Part II - ELECTRICAL ASPECTS
by D. Mackerras

1. INTRODUCTION

An investigation into some electrical aspects of thunderstorms is in progress in the Department of Electrical Engineering, University of Queensland. One objective has been to obtain information on which to base the lightning protection of electrical apparatus. A lightning observatory on the roof of the Physics Building at St. Lucia has facilitated the observation and recording of visual data concerning thunderstorms in the vicinity of Brisbane, the checking of lightning stroke counter performance, and the operation of apparatus for measuring electric and magnetic field changes caused by lightning strokes. Visual information concerning thunderstorms in other parts of South-East Queensland is forwarded monthly on a thunderstorm report form by employees of the Southern Electric Authority, the Brisbane City Council, and some other observers.

The determination of the number of thunderdays per year for this area and techniques for observing and recording storm position, movement and numbers of lightning flashes are fairly well established. (Prentice, 1955, 1957 and 1960). Particular attention is being given at present to the following problems:

(i) To estimate the ground stroke density, N (number of ground strokes per square mile per year), for this area.

(ii) To develop means of detecting and recording the electric and magnetic field changes caused by lightning strokes with the purpose of obtaining information concerning lightning stroke current waveshapes and to provide information on which to base lightning stroke counter design.

(iii) To develop a device which will count automatically lightning strokes to ground within some specified distance and be suitable for continuous operation in remote sites with only occasional attention.

The information presented here is confined to the last two thunderstorm seasons (1959/60 and 1960/61). Thunderstorm observations prior to this have been described by Prentice (1960).

Table 1 summarises observations made on thunderstorms which came within ten miles of the observatory between June 1959 and May 1961.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Thunderstorm Days</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Duration of Observation</td>
<td>35 hr. 35 mins.</td>
<td>45 hr. 10 mins.</td>
</tr>
<tr>
<td>Number of lightning flashes observed.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground strokes</td>
<td>382</td>
<td>568</td>
</tr>
<tr>
<td>Sky strokes</td>
<td>1605</td>
<td>1742</td>
</tr>
<tr>
<td>Unidentified flashes</td>
<td>Order of 4000</td>
<td>Order of 4000</td>
</tr>
<tr>
<td>Number of stroke counter operations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counter A</td>
<td>5951</td>
<td>6910</td>
</tr>
<tr>
<td>Counter B</td>
<td>300</td>
<td>157</td>
</tr>
<tr>
<td>Counter C</td>
<td>-</td>
<td>118</td>
</tr>
<tr>
<td>Number of ground strokes within two miles</td>
<td></td>
<td>57</td>
</tr>
</tbody>
</table>

Counter A: Electrostatic lightning flash counter designed by Pierce, modified by Electrical Research Association, U. K.

Counter B: University of Queensland electromagnetic lightning counter, Mark I.

Counter C: Photosensitive lightning counter designed by H. Linck. (Hydroelectric Power Commission of Ontario).

On the approach of a thunderstorm, the radar set is started up, the observatory is manned, and lightning counters and other apparatus are switched on. The observer classifies each stroke observed as ground stroke, sky stroke, or unidentified stroke. This information is recorded automatically, together with any operations of the automatic lightning stroke counters under test.

The observer classifies a lightning flash as a ground stroke only when an arc channel is visible, and it appears very probable that it has reached the earth. When the arc channel appears to proceed between two clouds, or between different parts of one cloud, the flash is classified as a sky stroke.
All flashes which are obscured by cloud or rain are classified as unidentified. A very large proportion of all flashes observed are unidentified; the vast majority of these appear to occur high in the thundercloud, i.e., most of the unidentified flashes, perhaps 90 per cent or more, are probably sky strokes.

It is of interest to estimate the average ratio of sky strokes to ground strokes, as this has a bearing on stroke counter design. Assuming that 90 per cent of unidentified strokes are sky strokes, the orders of the numbers of ground strokes and sky strokes occurring within about ten miles of the observatory during the 1959/1960 and 1960/1961 seasons are:-

<table>
<thead>
<tr>
<th>Number of ground strokes</th>
<th>≈ 1,700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sky strokes</td>
<td>≈ 10,500</td>
</tr>
<tr>
<td>Total number of strokes</td>
<td>≈ 12,200</td>
</tr>
</tbody>
</table>

Therefore

\[
\frac{\text{Number of sky strokes}}{\text{Number of ground strokes}} \approx 6
\]

3. ESTIMATION OF GROUND STROKE DENSITY

(a) General

The design of power transmission lines is, to an important degree, governed by the need to protect the power system from interference by lightning. The planning of lightning protection is based, directly or indirectly, on an assumed ground stroke density, \( N \). The estimates of \( N \) at present available are of insufficient accuracy, hence it is desirable to consider means of estimating \( N \) to a useful degree of accuracy, e.g., to within ± 40 per cent.

(b) Estimation of \( N \) by direct observation

The available records of strokes to ground observed can be used to estimate \( N \). Considering the 1960/1961 season (see Table 1), 568 identified ground strokes were observed within approximately ten miles of the observatory, giving \( N = 1.8 \)/square mile/year. The sources of error in this estimate are ground strokes classed as unidentified or not observed at all, and uncertainty concerning the area within which the strokes occurred. If 10 per cent of the unidentified strokes are ground strokes, the estimate of \( N \) becomes 3.1/square mile/year.

A reduction in the uncertainty can be achieved by considering only those ground strokes close to the observatory, say within two miles. A ground stroke within two miles will be identifiable on most occasions and the distance can be determined fairly accurately from time to thunder. For the 1960/1961 season, 57 strokes to ground were observed within two miles of the observatory, so
N = 4.5 ground strokes/square mile/year

The sources of error in this method are failure to observe some ground strokes and incorrect estimates of distance. While no great accuracy can be claimed for the figure given above, this method is considered to be, potentially, the most accurate, provided adequate observations are made on all thunderstorms which pass close to the observation point. Several years of records will be needed to smooth out yearly irregularities.

(c) Estimation of N from Lightning Counter Results

Two of the automatic ground stroke counters at present being tested at the University of Queensland lightning observatory have sufficiently satisfactory performances to make their registrations potentially useful for estimating N. These are Counters B and C (refer to Table 1). More information on these counters is given in Section 5, together with the method of estimating the effective range. To illustrate the method of estimating N, the results obtained with these counters are summarised in Table 2. Because of the short period of observation and the many possible sources of error listed below, the numerical values given should not be considered reliable.

**TABLE 2. Estimates of N from Lightning Counter Results**

<table>
<thead>
<tr>
<th>Counter</th>
<th>Estimated Effective Range, R. (Miles)</th>
<th>Thunderstorm Season</th>
<th>Number of Counts (C)</th>
<th>Estimate of N. Strokes per sq. mile per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>3.3</td>
<td>1959/1960</td>
<td>300</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1960/1961</td>
<td>157</td>
<td>4.6</td>
</tr>
<tr>
<td>C</td>
<td>4.3</td>
<td>1960/1961</td>
<td>118</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Possible sources of error in the estimates of N obtained as shown in Table 2 are listed below.

(i) The counters may not be in service when close ground strokes are occurring. Counter B is switched on only during thunderstorms and Counter C has had its photoelectric cell covered except during thunderstorms at night, so both counters require an observer in attendance.

(ii) Sky strokes may cause the counter to operate. Both counters reject most of the sky strokes occurring near the observatory.
(iii) Some operations may be caused by spurious signals such as mains switching surges. Counter B operates occasionally on mains switching surges, but not counter C.

(iv) There may be errors in the estimated effective range, and the sensitivity may be set incorrectly. This applies particularly if some complicated procedure must be followed in adjusting the sensitivity.

(v) The short period of observations, combined with the relatively small range of counters B and C, renders the results susceptible to patchiness in the spatial distribution of ground strokes; several years of records will be needed to smooth out spatial and temporal irregularities in ground stroke density.

These sources of error make estimates of N from lightning counter results less accurate than estimates based on direct observation. However the use of lightning counters may be the only way of obtaining information about N in remote sites where sustained observations are not possible.

4. ELECTRIC AND MAGNETIC FIELD CHANGES CAUSED BY LIGHTNING STROKES

(a) General

The first quantitative measurements of electric field changes caused by lightning strokes were made early in the 20th century by C. R. T. Wilson at Cambridge (Wilson, 1916 and 1920). This work was extended and refined by Appleton, Watson-Watt and Herd (1926) and later by Wormell (1953) and Pierce (1955a, 1955b, 1957 and 1960). The main advance in technique was in the introduction of the cathode ray oscilloscope to this class of work, enabling a considerable reduction in resolving time. In South Africa and elsewhere, Schonland, Malan, Clarence and others have carried out extensive studies, using electric field measurements, of charge distribution in thunder clouds, of electrical processes in lightning discharges, etc. The numerous publications of this group are recorded by Chalmers (1957).

Norinder (1935, 1937, 1945 and 1956) working at the Institute of High Tension Research, Sweden, was alone among workers in this field in preferring to study magnetic field changes caused by lightning strokes. He appears to have initiated the idea that detailed information concerning stroke current waveshape may be obtained from the recorded field change (a record of the variation with time of the magnetic field, in this instance), an idea which has recently been adapted by Wagner (1960) with the purpose of obtaining information concerning the fronts of stroke current waveshapes.
(b) The detection of Field Changes

The field changes caused by lightning strokes, i.e. the variation with time of the electric field \( E \) and the magnetic field \( H \), caused by the lightning stroke current \( I \), can be detected at a distant point by a suitable antenna. The voltage output of the antenna displayed on a C.R.O. gives a record of the waveshape of \( E \) or \( H \) (or their differentials) which can be interpreted in terms of lightning stroke structure and stroke current waveshape. Alternatively, in a lightning counter, the antenna voltage is applied to a suitable circuit with the output to a mechanical register.

The relation between stroke current and height, and the electric or magnetic field at a distant point has been derived from Maxwell's field equations by Lejay (1926).

In particular, with certain idealising assumptions, it can be shown that the rate of change of electric field, \( \frac{dE}{dt} \), is given by

\[
\frac{dE}{dt} = 2 \times 10^{-7} \left( \frac{c^2}{r^3} \frac{hI}{r^2} + \frac{1}{r} \frac{h}{dt} \frac{d^2I}{dt^2} \right) \text{ volt/metre sec}
\]

where \( c = 3 \times 10^8 \text{ metre/sec} \),

\( h = \) vertical height in metres of the part of the stroke channel in which the current \( I \) (amps) exists,

and \( r = \) distance from stroke to point of observation (metres).

A consideration of the available information concerning stroke current waveshapes (e.g., Berger, 1955), together with information obtained from stroke counter performance, indicates that the radiation component of the field change is predominant in determining the output of both loop antennae (sensing \( dH/dt \)), and open antennae with low resistance to earth (sensing \( dE/dt \)), at distances of more than about 5 km from the stroke.

Thus, an approximate expression for the maximum value of \( dE/dt \) is

\[
\left( \frac{dE}{dt} \right) \max \approx 2 \times 10^{-7} \frac{1}{r} \left( \frac{h}{dt} \frac{d^2I}{dt^2} \right) \text{ max.} \text{ volt/metre sec}
\]

The quantity \( \frac{h}{dt} \frac{d^2I}{dt^2} \max \) has been estimated on the basis of the performance of counter \( B \), and certain data described in Section 4 (d) to be of the order of \( 10^{19} \text{ metre amp sec}^{-2} \).
(c) The Measurement of $\frac{dE}{dt}$

An investigation has been carried out at the University of Queensland lightning observatory of the rate of change of electric field, $\frac{dE}{dt}$, caused by lightning strokes. An open antenna in the form of a 30 cm diameter sphere one metre above an earthed plane, with a correctly terminated coaxial cable lead-in, has been used to measure $\frac{dE}{dt}$. This "sphere antenna" is shown in Fig. 1.

During three thunderstorms on 19.2.1961, 25.2.1961 and 26.2.1961, observations were made of peak antenna voltage, $V_{\text{max}}$, caused by 28 ground strokes and 38 sky strokes. Distance to stroke, $r$, was determined from time to thunder.

As $V_{\text{max}}$ is proportional to $(\frac{dE}{dt})_{\text{max}}$, these observations were used to test for a relation between $(\frac{dE}{dt})_{\text{max}}$ and $r$. In addition, the waveshape of the antenna voltage was examined oscillographically using both a fast time base (1 to 10 micro-second/cm) and a slow time base (50 to 200 millisecond/cm) in conjunction with pulse stretching equipment.

(d) Notes on the Observations of $\frac{dE}{dt}$

The amount of data obtained so far is, of course, far too inadequate for definite conclusions to be drawn. However, the following points have been noted.

- 30 cm diameter hollow copper sphere supported on a wooden post. Sphere capacity, $G \approx 18pF$.
- Earthed plane defined by radial horizontal metal rods. (A large horizontal sheet metal surface would be better).
- Coaxial cable. Characteristic impedance approximately 70 ohms.
- $V \approx R \cdot G \frac{dE}{dt}$ volt
- $R = 70 \text{ ohm}$

Fig. 1 Sphere Antenna
(i) The antenna voltage waveshape consists of a succession of pulses of varying magnitude, typically about 20, spread over 0.3 to 1 or more seconds. These may be associated with the component strokes in a complete discharge.

(ii) The width of each pulse is between 0.2 and 2 microseconds, typically about 0.7 microseconds.

(iii) The maximum pulse magnitude during a particular discharge, \( V_{\text{max}} \), varies from about 0.1 volt for distant strokes (20 to 30 km) up to about 1 volt for close ground strokes. (This corresponds to \( (d\mathcal{E}/dt)_{\text{max}} = 8 \times 10^8 \) volt/metre sec.)

(iv) \( V_{\text{max}} \) and consequently \( (d\mathcal{E}/dt)_{\text{max}} \) are approximately inversely proportional to distance, \( r \). An average value of the quantity \( r (d\mathcal{E}/dt)_{\text{max}} \) has been found to be of the order of

\[
20 \times 10^{11} \text{ volt/sec for ground strokes}
\]

and \( 10 \times 10^{11} \) volt/sec for sky strokes.

(v) \( (d\mathcal{E}/dt)_{\text{max}} \) has not been observed to exceed \( 6 \times 10^8 \) volt/metre sec for any sky stroke, i.e., it appears that the inverse proportionality between \( (d\mathcal{E}/dt)_{\text{max}} \) and \( r \) breaks down when \( r \) is small, about 4 km.

The narrow width of the pulses of voltage suggest a radiating element not more than a few hundred metres long, in which very large values of \( d^2I/dt^2 \) exist for a period of the order of a microsecond. It seems probable that this occurs at the beginning of the return stroke when the leader stroke has reached a point a few hundred metres above the earth and the electric field between the tip of the leader and the earth is large and increasing rapidly, causing the air to break down rapidly.

Similar processes must occur in sky strokes to produce the observed values of \( (d\mathcal{E}/dt)_{\text{max}} \). However, the short portion of the arc channel from which intense radiation occurs will be a considerable distance above the ground and frequently will be unfavourably situated for producing a large value of \( d\mathcal{E}/dt \) at the observation point below. Thus geometrical factors only may be sufficient to explain the observed ceiling to values of \( (d\mathcal{E}/dt)_{\text{max}} \) caused by sky strokes.

Apart from the differences noted above, sky strokes and ground strokes appear to be similar in electrical characteristics. This view is supported by the observations of workers at the Banaras Hindu University, that sky strokes have many of the features of ground strokes, such as return strokes, many components, etc. (Tantry, 1957).
5. GROUND STROKE COUNTER PERFORMANCE, CALIBRATION AND DESIGN REQUIREMENTS

(a) Discrimination against Sky Strokes

The main problem in ground stroke counter design is to discriminate against sky strokes. Observations of electric field changes, and the performances of various stroke counters indicate that ground strokes and sky strokes are electrically similar, and that the only difference that should be relied on for stroke counter design purposes is that sky strokes are always a considerable distance above the ground, whereas in ground strokes the portion of the arc channel which radiates most intensely is close to the ground and approximately vertical, that is, in the best position to radiate to an observer on the ground.

(b) Performance of Counter A

The operations of counter A (refer to Table 1) have been directly correlated with observed strokes during 12 thunderstorms between 23-10-60 and 9-2-61 in the Brisbane area. The performance is analysed in Table 3.

**TABLE 3. Analysis of operations of counter A during a total period of 11 hours, when thunderstorms were within 10 miles of the observatory**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ground strokes directly observed</td>
<td>325</td>
</tr>
<tr>
<td>Number of ground strokes counted by counter A</td>
<td>196 (65%)</td>
</tr>
<tr>
<td>Number of sky strokes directly observed</td>
<td>1429</td>
</tr>
<tr>
<td>Number of sky strokes counted by counter A</td>
<td>550 (38%)</td>
</tr>
<tr>
<td>Number of unidentified strokes directly observed</td>
<td>2216</td>
</tr>
<tr>
<td>Number of unidentified strokes counted by counter A</td>
<td>1004 (45%)</td>
</tr>
<tr>
<td>Number of operations with no recorded stroke</td>
<td>733</td>
</tr>
<tr>
<td>Total number of operations</td>
<td>2483</td>
</tr>
</tbody>
</table>

The sensitivity of counter A to sky strokes makes it difficult to relate counter A registrations to ground stroke density in this area. (This difficulty may not arise in areas where the sky stroke/ground stroke ratio is small). Table 1 shows that counter A registrations correlate much better with total strokes observed than with ground strokes observed. It is difficult to estimate the effective range of counter A, but its observed performance suggests that it is of the order of 10 miles for ground strokes and somewhat less, perhaps 5 miles, for sky strokes.

During the 1960/61 season, with an estimated ground stroke density of about 5/square mile/year, there should have been about 1600 counts, whereas there were actually 5951 counts. So, to correct counter A registrations for sky strokes counted, it would be necessary to divide the registrations by about 4.
Another factor which makes interpretation of counter A registrations difficult is that the sensitivity of the instrument increases during storms because of changes in the ignition level of the cold cathode gas triode.

(c) Performance of Counter B

This counter was designed by M. W. Robson of the University of Queensland Department of Electrical Engineering on the basis of experience obtained with the lightning stroke counter designed by Trumpy (1954). The principle of operation is shown in block diagram form in Fig. 2.

It employs a pair of crossed loops as antennae and registers when the voltage induced in either loop exceeds a chosen threshold (approximately 1.5 volt) which can be varied. The discrimination against sky strokes is satisfactory only if the sensitivity is set so that the range is not more than about 3.5 miles.

Work is in progress on producing a transistorised version of this counter (U. Q. E. M. Mark II) which is battery operated and can be left switched on permanently.

Crossed loop antenna

Rectifier Stage

Amplifier

Flip-Flop

Output Stage

Mechanical Register

Calibrating Circuit

Power supply is operated from 240 volt A.C. mains.

Fig. 2 Principle of operation of University of Queensland Electromagnetic Counter Mk. I (denoted as Counter B)
(d) Performance of Counter C

This counter was designed on the basis of experience obtained with a lightning stroke component counter, described by Ellis and Linck (1958). The counter is fully transistorised and employs a photoelectric cell shielded so that only light from points close to the horizon can reach the cell. It also employs an open antenna, an R.F. channel and a gate circuit so that the counter only registers when a low light flash and an electric signal above certain thresholds occur simultaneously.

This counter discriminates satisfactorily against sky strokes. In three storms, during which 183 ground strokes, 863 sky strokes, and 966 unidentified strokes were observed, 7 out of the 66 operations coincided with identified sky strokes.

(e) Determination of the effective range of a counter

If the effective range be denoted as $R$ miles, then it must be defined so that the formula $N = \frac{C}{\pi R^2}$ ground strokes/square mile/year is correct, $C$ being the number of counts in one year. This is in accordance with the meaning of effective range given by Horner (1960). Assuming that the counter operates on a fraction $f$ of ground strokes between $r$ and $r + dr$ miles away, then in one year

$$\pi R^2 N = C = \int_0^{\infty} N f \, 2\pi r \, dr \, \text{counts}$$

So, $R = \left(2 \int_0^{\infty} f \, r \, dr\right)^{\frac{1}{2}}$ miles.

The $f/r$ relation for a particular counter can be determined only by detailed observation of the performance of the counter during several thunderstorms. It is necessary to record all strokes observed with distance from time to thunder where possible, and whether or not the counter operated. Approximate $f/r$ relations, called performance curves, have been determined only for counters B and C. From these, the effective ranges can be estimated. Both estimates are based on statistically meagre data and further observations will be required to improve their precision. The approximate performance curve for counter B is shown in Fig. 3.

for counter B, $\int_0^{\infty} f \, r \, dr = 5.60$ square miles

therefore effective range $(R) = \left(2 \int_0^{\infty} f \, r \, dr\right)^{\frac{1}{2}} = 3.3$ miles.
Fig. 3 Approximate performance curve of Counter B

(f) Summary of Ground Stroke Counter Design Requirements

Field experience with several forms of ground stroke counter and the need for an instrument which will yield reliable information about N in remote sites with the minimum of attention, have led to the following design requirements for a ground stroke counter.

(i) The counter should respond mainly to ground strokes, i.e., should reject most (say 98%) of the sky strokes near it.

(ii) The sensitivity should be fixed by stable, passive elements and relatively constant sources of e.m.f., e.g., open circuited dry cells.

(iii) Antenna site requirements should not be unduly critical.

(iv) The effective range, R, which is determined by the sensitivity and antenna arrangements, should not be more than about 5 miles so that R can be determined with reasonable accuracy by the method described in Section 5 (e).
(v) The counter should contain its own power supply and have a low quiescent current drain so that it can be left on permanently.

(vi) There should be an insensitive period of about one second after an operation to avoid counting the separate components of a complete discharge.

(vii) The counter should not respond to switching surges or have any tendency to instability which would cause spurious registrations.

(viii) The counter should be robust and simple to operate and maintain.

The observation that sky strokes do not cause a value of \( (dE/dt)_{\text{max}} \) greater than \( 6 \times 10^8 \) volt/metre sec (see Section 4 (d)) suggests a basis for a ground stroke counter design. A trial instrument has been constructed based on a threshold antenna voltage of 0.75 volt and the design requirements listed above; the performance of this instrument during the 1961/1962 thunderstorm season will enable the reliability of this design basis to be assessed.

6. CONCLUSIONS

The following conclusions are based on observations in Brisbane.

(i) The sky stroke/ground stroke ratio for the period June 1959 to May 1961 is approximately 6.

(ii) The potentially most accurate method of determining ground stroke density, N, is by direct observation of close ground strokes with distance obtained from time to thunder. By this method, there were 4.5 ground strokes per square mile during the 1960/1961 season.

(iii) Lightning counters may be useful in determining ground stroke density, but a high degree of discrimination against sky strokes is essential. The only known counters which are satisfactory in this respect are counters B and C.

(iv) At distances of more than about 5 km the maximum value of \( dE/dt \) (or \( dH/dt \)) caused by lightning strokes is determined mainly by the radiation component of the field change, that is by the quantity \( \frac{1}{r} \left( h \frac{dE}{dt} \right)_{\text{max}} \).

The radiation which causes the maximum value of \( dE/dt \) (or \( dH/dt \)) appears to originate from a few hundred metres of arc channel at the beginning of the return stroke when, for about a microsecond, very large values of \( d^2I/dt^2 \) occur.
(v) There appears to be a ceiling to values of \((dE/dt)_{max}\) for sky strokes but not for ground strokes, an observation which may be attributable to geometrical factors only, i.e. it is probable that sky strokes and ground strokes are electrically similar. This may provide a basis for ground stroke counter design.

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