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SIMULATION OF AN EARLY STREAMER EMISSION AIR TERMINAL FOR APPLICATION TO LIGHTNING PROTECTION

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1. INTRODUCTION

The ESE concept represents an attempt to improve the zone of protection offered by a conventional Franklin rod air terminal. The premise on which ESE lightning protection relies is this: the earlier an air terminal is able to launch an upward leader, during the attachment phase of a lightning discharge, the larger the zone of protection offered by that air terminal. The validity of the above premise and the quantification of any improvement in zone of protection (resulting from early leader inception) have become the subject of much controversy. The main reasons for dispute are documented elsewhere [1][2], and are beyond the scope of this document. Suffice it to say that much of the ESE debate has necessarily taken the form of theoretical arguments, since there is a dearth of 'hard' experimental data in the literature.

Obviously, field testing of ESE air terminals under natural lightning conditions could resolve the debate. However, the expense and time-consuming nature of this form of research are prohibitive, especially when the number of different ESE device types is considered. It is perhaps inevitable, then, that some reliance be placed on tests conducted in the laboratory.

In this paper the authors have adopted a methodical approach for examining, under laboratory conditions, the extent to which the discharge emanating from an air terminal can be influenced by voltage application to the tip of the air terminal - since such voltage application is one technique employed by ESE air terminals to expedite upward leader inception relative to a Franklin rod. The experimental method used and the preliminary observations of the study will be reported here.

2. BACKGROUND

A commercial ESE device, which works on this principle, has already been studied under laboratory conditions by Allen et al. [3]. The ESE device in question produced a decaying sinusoidal voltage at the air terminal tip. The unit tested was self-contained, and the energy required to produce the voltage at the air terminal tip was ultimately derived from the electric field to which the air terminal was exposed.

In addition to examining a commercial device, the authors of [3] also simulated an ESE air terminal by using a vertical (conducting) finial, to which a lightning impulse could be independently applied. The authors of this paper have used the same technique to simulate an ESE device.

Conclusions drawn in [3] will be briefly reported in the discussion section of this paper, since they are pertinent to this work.

3. EXPERIMENTAL APPARATUS

In order to study the behaviour of discharges emanating from the simulated ESE device, electrodes were arranged as shown in Figure 1. The height of the HV plane, H, was set at 2.5m and the finial had height, h = 1.5m. The remaining dimensions of the finial are illustrated in Figure 2. To enable a voltage to be applied to the finial, it was necessary to use insulation to 'isolate' the finial from earth potential. A 1MΩ resistance was inserted between finial and ground.

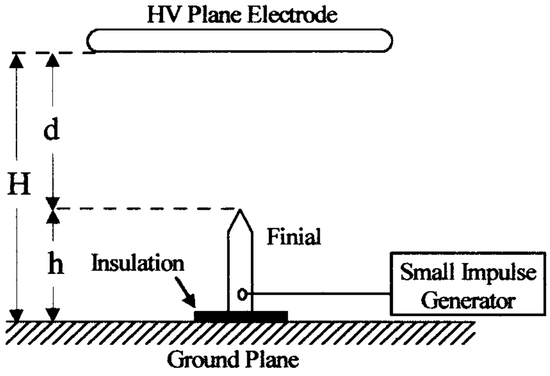

Figure 1: Configuration of Electrodes

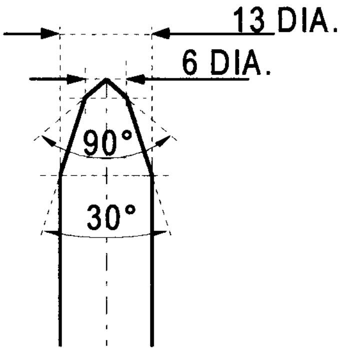

Figure 2: Dimensions of Finial Tip (Diameters quoted in mm)

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3.1 VOLTAGE APPLIED TO THE HV PLANE

A test circuit was configured such that a DC voltage and a switching impulse could be applied simultaneously to the HV plane. The DC component was necessary to represent the relatively static field generated at ground level by the charges within a thundercloud overhead. The impulse component was intended to simulate the time-varying field due to the approach of a downward stepped leader. Both components were negative in polarity.

The impulse voltage was produced using a 10-stage Marx generator (Main Impulse Generator or MIG), with parameters 0.14μF/200kV per stage. The generator was configured to produce an impulse of shape 180/1575μs. DC voltages were provided by a 4-stage Cockcroft Walton Voltage Multiplier, rated at 750kV.

3.2 VOLTAGE APPLIED TO THE FINIAL

A smaller Marx generator (Small Impulse Generator or SIG) comprising 4-stages, 0.05μF per stage, was employed to produce an impulse of shape 1.3/30μs. For the purpose of these experiments it was required that the duration of the lightning impulse be short relative to the time-to-crest of switching impulse. Therefore, the wavetail was chosen to be shorter than the standard 50μs value used in [3] since the time-to-crest of the impulse at the HV plane (180μs) was shorter than that employed in [3] (500μs). The maximum stage charging voltage of the generator was restricted to 10kV, a constraint of the stage voltage measurement rather than the capacitor rating (15kV). The output of the SIG was connected to the finial via an 8kΩ resistor. A sphere-sphere gap was connected across the finial in order to prevent damage to the SIG, in the event of the test gap breaking down. (With the SIG connected to the finial, the impedance between finial and earth is reduced due to the impedance of the integral components of the SIG).

3.3 THE TIME DELAY, T_D

It was necessary that application of the lightning impulse to the finial should occur after the switching impulse was applied to the HV plane, as illustrated in Figure 3. Controlled firing of the MIG was achieved using a trigatron arrangement located within the first spark gap of the generator. The signal to the MIG trigatron was processed and also used to fire the SIG. Controlled firing of the SIG was again achieved using a trigatron electrode arrangement. The 'fire' signal to the MIG was attenuated then passed to a delay unit. After the signal was delayed, by an amount T_D, it was stepped-up and fed to the triggering electrode of the SIG. It was necessary to optically isolate the delay unit, to prevent the SIG firing at the same time as the MIG as a result of the conducted interference accompanying the operation of the larger generator.

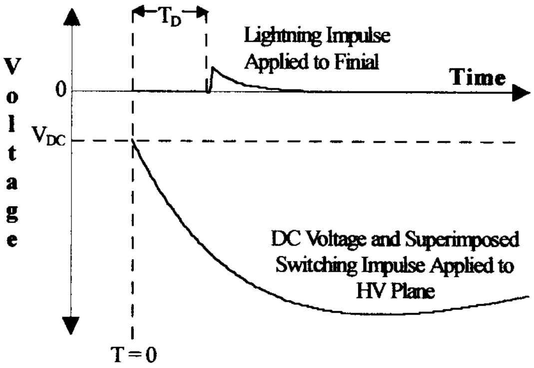

Figure 3: Application of Lightning Impulse to Finial with Respect to the Voltage at the HV Plane

3.4 MEASUREMENTS

Photomultiplier units, each fitted with a collimating slit, were focused at the rod tip and at distances of 20 and 40cm above the rod tip. The MIG output voltage was monitored, as was the output from the SIG. Because the finial had a high impedance to earth, the voltage at the finial comprised three components: (1) the voltage due to the SIG, (2) an attenuated version of the negative switching impulse at the HV plane, induced by means of capacitive coupling and (3) drops in potential due to the injection of positive charge into the gap during discharge propagation. Considering point (3), the voltage at the finial also provided a crude indication of the charge injection that occurred during discharge propagation.

4. TEST PROCEDURE

Discharge behaviour was studied under two basic sets of conditions. The first experiments were up-and-down tests, whereas the second set employed voltages greater than U_{50}. It is the preliminary results obtained during the up-and-down tests that will be reported here.

Initially, the DC voltage at the HV plane was set to zero. In the first instance, the lightning impulse was not applied to the finial, although the finial remained connected to the small impulse generator and the 1MΩ resistance. A 40-shot up-and-down test was then conducted, during which the time-to-breakdown was recorded for every breakdown event. Because no lightning impulse was applied during this first test, this formed the control experiment.

The up-and-down test was then repeated a number of times with the lightning impulse being applied to the finial. Delay times of 30, 60, 90, 120, 150 and 180μs were employed.

Similar experiments were also conducted with a DC pre-stress on the HV electrode, sufficient to cause corona at the rod tip, prior to application of either impulse. The effect of varying the magnitude of the lightning impulse was also examined. However, at this stage, the authors will concentrate on the case where no DC pre-stress was applied, and the lightning impulse had a peak magnitude of 14.3kV.

5. PRELIMINARY RESULTS

5.1 DISCHARGE MECHANISM

A typical light oscillogram is shown Figure 4, for the case where no lightning impulse was applied to the finial. The discharge development exhibited here is much like that reported in [4], where similar test conditions were employed. The discharge propagates in an intermittent manner, and breakdown tends to occur very abruptly.

In instances where the lightning impulse is applied to the finial, a burst of ionisation activity always occurs at T_D. This activity can clearly be seen in Figure 5 at a time T = 60μs. The size of this ionisation burst (as measured by the photomultipliers) is dependent upon T_D. The ionisation burst tends to attain a greater intensity as T_D increases from 30 to 90μs. This observation can be easily explained by considering the greater magnitude of field existing at the rod tip as T_D is increased.

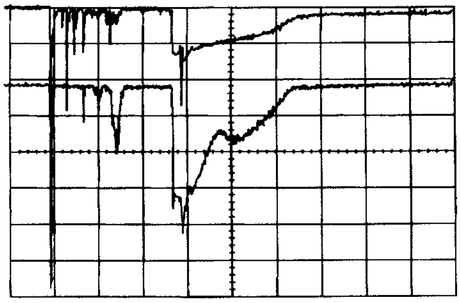

Figure 4: No Lightning Impulse, Time Base = 50μs/div.
Upper Trace: Light @ Rod Tip (Arbitrary Units or A.U.)
Lower Trace: Light @ 20cm from Rod Tip (A.U.)

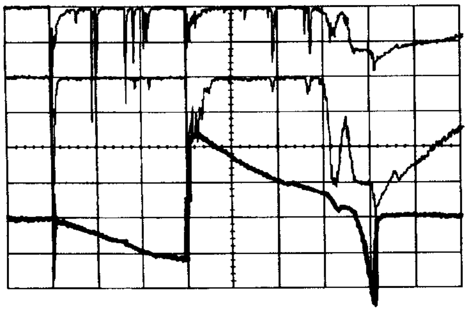

Figure 5: T_D = 60μs, Time Base = 20μs/div.
Upper Trace: Light @ Rod Tip (A.U.)
Middle Trace: Light @ 20cm from Rod Tip (A.U.)
Lower Trace: Voltage @ SIG Output (7.5kV/div.)

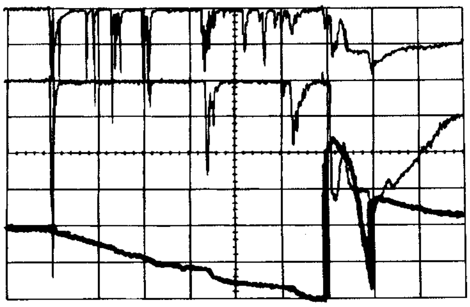

Figure 6: T_D = 120μs, Time Base = 20μs/div.
Upper Trace: Light @ Rod Tip (A.U.)
Middle Trace: Light @ 20cm from Rod Tip (A.U.)
Lower Trace: Voltage @ SIG Output (7.5kV/div.)

By examining the light oscillograms of withstand events (all oscillograms presented here are breakdown events) it appears that the size of the ionisation burst occurring at T_D is of similar magnitude for delay times of 90 to 180μs. For the lower values of T_D (30 and 60μs), a dark period always follows the burst of ionisation, as in Figure 5. In breakdown events, for values of $T_D \geq 90$μs, application of the impulse generally leads directly to breakdown, as illustrated by the oscillogram in Figure 6.

5.2 TIME-TO-BREAKDOWN AND U_{50}

Application of the lightning impulse to the finial has an effect on both the time-to-breakdown ($\bar{T}_B$) of the discharge and the 50% breakdown voltage (U_{50}) of the test gap. The more obvious trends in each of these parameters will be mentioned here.

A graph of $\bar{T}_B$ vs. T_D is shown in Figure 7. The dotted line indicates $\bar{T}_B$ for the gap when no lightning impulse was applied to the finial.

Referring to Figure 7, for T_D = 30μs $\bar{T}_B$ is approximately the same as for the control gap (i.e. the case where no lightning impulse was applied to the finial). However, the value of $\bar{T}_B$ for T_D = 60μs is 20μs greater than that associated with the control gap. Referring back to Figure 5, where T_D = 60μs, a dark period was always seen to occur after the burst of ionisation activity at T_D. The electric field at 60μs was unable to support the growth of a gap-bridging discharge, and the burst of ionisation at T_D always extinguished before breakdown was achieved. When discharge activity ceases, a cloud of positive space charge is left behind, which restricts further ionisation until the electric field has recovered. For the case where T_D = 30μs, it is speculated that, because the burst of ionisation accompanying lightning impulse application was necessarily smaller than that for T_D = 60μs, the subsequent retardation effect did not have an appreciable influence on $\bar{T}_B$. The minimum $\bar{T}_B$ during this up-and-down test occurred for T_D = 90μs. Under these conditions, $\bar{T}_B$ was approximately 10μs smaller than for the control finial, when no lightning impulse was applied. For values of T_D > 90μs, $\overline{T}_B$ increases almost linearly with T_D.

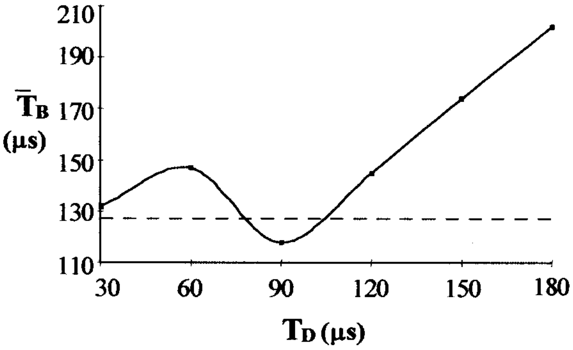

Figure 7: Average Time-to-Breakdown vs. Delay Time

It should be borne in mind that the average times-to-breakdown presented in Figure 7 were calculated during-up-and-down tests. Thus, the voltage applied to the HV plane varied slightly from test to test, since the U_{50} voltage was found to vary with T_D.

For the case where T_D = 30μs, U_{50} is approximately the same as for the control gap. For all other values of T_D, U_{50} is lower, tending to become lower, the larger the value of T_D. The minimum value of U_{50} was achieved when T_D = 150μs. This is the case where breakdown is induced to occur closest to the peak of the switching impulse (for T_D = 180μs, breakdown occurs after the peak). At T_D = 150μs the 50% breakdown voltage had a magnitude that was 93% of that associated with the control gap (corresponding to a composite voltage of magnitude 445kV as opposed to 476kV).

Looking forward to the application of these results to lightning protection, the U_{50} voltage determined in the laboratory has no direct equivalent parameter in the lighting attachment process. Therefore, U_{50} will ultimately be considered in conjunction with the instantaneous applied voltage at breakdown.

6. DISCUSSION & CONCLUSIONS

There is an obvious advantage in simulating an ESE device rather than using a commercial ESE device during testing. The parameters of the simulated device, in this instance the delay time and the lightning impulse magnitude, can be varied. This enables the effectiveness of a particular ESE technique (e.g. voltage application at the air terminal tip), as regards inducing early upward leader inception, to be studied in a thorough and methodical manner.

For the given set of experimental parameters, an optimum delay time exists (T_D = 90μs) in terms of inducing the lowest average time-to-breakdown. An optimum delay of T_D = 240μs was determined in similar experiments reported in [3], where a switching impulse with time-to-crest of 500μs was employed. Comparison with the results obtained in [3] emphasises the point that the optimum delay time is expected to vary with the time-to-crest of the switching impulse applied to the HV plane, or rather the rate of change of field (dE/dt) to which the air terminal is exposed. This consideration has major implications for lightning protection since the dE/dt associated with an approaching downward leader will be subject to variation. The timing of voltage application to the air terminal tip, under natural lightning conditions, is therefore of paramount importance. Furthermore, at the optimum value of T_D in the authors' experiments $\overline{T}_B$ was reduced by around 10μs compared to the case for the finial where no lightning impulse was applied. In [3], a reduction of 70μs was achieved at optimum T_D. This indicates that the maximum achievable advance in leader inception using this technique is also dependent upon the dE/dt to which the air terminal is subjected.

Only the preliminary observations have been presented here. Additional results and analysis, obtained during this experimental programme, will be reported in a future publication.

7. ACKNOWLEDGEMENTS

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