Lightning Phenomena

3.1   Mechanism of Lightning

Lightning is an electric discharge in the form of a spark or flash originating in a charged cloud. It has now been known for a long time that thunder clouds are charged, and that the negative charge centre is located in the lower part of the cloud where the temperature is about - 5^0C, and that the main positive charge centre is located several kilometres higher up, where the temperature is usually below - 20^0C. In the majority of storm clouds, there is also a localised positively charged region near the base of the cloud where the temperature is 0^0C. Figure 3.1 shows such a cloud located above a overhead transmission line.
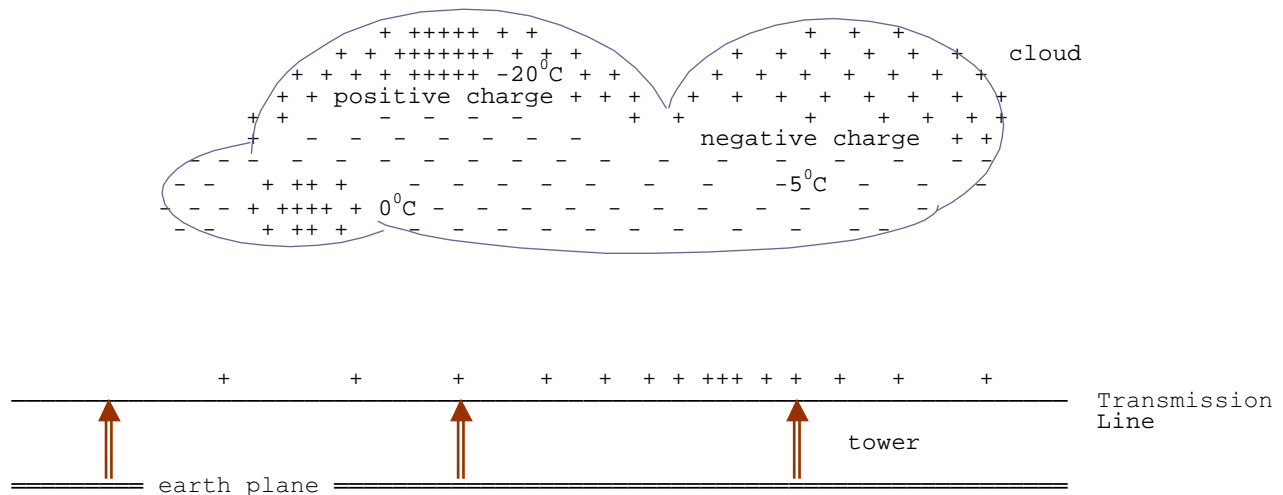

Figure 3.1 - Induced charges on transmission line

Fields of about 1000 V/m exist near the centre of a single bipolar cloud in which charges of about 20 C are separated by distances of about 3 km, and indicate the total potential difference between the main charge centres to be between 100 and 1000 MV. The energy dissipated in a lightning flash is therefore of the order of 1000 to 10,000 MJ, much of which is spent in heating up a narrow air column surrounding the discharge, the temperature rising to about 15,000 ^{0}C in a few tens of microseconds. Vertical separation of the positive and negative charge centres is about 2 - 5 km, and the charges involved are 10 - 30 C. The average current dissipated by lightning is of the order of kilo-amperes. During an average lightning storm, a total of the order of kilo-coulombs of charge would be generated, between the 0^0C and the -40 ^{0}C levels, in a volume of about 50 km^3.

3.1.1   Breakdown Process

Under the influence of sufficiently strong fields, large water drops become elongated in the direction of the field and become unstable, and streamers develop at their ends with the onset of corona discharges. Drops of radius 2 mm develop streamers in fields exceeding a 9 kV/cm - much less than the 30 kV/cm required to initiate the breakdown of dry air. The high field need only be very localised, because a streamer starting from one drop may propagate itself from drop to drop under a much weaker field.

When the electric field in the vicinity of one of the negative charge centres builds up to the critical value (about 10 kV/cm), an ionised channel (or streamer) is formed, which propagates from the cloud to earth with a velocity that might be as high as one-tenth the speed of light. Usually this streamer is extinguished when only a short distance from the cloud.

Forty micro-seconds or so after the first streamer, a second streamer occurs, closely following the path of the first, and propagating the ionised channel a little further before it is also spent. This process continues a number of times, each step increasing the channel length by 10 to 200 m. Because of the step like sequence in which this streamer travels to earth, this process is termed the **stepped leader** stroke. This process is shown diagrammatically in figure 3.2.
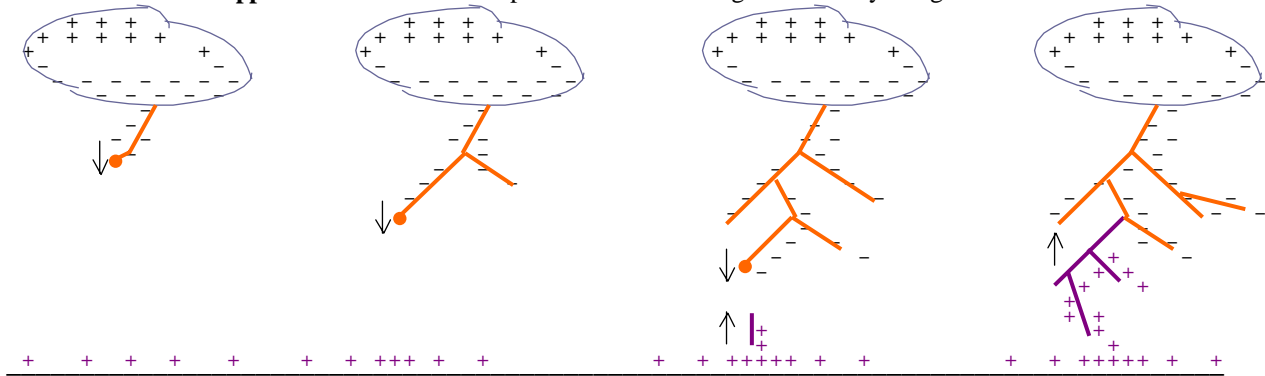

Figure 3.2 - Propagation of lightning channel

When eventually the stepped leader has approached to within 15 to 50 m of the earth, the field intensity at earth is sufficient for an upward streamer to develop and bridge the remaining gap. A large **neutralising** current flows along the ionised path, produced by the stepped leader, to neutralise the charge. This current flow is termed the **return** stroke and may carry currents as high as 200 kA, although the average current is about 20 kA.

The luminescence of the stepped leader decreases towards the cloud and in one instances it appears to vanish some distance below the cloud. This would suggest that the current is confined to the stepped leader itself. Following the first, or main stroke and after about 40 ms, a second leader stroke propagates to earth in a continuous and rapid manner and again a return stroke follows. This second and subsequent leader strokes which travel along the already energised channel are termed **dart leaders**.

What appears as a single flash of lightning usually consist of a number of successive strokes, following the same track in space, at intervals of a few hundredths of a second. The average number of strokes in a multiple stroke is four, but as many as 40 have been reported. The time interval between strokes ranges from 20 to 700 ms, but is most frequently 40-50 ms. The average duration of a complete flash being about 250 ms.

The approximate time durations of the various components of a lightning stroke are summarised as follows.

Stepped leader	=	10 ms
Return stroke	=	40 μs
period between strokes	=	40 ms
duration of dart leader	=	1 ms

For the purpose of surge calculations, it is only the heavy current flow during the return stroke that is of importance. During this period it has been found that the waveform can be represented by a double exponential of the form

$$i = I (e^{-\alpha t} - e^{-\beta t})$$

with wavefront times of 0.5 - 10 μs, and wavetail times of 30 - 200 μs. (An average lightning current waveform would have a wavefront of the order of 6 μs and a wavetail of the order of 25 μs).

The standard voltage waveform used in high voltage testing has a 1.2/50 μs waveform to take into account the most severe conditions. For the standard waveform, the coefficients α and β in the double exponential have values of $\alpha = 1.426 \times 10^4 \, s^{-1}$, and $\beta = 4.877 \times 10^6 \, s^{-1}$.

3.1.2 Frequency of occurrence of lightning flashes

A knowledge of the frequency of occurrence of lightning strokes is of utmost importance in the design of protection against lightning. The frequency of occurrence is defined as the flashes occurring per unit area per year.

However, this cannot be measured very easily, and without very sophisticated equipment. This information is difficult to obtain. However, the keraunic level at any location can be quite easily determined. The **keraunic level** is defined as the number of days in the year on which thunder is heard. It does not even distinguish between whether lightning was heard only once during the day or whether there was a long thunderstorm. Fortunately, it has been found by experience that the keraunic level is linearly related to the number of flashes per unit area per year. In fact it happens to be about twice the number of flashes/square mile/year. By assuming this relationship to hold good throughout the world, it is now possible to obtain the frequency of occurrence of lightning in any given region quite easily.

The isokeraunic level map, which shows contours of equal keraunic level, for Sri Lanka is shown in figure 3.3.

Figure 3.3 - Isokeraunic Level map of Sri Lanka

The map is based on the findings of the study "Lighning conditions in Ceylon,, and measures to reduce damage toelectrical equipment" by Dr Gi-ichi Ikeda in 1968 (Asian Productivity organization report, May 1969 – AP) Project TES/68)

3.2   Lightning Problem for Transmission Lines

The negative charges at the bottom of the cloud induces charges of opposite polarity on the transmission line. These are held in place in the capacitances between the cloud and the line and the line and earth, until the cloud discharges due to a lightning stroke. The figure 3.4 shows the problems facing the transmission engineer caused by lightning. There are three possible discharge paths that can cause surges on the line.
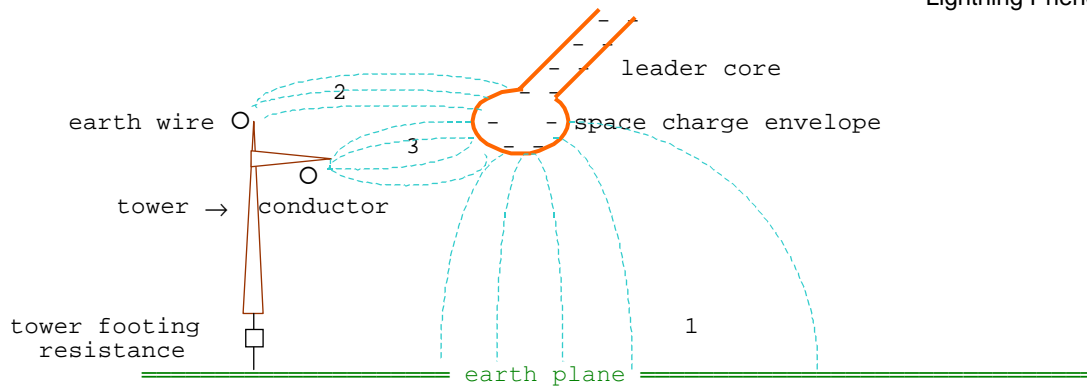
Figure 3.4 - Geometry of lightning leader stroke and transmission line

(a)   In the first discharge path (1), which is from the leader core of the lightning stroke to the earth, the capacitance between the leader and earth is discharged promptly, and the capacitances from the leader head to the earth wire and the phase conductor are discharged ultimately by travelling wave action, so that a voltage is developed across the insulator string. This is known as the **induced voltage due to a lightning stroke to nearby ground**. It is not a significant factor in the lightning performance of systems above about 66 kV, but causes considerable trouble on lower voltage systems.

(b)   The second discharge path (2) is between the lightning head and the earth conductor. It discharges the capacitance between these two. The resulting travelling wave comes down the tower and, acting through its effective impedance, raises the potential of the tower top to a point where the difference in voltage across the insulation is sufficient to cause flashover from the tower back to the conductor. This is the so-called **back-flashover** mode.

(c)   The third mode of discharge (3) is between the leader core and the phase conductor. This discharges the capacitance between these two and injects the main discharge current into the phase conductor, so developing a surge-impedance voltage across the insulator string.   At relatively low current, the insulation strength is exceeded and the discharge path is completed to earth via the tower. This is the **shielding failure** or direct stroke to the phase conductor.

The protection of structures and equipment from the last mode of discharge by the application of lightning conductors and/or earth wires is one of the oldest aspects of lightning investigations, and continue to do so.

3.2.1   Shielding by overhead ground wires

Overhead ground wires are provided on transmission lines to intercept direct strokes of lightning and thus keep it off the phase conductor, and to reduce the surge current and hence the overvoltage on a phase conductor by having currents induced in it.

The proportion of lightning flashes capable of causing sparkover of line insulation decreases as the system voltage increases. This is due to the fact that the magnitude of the overvoltage caused by lightning strokes are almost independent of the system voltage. Of course there is a slight dependence as the height of the towers also increase with the increase in voltage and a taller tower is more liable to a lightning strike. For a given magnitude of lightning overvoltage, the per unit value based on system voltage decreases as the system voltage increases. Thus as the system voltage increases, there are lesser number of flashovers caused by lightning.

Not only does the tall tower attract more lightning strokes, but also it requires a much better earth-wire coverage for a given degree of protection. The figure 3.5 illustrates this geometrically, by considering two identical configurations of conductors, but with the height of the tower different.
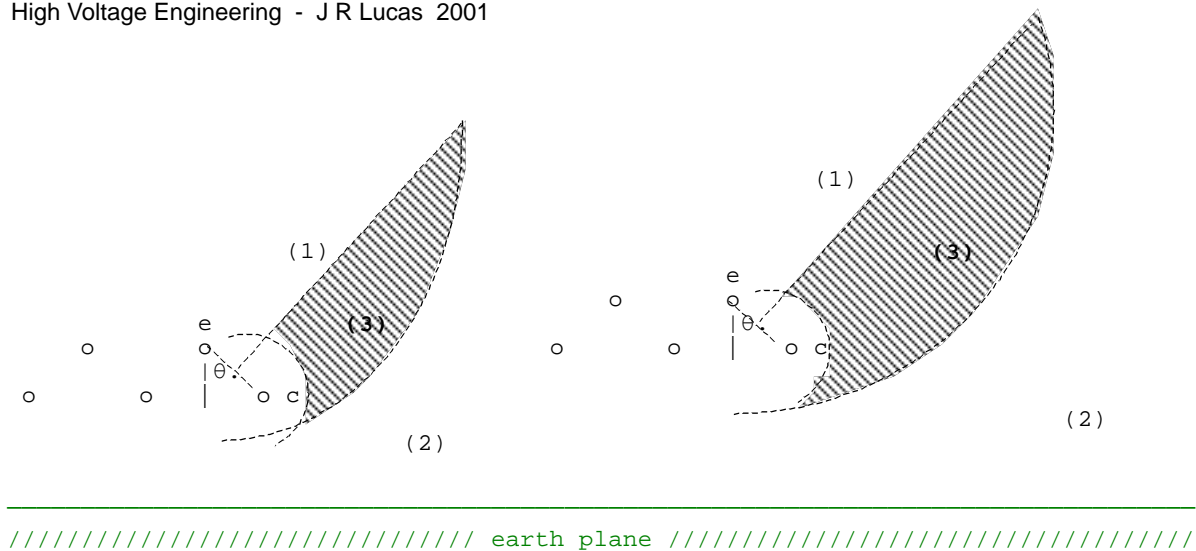
Figure 3.5 - Earth wire shielding - geometric model

The region marked (1) on the diagram, represents the region in which lightning will most likely strike the earth wire and thus provide protection against direct strikes. The locus of the lower boundary of this region is approximately defined by the perpendicular bisector of the line joining the phase conductor (the outermost for a horizontal arrangement and the uppermost in the case of a vertical arrangement) and the earth wire.

The region marked (2) on the diagram, represents the region in which lightning avoids both the overhead conductor as well as the earth wire but strikes some nearby object. The region has the upper boundary defined approximately by a parabolic locus. This locus is taken as equidistant from both the earth plane as well as the phase conductor. {This assumption is not exactly true as the phase conductor is a better attractor of lightning due to its sharper configuration).

Depending on the strength of the charge on the leader core, lightning will be initiated at a distance away from the object struck. Thus if the leader core could approach very close to the phase conductor before it discharges, then that particular stroke will be weak. This defines a minimum region within which lightning strikes terminating on the line does not do any damage. This region thus has a circular locus around the conductor, which need not be considered.

The region marked (3) on the diagram is the balance region, demarcated by the locus of region (1), the locus of region (2) and the circular locus where the stroke is too weak to cause damage. In this region (3) the lightning stroke is most likely to terminate on the phase conductor. The area (3) is thus a measure of the efficiency of the earth-wire protection. The smaller this region is the better the shielding provided by the overhead earth wires. It can be seen that for the same semi-vertical shielding angle θ, the taller the tower the lesser the efficiency of protection provided by the earth wire. Further it can be seen that if the semi-vertical angle of shielding is reduced, the area (3) reduces giving better protection. Thus to obtain the same degree of protection, taller towers require smaller protection angles.

3.2.2   Calculation of Shielding angle

The shielding angle of an overhead earth wire is defined as the semi-vertical angle between the line joining the most exposed conductor and the earth wire.

Consider the electrostatic interaction between the core of the downward lightning stroke and a single conductor and a single earth wire as shown in figure 3.6. As the leader channel propagates downwards, its equipotential lines will interact with both phase conductor as well as the earth wire. The earth wire may be at a lower potential than the phase conductor or vice versa. In the former case (a) protection will be afforded, and the shielding is effective. In the latter case (b) no protection will be afforded and non-effective shielding will occur.
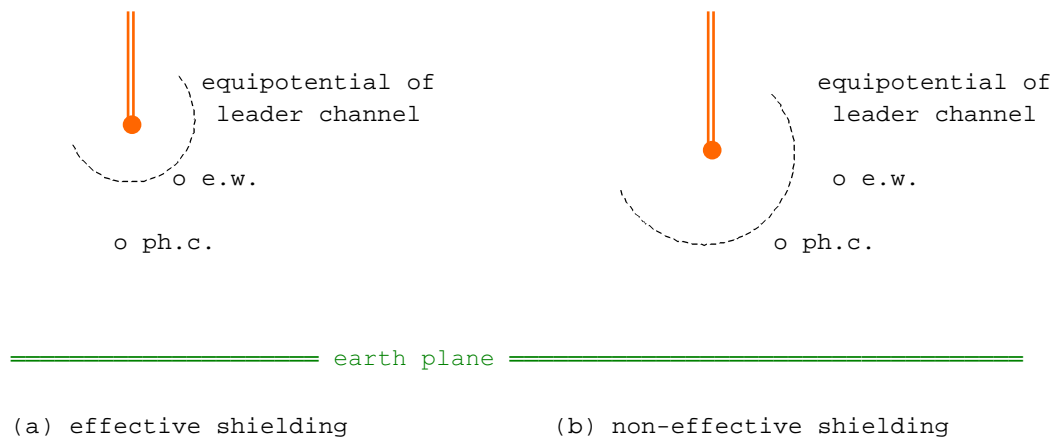
```
                equipotential of                        equipotential of
                leader channel                          leader channel

                      o e.w.                                  o e.w.

           o ph.c.                                      o ph.c.


============================== earth plane ================

    (a) effective shielding            (b) non-effective shielding
```

Figure 3.6 - Equipotentials of downward leader

For the same conductor configuration, both effective shielding and non-effective shielding could occur depending on how close the leader channel gets to the phase conductor. Thus it is necessary to know the critical distance at which various charges discharge. These have been obtained by various investigators and is illustrated in figure 3.7.

```
                    8 C
                    (160 kA)



        110 m
                              4 C
                              (80 kA)


                      60 m
                                            1 C
                                    20 m    (20 kA)

/////////////////////// earth plane ///////////////////////////
```
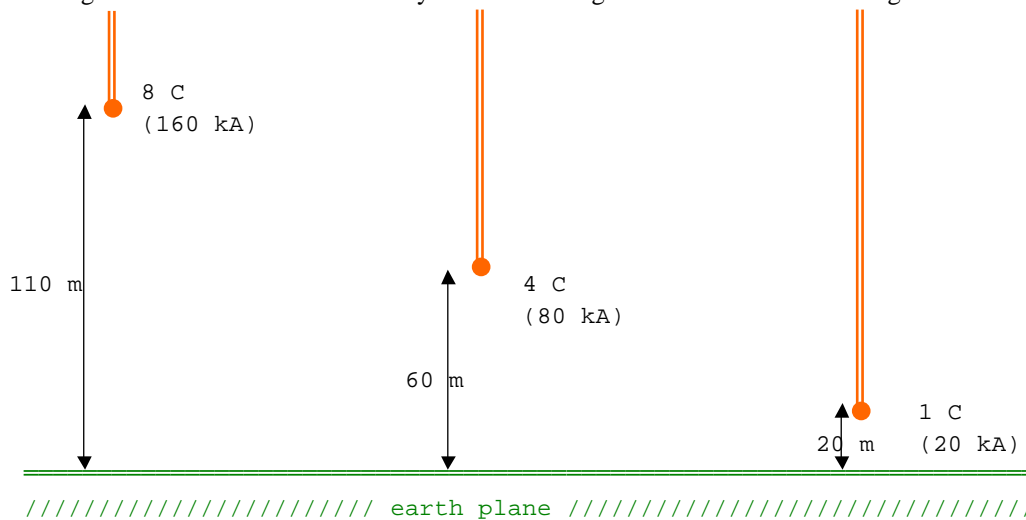
Figure 3.7 - Critical Distances associated with charges in stroke

The peak value of the return stroke current is approximately proportional to the leader charge, and the corresponding values are shown alongside the value of the charge on the diagram.

Figure 3.8 shows the distribution of magnitudes of the charges (and currents), in terms of the percentage of strokes exceeding a given current.
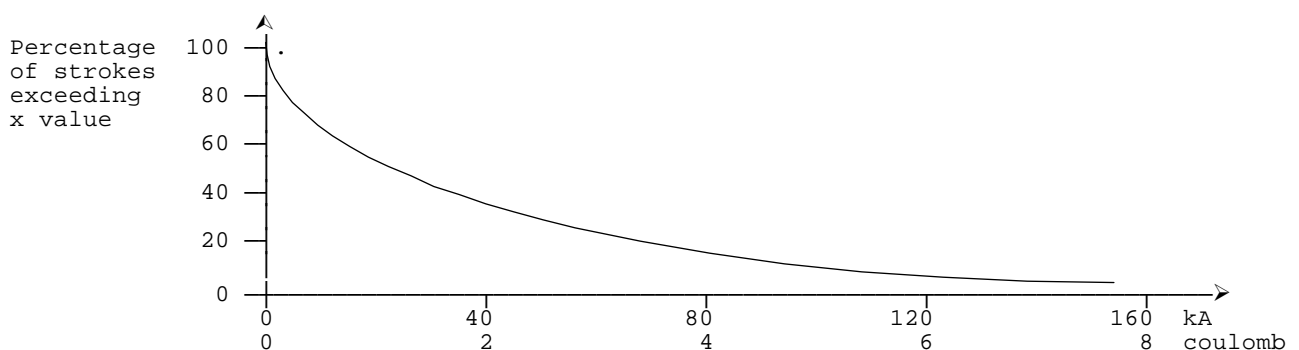
```
Percentage  100
of strokes
exceeding    80
x value
             60

             40

             20

              0
                  0        40        80       120      160  kA
                  0         2         4         6        8  coulomb
```

Figure 3.8 - Charge concentration in lightning

Based on the above, it has been found that a shielding angle of the order of 30^0 would give almost complete protection, where as an angle of nearly 90^0 would give almost no protection. Typical values used for the shielding angle are in the range of 22^0 to 48^0.

3.3   Area of attraction of transmission systems to lightning

Protective zone of lightning conductor: The area over which a lightning stroke will be attracted to and will terminate on a lightning conductor in preference to earth is termed the **protection range** or **protective zone**. Figure 3.9 shows this zone.
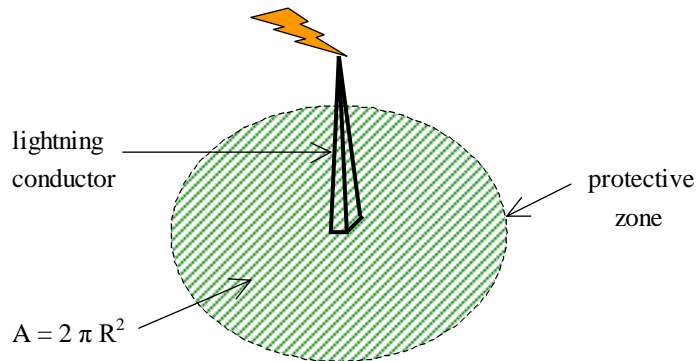

Figure 3.9 - protective zone of lightning conductor

The calculation of the area is based on a gradient of 3 kV/cm at the tower at which the upward streamer is initiated from the tower. It has been found that for the **average** stroke the **protective ratio** is approximately two for a lightning conductor or tower.

$$R = 2\,H \text{ (approx) at 20 kA}$$

That is, the area of attraction of a lightning conductor may be expected to be equal to an area around the base of the conductor with a radius of twice the conductor height. In the case of transmission lines, the earth wire is positioned to protect the phase conductors against lightning strokes and hence it is a protective conductor. However, the earth wire attracts strokes that would not normally terminate on the line. Similarly, phase-conductors themselves attract lightning strokes and it is hardly correct to talk of the **protective zone**. A more appropriate term is the **area of attraction**. Figure 3.10 shows the area of attraction of the transmission line and towers.
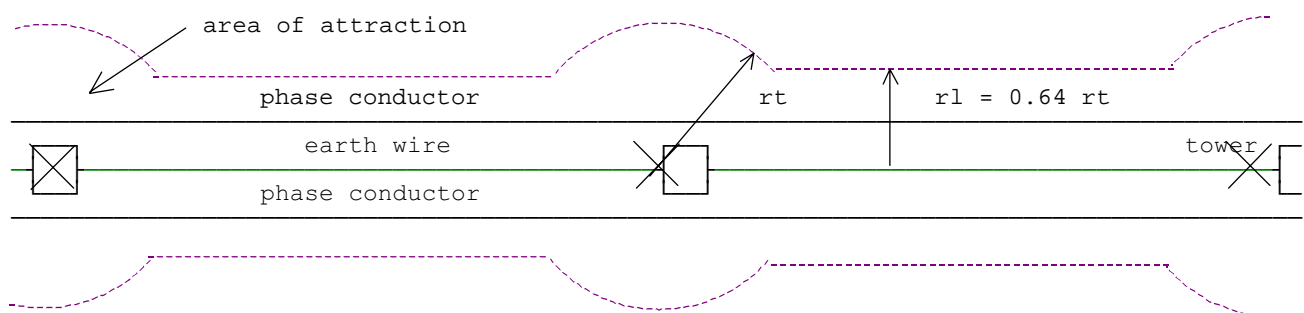

Figure 3.10 - Area of attraction of transmission line

Since the tower is like a lightning conductor, the area of attraction of the tower can be taken as equal to a circle with radius twice the tower height. An earth wire is more uniform that a transmission tower, in that it does not have a sharp point but a sharp line. It has been estimated that an area either side of the earth wire to a distance of 1.5 or 1.6 times the effective height of the earth wire multiplied by the length of the earth wire is a reasonable value to be taken. Further it must be noted that due to the sag of the earth wire, the effective height of the earth wire is itself only about 80% of the height at the tower. Thus a distance of 64% of the radius of attraction at the tower may be taken for the attraction distance of the earth wire. The phase conductor may be treated similarly, but with the height of the phase conductor being considered instead of that of the earth wire.

Thus if the line dimensions are known, it is possible to evaluate the total area of attraction that the line has to lightning strokes.

3.4   Effects of Lightning on a Transmission Line

Charged clouds induce charges on upstanding objects. These induced charges are distributed in such a way as to cause a concentration of potential at the upper end of the object, with the result that the electrostatic stress is very great. This causes the air in the immediate neighborhood to be ionised very rapidly, and charged particles are expelled from the pointed end. This produces a gradual lowering of the resistance of the discharge path between the cloud and the conductor until eventually the lightning discharge takes place.

3.4.1   Strokes to a Phase-conductor

The charged cloud could discharge directly onto the line. If the line is struck a long distance from a station or substation, the surge will flow along the line in both directions, shattering insulators and sometimes even wrecking poles until all the energy of the surge is spent. If it strikes the line immediately adjacent to a station, then the damage to plant is almost certain, since it is doubtful whether the ordinary lightning arrestor could divert to earth such a powerful discharge, without allowing a part to be transmitted to the terminal apparatus.

When lightning strikes an overhead phase-conductor, the magnitude of the current and the high frequency nature of the stroke causes voltage surges to be propagated in both directions from the point of the strike (Figure 3.11).
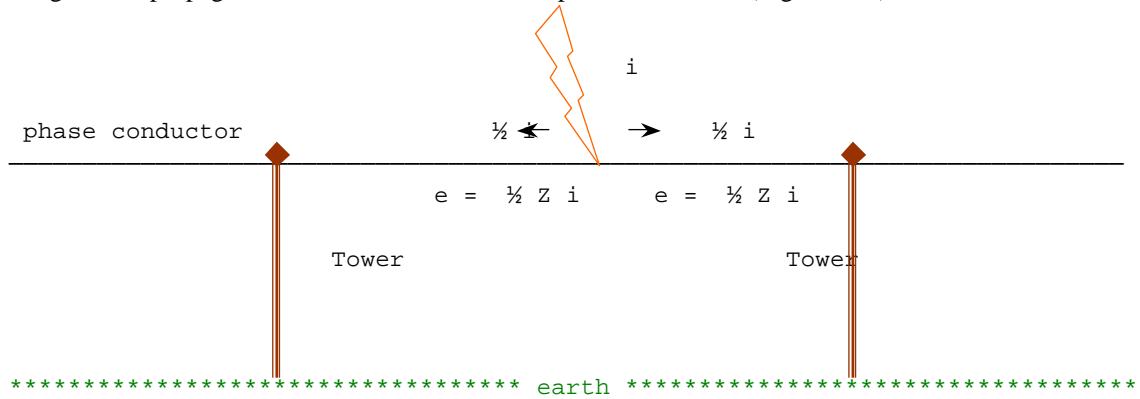

Figure 3.11 - Direct strike on phase conductor

The waveshape of these voltage surges is similar to that of the current in the lightning discharge. The discharge current splits itself equally on contact with the phase conductor, giving travelling waves of magnitude e.

$$e \ = \ \tfrac{1}{2} \, Z \, i \, (\, e^{-\alpha t} - e^{-\beta t} \,)$$

where Z is the surge impedance of the phase conductor.

Using a typical value for the line surge impedance (say 300 Ω) and an **average lightning current** (20 kA), the voltage waves on the line would have a crest value of

$$E = \tfrac{1}{2} \, Z \, i = (300/2) \text{ x } 20 \text{ x } 10^3 \ = 3 \text{ MV}$$

3.4.2 Strokes to a tower with no earth wire

Fortunately, direct strokes to the line are infrequent in occurrence compared to side strokes, the effects of which are not so severe. If there is a direct stroke to the tower, a current would be discharged through the metal work of the tower and there would be a potential difference between the top and bottom of the tower.

Figure 3.12 shows a steel tower (inductance **L**) of a transmission line with no earth wire. If the earthing resistance of the tower is **R** (= 5 - 100 Ω), and it is struck by lightning, then the potential built up on the tower top would be

$$R \, i + L \, \frac{d \, i}{d \, t}$$

If e_i is the induced voltage on the conductor due to the lightning, then the potential difference built up across the tower and the conductor is given by

$$e \ = \ R\,i + L\,\frac{d\,i}{d\,t} + e_i$$

If the value of e exceeds the line insulation strength, then a flashover occurs from the tower to the line and this is termed a **backflashover**.

3.4.3   Strokes to Earth Wire

When a lightning stroke terminates on the tower of a transmission line having an overrunning earth wire, or terminates on the earth wire of the transmission line, then the resulting current flow would be as shown in figure 3.13 (a) and (b).
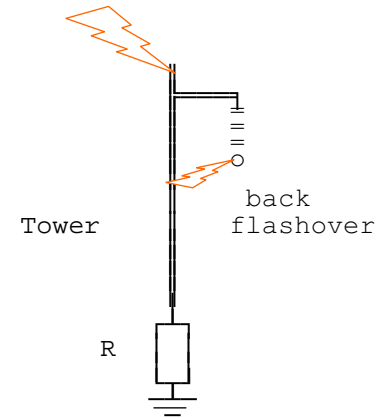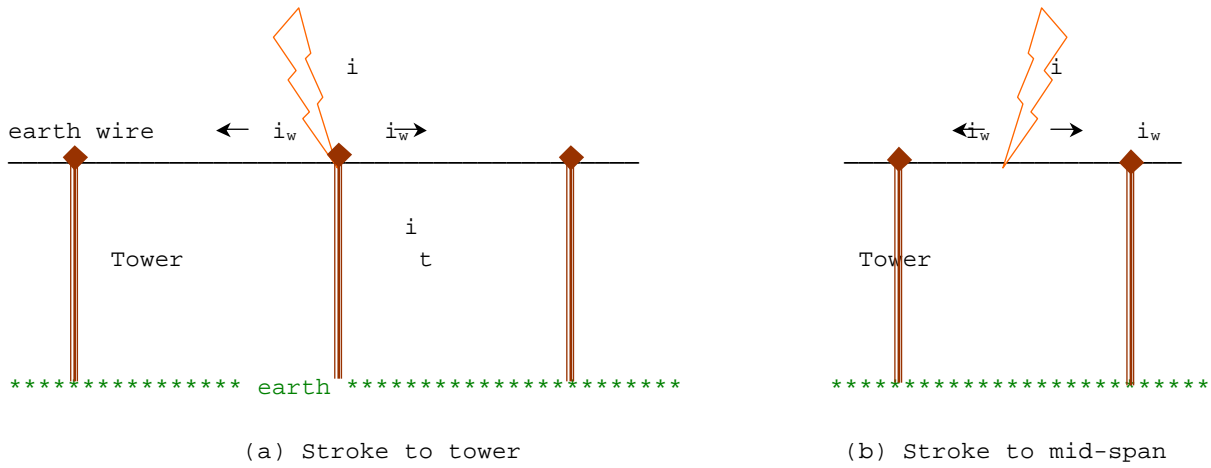

Figure 3.12 - Strokes to tower

Figure 3.13 - Stroke to earth wire

The voltage waves produced by the current i_w flowing along the earth wire will travel along the earth wire in both directions from the tower struck. On reaching the neighboring towers they will be partly reflected, and the reflected waves will arrive back at the tower after twice the transit time between the towers. Further reflections will take place as the waves travel further along the earth wire and reaches other towers. In calculation of the resulting voltage wave and hence the potential difference across the insulation it is useful to consider the **initial period**, **first reflection period**, **second reflection period** and so on and obtain separate equivalents.

For example, for the initial period and the first reflection period, the following equivalent circuits given in figures 3.14 and 3.15 may be used.
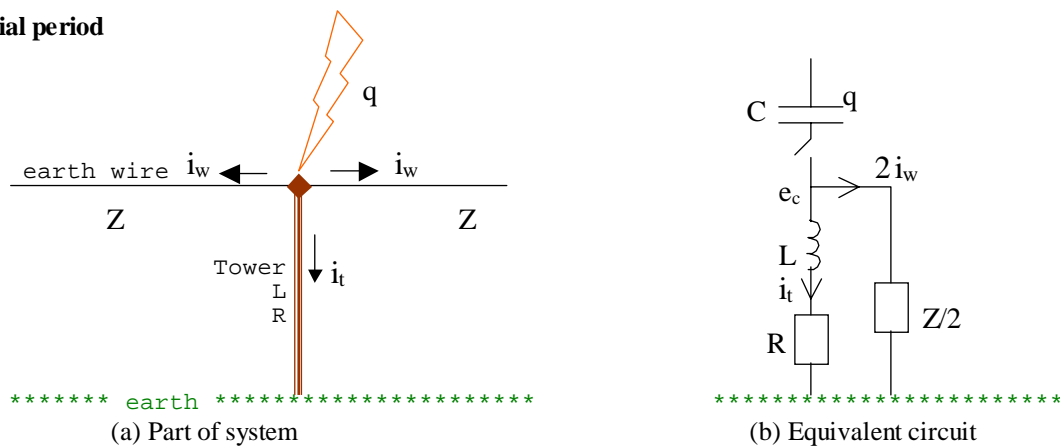
Initial period

Figure 3.14 - For initial period

In the figure 3.14, **L** is the effective inductance of the tower, **R** is the effective resistance of the tower and footing and **Z** is the surge impedance of the earth wire.

First Reflection period

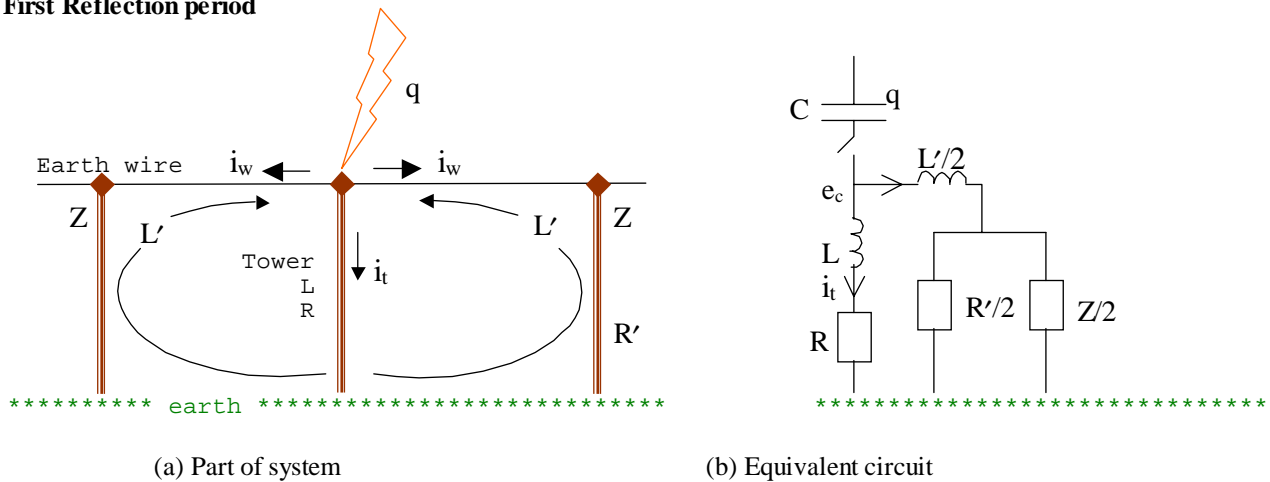| (a) Part of system	(b) Equivalent circuit

Figure 3.15 - For first reflection period

where **L'** is the inductance of the first span loop and earth return.

If instead of the actual tower being struck, the earth wire is struck somewhere near mid-span, then this can be regarded as two towers in parallel being struck for the second reflection period, with the impedance of the span struck acting as an extension to the lightning channel.

For a given tower footing resistance **R**, strokes to the tower generally develop about one-and-half times the potential at the top of the tower as compared with the strokes to mid span. For a typical lightning current of 20 kA and a tower footing resistance of 20 Ω, those struck at the tower develop voltages of the order of 200 kV.

3.4.4   Strokes to nearby objects (Indirect Strokes)

In any lightning discharge, the charge on the down coming leader causes the conductors of the line to have a charge induced in them (figure 3.16).
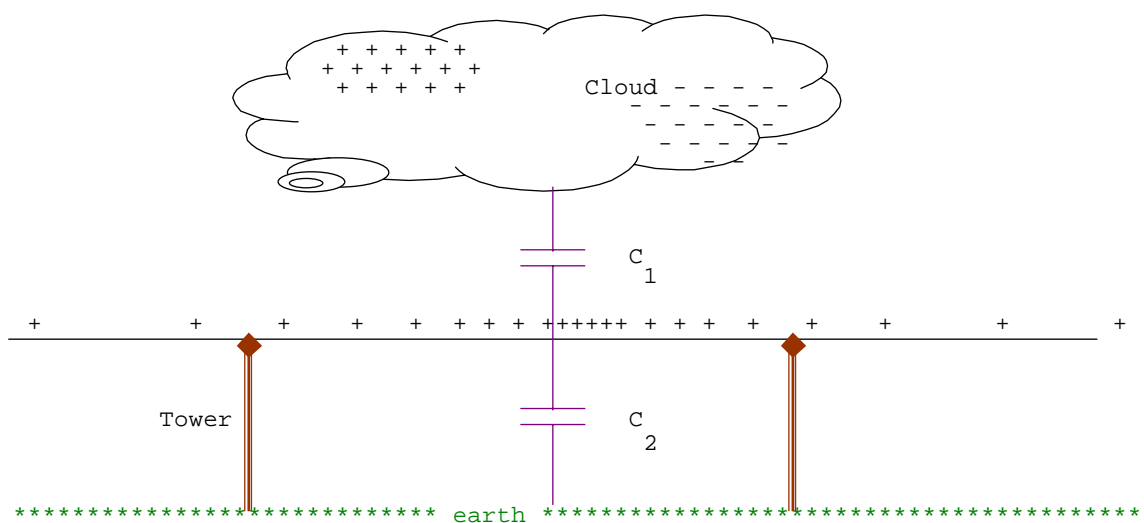

Figure 3.16 Induced charge on line

These charges are bound (held in that portion of the line nearest to the cloud) so long as the cloud remains near without discharging its electricity by a lightning stroke to an object. If however, the cloud is suddenly discharged, as it is when lightning strikes some object nearby, the induced charges are no longer bound, but travel with nearly the velocity of light, along the line to equalise the potential at all points of the line.

This bound charge collapse leads to a voltage wave to be generated on the line in either direction.
The value of this is given by

$$e_i = - E \cdot \frac{C_2}{C_1 + C_2} = \frac{q}{C}$$

where $\mathbf{q}$ = bound charge per unit length of line

$\mathbf{C}$ = capacitance per unit length of line

This potential will vary along the line depending upon the distance of each element of line from the lightning stroke.

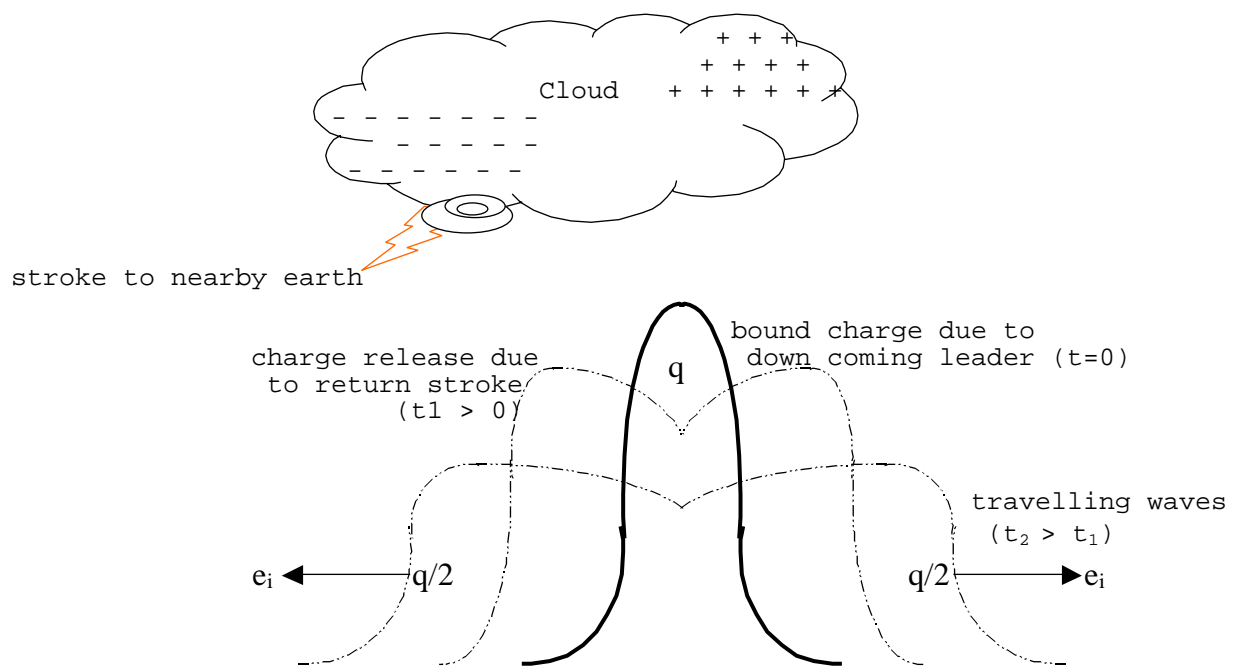The sequence of the travelling waves e_i propagating outwards is shown diagrammatically in figure 3.17

Figure 3.17 - Propagation of travelling waves