Shielding of Substations

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As compared to transmission lines, it is more important that overhead ground wires or vertical masts over substations be correctly located so as to provide shielding of the structure against direct strokes of lightning. In a previously published paper the authors discussed the shielding characteristics required for transmission lines. The present paper extends these investigations to the shielding of substations.

The previous paper indicated that the essential characteristics of natural lightning, that must be correctly simulated so that laboratory sparks and scale models can be used to study shielding effects, are the relative development of the initial streamers of the discharge. Schonland and his associates found that lightning strokes to ground or to relatively low objects, such as transmission line towers, are initiated by a streamer propagating from the cloud practically the total distance to ground. Only very short, if any, upward streamers from the ground end are found to be present. The path taken by a stroke and its resulting terminating point on the earthed end is determined by the initial downstream streamer, called by Schonland, the pilot streamer. The direction of propagation of the pilot streamer depends, at any point along its path, upon the electric field produced by the charges in the cloud, at the ground, and in the streamer itself, and upon localized conditions of ionization at the tip of the streamer. These localized effects tend to make the path erratic so that, as shown by laboratory tests, for the same configuration of cloud and ground, no two strokes will follow the same path.

It was found that, although natural lightning is predominantly negative in polarity, the relative streamer development is best represented in the laboratory by positive polarity sparks, that is, strokes from a positive cloud. For negative laboratory sparks, upward streamers are more likely to originate from the most exposed object and span the greater portion of the gap spacing, thus giving rise to more optimistic shielding results with models than would be expected for actual strokes in nature.

Description of Model Tests

As in the previous work, this investigation employed 1/5000-microsecond impulses of positive polarity at the minimum voltage required for breakdown of the gap. A vertical pointed rod was used as the cloud source of the stroke and a smooth metal plane for the ground plane. For the determination of the shielding properties of overhead ground wires protecting horizontal line conductors, the arrangement shown in Figure 1a was used, in which the symbols are clearly defined. Owing to the localized variations at the tip of the pilot streamer, all strokes from a given position of the cloud electrode do not follow the same path and terminate at the same point on the ground. Thus, the strokes divide between the three possible terminating points: the ground wire, the conductor, and the ground plane. It is found that the probability of the protected object being struck although decreasing as more favorable protection is afforded does not necessarily become zero.

Because the shielding characteristics are the same at any point along the line, they can be determined from a two-dimen-
sional plot such as shown in Figure 1b. This curve was determined by increasing A from zero and counting the proportional distribution between the three possible terminating points until A reaches such value that all strokes strike the ground. The ratio of area C to the sum of areas C and G represents the proportion of the total strokes to the system that strikes the conductor.

The shielding characteristics of a mast involve a three-dimensional problem, as shown in Figure 2a, which defines the symbols used. The origin of the stroke is located by the dimensions A and θ, and the distribution curves now become the three-dimensional surfaces of Figure 2b. The volume C, that resembles a rounded cone, represents the total strokes to the protected mast and the volume G, that resembles an inverted basin with the volume C removed, represents the total strokes to the shielding mast. The ratio of volume C to the sum of the two volumes is the proportion of the total strokes to the system that strikes the protected object. For a given position of the cloud electrode, 60 strokes were found sufficient to determine the percentage distribution of strokes between the three possible terminating points.

Since the effect of varying model size had been found negligible for positive polarity, a fixed ground wire or shielding mast height, h, of 10 inches was used for all the tests. To determine the effect of mast diameter, tests were made with rods having rounded tips varying in diameter from 1/8 inch to 1/4 inch. Substantially, the same results were obtained, regard-

Figure 1. Symbols utilized with stroke-distribution curves for overhead ground wires

Figure 2. Symbols used with stroke-distribution curves for vertical masts

96 TRANSACTIONS Wagner, McCann, Lear—Shielding of Substations
less of the size or combination of rods, as long as positive polarity was used, and the rod sizes were held within this range. From this it can be concluded that the data obtained with one rod size are applicable to practical construction. For subsequent tests 1/4-inch rods were used. Previous tests showed that the same conclusions apply to horizontal ground wires and conductors.

To determine the total effect of cloud height, the relative frequency with which strokes originate from a given height should be known. Sufficient data of this type are not available and considerable variance undoubtedly exists in different regions. It is known that the base of thunderclouds varies in height from a minimum of about 500 feet above ground to as high as 20,000 or 30,000 feet. A common minimum for relatively flat terrain is about 1,000 feet. Since more pessimistic results are obtained with lower cloud heights and ratios of H/h, minimum values should be used. A ratio of H/h of 5 was taken for this study, which for a 200-foot mast results in a 1,000-foot cloud height and for a 100-foot mast in a 500-foot height. The use of this ratio should give conservative results.

**Shielding of One Mast by Another**

In Figure 3 are plotted the results of the tests made with the configuration of masts shown in the insert. The strokes that contact the protected mast, expressed as a percentage of the strokes to the system of masts, are plotted as a function of the ratio of d/h and x/h.

The actual configuration of the equipment to be protected, such as a substation bus structure, may vary widely and it would be very difficult to make a study of all configurations. However, it will be shown that a few fundamental configurations, such as the one discussed, are sufficient for practical purposes. The performance of one mast protecting another is applicable to the case for which a single mast protects a structure having a single prominent projection.

**Shielding of a Ring of Masts by One Mast**

If a number of points on a structure have equal exposure with respect to a single shielding mast, the probability of at least one being struck is increased.

This can be seen with reference to Figure 2b. If there were another mast of the same height, d, and distance, x, from the shielding mast but at an angle θ equal to 180 degrees, there would be then another volume C, and the number of strokes to the two protected masts would be twice that to one. As the number of masts increases, forming a circular ring around the shielding mast, the exposure increases until the limit of an infinite number of such masts or a solid ring is reached. The distribution curves for such a case are independent of θ. A conservative estimate of the shielding performance of such ring can be obtained by assuming that these distribution curves are the same as that of a single protected mast for θ equal to zero.

Thus, the volume C is a single volume of revolution about the shielding mast whose cross section is the heavy curve of Figure 2b. This is somewhat conservative, because, as the number of masts in the ring is increased, they eventually become so close that more than one mast becomes involved in the distribution curve and less than the number indicated by the curve for one mast for θ equal to zero will strike any one of the masts.

It was in this manner that the data for the curves of Figure 4 were obtained. These data are directly applicable to a structure having all points of equal height and equal distance from the shielding mast. Almost all practical cases of shielding by means of a single mast will lie between this condition and that of one protected point.

![Figure 3. Exposure of an object protected by a single mast](image)

![Figure 4. Exposure of a ring of objects protected by a single mast](image)

**Table I. Record of the Number of Times Objects of Varying Heights Are Struck**

<table>
<thead>
<tr>
<th>Object and Location</th>
<th>Height (Feet)</th>
<th>Number of Years</th>
<th>Times Struck</th>
<th>Average (Number Per Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mast at North Wales substation (Philadelphia) of Philadelphia Electric Company</td>
<td>80</td>
<td>4</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>10 fire towers of the Pennsylvania State Department of Forests and Waters, western Pennsylvania</td>
<td>100</td>
<td>2</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>Radio tower of WWSW, Pittsburgh</td>
<td>100</td>
<td>3</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Radio tower of WBER, Cleveland</td>
<td>100</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Radio tower of WCLE, Cleveland</td>
<td>300</td>
<td>6</td>
<td>2</td>
<td>3.0</td>
</tr>
<tr>
<td>Radio tower of WADC, Akron</td>
<td>300</td>
<td>8</td>
<td>2</td>
<td>3.0</td>
</tr>
<tr>
<td>Cathedral of Learning of University of Pittsburgh</td>
<td>250</td>
<td>3</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Anaconda Copper Mining Company smoke stack at Great Falls, Mont</td>
<td>545</td>
<td>2</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Anaconda Copper Mining Company smoke stack at Anaconda, Mont</td>
<td>565</td>
<td>2</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>Empire State Building, New York, N. Y.</td>
<td>1,600</td>
<td>3</td>
<td>8</td>
<td>0.23</td>
</tr>
</tbody>
</table>

These objects are in regions of isoclimatic levels varying from 25 to 45 storm days per year.
Shielding of Two Horizontal Conductors by a Single Overhead Ground Wire

The shielding characteristics of two horizontal conductors protected by a single overhead horizontal conductor are given in Figure 5. These curves can be applied to such cases as an overhead wire shielding a substation or shielding the incoming lines to a substation.

Shielding of Objects Between Two Masts or Ground Wires

Data similar to that given above are presented in Figures 6 and 7 for a protected mast located midway between two shielding masts and for a single horizontal conductor located midway between two parallel overhead ground wires. The increase in shielding, which is obtained when several masts or ground wires are used and placed such that they more or less surround the protected equipment, is not generally realized. The area protected by two masts or two ground wires is considerably greater than twice the area protected by one.

Total Number of Strokes to Substations

The degree of shielding necessary for adequate protection can only be determined after it is known how frequently the system is struck. Data available to the authors on the number of times per year objects of varying heights are struck in regions of isoclimatic levels, varying from 25 to 45 storm days per year, are listed in Table I. All but the data on the Empire State Building were obtained from lightning investigations being conducted by the Westinghouse Electric and Manufacturing Company. The curve of Figure 8 was obtained by grouping the data of Table I into mean values of height and averaging the strokes per year for each group. The range of this curve as applied to substations, would fall below 200 feet. A mast of such height can be expected to be struck about once every one and one-half years, and a 100-foot mast about once every three years. Laboratory tests indicate that for strokes that do not have appreciable upward leaders, the strokes attracted to a mast increase linearly with the height of the mast. This relation is indicated by the general shape of the lower part of Figure 8. The upward trend of the curve for high objects is probably due to the upward streamers that occur in nature from objects of such height.

A further estimate of the number of strokes to a substation can be obtained from the data of Waldorf and others on the frequency of strokes to transmission lines. The average figure for lines of from 60 to 100 feet in height is one per mile of line per year. The previous model tests show that, in this height range, strokes will be drawn to the line from an effective lateral distance on each side of the line of about 3.5 times the height. Assuming an average height of 80 feet for the foregoing transmission lines, one stroke per line per year is thus equivalent to 5,280/(2×3.5×80) or 9.5 strokes per year per square mile of sky area. If W and L designate the width and length, respectively, in feet of the substation then the total strokes to the substation should be approximately, in the height range from 60 to 100 feet,

$$\frac{(W+700)(L+700)}{(5,280)^2} 9.5$$

The strokes to a substation for which \( W=L=100 \) feet, are

$$\frac{(800)(800)}{(5,280)^2} 9.5 = 0.22 \text{ per year}$$

or once every four and one-half years. This compares favorably with the data of Figure 8.

![Figure 8. Number of times per year objects of various heights are struck by lightning](image-url)

![Figure 9. Shielding characteristics of a single mast or ground wire for 0.1 per cent exposure](image-url)

![Figure 10. Height of shielding object above protected object, \( y \), plotted as a function of the horizontal separation, \( x \), and the height of the protected object, \( d \), for 0.1 per cent exposure](image-url)
Protection of Substations

To this point, consideration has been given to the protection afforded by one or two infinitely long wires, such as the overhead ground wires on transmission lines, to the protection afforded by one mast, and to the protection afforded to objects located at the mid-point of a line connecting two masts. Substation configurations are so diversified in construction that it becomes impossible to test each type individually. The best alternative is to convert the information already obtained to a form that can be utilized to best advantage.

A single mast protecting a substation offers no particular difficulty, the curves of Figure 10a being used directly. If the structure has a single prominent projection or several projections in a limited region, to be protected, such as a set of disconnects, the dotted curves should be used. On the other hand if live parts are more generally distributed at a given height, then the full-line curves should be used and applied to the most remote object.

For horizontal wires the data of Figure 10b apply to long spans, such as transmission lines. Substations involve much shorter lengths, some being so short that consideration must be given to the end effects. By comparing Figures 3 and 5 and Figures 6 and 7, for which Figures 3 and 6 approximate end conditions and Figures 5 and 7 apply to straight-away conditions, it may be seen that the per cent exposure for a given configuration is always slightly less for the end than for the straight-away. Thus, the working curves, Figures 10b and 10c, can be applied directly to ground wires, even if they are short and the per cent exposure figures apply to the total strokes to the substation structure.

If two masts are used to protect an area, the data presented give shielding information only for the point b, midway between the two masts, and for points on the semicircles drawn about the masts as centers as shown in Figure 11a. For given values of d and y, a value of z from Figure 10c and x from Figure 10a can be determined, which will give an exposure of 0.1 per cent. The locus shown in Figure 11a, drawn by the semicircles around the masts as centers and connecting the point b, represents an approximate limit of 0.1 per cent exposure. Any single point falling within the cross-hatched area should have better protection than 0.1 per cent. This arrangement is likely to leave some points of a rectangular substation protected by two masts with higher exposure than desirable. If, however, the distance between the masts is decreased, the protected areas are, at least, as good as the combined areas obtained by superposing those of Figure 11a. For example, if the distance between masts is halved, the resultant protected area is somewhat as shown in Figure 11b.

On this basis, to form an approximate idea of the width of the overlap between masts, first obtain a value of y from Figure 10c corresponding to twice the actual distance between the masts. The width of overlap is then equal to x corresponding to this y as obtained from Figure 10a. This undoubtedly gives a conservative width of substation that can be protected.

For three masts located at the points of an equilateral triangle or for four masts located at the points of a square, the protected areas are as shown in Figures 11c and d. The height of the shielding mast should be so chosen that the b points provide 0.1 per cent exposure as obtained from Figure 10c for the mid-point between two masts. The x radii are obtained from the data for a single mast.

Effect of High Earth Resistivity and Terrain

The data presented here apply to stations located in regions of relatively flat terrain and low earth resistivity. As shown in the previous work, high earth resistivity lowers the effective ground plane below the surface of the earth and results in poorer shielding for a given configuration. This effect is appreciable, however, only for very high values of resistivity, and, since most substations are provided with an extensive grounding...
Field Tests on High-Capacity Air-Blast Station-Type Circuit Breakers

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In January 1940 there was presented before the Institute a paper describing a new high-capacity air-blast circuit breaker. Since then, breakers of higher interrupting rating have been built, following out the general principles of design and construction disclosed at that time. As part of an organized development program, such breakers have been subjected to extensive interrupting tests underfactory laboratorv conditions. However, it is recognized that the final proof of the interrupting performance of high-capacity circuit breakers comes as a result of tests made on actual operating systems.

The engineers of the Consolidated Edison Company offered to make such tests up to the full short-circuit capacity available on the bus of the Hell Gate Station in New York.

First Series of Tests

A breaker rated 15 kv, 1,200 amperes, 1,600,000-kva, 8 cycles, mounted in a steel cell, was submitted for field interrupting tests in September 1940. Out of seven tests, up to 1,480,000 kva, the breaker failed to clear on two occasions, resulting in a fault to ground inside the steel cell, which was cleared by the backup protection. On the first of these, there was no damage whatever to the test breaker, and after the parts were inspected and the insulators cleaned, the tests were resumed. In the second case damage was limited to the upper barrier of the arc chute in the test breaker, and the glaze of some of the porcelain insulators. Adjacent equipment, such as the control equipment and current transformers located in the test cell, and the sand bags and tarpaulin outside and at the top of the test cell, was undamaged. Arc durations were unexpectedly long as compared with those found in factory tests. This caused gas to escape around the blade, and produced the faults to ground. When the breaker was returned to the test laboratory, it was found possible to reproduce this condition, and it was then discovered that alterations inadvertently made just prior to the field tests had interfered with the full flow of air across the contacts and had, therefore, resulted in long arcing time.

This specific difficulty was corrected, and, in addition, further development work, using the improved synthetic method of testing as the basis of study, produced other refinements in the design of the interrupting structure, vastly increasing its margin of safety. A breaker with these refinements performed perfectly in a second series of field tests in May 1941.

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Description of Breaker

The breaker which successfully passed this second series is shown in Figure 1. As in the earlier breaker, the mechanisms and air tank are mounted on top, the contacts and arc chute of the individual phases are mounted in separate steel compartments immediately below, with provision for conveying the exhaust gases up past the mechanism to openings at the top.

Without any sacrifice in operating performance or efficiency, this arrangement of major components provides adaptability to back or bottom connection equal to that of any oil circuit breaker.

Figure 2 shows one of the arc chutes with one side plate removed. The stationary finger contacts are shown in the bottom of the left-hand chamber. The moving blade passes down through openings in the top walls of this chamber to make contact with the fingers and thus close the circuit. To interrupt the circuit, the blade contact is withdrawn upward, and a blast of air is blown across the arc from the opening visible at the left. This forces the arc against the cross barriers on the right-hand side of the chamber where it is extinguished at current zero.

The arcing chamber through which the blade passes is narrow, and beyond the leading tips of the cross barriers, the path expands rapidly, both horizontally and vertically so as to increase the cross-sectional area available for exhaust of the gases. Beyond the stacks of copper cooling plates all four passages lead into a common chamber whence the gases are carried off by the vertical exhaust tube.

In the full open position the moving blade pulls clear out of the opening in the top of the chute. In order to prevent the escape of gas around the blade at some intermediate position during the inter-

References


5. Experience With Preventive Lightning Protection of Transmission Lines, S. E. Waldorf. AIEE TRANSACTIONS, volume 60, 1941 (June section), pages 249-54.