Tests of the 'early streamer emission' principle for protection against lightning

N.L.Allen
K.J.Cornick
D.C.Faircloth
C.M.Kouzis

Indexing terms: Early streamer emission principle, Lightning protection, Simulation testing

Abstract: Experiments are described which are designed to test two devices based on the 'early streamer emission' (ESE) principle, for lightning protection, against the traditional Franklin rod. In all three cases, the device was subjected to a steady negative electric field from a sphere, simulating the field beneath a thundercloud, prior to application of a superimposed negative impulse field, simulating the field due to the downward leader. The first device consisted of a vertical rod to which a subsidiary 1/50μs positive impulse voltage, variable up to 40kV peak, could be applied with varying delays from the start of the negative impulse field. Energising of the rod was thus independent of the applied, negative, field. The second device was a commercial product, energising of which was controlled by its own power supply. Sparkover voltages in the sphere/device gaps and times to breakdown were measured. It is shown that the ESE devices showed a small advantage, in time to breakdown, over the Franklin rod.

1 Introduction

The traditional 'Franklin rod', used in lightning protection, depends for its effectiveness upon development of a corona discharge at its tip as the result of high electric fields developed in a lightning storm. With the approach of a downward leader, the resulting rapid increase in field augments corona activity. Under favourable conditions, one of the streamer filaments which constitute the corona may undergo sufficient heating to develop into a highly conducting, arc-like 'upward leader' which can then propagate for considerable distance in a comparatively low electric field. It may thus progress towards the downward leader, effect an attachment and allow the subsequent high-current discharge to pass down the conducting path so formed.

A simple passive Franklin rod, on the roof of a large building, may not give full protection against a strike to the fabric, since upward corona may be initiated at parts of the structure more favourably placed in relation to the downward leader. However, if the corona can be activated at an earlier time in the downward progress, development of the upward leader may be advanced sufficiently, by such an activated rod, to overcome the distance disadvantage and effect an attachment before corona at other sites can develop sufficiently to compete with it. Extension of this argument suggests that the corona set up at the active rod, placed centrally, for example, could replace the coronas from the separate passive rods placed in a conventional system around the roof of the building.

This principle forms the basis of the so-called 'early streamer emission' devices which have been developed in recent years. The success of such a device depends on the timing of the corona initiation in relation to the downward leader approach and the rapidity with which the leaders can attach compared with the time that would have been taken with passive rods.

In this paper, tests are described in which the characteristics of the Franklin rod have been examined, under simulated lightning storm conditions, and compared with those of two ESE devices, one in which a rod has been energised by an independent pulsed voltage, the other a commercial device with its own power supply.

2 Test techniques

Prior to initiation of a lightning discharge, the average 'steady' electric field at the ground increases to several tens of kilovolts per metre, due to the charge on the cloud above [1]. The field at the tip of an exposed lightning conductor terminal can thus be expected to be much higher. These conditions can be simulated in the laboratory by application of a DC voltage to a large object suspended above a conductor. The subsequent descent of the leader is simulated by super-imposition of an impulse voltage to the gap, of rise time approximating to that of the field produced by an approaching leader. A critical test requires not only measurement of the respective probabilities of striking to active and passive rods, but also information on the time during the impulse at which the strike occurs.

These conditions were partly satisfied by Bouquegneau [2] in which the numbers of strikes were measured, out of two groups of 100 trials, to an active and a passive rod mounted 1m and 2m apart and symmetrically placed relative to an upper rod electrode suspended vertically above the mid-point of the line

---

IEE Proceedings online no. 19982209

Paper first received 9th February and in revised form 30th April 1998

N.L. Allen, D.C. Faircloth and C.M. Kouzis are with the High Voltage Laboratory, UMIST, Manchester M60 1QD, UK

K.J. Cornick was with UMIST and is now with Power Grid Ltd, Singapore 118485

joining the bases of the two rods. An impulse voltage (1.2/50μs) was applied to the upper rod. The active rod was excited by a steady 25kV voltage applied from a separate supply; active corona is assumed to have been set up. The results showed no significant difference between the rates of striking to the active and passive rods. The tests, however, could not be regarded as conclusive, since the impulse voltage to the upper rod was too fast to simulate the effects of the leader descent and no preceding steady electric field was provided. Generally similar tests have been carried out more recently by Grzybowski *et al.* [3] on commercial devices with similar results.

In large-scale tests at the Les Renardières High Voltage Laboratory, Berger and others [4–6] placed a commercial ESE device, based on a vertical rod, beneath a large metal plane 15 × 20m, suspended at a height of 13m above the ground plane, and to which high voltage impulses were applied. Comparisons were made with a passive Franklin rod placed in separate, identical tests in the same position. The gap between the plane and the tips of the respective rods was always 9.5m but two experimental arrangements used rods of lengths 3.5m and 1m standing vertically on the ground plane. Steady negative voltages were applied to the plane to simulate the field beneath a thundercloud and negative impulse voltages, rising to peak in 500μsec were superimposed, so simulating the increasing field due to the approach of a leader.

The mode of operation of the ESE device was not disclosed. However, image convertor photography showed that whereas the Franklin rod required several ionisation steps before continuous leader propagation was achieved, the ESE device initiated a continuous leader about 100μs earlier. Thus, the energisation of the rod of the ESE device supplied sufficient energy to convert the early streamers into a leader. The velocity of advance of the leader was shown, however, to be exactly the same in the two cases, namely 2×10^4 ms^{-1}.

Results were quoted in terms of the mean field between plane and ground, disregarding the perturbation due to the rod. For the 1m and 3.5m rod, the mean fields at which continuous leader development was initiated were as in Table 1.

Table 1: Mean fields for initiation of continuous leader development

Rod length	Franklin rod	ESE rod
1m	285kVm^{-1}	190kVm^{-1}
	(100%)	(66.7%)
3.5m	213kVm^{-1}	127kVm^{-1}
	(100%)	(59.6%)

Lower fields, recorded for the ESE rod, correspond to earlier initiations during the negative impulse applied to the plane above. Examination of Fig. 3 of [5] shows, however, that the leader from the Franklin rod, despite initial intermittent development, has reached the same distance from the tip, at the same time, as the continuously developing leader from the ESE device. The physical meaning of leader initiation in relation to the attachment process thus requires careful consideration.

No comparison is given between the respective sparkover voltages and the times to sparkover, in these experiments. Since the efficacy of both types of rod depends upon the velocities of the upward and downward leaders up to the time of their attachment, it might be expected that a measurement of the time to sparkover, in identical plane-rod gaps, would be critical in making comparisons between them.

This question has been examined in a critical review by Mackerras *et al.* [6], who considered the paths taken by leaders in the neighbourhood of simple structures protected by ESE or Franklin rods. These authors disputed claims that an appropriate leader velocity was of the order $10^6 ms^{-1}$ and that a lower value of the order $2 \times 10^4 ms^{-1}$ is more appropriate when estimating the attachment position of upward and downward leaders and hence, the time of attachment, which is simulated in laboratory experiments by the time to breakdown. Uman [1], in a review, points out that measured downward leader velocities vary between 6×10^4 to 2.6×10^6 ms^{-1} and that upward leader velocities vary from a minimum of 2×10^4 ms^{-1}.

3 Test arrangements

Test conditions require that lightning conditions be simulated by first, a steady electric field between 'cloud' and ground, followed by a superimposed impulse field to provide an approximation to the increasing field set up by an approaching downward leader. In the present experiments, the cloud was simulated by a 0.75m diameter sphere, to which the high negative voltages were applied, suspended above the air termination to be tested, which was mounted on the laboratory floor. Its role was to generate in the test space the same electric fields as encountered in nature and that it should be corona free.

The conditions were produced by the circuit of Fig. 1. A steady voltage was applied to the sphere from a DC set producing voltages variable up to 750kV. A negative impulse voltage, of rise time 500μs to peak, was selected for this work since Berger [4] has shown that this provides a fair approximation to the rising field of an approaching leader. The impulse was supplied by a conventional Marx generator, of maximum peak voltage 2MV, coupled to the sphere through a capacitor of 550pF, which served to block direct current from the generator circuit. Impulse voltages applied to the gap were measured by means of a potential divider created by the series connection of the capacitance of the large sphere gap, and a low voltage capacitance C2. The DC set was protected from voltage impulses by a series resistance and parallel capacitance, as shown.

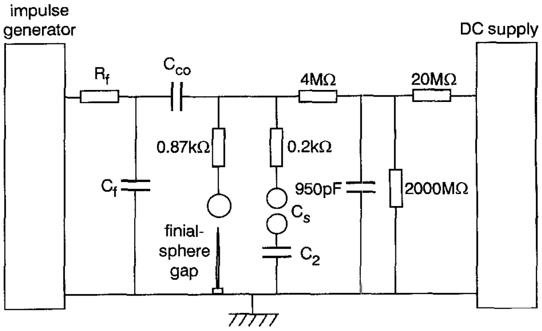

Fig. 1 *Combined impulse and direct voltage circuits for producing a composite high voltage*
R_f = 175kΩ, C_{co} = 550pF, C_f = 200pF, C_s = 97pF

For tests with the independently energised Franklin rod air termination (the 'active Franklin rod') a small impulse generator, providing voltage pulses up to +40kV was used (omitted for clarity in Fig. 1). This generator could be triggered at any desired time within the impulse provided by the main generator by operation of a delay circuit linking the two through fibre-optic cables. The sequence is shown in Fig. 2. The small generator was protected, in the event of sparkover to the rod, by a small parallel spark gap and series resistor of 8kΩ.

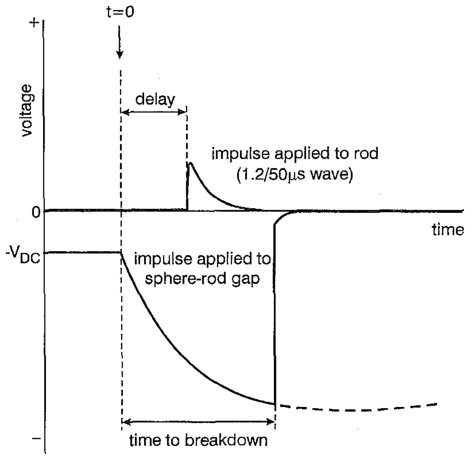

Fig. 2 *Sequence of voltage applications at sphere–rod gap*

The tests with the commercial ESE air termination were carried out in the same arrangement, (Fig. 1) but were preceded by additional tests to demonstrate its mode of operation. These consisted of the measurement of the amplitude and frequency of the voltage pulses, generated by the device itself when the tip was exposed to an electric field set up by the voltage on a separate sphere. Fuller details of these experiments are given in Section 5.

In all the experiments, initiation of corona at the terminations was detected by photomultiplier observation of the light emission. Time to sparkover, between sphere and termination, was found from the potential divider observation of the collapse of voltage across the gap, which was correlated with photomultiplier observations.

4 Tests with the Franklin rod

4.1 Passive Franklin rod

For these tests, a sphere-termination spacing of 0.75m was adopted. The tip of the termination was 0.75m above the laboratory floor. The end of the rod was machined to a 20° cone.

Since Franklin rods are commonly mounted on prominences on buildings, rather than on a flat plane, steady corona normally precedes the augmented streamer emission resulting from the approach of a downward leader. Related work in the same high voltage arrangement [7] has also shown that where the steady voltage is insufficient to initiate corona at an electrode, it has no significant effect on the corona and sparkover occurring on application of a superimposed impulse voltage. Therefore, although producing a general field near the ground plane which is greater than that normally encountered in lightning storms, it was decided to apply a steady voltage to the sphere sufficient to cause a small visible positive corona at the termination. This voltage was –150kV.

The first test was carried out without the steady field. The 50% sparkover voltage at this condition, was –491kV. For further tests with the Franklin rod the peak impulse voltage was then increased to –725kV, so that breakdown on the front of the wave could be assured, thus simulating the rise in field experienced by the termination as a downward leader approaches. The degree of approximation is shown in Fig. 3 where comparison is made between the field strength at ground level (disregarding the termination) under the laboratory impulse and that calculated according to Berger [4] for the case of the leader of a 5kA lightning stroke. With this impulse, the mean time to breakdown of the passive Franklin rod gap was 310μs where, as Fig. 3 shows, the laboratory and calculated leader fields are reasonably close.

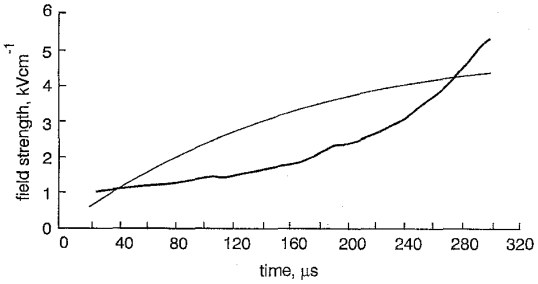

Fig. 3 *Comparison between calculated field due to an approaching leader and field at ground produced by an impulse voltage reaching peak value of –725kV at 500μs*
——— impulse –725kV
——— computed, I = 5kA

Subsequent tests were carried out with the steady voltage of –150kV at the sphere. Here, a composite voltage of –535kV (that is, a superimposed impulse of –385kV) was sufficient to cause breakdown on the wavefront; the mean time to breakdown was 117μs.

4.2 Active Franklin rod

These tests were also carried out under conditions first, with zero steady field and second, with the steady field provided by a voltage of –150kV at the sphere.

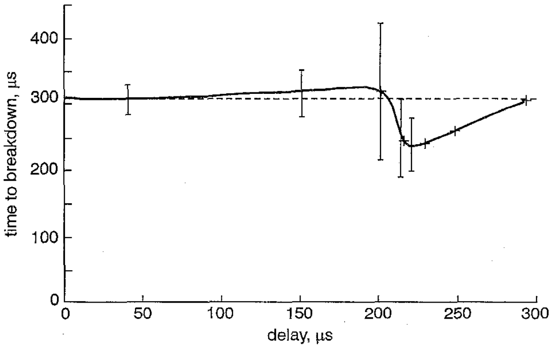

Fig. 4 *Times to breakdown of sphere/active Franklin rod gap under simple impulse voltage as function of time delay to application of 1.2/50μs auxiliary impulse at rod*
Steady voltage = zero. Time to breakdown of sphere/passive rod shown as horizontal dashed line. Limits of dispersion about the mean are shown.

With zero steady field, the –725kV impulse was applied to the sphere and an auxiliary +40kV peak lightning impulse (1.2/50μs) applied to the rod at various times after the start of the main impulse. The sequence is shown in Fig. 2. Times to breakdown were measured as a function of the time delay to application of the lightning impulse; the results are shown in Fig. 4 where comparison is made with the passive rod. It is clear that the auxiliary impulse had no significant effect upon the average time to sparkover of the main gap, that is, about 310μs, until it was delayed by more than 200μs from the start of the main impulse. There was then a sharp reduction of about 70μs in time to breakdown at ~240μs delay accompanied by a reduction to an insignificant level of the dispersion in breakdown times. For longer delays, the times to breakdown then approached the value in the absence of the auxiliary impulse.

Using the –150kV steady voltage at the sphere, two sets of tests were carried out, with +10kV and +20kV auxiliary impulses at the rod. The peak value of the main impulse in these tests was –385kV which, when added to the steady voltage, gave a composite voltage at the sphere of –535kV. Times to breakdown were measured; the results are shown in Figs. 5*a* and *b*.

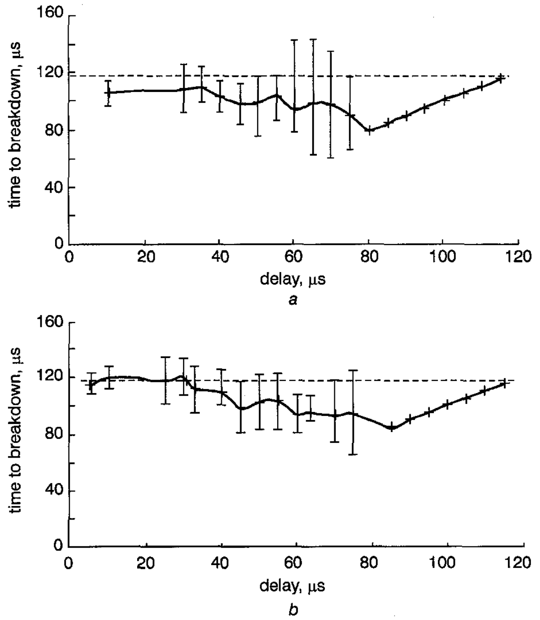

Fig. 5 *Times to breakdown obtained as in Fig. 4, but with a steady voltage of –150kV at the sphere*
a +10kV peak impulse at rod
b +20kV peak impulse at rod

In the absence of the auxiliary impulses, the mean time to breakdown was 117μs. When +10kV auxiliary impulse was applied with delays less than 80μs, there was a reduction in time to breakdown which was nevertheless small and hardly significant. At 80μs delay, the time to breakdown was reduced from that for the passive rod by about 40μs, to be compared with 70μs in the previous case described where the steady field in the gap was zero. When the +20kV auxiliary impulse was applied, the result was generally similar. As in the case with zero steady field, the dispersion in the results was reduced to insignificance at the time delay corresponding to the maximum reduction in the time to sparkover.

Thus, with or without the steady field, the effect of the auxiliary impulse voltage was to advance the sparkover between the sphere and the Franklin rod by between 40μs and 70μs.

5 Tests with a commercial ESE device (the 'Pulsar')

5.1 Functioning of the device

It is known that most commercial ESE devices operate by application of a pulsed voltage to a pointed termination. For meaningful tests, therefore, it was necessary to characterise the device being tested, known as a 'Pulsar 7'. This device consisted of a rod, 0.75m long, tapering to a tip of radius 1mm approximately. The rod surmounted a cylindrical 'can', containing a power unit.

This was sealed, self-contained and integral with the device. It was evident, therefore, that the energy required for the high voltage pulses must be derived from the corona set up at the tip of the rod in the enhanced electric field existing throughout a lightning storm. The energy is stored until the power unit discharges to produce a pulse of high voltage which then, presumably, produces a more energetic corona.

In these experiments, the tip of the device was placed a few centimetres below a sphere, of diameter 0.25m, which was connected to a variable DC supply up to 30kV (Fig. 6). Voltages and sphere-rod gap were arranged so that corona was set up at the tip. The resulting voltage developed on the rod itself, by the functioning of its power supply, was monitored via a 1000:1 Tektronix divider probe of input resistance 100MΩ and input capacitance 3pF and a further 10:1 divider. The tip of the rod was viewed by a photomultiplier. The voltage and photomultiplier signals were displayed simultaneously on an oscilloscope.

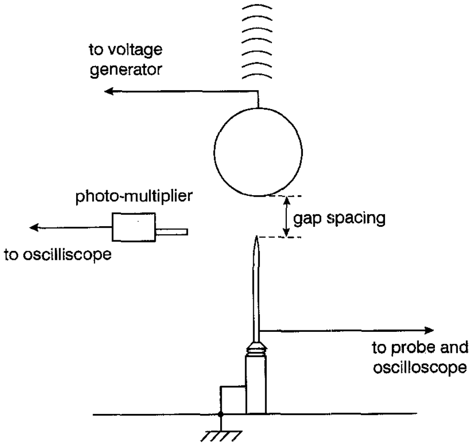

Fig. 6 *Preliminary experiment: arrangement of sphere, rod and associated measurements of rod voltage and corona light output*

An example of the voltage oscillogram is shown in Fig. 7*a*. Here, the tip of the rod was placed 4cm below the sphere, to which a steady voltage of –29kV was applied. The oscillogram shows that repeated negative charging of the rod occurred, between large, fast voltage excursions; the cycle was approximately 25ms, that is, a frequency of 40 Hertz for the sphere voltage used. Use of a faster sweep showed that the voltage excursions were oscillatory as in Fig. 8*a*; here the oscillation frequency was approximately 40kHz and the peak to peak amplitude was found to be constant, from shot to shot at approximately 7kV. (The variation in amplitudes apparent in Fig. 7*a* was a function of the sampling process of the oscilloscope on this very slow sweep).

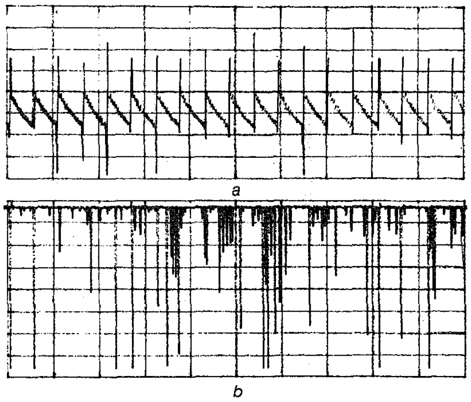

Fig. 7 *Oscillograms: tip of rod 4 cm from sphere at –29 kV*
Horizontal scale 30 ms/div
a Voltage at rod, recorded by probe arrangement, arbitrary units
b Photomultiplier record of light emitted by corona pulses

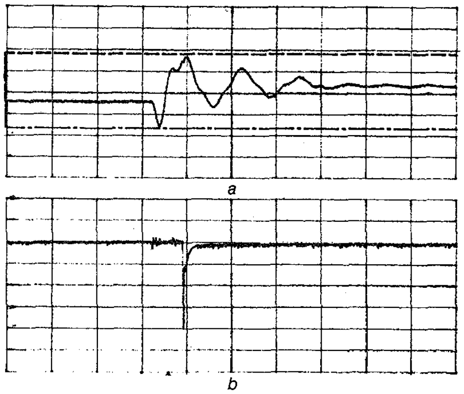

Fig. 8 *Oscillograms: conditions as for Fig. 7*
Horizontal scale: 20 μs/div
a Voltage at rod, recorded by probe arrangement, arbitrary units
b Photomultiplier record of light emitted by corona pulses

The repetition rate of charging, the frequency and the amplitude of the fast voltage oscillations were measured in two ways:

(*a*) by varying the sphere voltage at constant sphere-tip distance; results are given in Table 2.

Table 2: ESE device characteristics at constant sphere-tip distance of 3.2 cm

Sphere voltage, kV	Charging frequency, Hz	Oscill. frequency, kHz	Oscill. amplitude, kV
21	6.4	35.0	6.8
23	11.4	36.4	6.7
25	16.7	36.4	6.8
26	19.5	37.7	6.9
27	22.7	37.7	7.1
29	28.4	37.6	7.0
29.7	31.2	37.7	7.1

(*b*) by varying the sphere-tip distance at constant sphere voltage; these results are shown in Table 3.

A general consistency is evident between the charging frequencies obtained by the two procedures but under all conditions, the oscillatory frequency and amplitudes remained about constant. The results implied that the oscillation was a characteristic of the circuit in the power supply and that the charging time and, therefore the repetition rate of the oscillations, depended upon the field at the tip of the device. In Tables 2 and 3 the increase in voltage and the decrease in gap length were respectively taken to limits beyond which breakdown would have ensued.

Table 3: ESE device characteristics at constant voltage of 25 kV

Gap distance, cm	Charging frequency, Hz	Oscill. frequency, kHz	Oscill. amplitude, kV
4.4	2.6	35.7	6.2
4.1	6.3	36.4	6.3
3.5	13.2	35.8	6.4
3.0	18.8	35.9	6.8

Figs. 7*b* and 8*b* show photomultiplier signals corresponding to the voltage oscillograms. Each downward peak represents light from a corona pulse. Amplitudes in Fig. 7*b* are variable; this, again was a function of the sampling process. Some light peaks clearly coincided, in this event, with peaks of oscillatory voltage, shown on an expanded time scale in Fig. 8*b*. However, corona did not always occur at voltage peak. Such a case is shown in Fig. 9*b* where, for the same voltage excursion as in Fig. 7, a corona pulse occurred near the end of the charging period, but not during the oscillation. It is assumed that this pulse, with others observed in Fig. 7*b*, was due to coronas occurring during the charging period which thus contributed to the subsequent high voltage oscillation.

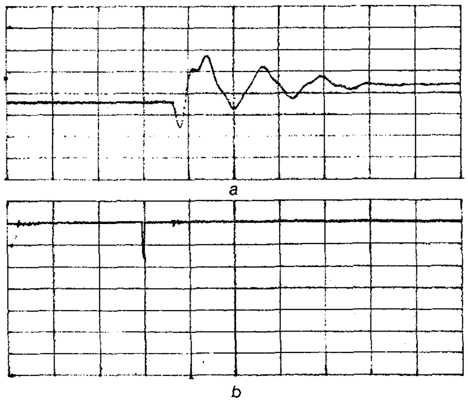

Fig. 9 *Oscillograms: conditions as for Figs. 7 and 8*
Horizontal scale: 20 μs/div
a Voltage at rod, recorded by probe arrangement, arbitrary units
b Photomultiplier record of light emitted by corona pulses

Table 4: Probability of corona pulse during voltage oscillation

Sphere voltage (kV)	Probability of corona pulse
–20	0.37
–22	0.40
–24	0.60
–25	0.83

Gap = 3.5 cm

It was found that the probability of corona occurring at the peak of the oscillation increased with the applied voltage at the sphere, despite the constancy of amplitude of this oscillation, Table 4. The reason for this behaviour is not apparent. It may be associated with changes in the ion space charge set up around the tip, since the rate of change of tip voltage changes with sphere voltage.

The highest sphere voltages used in these experiments yielded an average stress in the gap of the order 900kVm^{-1}, which approaches values encountered in a lightning storm. No corona could be detected below ~200kVm^{-1}. Thus, the experiments covered much of the range of conditions under which the device could function.

5.2 *Performance in tests under impulse voltage*

The sphere-rod test arrangement was used again, as with the passive and active Franklin rod. The tip of the pulsar was 1m above the ground plane. Comparison was again made with the characteristics of a passive Franklin rod of similar length, with a hemispherical tip of diameter 10mm. Two sets of experiments were carried out, using sphere-rod gaps of 1.0m and 1.4m.

Prior to testing with the combined circuit of Fig. 1, the DC voltage alone was raised from zero to determine the condition at which the Pulsar would start to function. It was found that it started to charge at sphere-voltages of –50kV and –60kV respectively for the 1.0 and 1.4m gaps and voltage pulses commenced at –204kV and –206kV. The voltage measuring circuit was removed from the Pulsar during these tests to avoid the risk of damage at sparkover.

Sparkover voltages were measured, first in the 1.0m gap using simple negative impulse only and then in both gaps, using pre-stress negative voltages of –250kV (1.0m gap) and –300kV (1.4m gap) to assure repeated operation of the device. Simultaneous measurements were made, over 50 shots in each case, of times to (*a*) the first corona after the start of the impulse, in the 1.0 m gap, (*b*) the breakdown in the 1.0m and 1.4m gaps. The results are shown in Table 5.

Table 5: Sparkover voltages, average times T_I to first corona and average times T_B to breakdown

ESE rod	Gap = 1 m	Franklin rod	Gap = 1m
$V_{DC} = 0$	–250kV	0	–250kV
$V_{50} = -712$kV	–745	–709	–724
$T_I = 14$µs	9	15.5	11
$T_B = 247$µs	219	219	221
ESE rod	Gap = 1.4m	Franklin rod	Gap = 1.4m
$V_{DC} = 0$	–250kV	0	–250kV
V_{50} = —	–992	—	–985
T_I = —	—	—	—
T_B = —	195	—	233

Impulse voltage = 200/1400µs approximately

For both rods, sparkover voltages in the 1.0m gap were significantly increased by application of the negative prestress voltages; times to the first corona were, on average, reduced. Times to breakdown with both passive Franklin rod and Pulsar did not significantly differ from each other, either under simple impulse or with the prestress voltage. In the 1.4m gap, however, the average time to sparkover was 38µs less, for the Pulsar than for the Franklin rod, though this difference was within the respective standard deviations.

6 Discussion and concluding remarks

In these experiments, the passive and active Franklin rods and the Pulsar have been compared under simulated lightning storm conditions. The average stresses applied to each sphere-rod gap were similar, but in the active Franklin rod case, it constituted an overvoltage, whereas in the Pulsar case, it was a threshold voltage for sparkover. Absolute rates of rise of voltage were similar in each case, and a comparison between the two devices can therefore be made. With the active Franklin rod, working at approximately 40% overvoltage for the gap, it was shown that independent energising of the rod reduced the time to sparkover by between 40µs and 70µs, compared with that for the passive Franklin rod. This reduction was obtained, however, only over a narrow range of times of application of the auxiliary 1.2/50µs impulse at the rod, which themselves extended over 70µs prior to the breakdown time of the passive rod. These results were obtained whether or not the applied impulse, to the sphere, was preceded by a steady electric field. Thus, the time of energisation of the active rod was critical in achieving an advance of the breakdown time. Only one time-to-peak was used here; it was chosen to simulate the rate of rise of average field indicated in Fig. 3. It must be expected that a different advance would be obtained with a different time-to-peak and it follows that other average stresses, over a range that might be expected from the leaders occurring in nature, would also affect the results.

Comparison of the Pulsar rod with the passive Franklin rod showed little difference in sparkover characteristics, except at the longer gap used, where a possible time advantage to the Pulsar of 40µs was noted. The nature of the tests precluded observation of the timing of the Pulsar's oscillatory voltage pulse, however, and direct comparison in this respect with the active Franklin rod is not possible. The preliminary tests showed an increase in the repetition rate of this pulse with applied stress, but this was always less than 25 Hertz and absolute values may have been affected by the presence of the measurement circuit. The pre-breakdown corona showed a higher frequency of corona pulses than the Franklin rod, probably due to the sharpness of the point. There was no clear evidence of an effect due to the oscillatory voltage pulse on this corona, which was assumed to be due to the main impulse voltage on the sphere.

Thus, the maximum reduction in time to breakdown, T_B was from 310µs to 240µs, achieved with the active Franklin rod. Reference to the measured impulse waveform shows this to correspond to a reduction in stress from 86% of that at peak voltage to 76%, that is, a reduction to 88% of the value for the passive rod. Direct comparison with the work of Berger [4], is not possible, because only times to leader inception were presented there.

Differences in time to sparkover must depend on gap length, since the growth of the upward leader must determine the breakdown time. Since the maximum time advance found in the present work was 70µs and since the velocity of the leader with both active and passive rods can be assumed to be the same, that is, about 2×10^4ms^{-1} [5], it is clear that the maximum time advantage for leader formation found in this work is 70µs. This is to be compared with ~100µs in [5] for a gap of 9.5m.

These results, and the comparison with [4, 5] indicate that the time advantage may not depend strongly upon the gap, and Table 5 indicates that the variation with stress is not strong. The most important result is the critical nature of the timing of energisation of the rod; in nature, therefore, it would be essential that a self-powered device such as the Pulsar must energise the rod at an optimum time in relation to the rate at which the field due to the downward leader is increasing. This rate of increase is variable due to the great variation in measured velocities of the approaching downward leader [1]; however, the present work shows that the pulsed oscillations occur at only low repetition rates over a wide range of fields. Further work would be needed to show that such a device is able to energise itself at a time which provides a significant time advantage in leader initiation.

7 Acknowledgment

The authors thank English Heritage for their financial support for this work.

8 References

1 UMAN, M.A.: 'The lightning discharge' (Academic Press, 1987), Chapter 3

2 BOUQUEGNEAU, C.: 'Laboratory tests on some radioactive and corona lightning rods'. Proceedings 18th international conference on *Lightning protection*, Munich, 1985, pp. 37–45

3 GRZYBOWSKI, S., LIBBY, A.L., GUMLEY, J.R., and GUMLEY, S.J.: 'Comparative testing of ionizing and non-ionizing air terminals'. Proceedings 10th international symposium on *High voltage engineering*, Montreal, 1997, Vol. 5, pp. 331–334

4 BERGER, G.: 'Determination of the inception electric field of the lightning upward leader'. Proceedings 8th international symposium on *High voltage engineering*, Yokohama, 1993, Paper 70.02

5 ALEKSANDROV, G.N., BERGER, G., and GARY, C.: 'New investigations in the lightning protection of substations'. CIGRÉ, Paris, 1994, Paper 23/13–14/

6 CRISTESCU, D., and GARY, C.: 'Laboratory simulation of the lightning impact to the ground'. Proceedings symposium *Lightning and mountains*, Chamonix, 1994

7 MACKERRAS, D., DARVENIZA, M., and LIEW, A.C.: 'Critical review of claimed lightning protection of buildings by early streamer emission air terminals', *IEE Proc Sci. Meas. Technol.*, 1997, **144**, pp. 1–10

8 ALLEN, N.L., HUANG, C.F., CORNICK, K.J., and GREAVES, D.A.: 'The sparkover of air gaps under composite/direct voltages'. Proceedings 10th international symposium on *High voltage engineering*, 1997, Vol. 3, pp. 157–160