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Effect of the Non-Standard Lightning Current and Waveshape on Lightning Surge Analysis

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Abstract: The withstand capability of the insulation system of an equipment under lightning overvoltages is measured by the international standard 1.2/50 μs waveform. Many workers and designers of the power apparatus equipment have dedicated their research tried to understand how the insulation behaves under the non-standard waveform. The fact that the lightning-caused transient voltage can have very fast components and the need for higher reliability and cost effectiveness have added the impetus in recent years to better understand the effects of a non-standard lightning voltage on the power system. As far as the lightning is concerned, much attention has been paid to the breakdown occurring at extremely fast rise times, which could be in nanosecond regime. This research provides some reviews on the non-standard waveform of the lightning and focuses on the simulation of the effect of the non-standard lightning current and waveshape on lightning surge analysis using the PSCAD/EMTDC software.

Key words: Insulation coordination, non-standard lightning, backflashover, PSCAD/EMTDC, volt-time

INTRODUCTION

The international standard 1.2/50 μs voltage wave has helped designers and application engineers to test, specify and evaluate power apparatus and protective equipment with a high degree of reliability and cost effectiveness (IEEE Task Force 15.09, 1994a; IEEE Task Force 15.09, 1994b). However, a lightning caused transient voltage seldom has a standard waveshape and therefore, a better understanding of insulation system behaviour under non-standard lightning voltages is needed (CIGRE, 1991). According to IEEE Std. 1243-1993 (IEEE Power Engineering Society, 1997), non-linear effects such as corona, soil ionisation, tower surge response and reflection from adjacent towers, tend to distort the surge voltages from the standard impulse waveshape. The partial chopping that occurs when reflections return from adjacent towers is also particularly important.

BREAKDOWN CHARACTERISTICS OF AIR GAPS

Since the first report, as recorded by (IEEE Task Force 15.09, 1994b), on impulse flashover voltages under non-standard lightning was published in 1934, it has been thoroughly investigated for various gap configurations and waveforms. According to IEEE Task Force 15.09 (1994b), Hagenguth's experiment in 1941, has shown that a longer front time, t_f, would significantly decrease the breakdown voltage level (under both polarities) of a 20-inch rod-rod air gap.

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Most of the recorded and published results are concerned more with the negative polarity waveform than the positive polarity (Kuffel and Abdullah, 1966; Linck, 1965). The IEEE Task Force 15.09 (1994b), reported the results from the USA that showed the positive polarity flashover voltage is lower in magnitude than that under negative polarity voltages for the 1/5 and 1.5/40 μs waveshape. However, much attention has been paid to the breakdown occurring at extremely fast rise times (Grzybowski and Jacob, 1990; Miller *et al*., 1990; Naidu *et al*., 1989). Such short and steep front times of transient voltages can be caused by lightning.

As documented in (IEEE Task Force 15.09, 1994b), Wiesinger had tested rod-rod, rod-plane, rod-sphere and sphere-sphere air gaps, which in the range of 3 to 10 cm long with voltages of rise time from 5 ns to 2.7 μs and time to half value of 550 μs, in 1966. He observed that the impulse withstand voltages of sphere gaps were insensitive to the front time and to the polarity of the applied voltage wave. However, for the other gaps having nonuniform electric fields, the impulse withstand voltages of positive polarity were lower than those of negative polarity; the negative-polarity withstand voltage increases with front time and the positive-polarity withstand voltages were insensitive to front time.

Panek *et al.* (1992) reported full-scale tests of a 550 kV BIL substation assembly with a simulated backflashover voltage. They generated a 0.3/170 μs wave to simulate the backflashover. The test results were compared with results from tests with the standard 1.2/50 μs waves. Both phase-to-ground and phase-to-phase tests were performed. The critical breakdown voltage, U_{50}, with the 0.3/170 μs was about 94% of that with the 1.2/50 μs wave. They also performed laboratory tests on a 550 kV BIL substation post insulator with three voltage waves: 1.2/50, 1.2/250 and 0.5/50 μs. They concluded that the substation withstand voltage is lower than the BIL of its individual components. They also concluded that the withstand level is higher for shorter front times and lower for longer wave tails.

The evaluation of the strength of line insulation when exposed to non-standard waves has been widely investigated by the workers such as Pigini *et al.* (1989) and Darveniza and Vlastos (1988). The results obtained by Pigini *et al.* (1989) for instance showed that by reducing the tail duration, the breakdown voltage would be increased.

MODELLING THE EFFECT OF NON-STANDARD WAVESHAPE

The use of non-standard waveshape is very important in presenting the nature of lightning, which is unpredictable phenomenon. For this analysis, three different impulses waveshape were used and shown in Table 1.

For each case, three different currents were injected on the top of the tower as per Fig. 1. The lowest current for each case is the critical current, I_c and the highest is the current that will always gives a breakdown. Meanwhile the last one is the current obtains in between of these two values. All the breakdown characteristic parameters such as leader velocity, leader length and the v-t curve will be obtained and plotted.

Further of specific details relating to the model are described in Table 2. For Case A, the front time is very short compared to the standard waveshape. However, the tail time of 47 μs is not much different with the standard tail time of 50 μs. Meanwhile for the second case, the front time of 1.1 μs is close to the standard front time of 1.2 μs. But this time, a tail time of 6 μs is chosen which means the waveform is faster reaching its half value. The last waveshape used for this analysis has a long front time but almost the same tail time with the standard. The results for each case will be compared and grouped based on their breakdown characteristics.

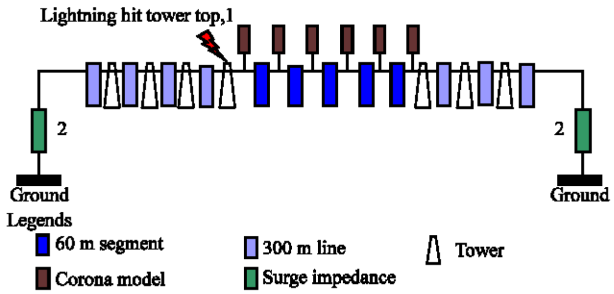

Fig. 1: System modelled for the studied cases

Table 1: Parameters and values for the non-standard lightning current and waveshape modelling

Case	Waveshape (μs)	Polarity	Current injected (kA)
A	0.7/47	Negative	72, 75 and 80
B	1.1/6	Negative	130, 135 and 140
C	1.92/52	Negative	125, 130 and 135

Table 2: Key parameters used for modelling the system

Model	Sub-component	Details/Reference
Lightning strike		Double exponential current source with a varying front time according to the peak current (CIGRE, 1991).
Overhead line	Phase conductor	Single phase conductor, 1.43 cm radius (Zebra), 300 Ω surge impedance, lowest phase conductor at 20 m. Modelled with frequency dependent travelling wave model.
	Corona model	According to Carneiro and Marti model (Carneiro and Marti, 1991) implemented every 50 m along line
Tower	Main structure	Surge impedance of 155Ω and travelling wave velocity of speed of light modelled with a Bergeron model
	Tower footing	DC resistance of 10 Ω in a soil resistivity of 100 Ωm. Soil ionisation modelled (Woodford, 1998).
	Coordination gap	Rod-rod gap with distance of 2.79 m

RESULTS AND DISCUSSION

Relationship Between Instantaneous Voltage and Leader Length

Figure 2 shows the relationship between instantaneous voltages applied to the 2.79 m gap with these three waveshape. The plots show that during the leader development, instantaneous voltages are strongly dependent on the leader length and weakly dependent on the peak voltages.

The similar trends were obtained for all cases. As the voltages increase, the leader length also increases before gradually decreases toward the breakdown. At this stage, the leader length is already equal or greater than gap length d_g, which is 2.79 m.

Relationship Between Leader Length and Time

Meanwhile in Fig. 3, the results show that the leader development with respect to the time. For all three cases with three different peak voltages, it is clearly shown that the voltage can influence the growth of the leader. The larger the peak the quicker the breakdown process. As shown by case A, for V_{peak} of -5.5 MV, it only takes approximately 0.33 μs for the gap to breakdown. The same situation also showed by other cases. Higher the voltage tends to increase the leader development and as well as the time to breakdown.

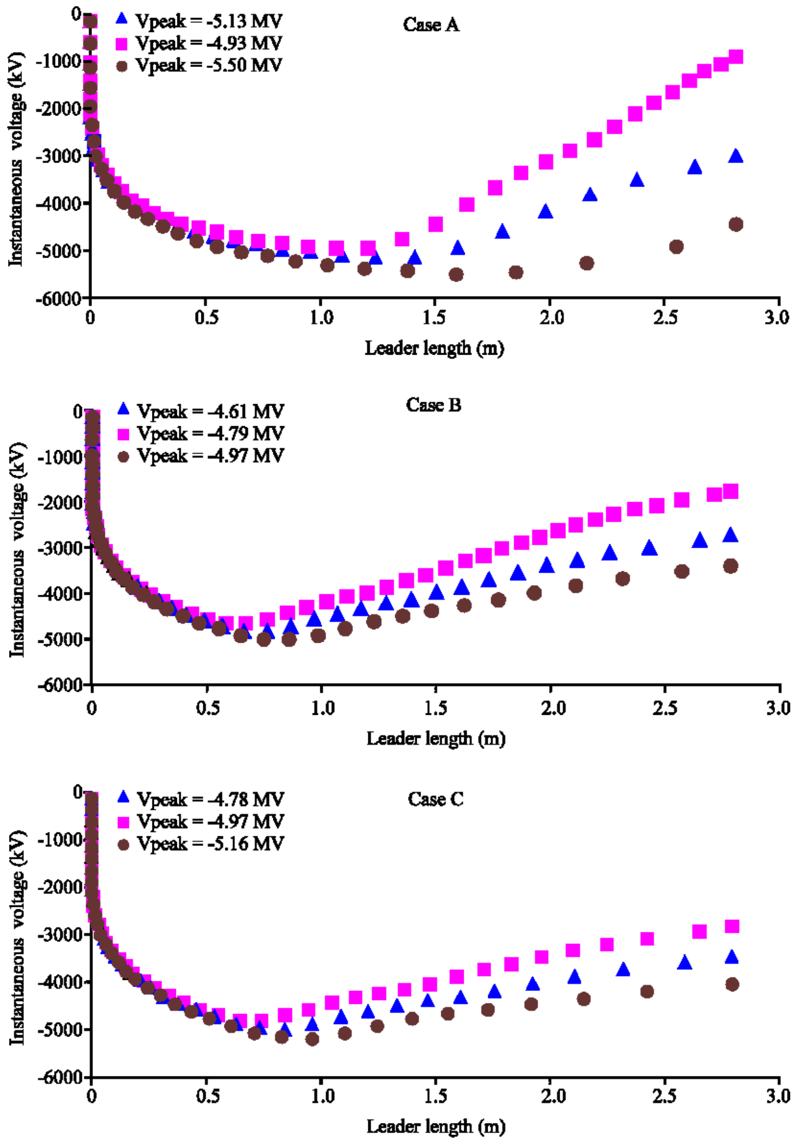

Fig. 2: Relationship between instantaneous voltage and leader length

Relationship Between Leader Velocity and Leader Length

Figure 4 shows the leader velocity as a function of leader length, obtained from the simulation. It can be seen that the velocity of the leader is dependent on the peak voltage despite the distortion of the voltage wave.

In case A, both plots for Vpeak of -5.13 and -5.47 MV show an increase in velocity as the leader length increases because of more electric field will be created. However, the plot for Vpeak of -4.39 MV shows the decrease in velocity after the leader length approximately grown up to 1.2 m. This is because the distortion of the voltage waves, which is in fact, reduced the voltage across the gap. As a result, the velocity also starting to reduce approximately up to 1×10^{7} m sec^{-1} by the time gap is breakdown.

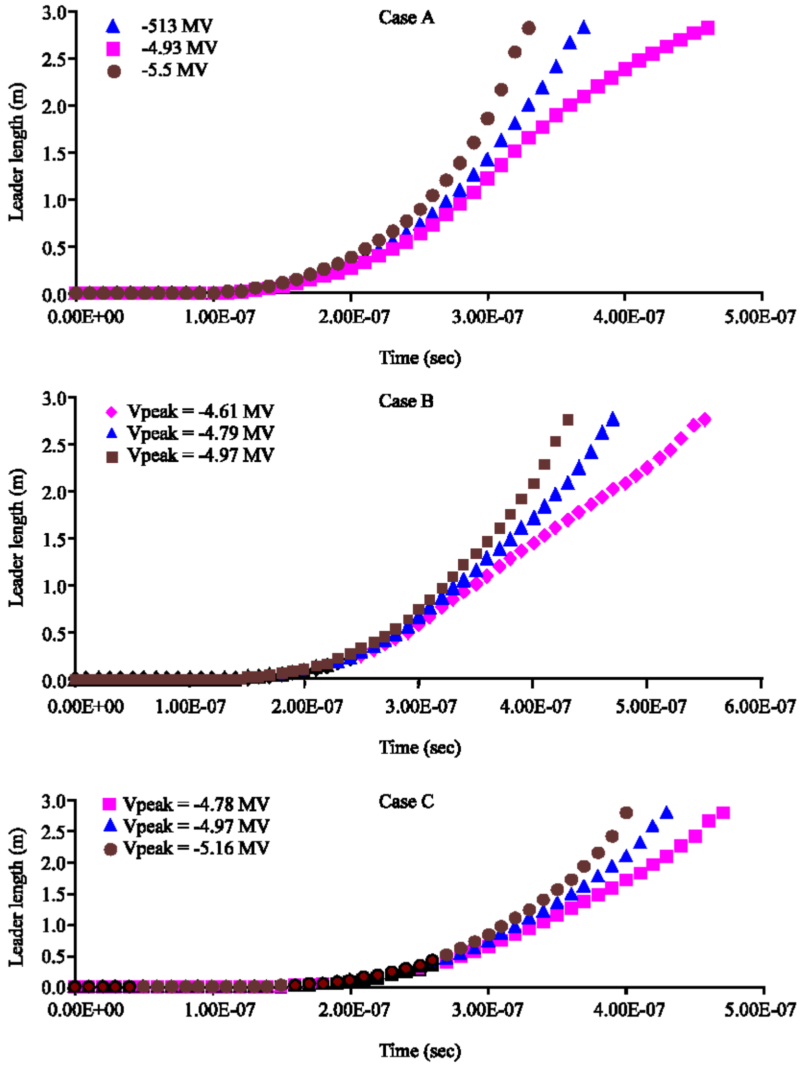

Fig. 3: Relationship between leader length and time

For case B and C, the plots show there is no significant difference between those three peak voltages. The leaders start to accelerate when the leader length is approximately 1.5 m.

Relationship Between Leader Velocity and Time

Some leaders, especially with the lower peak voltage such as in case A, the velocity is very low compared to the others during the breakdown. As shown in the previous graph, this is due to the lower voltage, which reduced the velocity towards the breakdown. According to Shindo and Suzuki (1985), this is due to the predischarge current, where the higher the applied voltage, the larger the predischarge currents flow through the gap. As a result, the applied waveform became more distorted.

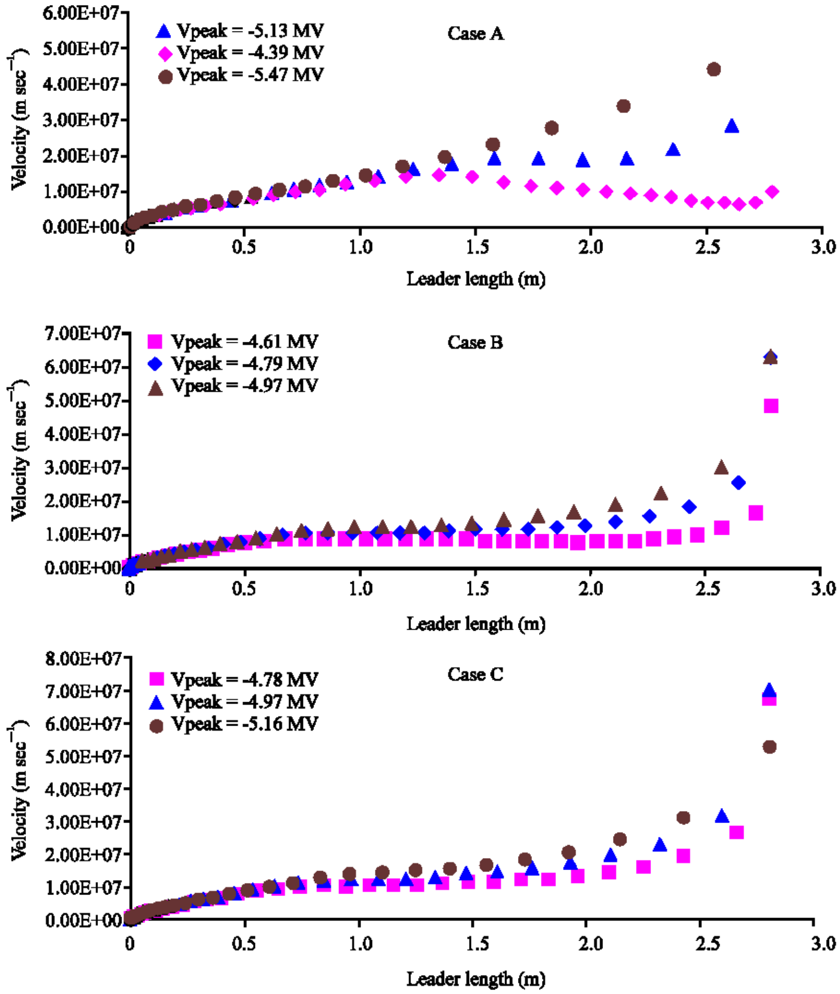

Fig. 4: Relationship between leader velocity and leader length

The graphs in Fig. 5 show the relationship between the propagation velocities of the leader with respect to the time. Results have shown that the higher the peak voltages, the faster the leader velocities with respect to time. This is particularly true for case A for instance, whereby at V_{peak} equal to -5.5 MV, the time taken to reach to one third of the speed of light is approximately 3.5 μs. In addition, the higher the peak voltages also tend to increase the leader velocity and decrease the time to across the gap. This is true for all cases analysed.

Volt-Time Curve

The last part of this analysis is to obtain the voltage-time (v-t) curve for each case of the waveform. As far as the non-standard waveform is concerned, the v-t curve is not the same as for the standard waveform of 1.2/50 μs. The use of this v-t curve is very useful as a comparison between the simulation and experimental results.

Figure 6 shows the results obtained for those three cases. These plots show the relationship between the peak and breakdown voltage versus time to breakdown. For all cases, the simulations were

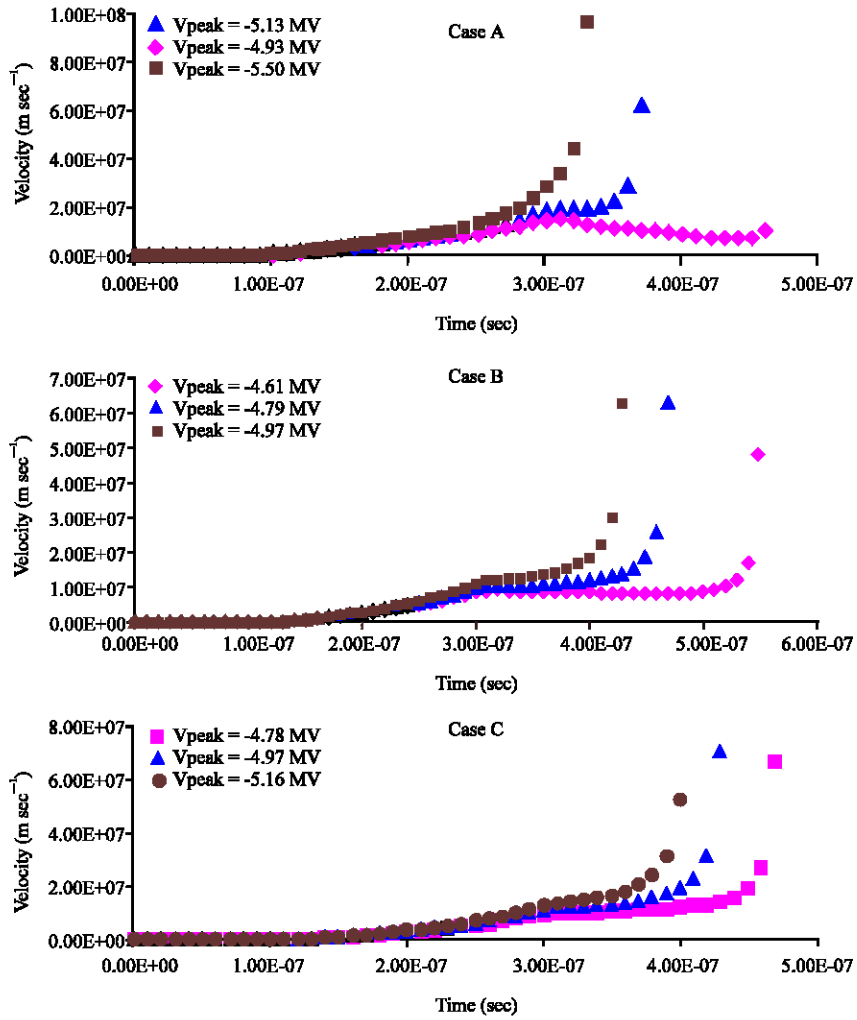

Fig. 5: Relationship between leader velocity and time

run for 21 times with different range of injected currents. For case A, the current from -70 to -90 kA were injected on the tower top. Meanwhile for case B, -130 to -150 kA was used as the injection current and -125 to -145 kA were chosen for the case C.

Theoretically, as the injection current increases, the time to breakdown becomes shorter. This corresponding time to breakdown will result in higher breakdown voltage. The plots for case B and C show the same shape of v-t curves, as it would be expected for the non-standard waveform. However, in case A, as shorter time to breakdown, the measured of breakdown voltages become closer to the peak voltages before giving the same value once the breakdown time reached approximately 0.65 µs.

This is because the breakdown of the gap, which is occurred very fast, compared with case B and C. As a result, the voltage has been chopped at the crest value, before reaching the 90% level at 0.7 µs.

However, it is important to note that these volt-time curves are only obtained for the rod-rod gap. Therefore, it might be different for other configurations and geometries.

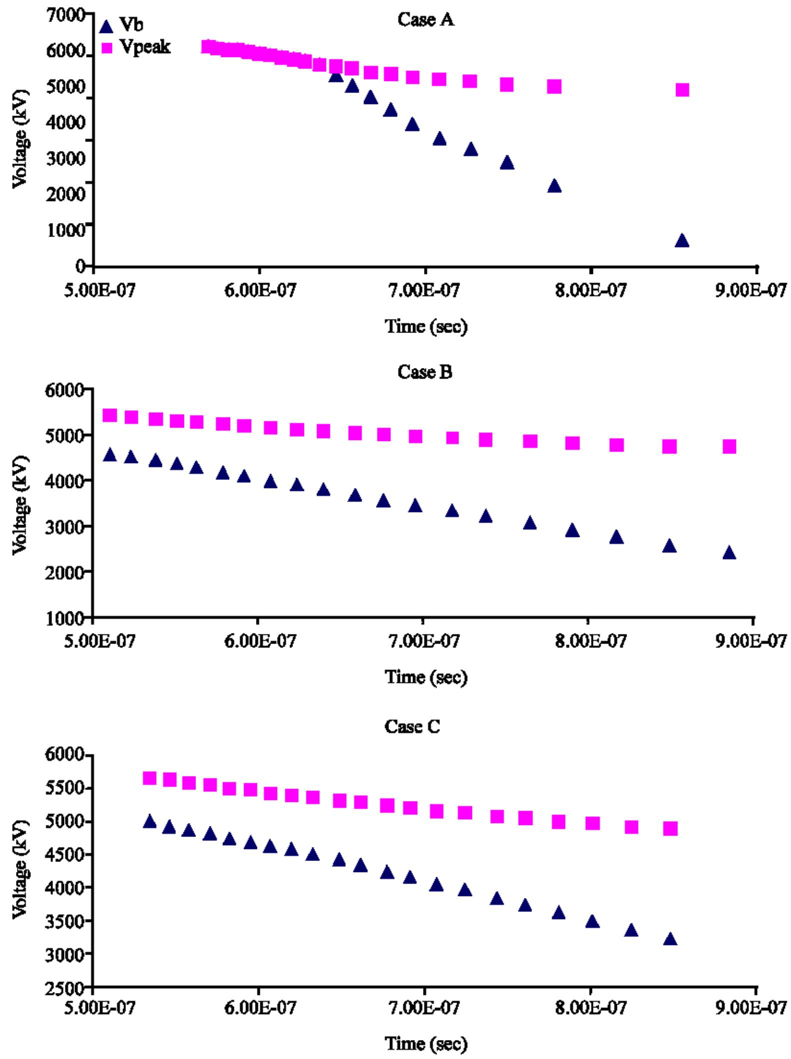

Fig. 6: Breakdown volt-time characteristics of 2.79 m coordination gap

CONCLUSION

Results for all cases have clearly shown that the non-standard lightning current and waveshape gave variations in lightning surge analysis results if compared to the standard one. As far as the breakdown processes are concerned, results have also shown that the instantaneous voltages are strongly dependent on the leader length and weakly dependent on the peak voltages. Furthermore, the velocity of the leader is dependent on the peak voltage despite of distortion of the voltage wave whilst increasing in velocity will increase the leader length. The effect of the non-standard shapes of lightning was successfully been modelled for simulation testing and this has allowed the system to be run naturally as observed in practice.

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