Laboratory investigations of RF plasmas relevant to CW arc pluming at high-power aerials. Pt. 2: Relevance of scale-model studies based on pulsed RF techniques


Indexing terms: Discharges, electric, Arcing, Plasmas, Discharges, gas

Abstract: The paper describes experiments which extend the observations of RF breakdown events in nonuniform fields reported in Part 1 of the paper. In particular, emphasis is given to examining the relevance of laboratory observations on pulsed RF discharges to the understanding of the 'pluming' phenomenon occurring under CW conditions at high-power aerial arrays. This is achieved by examining the effects of various scaling factors on the breakdown characteristics using both scaled sphere-to-plane and scaled toroid-to-plane geometries. It is shown how the intrusion of objects with needle-point geometries can lead to dramatic reductions in the critical electric fields needed to initiate the unwanted 'pluming' phenomenon.

1 Introduction

Laboratory experiments with pulsed RF discharges were described in Part 1 of the paper [1]. The importance of such discharges for the serious engineering problems caused by pluming at high power aerials raises the question as to the relevance of laboratory experiments for such situations. The purpose of the present paper therefore is to examine the effects of various scaling factors on the breakdown events under RF conditions.

The breakdown processes preceding the establishment of high frequency discharges have been studied extensively [2, 3], and high frequency breakdown potentials have been measured [4, 5, 6]. However, the evidence established in Part 1 of this paper for the influence of sharp needle-like geometries on the values of the critical RF corona onset voltages suggests that more thorough examination of the isolated needle-point-to-plane geometry should be undertaken. Unfortunately, however, it was not possible to do so with the equipment available to us. The needle points of direct practical interest created such large electric field distortions in the absence of the surrounding plane electrode, that corona onset occurred at voltages too low for us to maintain in the present apparatus [7].

Using isolated sphere-to-plane geometry, however, the electric field between the electrodes is more uniform and it was then possible to observe onset of corona. As will be seen later, in the context of the scaling factors required to demonstrate relevance for the field situation, such an approach is useful. Subsequently, the specific influence of needle-point geometries was examined for the actual geometry on which the 'pluming' phenomenon was observed, namely a toroidal corona ring with a point protrusion.

2 Scaling limitations and experimental procedures

The significant dimensions of the dipole components of an aerial array experiencing 'pluming' effects are shown in Fig. 1A. The dimension $h = 200$ cm cannot be reduced by more than a factor 100 if we are to retain a gap separation, $d'$, equivalent to 20 mm in the laboratory apparatus. This has several consequences for the achievement of appropriate dimensions in the scaled-down situation. First, on the

![Fig. 1A Dimensions of the dipole components of the transmitter aerial array](image)

Typical values: $d_M = 40$ cm, $d_s = 12$ cm, $h = 200$ cm and distance to ground plane $d = 10$ m

basis that the actual distance to the ground plane at the field transmitter is $\sim 10$ m, the corresponding value of $d'$ should be 100 rather than 20 mm. Secondly, scaling a toroid by this factor would require a toroidal minor axis ($d_M$) of 1.2 mm and a major axis ($d_M$) of 4 mm, which poses some manufacturing difficulties. As a first step, therefore, we undertook some measurements to check scaling influences, especially those associated with $d'$, by using a series of spherical brass conductors of varying diameter. The diameters chosen were those corresponding to the minor diameters of the corona rings and included the limiting case of a reduction of 1:100. A total of nine brass spheres provided diameters varying from 1.22 mm to 11.82 mm and corresponding to scaling factors of 100, 80, 40 and 10. For these experiments the upper Rogowski-profiled electrode [1] was removed and the spheres attached to an insert at the top of the ionisation chamber by a supporting rod of diameter $\sim 0.9$ mm and length $\sim 10$ mm.

All experiments were performed in air, at pressures varying between 50 torr and atmospheric, using 10 $\mu$s RF pulses at a repetition rate of 50 Hz. A flat detuned waveform, in which the maximum envelope voltage was maintained for some 9 $\mu$s after the initial rise, was used in order to avoid any of the possible temporal effects on the breakdown voltage referred to in Part 1 of this paper. The gap was continuously irradiated with UV photons from a mercury vapour lamp source to ensure an effectively zero
statistical time lag. As in Part 1, the criterion for breakdown was the visual observation of the weakly ionised corona plasma itself and the peak voltage $V_{pk}$ was recorded in each case.

The gap distance $d'$ (see Fig. 1B) could be varied between 10 and 20 mm by adjusting the position of the lower planar stainless-steel electrode.

### 3 Observations with sphere-plane geometry

Typical of the results obtained are those shown in Fig. 2 for sphere diameters of 1.22 and 11.82 mm and electrode separations of 10, 15 and 20 mm, respectively. These spheres represent the two extremities in our scaling parameter ($\times 100$ and $\times 10$, respectively). The measurements for the other seven spheres were found to fall between those shown in Fig. 2. The slope of each curve of $(V_c)_{pk}$ as a function of $p_{20}d'$ represents the macroscopic value, useful in the engineering context, of $(E_c)_{pk}/p_{20}$ at the onset of visual coronal plasma. These values are summarised in Table 1, which shows a variation in this value from 5.24 $V_{pk}$ cm$^{-1}$ torr$^{-1}$ for the smallest sphere at largest gap separation, to 26.90 $V_{pk}$ cm$^{-1}$ torr$^{-1}$ for the largest sphere at smallest gap separation. They are consistent with the expected trend towards a value appropriate to a plane-parallel gap, i.e. 39 $V_{pk}$ cm$^{-1}$ torr$^{-1}$. For a constant pressure and gap separation there is a linear variation of corona onset voltage $V_c$ with sphere radius $r$. Furthermore, for a constant sphere radius, the macroscopic value of $(E_c)_{pk}/p_{20}$ at which the corona onset is observed becomes smaller the larger the electrode separation ($d'$). This is a consequence of the increasing nonuniformity of the electric field.

### 4 Observations of scaling effects

The scaling effects are best examined with reference to the ratio of the two parameters $r$ and $d'$ referred to in Section 3. The significance of the ratio $r/d'$ can be established by applying the method of electrostatic images [8] to the case of a sphere-plane gap. It can be more simply appreciated by considering a concentric spherical geometry for which the sphere-plane configuration is a special case corresponding to large $d'$ and small $r$. At any position $l$ (Fig. 1B) the field $E'$ due to an applied voltage $V_s$ is given by:

$$E' = \frac{V_s}{r^2 \left( \frac{1}{r} - \frac{1}{r + d'} \right)}$$

At the surface, $l = r$, the field becomes:

$$E' = \frac{V_s}{r^2 \left( \frac{1}{r} - \frac{1}{r + d'} \right)} = \frac{V_s}{d'} \frac{1}{(r/d') \left( \frac{r}{d'} + 1 \right)}$$

and when $r \gg d'$ this field reduces to the uniform field value $E = V_s/d'$. For a critical field at corona onset of $E$, it then follows that the ratio of the applied voltages required for the concentric sphere and uniform-field geometries, respectively, is given by:

$$\frac{V_c}{V_s} = \frac{y}{y + 1}$$

where $y = r/d'$.

The variations of $V_c/V_s$ with $r/d'$ for both the uniform-field and concentric sphere conditions are shown in Fig. 3A. Included also is the corresponding variation observed in our scale-model experiments. As expected, this falls between the two extreme cases considered. Details of the individual corona onset measurements are given in the plot of $(V_c)_{pk}/p_{20}d'$ as a function of $r/d'$ shown in Fig. 3C. Although the variation is nonlinear, the near coincidence of all the points to the single curve indicates that a scaling
factor can, in fact, be used to anticipate the breakdown requirements for a scaled-up experiment. This is confirmed by analysing the changes with \( r \) and \( d' \) separately. For example, doubling \( r \) for a constant \( d' \) increases \( V_{p20}/p20 \) by a factor \( \sim 1.5 \), whereas doubling \( d' \) for a constant \( r \) increases \( V_{p20}/p20 \) by a factor 1.1. This figure corresponds, within the approximate scatter of \( \pm 10\% \), to the fitted curve of Fig. 3C.

We therefore assume a 1:1 scaling factor in order to make an estimate of the onset voltages that must be applied to a scaled-up sphere-plane geometry to initiate corona. Using the representation of Fig. 3B we see that for a sphere of diameter 12 cm situated 0.5 m from a plane surface, i.e. \( r/d' = 0.12 \), \( V_r/V_o = 0.26 \). Since, as indicated above, \( E_r/p \sim 39 \text{ V cm}^{-1} \text{ torr}^{-1} \), then \( V_r \) for uniform-field conditions at atmospheric pressure is given by \( V_r = 39 \times 760 \times 50 \). The value for \( V_r \) would then be 0.26 \( \times 39 \times 760 \times 50 = 385 \text{ kV} \). The same conclusion is reached by analysis of the \( V_r/p20 \) against \( r/d' \) information shown in Fig. 3C.

For an aerial array, \( d' \) will be \( \geq 0.5 \text{ m} \), so that for the same diameter sphere we need to know the onset voltages extrapolation of the curve of Figs. 3A–C to lower values of \( r/d' \). There are obvious limitations to increasing \( d' \) in the laboratory experiments, but we can be guided to some extent by the experience gained at the aerial sites themselves. For example, at the Darwin transmitter arc plumes have been observed in the presence of maximum macroscopic voltage gradients calculated to be in the range 2.3 to 6.4 kV(pk) cm\(^{-1}\) [8]. This is consistent with the conclusion in Part 1 of this paper that voltage gradients of only 2.5 kV(pk) cm\(^{-1}\) will trigger the onset of corona (see, for example, the gradient of the \( V_r \) against \( p20 \) curve for air in Fig. 8A of Part 1). Consequently, if we now assume that for the small \( r/d' \) value appropriate to the Darwin geometry arc plumes were indeed triggered by voltage gradients \( \sim 2.5-3.0 \text{ kV(pk) cm}^{-1} \), a limiting value for small \( r/d' \) of \( V_r/p20 \) can be set as 3-4 V(pk) cm\(^{-1}\) torr\(^{-1}\) (\( \ast \)). Fig. 4 shows the extrapolation based on this limiting value (\( \ast \)), and confirms that our own values appear to match those of the actual aerial situation.

Also shown in Fig. 4 is an extrapolation of our experimental results to the other limiting case of large ratios of \( r/d' \). For the sphere-plane geometry, the macroscopic electric field between the electrodes may be considered uniform [9] for \( r/d' \geq 3 \). For this ratio, the value of \( V_r/p20 \) will approach \( 39 \text{ V cm}^{-1} \) torr\(^{-1}\) (\( \ast \)).

On this basis, we have available in Fig. 4 a curve of \( V_r/p20 \) against \( r/d' \) that allows us to predict the onset of corona for a variety of sphere-plane configurations. Appropriate design consideration should then determine a combination of applied voltage and \( r/d' \) to ensure operation

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well within the shaded area of Fig. 4, for example point A, where no coronal discharge can be established. If, however, roughness was examined by carrying out experiments on one highly polished corona ring in each case. Furthermore, a facility was provided for introducing a sharp needle-point protrusion from the largest of the corona rings so that the influences of local changes in the electric field could be examined. All observations were made in air using the same experimental conditions as for the spherical conductors, i.e. flat detuned 10 µs RF pulses at 10 MHz, with UV irradiation from a mercury vapour lamp to ensure negligible statistical time lag. Fig. 5 shows the

![Corona rings used to study corona onset voltages](image)

Fig. 5 Corona rings used to study corona onset voltages

corona ring electrodes and their dimensions are given in Table 2.

The criterion for a breakdown event was again a visual observation of the onset of small-volume corona. Each corona ring was set parallel to the lower electrode and the corona onset voltage recorded as \( p_{20}d' \) was varied. In this case the visual corona was located on the lower, inner surface of the toroid and was evenly distributed around the major circumference. No visual corona were detected at any time on the supporting wires. No difference was observed between the highly polished and roughened surfaces for each scaling factor, and all subsequent measurements were carried out on highly polished rings. Fig. 6 shows the results for three differently scaled corona rings for values of \( d' \) of 10, 15 and 20 mm. For the largest ring \( (d_m = 11.50 \text{ mm}) \) no corona onset could be detected for \( d' = 10 \text{ mm} \). The observed breakdown was of the continuous form [1] indicating that at this separation the field distortions were not sufficiently large to allow the local breakdown process to be sustained. Analysis of the gradients of the curves of Fig. 6 showed that the macroscopic values for the parameter \( (E_x)_{P20} \) at atmospheric pressure (760 torr) varied between 8.02 and 36.10 V/(pk) cm\(^{-1}\) torr\(^{-1}\), for the smallest to largest corona ring, respectively. The results show that the larger the gap separation, the smaller the ratio \( (E_x)_{P20} \) at which corona onset is observed. This was also noted for spherical conductors, for which, because of the greater nonuniformity in electrical

![Graph](image)

**Table 2: Dimensions of the corona rings used to study the corona onset voltages (see Fig. 1A)**

<table>
<thead>
<tr>
<th>Corona ring number</th>
<th>Major diameter ( d_m ), mm</th>
<th>Minor diameter ( d_m ), mm</th>
<th>Electrode length ( h ), mm</th>
<th>Approximate scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.05</td>
<td>1.50</td>
<td>16.50</td>
<td>1:80</td>
</tr>
<tr>
<td>2</td>
<td>4.80</td>
<td>1.50</td>
<td>17.50</td>
<td>1:80</td>
</tr>
<tr>
<td>3</td>
<td>10.00</td>
<td>2.96</td>
<td>16.96</td>
<td>1:40</td>
</tr>
<tr>
<td>4</td>
<td>9.95</td>
<td>3.21</td>
<td>18.21</td>
<td>1:40</td>
</tr>
<tr>
<td>5</td>
<td>38.20</td>
<td>11.50</td>
<td>14.50</td>
<td>1:10</td>
</tr>
<tr>
<td>6</td>
<td>38.20</td>
<td>11.50</td>
<td>16.50</td>
<td>1:10</td>
</tr>
</tbody>
</table>

Odd-numbered rings had roughened surfaces
Even-numbered rings were highly polished

5 Observations using scale-model corona rings

Experiments using scale models were confined to scaling factors of 1:10, 1:40 and 1:80. The influence of surface

field, the differences in the ratios were more pronounced. As would be expected, the toroidal configuration is more favourable for inhibiting spurious breakdown at low values of $E/p$.

The appropriate parameter involved in examining the effects of the scaling with toroidal corona rings is the ratio $(d_m/2)/d'$ (cf. $r/d'$ for spherical conductors). Consequently, the variations of both $V_c/V_a$ and $(V_c/p)_{pk}/p_20 \cdot d'$ for $p_20 = 760$ torr with this ratio are also shown in the Figs. 3A, B and C. Fig. 3A shows clearly that the toroidal-plane geometry provides more uniform-field conditions than the sphere-plane geometry, and that observations of critical corona onset voltages made with scale models of the aerial array are again relevant for consideration of the conditions appropriate to the actual system. Before examining this situation it should be noted that for $(d_m/2) = 5.75$ mm, $d' = 10$ mm, the value of $(E_{pk})_{pk}/p_20 = 36.10$ V cm$^{-1}$ torr$^{-1}$ is close to the figure of 39 V cm$^{-1}$ torr$^{-1}$ observed in the uniform field of a plane-parallel electrode geometry.

In order to estimate voltages necessary to initiate the onset of a coronal breakdown event at the actual aerial array, we note that the corona rings used had a major diameter $d_m = 40$ cm and a minor diameter $d_m = 12$ cm. Assuming that one such ring was situated at $d' = 10$ m from the ground plane, the value of $(d_m/2)/d' = 0.006$. From Fig. 3B $V_c/V_a \sim 0.025$ so that $V_c \sim (E/p)_{pk} x \times 0.025$. For $p_20 = 760$ torr, therefore, the voltage for which corona onset should be observed is $\geq 740$ kV. The maximum voltage at the end of the actual radiating element, referred to as neutral plane, is 28 kV(RMS) or nearly 40 kV(pk) [8]. What now needs to be understood, therefore, is the mechanism by which a voltage of 40 kV(pk) can, in fact, lead to a breakdown event causing arc pluming when the ground plane is many metres from the radiating element. As we shall see in Section 6 small perturbations to the corona ring geometry are sufficient to distort the local electric field to such an extent that the onset of corona is possible under low voltage conditions.

Fig. 6 Corona onset voltages for three differently scaled corona rings at gap separations $(d')$ of 10, 15 and 20 mm

- $d' = 10$ mm
- $d' = 15$ mm
- $d' = 20$ mm

6 Observations using corona rings with point protruberances

The effect of a point protrusion was examined on the largest corona ring because this gave the most favourable voltage gradients for inhibiting the corona onset. The needle point, similar to the one used in Part I, was inserted vertically into the corona ring as shown in Fig. 5. Breakdown voltages for the corona onset were recorded for protrusions between 0 and 3 mm. As shown in Fig. 7 large reductions in $(V_c)_{pk}$ were observed for the four protrusions. The characteristic feature of the observations is the different saturation values of $(V_c)_{pk}$ as $p_20 \cdot d'$ values increase. The smaller the protrusion, the smaller the value of $p_20 \cdot d'$ at which saturation occurs. Also, as the needle point increases in length, the curves tend to saturate at small voltages following more extensive ranges of linear variation. For the 0.5 mm protrusion the plateau voltage of $(V_c)_{pk} = 10.9$ kV is maintained for $p_20 \cdot d' > 500$ torr cm. Unfortunately, on the laboratory scale, we have been unable to examine regions of small $x$ values with any reliability.

Several other uncertainties make it difficult to examine the causes of the Darwin pluming phenomenon in greater detail at this stage. For example, the value estimated (40 kV pk) for the maximum voltage at the end of the radiating element in the Darwin system should presumably be associated with the observed arc plume phenomenon. The actual voltage appropriate to the onset of those corona at sharp protrusions that may be responsible for initiating the growth to the arc-plume stage, may, in fact, be considerably lower. Furthermore, whilst the validity of the scaling factor approach has been shown to be valid for both the sphere-plane and toroid-plane geometries it is not yet clearly established to what extent this would be true for any substantial protrusions from the toroidal rings. Also, in the absence of any guidelines concerning the most probable radii of curvature of needle-like protrusions that are likely to be present, it is not particularly helpful to proceed.

Fig. 7 Corona onset voltages, for the largest corona ring through which a needle point protruded to distances $x = 0.5, 1, 2$ and 3 mm ($d' = 15$ mm)

- $d' = 15$ mm, $x = 0$ mm
- $d' = 14.5$ mm, $x = 0.5$ mm
- $d' = 14$ mm, $x = 1$ mm
- $d' = 13$ mm, $x = 2$ mm
- $d' = 12$ mm, $x = 3$ mm

further without more extensive information on such matters. It can be seen from the observations made so far, however, that with neutral planes many metres from the radiating element, there can be no constraints imposed by values of \( d' \), and it is easy to appreciate how it is possible for a corona breakdown event to be initiated. Indeed, in the presence of sharp points it matters little if the neutral plane is removed to large distances since no increase in corona onset voltage would be required. As far as the creation of arc plumes is concerned, the presence of the neutral plane appears to be largely irrelevant.

7 Discussion and conclusion

The laboratory observations reported here have shown that it is possible for sharp conducting objects, perhaps as small as 5 mm in length, to initiate a corona event that may lead to an arc plume at aerial arrays associated with high power transmitters. Clearly, the larger and sharper the object the more probable this will be. This would seem to place the arc-plume phenomenon well within the realm of the influences of insects and other natural objects. Furthermore, it has been demonstrated that the use of pulsed RF techniques in laboratory experiments provides information directly relevant to the complex phenomenon occurring at the transmitter site. The fact that the location of the neutral plane appears to have little significance and that it is the local electric field distortions that dominate the situation confirms the importance of developing a thorough understanding of these effects created by the presence of sharp objects. Whilst DC studies [10] with point protruberances have been carried out there is need obviously for further RF studies on both metallic conductors and similar partial conductors more appropriate to insect influences. Furthermore, given appropriate information about the radii of curvature of sharp points associated with those insects, investigations should be extended to embrace a range of radii of curvature other than the 20 \( \mu m \) used in our laboratory experiments.

It should also be stressed that, so far, our laboratory studies have considered only sharp-point protrusions from the surface of the aerial system. An insect approaching such a surface may create local spatial distortions of the electric field which could catalyse a breakdown event leading to the rapid development of large volumes of plasma. Any attempt to understand such phenomena must recognise the different characteristics of the positive point-to-plane and negative point-to-plane discharges, and consequently that there might be distinctly different influences under RF conditions during the positive and negative half-cycles of the amplitude variations. Further insight into these situations requires a time resolution for image-convertor/image-intensifier techniques that would permit 5–10 ns snapshot records of the discharge development during each 50 ns half-cycle of the 10 MHz RF voltage pulse. Such observations, coupled with the corresponding time-resolved spectral output, would provide the information necessary to monitor the time-dependent changes in local space-charge distributions, and hence electric field variations. Such an approach is essential if we are to overcome the limitations of the semiempirical approach involving only macroscopic fields. An extensive investigation using improved microchannel plate image intensification and an optical multichannel analyser for spectroscopic analysis has now been undertaken and will be reported in a further paper.

8 Acknowledgments

The authors wish to acknowledge helpful discussions with Dr N. Sato, Visiting Research Fellow on leave from the Faculty of Engineering, Hokkaido University, Sapporo.

Financial and technical support for the work has been provided by the Australian Telecommunication Commission and both the Radio and Electrical Research Boards.

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