationship but for a gap distance of 125 mm. The range of voltages is lower than those for the 150 mm gap. This is to be expected if the same range of breakdown probabilities (10% to 100%) is to be obtained for the smaller gap size.

The time-to-breakdown values are within the same range (2 µs to 5.9 µs) but the relationship between peak voltage and time-to-breakdown is not as distinct as in figure 8. While lower voltages lead to larger time-to-breakdown values, the range of time-to-breakdown values occurring at higher voltages is greater than that of the previous case. In the voltage range of 110 to 112 kV, time-to-breakdown values of 2.3 to 5.7 µs occur. The distribution of time-to-breakdown values for the 125 mm gap distance has become less evenly distributed and, consequently, less predictable.

This observation continues in figure 10 which once again shows the same relationship but for a gap size of 100 mm. The voltage ranges from 87 to 97 kV due to the smaller gap sizes and once again a range of 10% to 100% breakdown probabilities are observed.

As with figure 9 the relationship between the distribution of time-to-breakdowns and the peak impulse voltage is not as defined as it is at a gap size of 150 mm. It seems that, even at lower peak voltages, time-to-breakdown may occur within a range of 2 to 4 µs, whereas, in figure 7, the peak voltage had to be in the high probability of breakdown range for breakdown to occur in 2 µs.

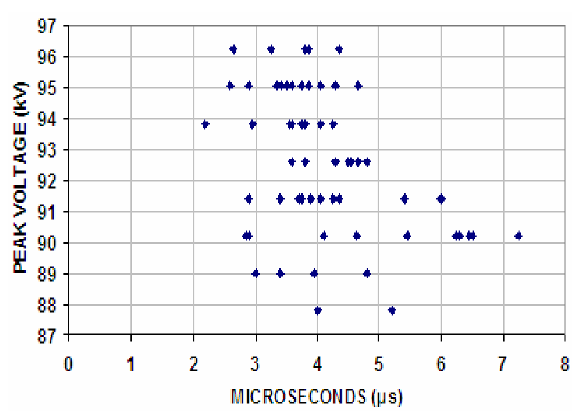

Figure 10: Peak Impulse Voltage (kV) against Time-to-Breakdown (µs) for 100 mm Rod-Rod gap geometry.

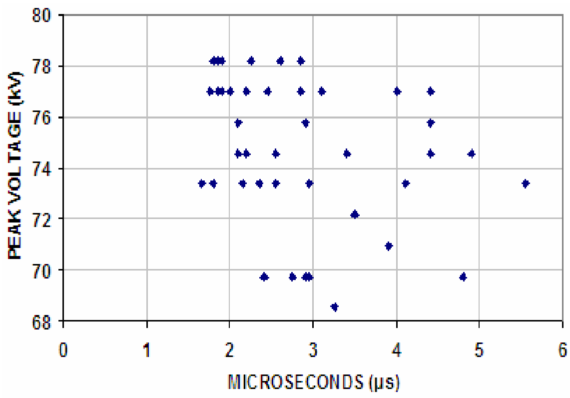

Figure 11: Peak Impulse Voltage (kV) against Time-to-Breakdown (µs) for 75 mm Rod-Rod gap geometry.

Finally, figure 11 shows the same relationship for a gap size of 75 mm. The voltage range of 68 to 79 kV covers the required probability of breakdown range for this gap size and, as with the previous figure, the distribution of times for differing probabilities of breakdown is becoming less and less predictable

6 DISCUSSION

Figure 12 shows the time-to-breakdown probability distributions for all the gap sizes including the 12 mm gap geometry from the experiments. The time-to-breakdown values included are those that were obtained at peak impulse voltages for mean probabilities of breakdown.

The distributions are obtained by categorizing all the time-to-breakdown results into histogram bin sizes of 0.4 µs. The probability is then calculated by dividing the number in each bin by the total number of time-to-breakdown values in the distribution.

Table 1 shows the statistical characteristics of the distributions show in figure 12. The average value (mean) of the distributions can be seen to increase as the gap size increases except in the case of the 150 mm gap which is less than that of the 125 mm gap. A more meaningful parameter is the mode of the distribution (the time-to-breakdown that occurs the most) which can also be seen to increase as the gap size increases. Once again, this is not the case for the 150 mm gap.

Table 1: Statistical characteristics of distributions shown in figure 11.

Gap Size (mm)	Mean (µs)	Median (µs)	Mode (µs)	St. Dev. (µs)	Max. (µs)	Min. (µs)
12	2.86	2.05	0.95	2.186	10.4	0.8
75	2.59	2.25	2.85	0.86	4.4	1.75
100	3.6	3.675	3.8	0.55	4.65	2.2
125	3.762	3.625	3.4	0.61	5.65	2.5
150	3.313	3.3	3.2	0.268	3.8	2.6

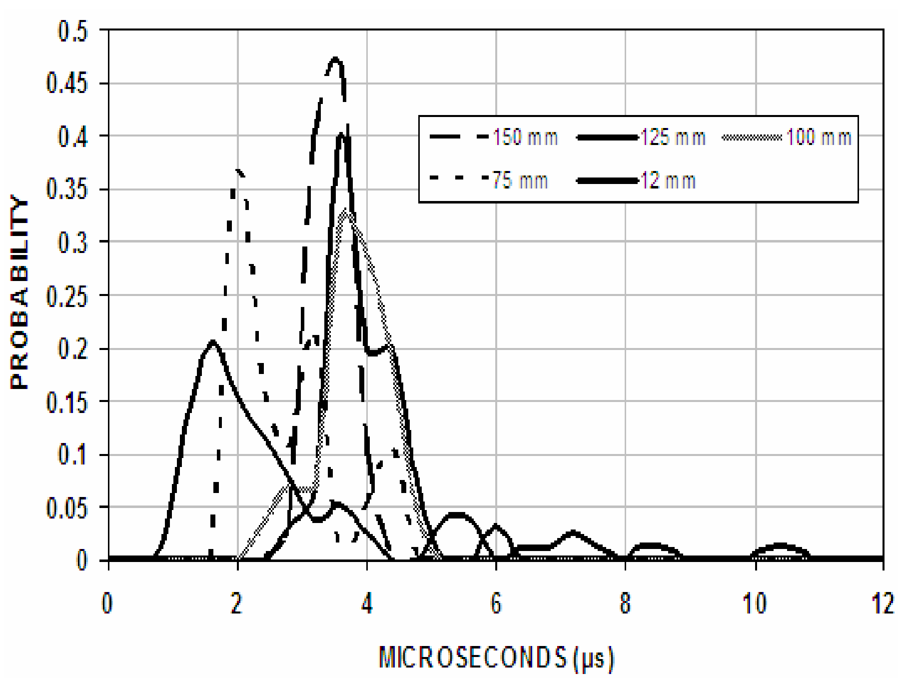

Figure 12: Distribution of time-to-breakdown results for all gap sizes including 12 mm gap results

The standard deviation of a distribution can be taken as an indication of how evenly distributed the values are. It shows how much variation there is from the mean of the distribution. The standard deviation for the 12 mm gap is 2.186 µs which is more than an order of magnitude larger than that of the other gaps. This can be seen in figure 11 where the distribution for the 12 mm gap covers a wide range of times.

The standard deviation is lower for the 75 mm gap and decreases more still for the 100 mm gap. It increases for the 125 mm gap but then decreases again to the lowest value for the 150 mm gap. Overall, the larger gap sizes have smaller standard deviations indicating that their time-to-breakdown distributions are less varied and more evenly distributed. This was seen in Section 4 by looking at the distribution of time-to-breakdowns against voltage.

7 CONCLUSION

For a gap size of 150 mm, the distribution of time-to-breakdown values is evenly distributed and the relationship between the time-to-breakdown and the peak voltage of the applied impulses is as expected. As the gap size decreases, however, the distribution of the time-to-breakdown values become increasingly less even. This is indicated by the standard deviation of the distributions increasing for a decrease in gap sizes. Consequently, the relationship between peak voltage and time-to-breakdown becomes less predictable since it is not known with confidence what the time-to-breakdown will be for an applied peak impulse voltage.

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