National Lightning Safety Institute

April 21, 2009

Email NLSI for schedule of our next Lightning Protection for Engineers workshop.

We teach.

We consult.

We research.

~ 50 deaths/yr. in U.S. (x10 inj.)
~ 30,000 ltg fires/year
~ $4B aviation costs/year
~ $0.5B personal insurance claims.

National Lightning Safety Institute (NLSI) is an independent, non-product advocate of lightning safety for both people and structures:

Personal Lightning Safety means anticipating a high-risk situation and moving to a low-risk location. Result: Improved ES&H practices.

Structural Lightning Safety means using various exterior and interior defensive systems in a detailed, site-specific process. Result: Improved power quality assurance.

NLSI provides objective assistance on many kinds of lightning problems, including experience with:

- Informative classes, lectures, seminars, and workshops
- On-site technical assessments, audits, and inspections

NLSI is an "authority having jurisdiction" (AHJ), qualified to approve, certify, and inspect equipment, installations, materials, and procedures.

As AHJ for a client, NLSI can base acceptance of a lightning protection system on compliance with NFPA or any other code or standard of practice.

We have considerable experience in the following economic sectors: aviation; communications and IT; defense, including explosives; mining; petrochemical; and power generation.

Our website provides a wealth of training materials, maps, photos, and factual details about lightning issues, written by both NLSI and other lightning experts.

~ 1/3 of Power outages are caused by lightning

NLSI

~ National Lightning Safety Institute ~

Section 4.1

Decision Tree for Personal Lightning Safety

by Richard Kithil, President &CEO, NLSI

NLSI recommends that all organizations prepare a Lightning Safety Plan and inform all personnel of its contents. In a sentence, lightning safety is "anticipating a high-risk situation and moving to a low-risk location." Lightning Safety Plans should be site-specific, but they all share a common outline:

1. **Advanced warning of the hazard.** Some options:

   1.1 "If you can see it, flee it; If you can hear it, clear it."

   1.2 TV Weather Channel; NOAA Weather Radio

   1.3 Fancy lightning detectors; off-site meteorological services

2. **Make decision to suspend activities and notify people**.

   2.1 The 30/30 Rule says to shut down when lightning is six miles away. Use a "flash to bang" (lightning to thunder) count of five seconds equals one mile (10 = 2 miles; 20 = 4 miles; 30 = 6 miles).

   2.2 Notify people via radio, siren or other means.

3. **Move to safe location.**

   3.1 A large permanent building or metal vehicle is best.

   3.2 ***Unsafe*** places are near metal or water; under trees; on hills; near electrical/electronics equipment.

4. **Reassess the hazard**.

   It's usually safe after no thunder and no lightning have been observed for thirty minutes. Be conservative here.

5. **Inform people to resume activities.**

Fig. 314. — Le paratonnerre portatif, ou le parapluie-paratonnerre de Barbeu-Dubourg.

A personal lightning protection system proposed to Benjamin Franklin by Jacques Barbue-Dubourg in a letter dated 1773. See Section 7.4 for more details.

The Art and Science of Lightning Protection

Martin A. Uman

University of Florida

CAMBRIDGE UNIVERSITY PRESS

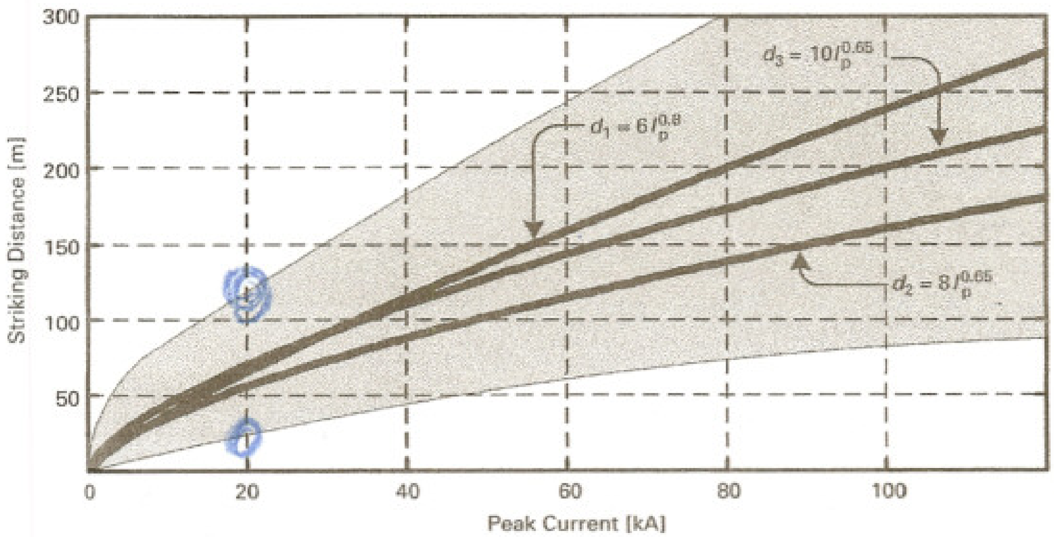

Fig. 3.6 Striking distance vs. first return stroke peak current for lightning to flat ground. Three common curves representing Eq. (3.2) with different values of the parameters A and b are plotted. The shaded region illustrates the approximate range of published calculations relating striking distance to peak current.

$d = K_0 + K_1 I_p^{\beta}$

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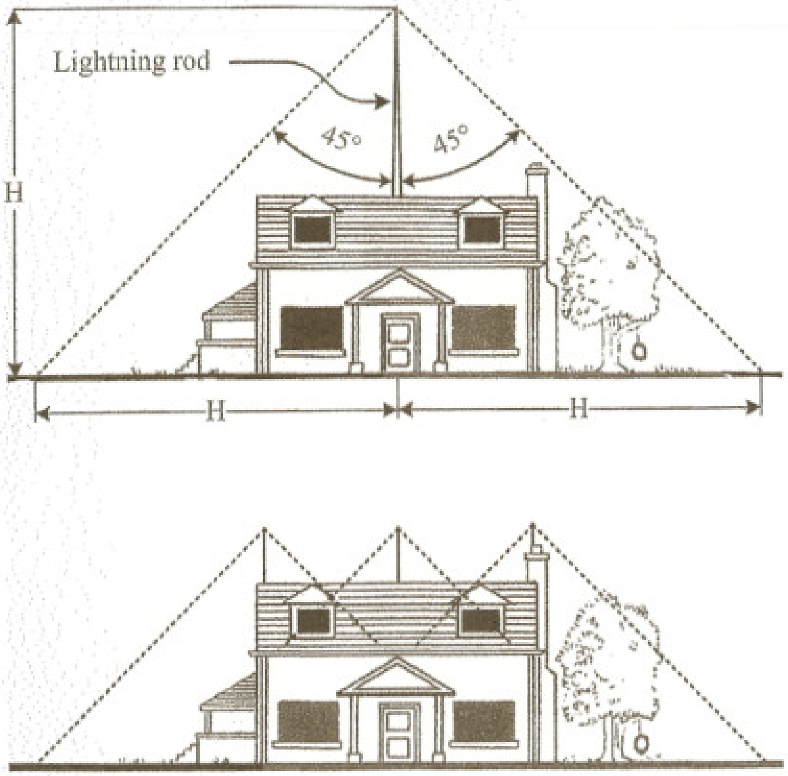


The cone of protection method assuming a 45° cone with a single lightning rod (top), and multiple rods (bottom). Note that there are unprotected parts of the tree and, in the lower figure, of the roof that would, in theory, be protected if a 60° cone of protection had been assumed. Adapted from Uman (1986).

In 1777 a building in Purfleet, England, near London, that was used to store explosive materials sustained lightning damage on the edge of the roof at a horizontal distance of about 38 feet (11.6 m) from a vertical lightning rod mounted at the center of the structure. The top of the rod was 24 feet (7.3 m) above the roof edge, the lowest part of the roof. The ratio of the maximum horizontal distance from the rod within which the lightning was thought to be unable to strike (in this case, about 38 feet) to the rod height (24 feet) was termed the protective ratio (see Section 1.5), which for this example was equal to $(38/24) \cong 1.6:1$. The lightning protection system on this structure had been designed by a committee of which Benjamin Franklin was a member (Cavendish *et al.* 1773). A sketch of the building and other information is found in Golde (1977). Apparently, this was the first recorded case of the limited protection (the building was struck) provided by a grounded lightning rod, although the damage was minor considering that the building housed explosives. About 50 years later, in what might be considered the

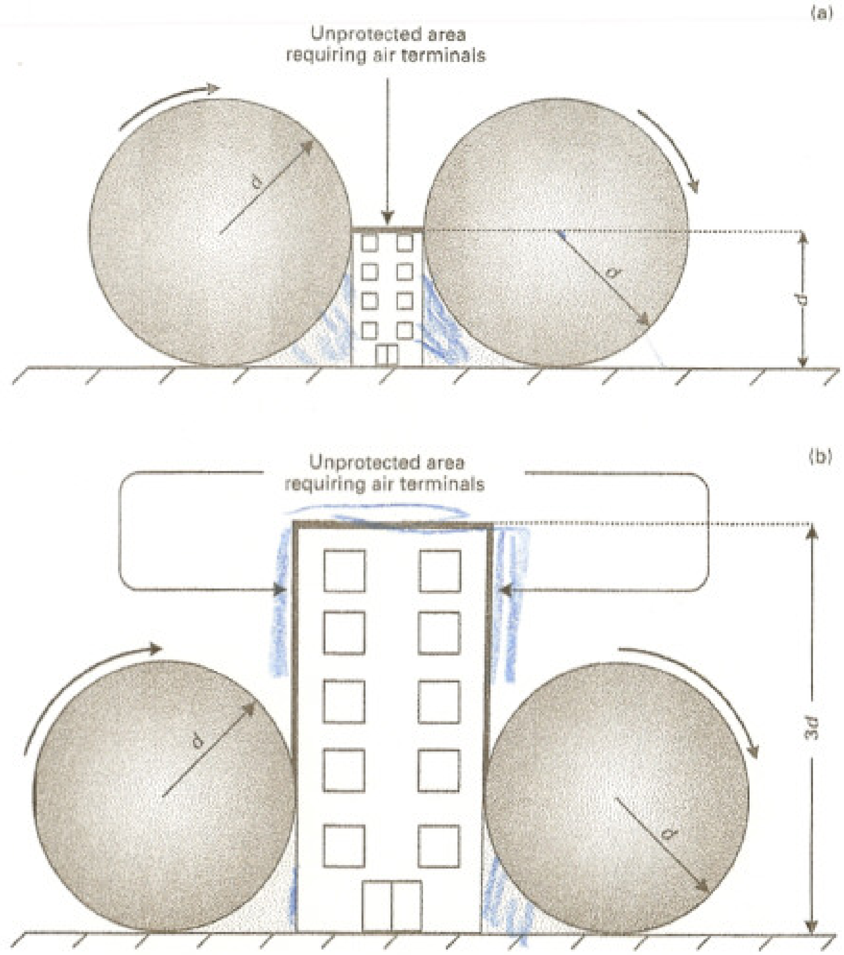


Fig. 3.9 Two examples of the application of the rolling sphere method. (a) The sphere is rolled over a structure whose height is equal to or less than the sphere radius (striking distance). The structure can only be struck by lightning on its top. (b) The sphere is rolled over a structure whose height is greater than the sphere radius (striking distance). The structure can be struck by lightning on its sides as well as its top. In both (a) and (b) the shaded volume is protected whereas the darkened surfaces on the structures may be struck.

earliest standard for lightning protection (Gay-Lussac and Pouillet 1823), the French Academy of Sciences concluded that a vertical rod would protect a circular area around its base whose radius was twice the rod height, a protective ratio of 2:1. Apparently, the Purfleet case was not considered or was forgotten. Additionally significant, from an historical point of view, are the laboratory work of Preece (1880) who concluded that the proper protective ratio was 1:1, the book by

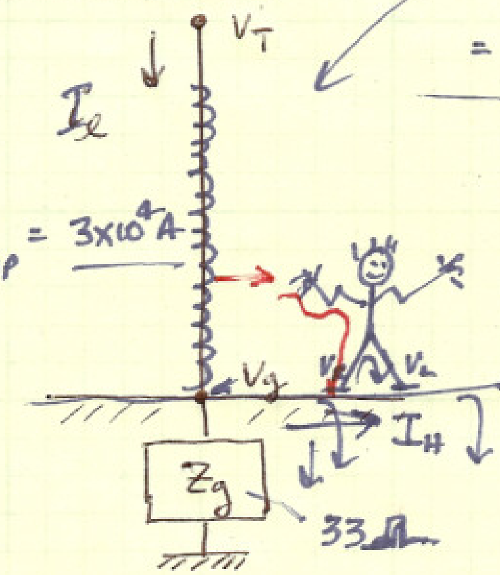
Down-Conductors

"Peak Analysis"

10 m

$= 1 \mu H/m$

$\max \frac{dI}{dt} \simeq 10^{11} A/s$



$$V_T = V_L + V_g$$

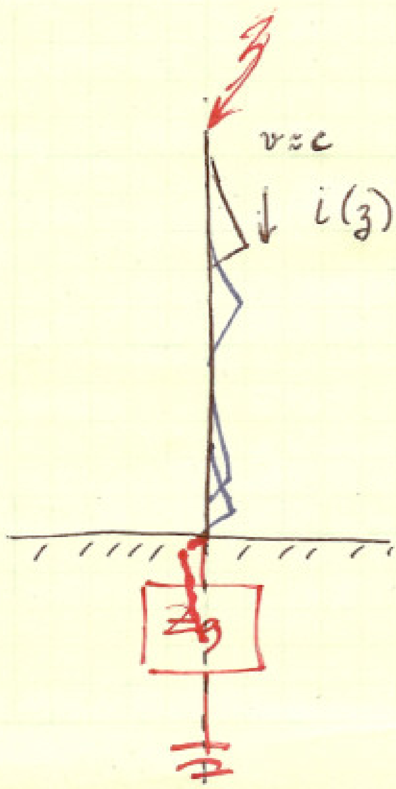
$$= L\frac{dI}{dt} + IR_g$$

$$= 10^{-5} \times 10^{11} + 33.3 \times 10^4$$

$$= 10^6 V + 10^6 V$$

$$= 2 \times 10^6$$

Time Element



$$i(z) = i(t - z/c)$$

ELECTRICAL TRANSIENTS IN POWER SYSTEMS

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WILEY-INTERSCIENCE
a Division of John Wiley & Sons, Inc.
New York · London · Sydney · Toronto

9 Traveling Waves on Transmission Lines

9.1 Circuits with Distributed Constants

The first eight chapters of this book have been concerned with circuits in which the constants R, L, and C have been lumped or concentrated, or where they could be so approximated. We realize that these parameters are really distributed in any circuit or piece of equipment, so it is perhaps surprising and gratifying to find how accurately the transient behavior of such circuits can be calculated on the basis of lumped circuit analysis. However, there are important parts of a power system where this approach is inadequate because the approximations are too great. The most obvious example is the transmission line. Here each meter of its length is much like every other meter. It possesses a certain inductance, capacitance, and resistance, so that these quantities are truly distributed over tens or hundreds of miles. A less obvious example is the machine winding. Heretofore, a transformer or rotating machine has been represented by an inductance, sometimes with capacitance at its terminals. Such a representation is adequate if the focus is on the action of the winding as a whole, as a component in the circuit. If, on the other hand, we are concerned with phenomena occurring within the winding, we must take cognizance of the distributed nature of the winding inductance, capacitance, and resistance.

A distinguishing feature of the circuit with distributed constants is its ability to support traveling waves of current and voltage. How this occurs will be presented first in a qualitative way, in order to establish a physical picture of what is taking place. Consider the two-wire circuit shown in Fig. 9.1*a* in which, by closing the switch S, the transmission line is connected to a source of voltage V, which will be assumed, for the time being, to have zero impedance. The action of closing the switch can be likened to opening a sluice or valve at the end of a channel or pipe, thereby admitting water to considered Eq. 9.2.5 instead, we would have focused on a particular point on the line and noticed that regardless of the point we chose, sooner or later, the voltage distribution would pass by, moving with a velocity v. As we have said already, this is just two different ways of looking at the same phenomenon.

Recapitulating, we come to the important conclusion that on loss-free transmission lines the current and voltage waves have the same shape, being related by the characteristic impedance of the line, and travel undistorted. A current wave in what has been arbitrarily chosen as the positive direction of x has the same sign as the voltage wave with which it is associated. Current waves traveling in the opposite direction have their sign reversed with respect to their voltage waves.

The concept of a negative current wave presents some latitude for misunderstanding. It is most readily comprehended by considering what is physically occurring when a wavefront travels down a line. At the wavefront there is a discontinuity. If the line is initially dead, the electrons in the conductor ahead of the front are at rest, or more correctly engaged in random motion as in any other piece of conducting material. Immediately behind the front they are experiencing a net drift along the conductor in a direction which may be the same as or opposite to the direction of the wavefront. If their drift is in the direction which has been arbitrarily chosen as positive for x, by definition their motion constitutes a negative current, since they are negative charges. If they are drifting in the negative direction, they constitute a positive current, regardless of the direction of travel of the wavefront. Figure 9.5 shows some combinations of current and voltage waves. We note

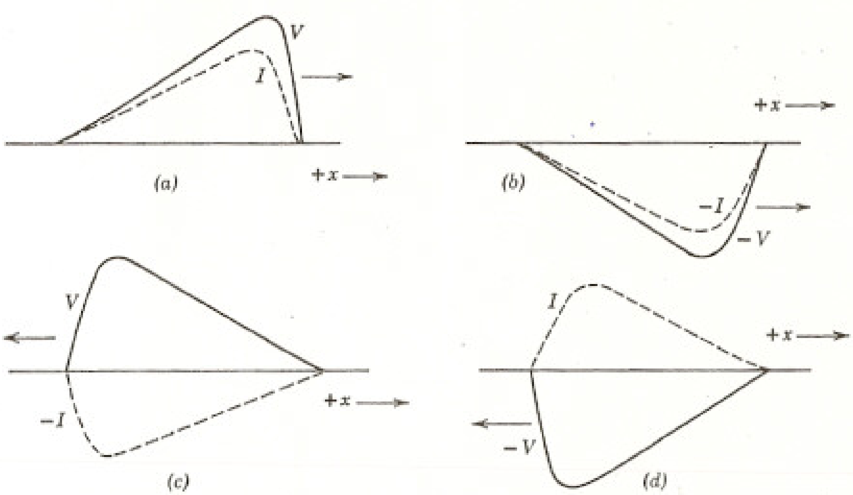


Fig. 9.5. Various combinations of voltage and current waves.

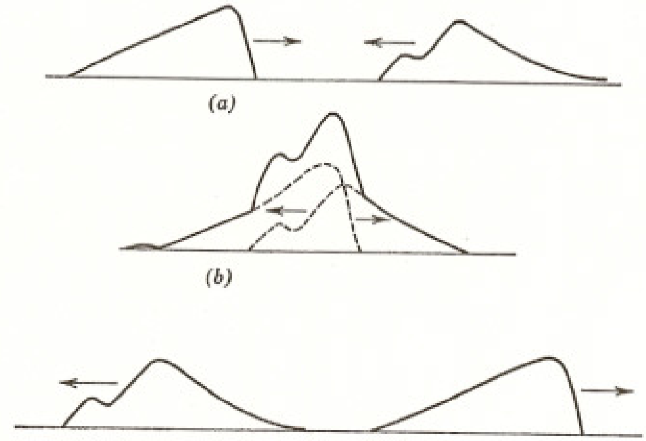


Fig. 9.6. Opposing waves (*a*) approaching, (*b*) combining, and (*c*) passing.

that V and I have the same sign when traveling to the right and opposite signs when traveling to the left. Figure 9.5*c* contains a negative current wave traveling in the negative direction, while Fig. 9.5*d* shows a positive current wave traveling in this direction. When two waves traveling in opposite directions meet, they add algebraically as they pass through each other. This is illustrated in Fig. 9.6.

9.3 Reflection and Refraction of Traveling Waves

We have seen that there is a strict proportionality between voltage waves on transmission lines and their associated current waves. The proportionality factor is the characteristic impedance Z_0 of the line. When a wave arrives at a discontinuity in a line, where the characteristic impedance of the line changes, some adjustment must occur if this proportionality is not to be violated. This adjustment takes the form of the initiation of two new wave pairs. The reflected voltage wave and its companion current wave travel back down the line superimposed on the incident wave. The refracted wave penetrates beyond the discontinuity. The amplitudes of the reflected and refracted waves are such that the voltage to current proportionalities are preserved for each, as demanded by the characteristic impedances of the lines on which they are traveling; current and voltages at the line discontinuity are themselves continuous, and energy is conserved. It will be found that energy conservation is automatically satisfied if the other two requirements are met.

Consider the junction between lines of characteristic impedances Z_A and Z_B and let us suppose that $Z_A > Z_B$. For example, this might be the junction

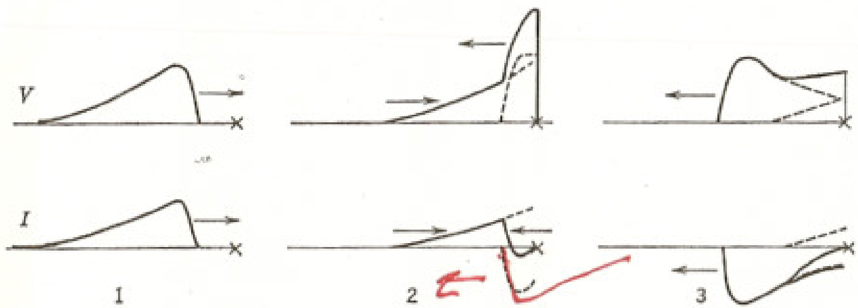


Fig. 9.12. Surge of double exponential form reflected from an open circuit.

in the electric field, and half in the magnetic field. τ seconds later, $2VI\tau$ joules will have been imparted to the line, but this is now all in the electric field. There is now four times the energy in the electric field that there was at time τ, the voltage along the line must be twice as high, since energy varies directly as the square of the voltage. Voltage surges can have very destructive effects on terminal equipment. The doubling effect just described is therefore of considerable practical importance, for it doubles the potency of the wave.

So far we have been concerned only with traveling waves of step-function form. To restrict our study to these alone is unrealistic and can be misleading. A surge waveform which is closely approximated by many practical surges is the double exponential,

$$V = V_0(\epsilon^{-\alpha t} - \epsilon^{-\beta t})$$

Figure 9.12 shows how such a wave is reflected from an open circuit.

c. General Termination. Transmission lines are most frequently terminated in some type of equipment, usually one or more transformers. To find out what happens when a traveling wave reaches such a termination we make use of the reflection and refraction coefficients computed in Eqs. 9.3.7 and 9.3.8. These are reproduced here for convenience.

$$\text{reflection coefficient} = a = \frac{Z_B - Z_A}{Z_B + Z_A} \tag{9.4.1}$$

$$\text{refraction coefficient} = b = \frac{2Z_B}{Z_B + Z_A} \tag{9.4.2}$$

The wave approaches down the transmission line of surge impedance Z_A and impinges on the terminal equipment which has an impedance Z_B. We write these quantities as operational impedances as described in Section 2.5.

In this form Z_A behaves as a resistor independent of s, since it is $(Ls/Cs)^{1/2}$. Suppose now that the terminal equipment is a capacitor C_1, then

$$Z_B(s) = \frac{1}{C_1 s}$$

and the reflection and refraction coefficients are

$$a = \frac{1/C_1s - Z_A}{1/C_1s + Z_A} \tag{9.4.3}$$

$$b = \frac{2/C_1s}{1/C_1s + Z_A} \tag{9.4.4}$$

If the traveling wave is a step function of amplitude V_1, its transform will be $v_1(s) = V_1/s$. Thus the transform of the reflected wave will be

$$v_2(s) = av_1(s)$$

which with appropriate substitution from Eq. 9.4.3 gives

$$v_2(s) = \frac{V_1}{s}\left[\frac{1/C_1s - Z_A}{1/C_1s + Z_A}\right]$$

$$= \frac{V_1}{s}\left[\frac{1/C_1Z_A - s}{1/C_1Z_A + s}\right] \tag{9.4.5}$$

Remembering that Z_A has the dimensions of a resistance, C_1Z_A is a time constant, in fact the time constant to charge C_1 through the characteristic impedance Z_A of the line. Let

$$\frac{1}{C_1Z_A} = \alpha$$

then Eq. 9.4.5 can be rewritten as

$$v_2(s) = V_1\left[\frac{\alpha}{s(s+\alpha)} - \frac{1}{(s+\alpha)}\right] \tag{9.4.6}$$

These are two simple, recognizable transforms:

$$V_2(t) = V_1(1 - \epsilon^{-\alpha t} - \epsilon^{-\alpha t}]$$

$$= V_1[1 - 2\epsilon^{-\alpha t}] \tag{9.4.7}$$

This is the wave that will travel back down the line superimposing itself on the incident wave. Inasmuch as the sum of the incident and reflected waves must equal the refracted wave, it is evident from Eq. 9.4.7 that

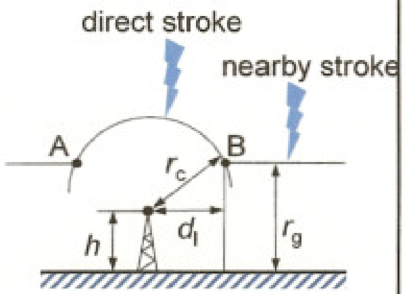
$$V_3(t) = V_1[2 - 2\epsilon^{-\alpha t}] \tag{9.4.8}$$

Direct lightning and indirect lightning *Cont.*

Electrogeometric models

When the lightning leader approaches ground, is continues its downward motion unperturbed unless critical field conditions develop so that it initiates a juncture with the nearby tower, called **final jump**.

By assuming the leader channel perpendicular to the ground plane, it is generally accepted that the flash will stroke the tower if its prospective ground termination point, i.e. its stroke location in absence of the tower, lies within the attractive radius *r*.



$N_g * A$

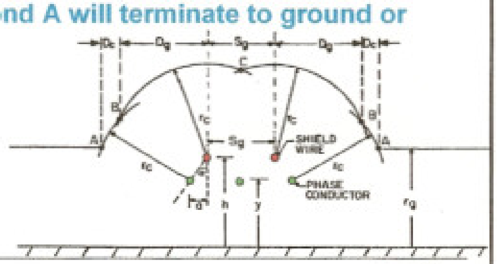
$= N_g * \pi r_c^2$

$r_c(I_p)$

Lightning performance of transmission lines

Shielding failure: basic concept of the geometric model

For a specific value of stroke current, arcs of radii r_c are drawn from the phase conductors and from the shield wires with the horizontal line at a distance r_g from the earth's surface. The intersections of these arcs and the intersection of the arcs with the horizontal line are marked **A**, **B**, and **C**. **Downward leaders that reach the arc between A and B will terminate on the phase conductor. Those that reach the arc between B and C will terminate on the shield wires, and those that terminate beyond A will terminate to ground or earth.**

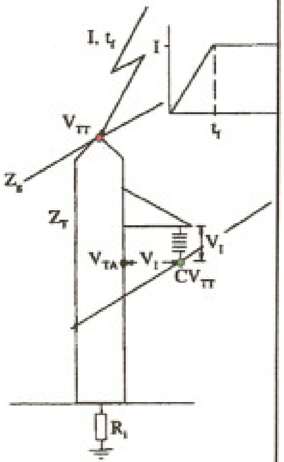


Lightning performance of transmission lines *Cont.*

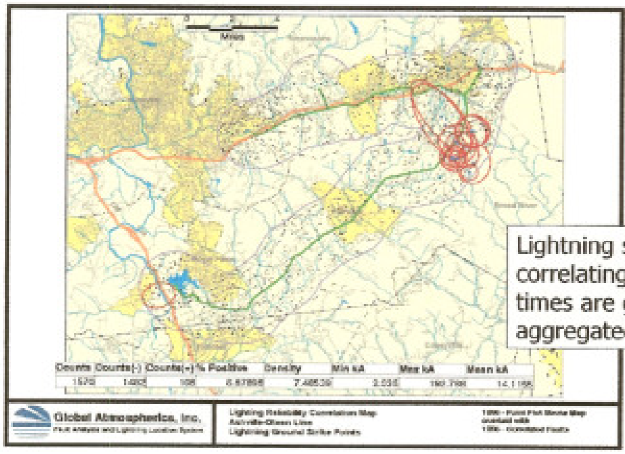
Backflashover: basic concepts

In the previous section, the overhead shield wires have been located to minimize the number of lightning strokes that terminate on the phase conductors. Then, the remaining and the vast majority of strokes terminate on such shielding wires. A stroke that terminates on such a wires forces currents to flow down the tower and out on the shielding wires. Thus voltages are built up across the line insulation. **If these voltages equal or exceed the line CFO, flashover occurs.**
This event is called a **backflash** and the corresponding lightning current **critical current**

Cross-arm impedance is here disregarded.



Correlate interruptions and events with specific lightning strikes and amplitudes.



Lightning strokes correlating to event times are geographically aggregated on this line.