Chapter 15
Direct and Indirect Effects of Lightning Flashes

15.1 Introduction

A lightning flash can interact with any object either electrically or mechanically or both. In this chapter, both direct and indirect effects of lightning flashes are described. Following a description of the basic physical phenomena associated with direct and indirect lightning strikes, these effects are illustrated here by considering the effects of lightning strikes on residential houses, wind turbines, trees, airplanes, and power lines.

15.2 Generation of Thunder

During a return stroke, the lightning channel (approximately 1 cm radius; Sect. 15.3) through which the return stroke current propagates is heated very rapidly to approximately 25,000–30,000 K (how this is measured is described in the next section). This heating of the channel causes a rapid increase in the pressure of the channel to approximately ten times above atmospheric pressure. This rapid increase in the pressure creates a shock wave in air, and after traveling a few meters from the channel, it transforms into a sound wave. This sound wave is called *thunder*.

Since there are many return strokes in a lightning flash in general, the process of heating and generation of thunder or the shock wave takes place repeatedly during each return stroke. Now, a typical lightning flash may last for around 200–300 ms and in extreme cases for around 1 s. On the other hand, the generation of thunder from the return stroke channel (or the heating of the channel) takes place almost instantaneously along the whole channel during the return stroke. So then why does the thunder generated by a lightning flash last much longer than 1 s? Because sound travels in air at a speed of approximately 330 m/s. Suppose that an observer is located 1 km from the point of a lightning strike. The entire lightning channel is

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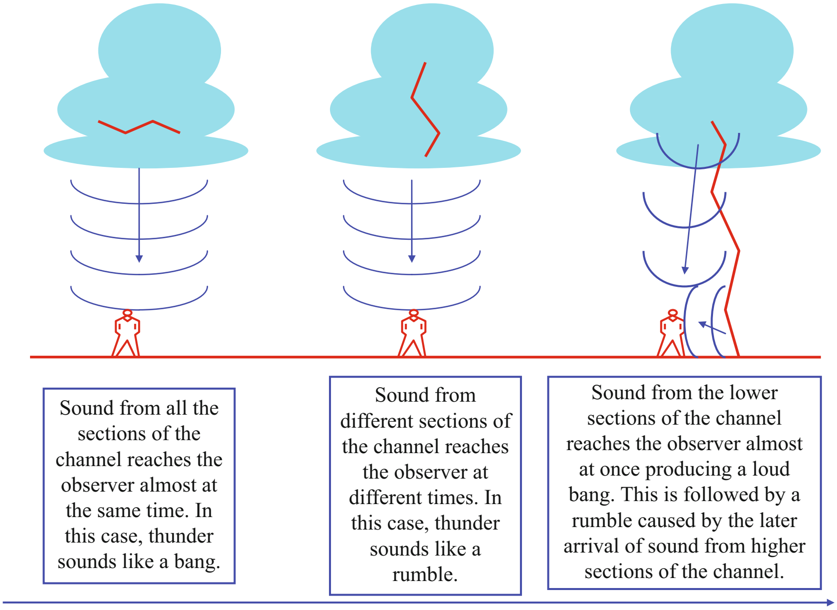


Sound from all the sections of the channel reaches the observer almost at the same time. In this case, thunder sounds like a bang.

Sound from different sections of the channel reaches the observer at different times. In this case, thunder sounds like a rumble.

Sound from the lower sections of the channel reaches the observer almost at once producing a loud bang. This is followed by a rumble caused by the later arrival of sound from higher sections of the channel.

Fig. 15.1 Lightning produces a rich variety of sounds (Figure created by author)

approximately 7,000 m long, and therefore the top of the channel is approximately 7,071 m from the observer. Now, since sound travels at a rate of 330 m/s, the sound from the bottom of the channel reaches the observer in approximately 3 s (i.e., 1,000/330) and the sound from the top of the channel reaches the observer in approximately 23.6 s (i.e. 7071/330) (Fig. 15.1). So thunder lasts for approximately 20 (23 – 3) s. In fact, the duration of the thunder can be used to obtain a rough length of the lightning channel. If the duration of thunder is measured in seconds then dividing that number by 3 will give the minimum length of a lightning channel in kilometers. The actual length of the channel is larger than the length one would estimate by this method. Of course, this approximation is valid if the lightning channel is vertical. In reality, with large horizontal channel sections inside clouds, lightning channel geometry is much more complex. This makes the connection between the duration of thunder and the channel length much more complicated than the simple relationship given previously.

The thunder signal from a lightning flash is not just a monotonic sound but contains peals, claps, and rumble. This rich variety of sound modulations in thunder is caused by the branches and the tortuous nature of the lightning channel. Thunder generated by branches and other channel sections located at different orientations in space reach the observer at different times. Sometimes the thunder generated by all the points along a channel section may reach the observer simultaneously, producing a loud clap. In other cases, sound from different channel sections may reach the observer at different times, producing a rumble. Furthermore, the strength of the sound decreases as it moves in air. If an observer is located close to a lightning strike, the sound from the bottom of the channel, which is located close to the observer, produces a loud clap and the sound from the upper sections of the channel produce a diminishing rumble. If an observer is located very close to a lightning flash, say 100 m or less, thunder sounds like a crack or hissing sound followed by a loud bang. The crack and hissing sound is produced probably by intense corona and connecting leaders generated by objects at ground level. Usually observers can only hear the thunder from a lightning flash when they are located within approximately 20 km away from it.

During a lightning strike to an object, the lightning current may follow the path of least resistance to the ground. This path may contain moisture. An example is when a lightning flash strikes a tree. The lightning current may flow in the inner part of the tree where there is a high moisture content. The rapid heating of the water causes a rapid expansion, leading to an explosion that splits the tree into parts. The same effect can be observed in cases where lightning strike grounded structures. When that happens, the current may travel through building materials such as clay or wet concrete, causing the water vapor to expand explosively, leading to the ejection of material.

15.3 Temperature of a Lightning Channel and How It Is Measured

As mentioned earlier, thunder is generated by the rapid heating of air to approximately 25,000–30,000 K during a lightning flash. But how do we measure this temperature? The procedure used by scientists to measure the temperature of a lightning channel is as follows. First, the light signal generated by the lightning channel is separated into spectral components using a specially designed diffraction grating, and the resulting spectrum is recorded either digitally or on photographic paper. From this spectrum two spectral lines located very close to each other are selected and their intensity measured. Multiplets of doubly ionized nitrogen atoms centered at 399.5, 404.1, 443.3, 463.0, and 567.9 nm had been used for this purpose [1]. If the lightning channel is at thermodynamic equilibrium, then the ratio between the two intensities is related to the temperature of the channel. Thus, by measuring the intensity of two very closely spaced spectral lines (i.e., multiplets of a spectral line), it is possible to estimate the temperature of the lightning channel. In the foregoing statements, *thermodynamic equilibrium* means that all particles in the channel, i.e., neutral atoms, ions, and electrons, are at the same temperature. This is not exactly true in a lightning channel because electrons, which gain energy from electric fields, are usually at a higher temperature than ions and neutral atoms.

On the other hand, the electron densities that occur in a lightning channel can be obtained by measuring the Stark broadening of the spectral lines without making any assumptions concerning thermodynamic equilibrium. Stark broadening of spectral lines is a consequence of the interactions of the electric fields inside a channel with atoms that radiate the spectral line. The electric field experienced by the atoms is related to the electron density in the channel. Thus, measuring the Stark broadening of spectral lines makes it possible to obtain the electron density in a channel. Using this procedure the free electron densities in lightning channels were estimated to be in the range of 10^{17} to 5×10^{18} e/cm^3 [1].

15.4 Thickness of a Lightning Channel

The thickness of a lightning channel can be estimated by photographing it. However, this method always overestimates the thickness of the channel because of the scattering of light on the photographic plate. In the pioneering days of lightning research, researchers estimated the size of lightning channels by placing fiberglass screens across the path of the lightning and measuring the holes created by the lightning in it (Fig. 15.2) [2]. The diameter of a lightning channel can also be calculated using theories on electrical discharges [3]. On the basis of such analyses scientists have estimated that a hot lightning channel is approximately 1 cm in radius.

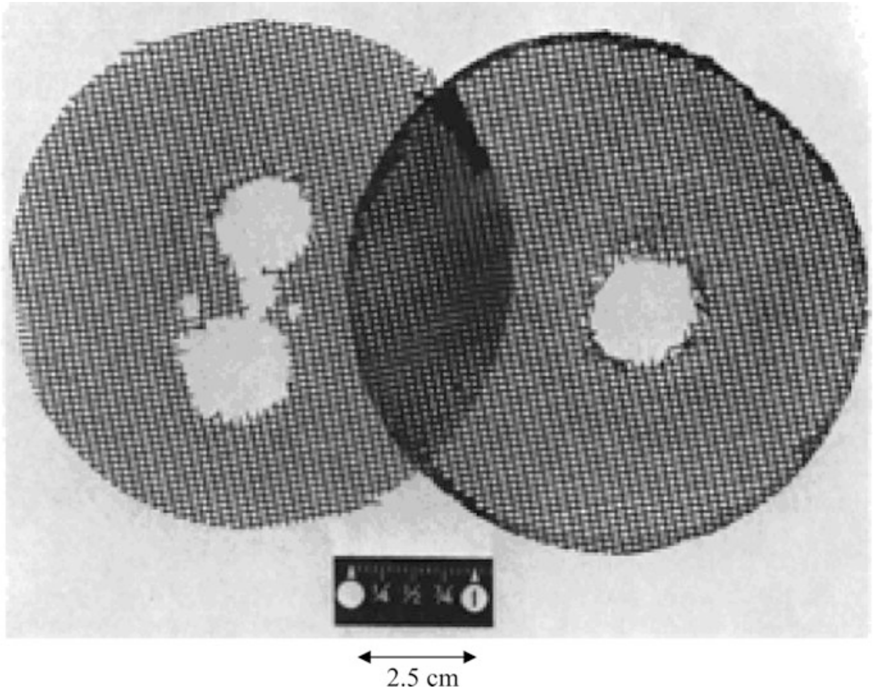


Fig. 15.2 Holes melted in two fiberglass screens by lightning. Four strokes passed through left screen and one through right screen [2]. The size of the holes gives a rough estimation of the thickness of the hot core of the return stroke channel

15.5 Melting of Material

In Chap. 8 was given a description of how to evaluate the energy transferred to a metal in contact with a lightning channel. This energy is directly proportional to the charge transported by the lightning channel and the cathode voltage V_c, which is approximately 15–20 V. Thus, the heat energy, W, that is transferred to the metal across the cathode layer is given by

$$W = QV_c, \tag{15.1}$$

where Q is the charge dissipated in the process under consideration. This heat leads to the melting of metal when the lightning channel is in contact with a metal surface. The amount of metal volume V (in m^3) being melted is given by the formula [4]

$$V = (W/\gamma)\frac{1}{c_w\theta_s + c_s}, \tag{15.2}$$

where γ is the density of the material, c_w is the specific heat capacity (in J/kg.K), θ_s is the temperature at which the material melts, and c_s is the specific heat of melting (in Joules per kilogram). These parameters for different types of metal that are used in lightning protection practice are given in Table 15.1. Using the preceding equation and the parameters given in Table 15.1 it is possible to calculate the volume of material melted once the charge Q is given.

Consider a lightning flash transferring 10 C of charge in contact with an aluminum surface. If $V_c = 20\,\mathrm{V}$, then 200 J of energy is transferred to the surface. For aluminum, $\gamma = 2{,}700$, $c_w = 908$, $\theta_s = 685$, and $c_s = 397 \times 10^3$. Using these parameters we find that the volume of material melted is 73 mm^3. That is, each coulomb of charge will melt a volume of 7.3 mm^3 of aluminum.

Table 15.1 Various parameters pertinent to calculation of heat dissipation and melting effects during lightning strikes

Parameter	Unit	Aluminum	Copper	Iron
γ	$\mathrm{kg/m^3}$	2,700	8,920	7,700
θ_s	°C	685	1,080	1,530
c_s	J/kg	397×10^3	209×10^3	272×10^3
c_w	J/(kg K)	908	385	469
ρ	Ωm	29.0×10^{-9}	17.8×10^{-9}	120×10^{-9}
α	1/K	4×10^{-3}	3.92×10^{-3}	6.5×10^{-3}

15.6 Heating of Material as Lightning Current Passes Through an Object

Consider a lightning strike to an object having a resistance R. The amount of energy dissipated in the object as the lightning current passes through it is given by (Chap. 8)

$$W = R\int_0^{\infty} i^2(t)dt. \tag{15.3}$$

The release of this energy in the material causes its temperature to rise. The increase in temperature can be calculated easily for an object in the form of a cylinder. Assuming a cylindrical geometry, the increase in the temperature (in degrees Kelvin) of 1 m of material is given by [4]

$$\Delta\theta = \frac{1}{\alpha}\left\{ \exp\frac{\alpha\rho\int i^2(t)dt}{a^2\gamma c_w} - 1 \right\}, \tag{15.4}$$

where α is the temperature coefficient of the resistance, ρ is the resistivity of the material of the conductor, and a is the cross-sectional area of the conductor. The preceding equation shows that the thinner the conductor, the larger the rise in temperature. If the action integral of the current (i.e., the integral in Eq. 15.3) is 10^6 A^2s, then the rise in temperature of a 16 mm^2 copper conductor is 21 K. If the temperature rises above the melting point, it could melt and vaporize explosively. Thus, in selecting the diameter of conductors in lighting protection systems it is important to select the diameter of the conductors such that heating effects can be neglected.

15.7 Attraction of Two Current-Carrying Conductors

During a lightning strike parts of the lightning current might propagate along different conductors. This flow of current along conductors located in the vicinity of each other can cause mechanical stresses on the conductors and, in the worst case, dislodge them from their secured positions. Assume, for example, that the return stroke current is divided into two parts and flows along two parallel conductors (Fig. 15.3a). Denote the separation between them by s, and assume that the radii of the conductors are much smaller than s. Then the force (in Newtons) experienced by per unit length of the two conductors at any given time t is

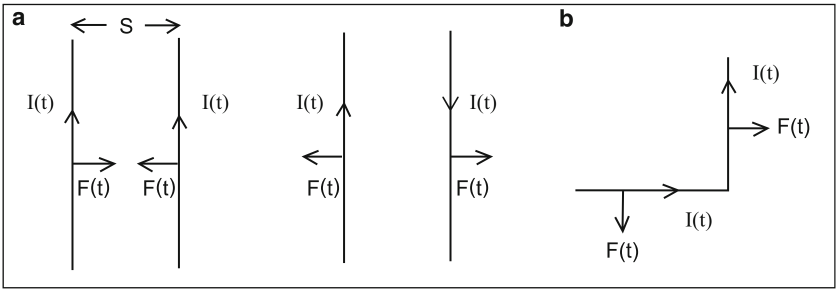


Fig. 15.3 (**a**) When a lightning current passes through two conductors, there is a force between them. The force is attractive if the current is flowing in the same direction along the two conductors and repulsive if the current is flowing in the opposite direction. (**b**) When a lightning current flows along a bent conductor, there is a force on the two branches. The force is such that it will act in a direction to straighten the conductor (Figure created by author)

$$F(t) = \frac{\mu_0}{2\pi s} I_1(t) I_2(t). \tag{15.5}$$

If the current is flowing in the same direction along the conductors, then the force is attractive (first diagram of Fig. 15.3a). If the current is flowing in the two conductors in opposite directions, then there will be a repulsive force between them (second diagram of Fig. 15.3a). If the return stroke current $i(t)$ is divided equally among the conductors, then $i_1(t) = i_2(t) = i(t)/2$, and the force between them can be written as

$$F(t) = \frac{\mu_0}{8\pi s} i^2(t). \tag{15.6}$$

Then the impulse I acting between the two conductors because of the flow of the return stroke current through them is

$$I = \frac{\mu_0}{8\pi s} \int_0^{t_d} i^2(t)\,dt, \tag{15.7}$$

where the upper limit of integration t_d is the duration of the return stroke current. This impulse is responsible for the mechanical action or movement of the two conductors. Observe that the impulse is proportional to the action integral of the return stroke current. It is important to remember that the force acts not only on parallel conductors but also when the two current paths form an angle (Fig. 15.3b). In this case, the force acting on the two branches is such that it will try to make them straighter. For this reason, it is necessary to avoid sharp bends in the down conductors used in lightning protection.

15.8 Induction of Voltages Due to Lightning-Generated Magnetic Fields

Consider a lightning strike to a lightning conductor located in a building, as shown in Fig. 15.4a. The current passing through this conductor generates a time-varying magnetic field that can induce voltages in any metallic loop located in its vicinity. To simplify the mathematics, assume that the conductor through which the lightning current is flowing is infinitely long. A conducting loop is located in the vicinity of this conductor, as shown in Fig. 15.4b. The magnetic field generated by the lightning current flow at a radial distance of r from the conductor is

$$B = \frac{\mu_0 i(t)}{2\pi r}. \tag{15.8}$$

The total magnetic flux passing through the loop can be calculated by dividing the loop into infinitesimal strips (dr in width) parallel to the conductor and summing the contribution from all the strips by integration. Thus, the total flux of the magnetic field passing through the square loop of width b is

$$\varphi = \int_{r1}^{r2} \frac{\mu_0 i(t)}{2\pi r} b dr. \tag{15.9}$$

After performing the integral we obtain

$$\varphi = \frac{\mu_0 b i(t)}{2\pi} \ln\left(\frac{r_2}{r_1}\right). \tag{15.10}$$

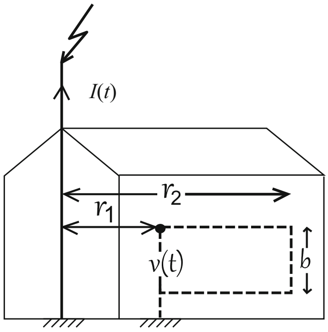


Fig. 15.4 The A lightning current passing through a conductor can induce voltages in conducting loops located nearby. This example is used in the text to evaluate the voltage induced in a conducting loop (*dotted lines*) by the time-varying magnetic field produced by the current flowing in the lightning down conductor (Figure created by author)

The voltage induced in the loop is then given by

$$V = \frac{\mu_0}{2\pi} \frac{di(t)}{dt} b \ln\left(\frac{r_2}{r_1}\right). \tag{15.11}$$

The peak voltage induced in the loop is given by

$$V_m = \frac{\mu_0 b \ln(r_2/r_1)}{2\pi} \left(\frac{di(t)}{dt}\right)_{\max}. \tag{15.12}$$

Thus, the maximum voltage is proportional to the maximum derivative of the current. If the resistance of the loop is equal to R, then the maximum current that will flow through the loop is V_m/R. The maximum voltage induced in the loop can be written as

$$V_m = M\left(\frac{di(t)}{dt}\right)_{\max}. \tag{15.13}$$

The parameter M is the mutual inductance between the lightning channel or the conductor through which the current is flowing and the loop. It depends on the geometry of the loop and its location. In the example shown in the figure, M is given by

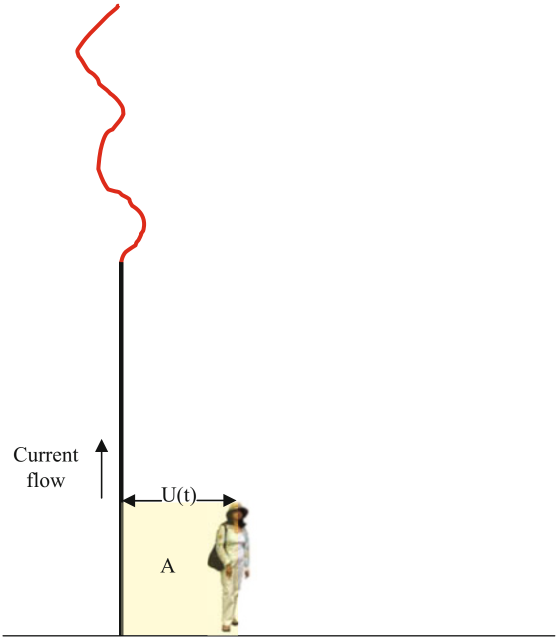
$$M = \frac{\mu_0}{2\pi} b \ln \frac{r_2}{r_1}. \tag{15.14}$$

Thus, a 1 m^2 square loop located at a distance of 10 m from a conductor carrying a return stroke current whose maximum rate of change is 100 kA/μs will generate a peak voltage of approximately 2 kV in the loop. It is important to remember that the loops in the vicinity of a lightning path can be formed in various ways. For example, in the case of a person located as shown in Fig. 15.5, a voltage is generated between the person's head and the lightning current path due to induction caused by the magnetic field passing through area A.

15.9 Induction Due to Electric Field

It is not only the magnetic field generated by lightning flashes that can generate voltages and currents because of induction. An electric field can do the same. To illustrate this, consider a small metal sphere located at height h above a perfectly

Fig. 15.5 When a human is located in the vicinity of a conductor struck by lightning, there is a voltage difference between the head and the conductor $U(t)$ because of the magnetic flux passing through the area marked A between the human and the conductor. This voltage is proportional to $A(dI(t)/dt)$, where $dI(t)/dt$ is the rate of change of the current (Figure created by author)



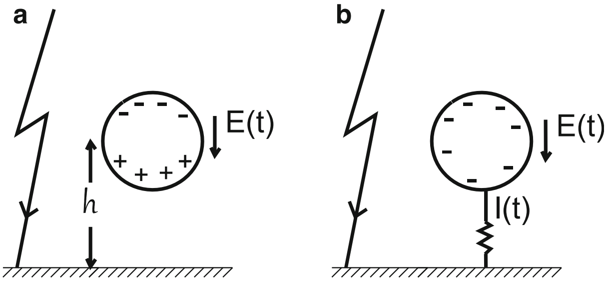


Fig. 15.6 (**a**) Isolated conducting sphere located in an electric field of a lightning flash. Because of action of electric field, charges are displaced on the sphere while keeping the net charge equal to zero. (**b**) If the sphere is connected to the ground, the positive charge flows to the ground (of course, the polarity of this charge depends on the direction of the background electric field), leaving a net negative charge on the sphere. As the electric field varies with time, the net charge on the sphere varies and there is a current flow across the resistor. In this way, an electric field can induce a current in conductors connected to the ground (Figure created by author)

conducting ground at a certain distance from a lightning strike (Fig. 15.6). Let the electric field produced by the lightning flash or the return stroke be $E(t)$. If the sphere is isolated (Fig. 15.6a), this electric field will change the charge distribution on the sphere while keeping the net charge equal to zero. Now, if the sphere is grounded while under the influence of the electric field (Fig. 15.6b), positive charge will go to the ground, leaving behind a net negative charge on the sphere. The charge Q on the sphere is given by

$$Q = hE(t)C, \tag{15.15}$$

where C is the capacitance of the sphere. This depends on the dimension of the sphere and the height where it is located. In the preceding equation, the influence of the conductor connecting the sphere to the ground is neglected. Moreover, it is assumed that the radius of the sphere is much less than h. As the background electric field changes, the charge on the sphere changes, leading to a current flow along the wire to the ground. This current is given by

$$i(t) = h\frac{dE(t)}{dt}C. \tag{15.16}$$

Thus, the electric field causes an induction of current in the conductor connecting the sphere to the ground. Of course, in writing down the preceding equation it is assumed that the capacitance C of the sphere and the resistance R of the conductor satisfy the inequality $RC \ll \tau$, where τ is the time scale where significant change in the electric field takes place. Even if this condition is not satisfied, there will still be a current flowing along the conductor, but this current flow will not follow the rate of change of the electric field exactly as written in the preceding equation (Chap. 9). Note that in reality the object need not be a sphere. It could simply be a conductor connected to the ground or any other metal object connected to the ground. Thus, the voltages and currents that are induced during lightning strikes are caused by both the magnetic and electric fields.

15.10 Energy Dissipation During a Lightning Strike

In Chap. 14 it was estimated that the potential of a thundercloud that gives rise to a typical first return stroke with a 30-kA current is approximately 50 MV and its value may decrease to approximately 20 MV during subsequent return strokes. Let us assume therefore that an average potential of approximately 35 MV exists during a typical lightning flash. During a typical lightning flash approximately 7.5 C of charge is transferred from cloud to ground [5]. When this charge is transferred across a potential of 35 MV, the amount of energy released is approximately 2.5×10^8 J. This energy will be released along the lightning channel, and if the length of the lightning channel is approximately 5 km, then the energy released per meter is approximately 5×10^4 J/m. Some part of this energy will be released during leader processes and the rest during the return strokes. In Chap. 14 it was estimated that during the first 100 μs of a typical first return stroke the energy released is approximately 10^4 J/m. This energy is released explosively because it is released within 100 μs. Thus, the average power associated with this energy release is on the order of 10^8 W/m. The peak power dissipation can be approximately ten times greater than this average value. This explosive release of energy during the first return stroke can cause mechanical effects in objects located in the vicinity of the lightning channel.

One interesting question that occupies the lightning research community is whether this energy can be utilized. Let us look for an answer to this question. Each second approximately 100 lightning flashes take place in the atmosphere. If each lightning flash dissipates approximately 2.5×10^8 J of energy on average, then the total energy released per second or the total power generated by lightning flashes is 2.5×10^{10} W. The amount of energy released each year is approximately 200 TWh. This is a considerable amount of energy. To put that in perspective, in Sweden the yearly consumption of electrical energy is approximately 220 TWh. However, if one tries to acquire this energy, several obstacles must be overcome. First, recall that lightning flashes are distributed around the globe and only a small fraction of them is available in a given region. Second, most of the energy from those flashes is dissipated in heating the air in the lightning channel and in creating a shock wave. Only a small fraction of the energy is available at ground level. However, if all that energy were somehow collected, then the energy distributed in each square kilometer of the Earth would be approximately 50 W. Recall that most of this energy is dissipated in the air and only a fraction of it is available at ground level. Of course, this estimate depends on the assumed potential of clouds and the amount of charge dissipated in lightning flashes. However, the estimate is sufficient to illustrate that attempts to generate electric power by storing the energy of lightning flashes is not very viable economically.

15.11 Effects of Direct Lightning Strikes on Structures

The effects of direct strikes on various structures may manifest in various ways depending on the geometrical and electrical characteristics of the given structure. Let us consider several typical structures and try to understand the possible consequences.

15.11.1 Direct Lightning Strike to a House

A direct strike to a residential house may cause damage depending on the type of construction and material used. Most of the damage can be avoided by implementing a lightning protection system. Usually, if a house is not protected by a lightning protection system, then a strike will take place to the roof of the house. If the roof is made of flammable material, then the strike can set it on fire, especially if the lightning flash contains a long continuing current. Long continuing currents keep hot channels in contact with roofing materials for a longer time period and therefore can set fire to the material more easily than a lightning strike without a continuing current. If the roof is metallic, then, depending on the thickness of the metallic sheet, the lightning flash may create a hole in the metal, igniting the material located underneath. If the metal roof is not grounded, then there could be sparks jumping directly from the roof to the interior of the house. With tiled roofs, the lightning current may creep through the space between the tiles, again creating a shock wave that could explosively displace them. If the roof is concrete, parts of the concrete could be damaged as a result of water vaporization caused by sparks formed inside cracks in the concrete.

Since modern houses are equipped with electricity, the lightning current may enter into the electrical system. In the worst-case scenario, the current may flash over across phase and ground wires of the electrical system, creating a spark. If the power system is not equipped with a circuit breaker (though circuit breakers can also be fused together by lightning currents, making them ineffective), the spark thus created may not extinguish itself after the cessation of the lightning current because it will be fed with an alternating current by the power line voltage. This long-lasting spark may set fire to any nearby flammable material.

The large currents flowing in the electrical system may destroy most of the electrical devices connected to the power system. These currents may also destroy (sometimes explosively) part of the electrical system itself, for example, switch boxes. They may also cause power surges in other systems not directly connected to the power system through electrical or magnetic induction. Thus, even an electrical apparatus not connected to the power system may still experience an induced voltage due to induction.

A lightning current can cause overvoltages in other systems of conductors such as water pipes, and their voltage can rise to dangerous levels, causing sparks to jump to other objects in their vicinity during the lightning strike, depending on the grounding conditions.

15.11.2 Direct Strike to Trees

In the countryside, trees generally are the highest objects in the area. No wonder, then, that most lightning strikes on land hit trees. Forest fires are the common result. When the lightning stepped leader gets close to the ground, trees, being the highest objects in the vicinity, "reach out" through connecting leaders to meet the downward moving stepped leader. The winning tree of this competition is decided by its height and the conductivity (the ability to transport electric current) of the tree's wood. The conductivity of the wood depends mostly on its moisture content.

The taller the tree and the higher the conductivity of its wood, the greater its chances of becoming attached to the lightning flash. The ability of a tree to attract a lightning flash may, to some extent, also depend on its shape. The reason for this is that the concentration of positive charge that builds up at the top of the tree, and hence the field enhancement when the stepped leader comes down, depends on the shape of the tree. The higher the field enhancement, the easier it is to launch a connecting leader. The ability to launch a connecting leader may also depend on the type of soil on which the tree stands and on its system of roots. The current necessary for the connecting leader is ultimately provided by the soil, and if the soil is moist and conducting, it will facilitate the launching of a connecting leader by the tree. Furthermore, even if the surface soil is not conducting, the roots of some trees may penetrate deep into the ground, where there maybe highly conducting moist layers of soil.

When a lightning flash strikes a tree, a current of the order of 30,000 A on average passes through the tree to the ground. The type of damage sustained by the tree depends on the path taken by this current in its journey toward the ground [6, 7]. The path of least impedance (or resistance) offered by a tree for the path of passage of a lightning current is decided by the way the moisture is distributed within the tree trunk. Usually, the cambium layer (Fig. 15.7) of wood located directly beneath the bark contains a high percentage of moisture, and it therefore provides the path of least resistance for the current to propagate. When the lightning current flows along this path, it heats up this moisture and it vaporizes. As moisture vaporizes to form steam, it expands; in the case of lightning-induced expansion, this happens explosively, blasting the bark from the tree (Fig. 15.8a). Sometimes a striplike furrow can be observed spiraling down the trunk of the tree. In other cases, the bark may be thoroughly soaked with rain water and its surface may provide the least resistive path to the lightning current. Then the current may pass along the surface of the tree, causing little damage other than superficial bark flaking. On the other hand, if the bark is dry and the sapwood (i.e., the layer of wood beneath the

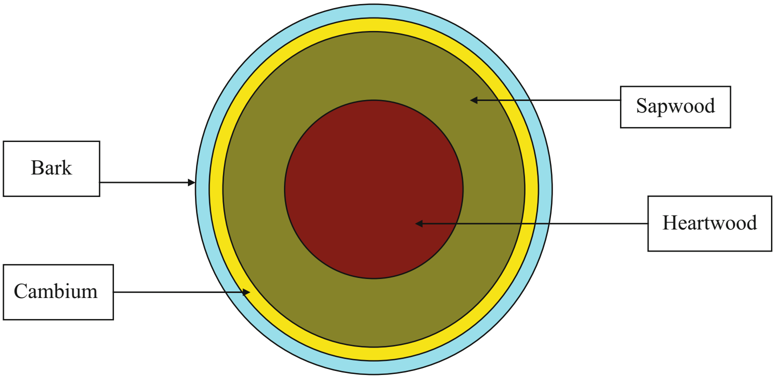


Fig. 15.7 Lightning can damage trees in various ways. A cross section of a tree is shown in the diagram. The damage suffered by a tree during a lightning strike depends on the path taken by the current. If the bark is thoroughly soaked with water, the current may flow along the surface of the tree without causing much damage. If the bark is dry, the current flows through the moist cambium layer. The rapid vaporization of the water as the current flows may cause the bark to split. If the sapwood of the tree contains much moisture, the current may flow deep in the tree instead and the rapid vaporization of water may shatter it (Figure created by author)

Fig. 15.8 (**a**) A tree where the bark is damaged by a lightning strike. (**b**) A tree completely shattered by a lightning strike (Adapted from [6])

cambium) contains a lot of moisture, the lightning current may flow deep in the trunk of the tree. In this case, the explosive expansion of moisture may shatter the tree completely (Fig. 15.8b).

There are instances where a single lightning flash can damage several trees [7]. In countries like Sri Lanka, India and Malaysia, lightning flashes cause significant damage in coconut plantations. A coconut tree may take up to 20 years to mature and peak its coconut production. A single lightning flash can destroy many fruit bearing coconut trees causing significant economical losses to the farmers. Figure 15.9 shows the locations of 16 fruit bearing coconut trees (about 10–20 m high) killed by a single lightning flash. The lightning flash struck the tree at the center (marked 0) and killed all the trees located around it up to a distance of 71 feet. The distance to each tree from the tree struck by lightning is given in feet in the diagram. There are three possible ways that several trees can be damaged by a single lightning flash. The first possibility is as follows. As mentioned previously, when the stepped leader approaches the ground, several trees compete to make the connection between the downward moving stepped leader and the ground. These connecting leaders, even if they are unsuccessful in capturing the lightning flash, may carry several tens of Amperes of current, which may be strong enough to cause damage to these trees. Moreover, during the return stroke, the currents in the unsuccessful connecting leaders may rise momentarily to several kiloamperes during back flashover caused by the sudden reduction in the background electric field [8]. In this way, several other trees in the vicinity of a tree that is being struck by a lightning flash could be damaged. The second possibility is as follows. As explained in an earlier chapter, lightning flashes consist of not one but several return strokes. In general, downward moving dart leaders follow the same path taken by the stepped leader and, as a consequence, all return strokes end up at the same point. However,

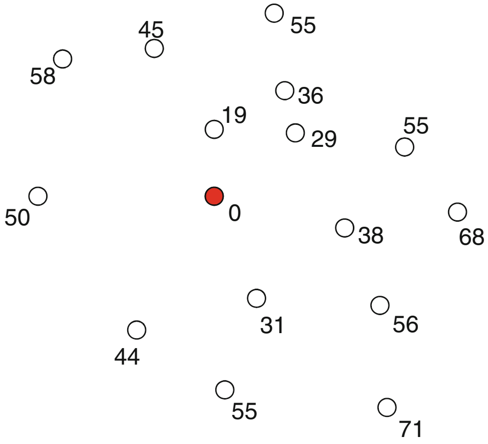


Fig. 15.9 Location of 16 coconut trees killed by a single lightning flash. The distances to the trees from the tree struck by the lightning flash (marked 0) are given in feet in the figure (Diagram courtesy of Mr. Chandra Fonseka)

sometimes the dart leaders deviate from the path taken by the previous leader. In these cases, different return strokes in a single flash may end up on different trees, thereby inducing damage in several of them. The third possibility is as follows. When a lighting flash strikes a tree, the current flows along the tree and, when it reaches the base of the tree, flows radially out into the soil. This ground current can damage the roots of neighboring trees. In the case of the first and third scenarios, i.e., damage caused by connecting leaders and ground currents, the damage may not be visible immediately. But it could weaken the tree's defense system against insects and disease without causing immediate damage, making it more vulnerable to subsequent damage from disease or insects. Its eventual death may be caused by this secondary damage.

A significant fraction of forest fires on Earth are caused by lightning. In the United States approximately 50 % of forest fires are caused by lightning flashes. Figure 15.10 separates the forest fires that occurred in Everglades National Park by cause. Note that approximately 50 % of the fire damage is caused by lightning, and these events are concentrated in the summer months when lightning frequency is high. It is important to note, however, that not all lightning flashes that strike forests cause fires. The probability of a forest fire increases with the duration of the continuing current when other parameters remain the same. In the case of lightning flashes without continuing currents, pieces of wood are heated during return strokes, but the current ceases quickly and the temperature of the lightning channel decreases. To set fire to a piece of wood, the flame (i.e., the lightning channel) must be in contact with the wood for a considerable amount of time. In the case of lightning with long continuing currents, the wood is heated to a high temperature and kept in that state for a long time, thanks to the long duration of the current, so it starts burning. Once the burning process is under way, it can progress without the help of the so-called lightning flame.

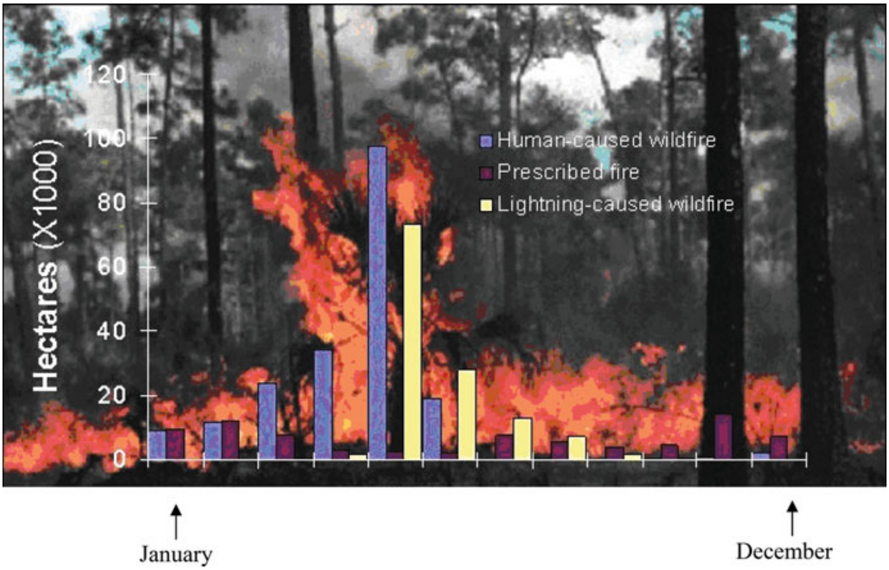


Fig. 15.10 Statistics of area of forest burned in Everglades National Park in the United States as a result of various causes. Note that lightning-caused fires take place during the summer time. http://sofia.usgs.gov/geer/2000/posters/fire/, 2014

15.11.3 Direct Strike to an Airplane

Statistics show that every commercial airplane is struck by lightning once every 3,000 h of flight, or approximately once a year. The infrequency of lightning-caused accidents at present is evidence that present-day airplanes can withstand lightning strikes without experiencing much damage. Of course, from time to time minor electronic problems are experienced during some lightning strikes, and in these cases the planes are diverted to the closest airport for safety reasons.

There are two ways for an airplane to be struck by lightning. The first one is that it intercepts an ongoing lightning strike. For this to happen the airplane must be located in the right place and at the right time to intercept a stepped leader that is moving toward the ground. Such an occurrence is rather rare. For example, at altitudes less than approximately 7 km, only around 10 % of lightning strikes to airplanes are intercepted. At higher altitudes, the percentage is close to zero. What happens frequently is that the airplane itself contributes to the initiation of a lightning flash. Figure 15.11 shows a lightning flash initiated by an airplane during takeoff. Strong electric fields may exist close to the cloud's charge centers. An airplane traveling in the vicinity of thunderclouds is exposed to these high electric fields. As shown in Fig. 15.12, a high electric field may initiate leader discharges of opposite polarity from the extremities of the airplane. One of the leaders may propagate toward one of the charge centers in the cloud and the other leader may travel toward a charge center of opposite polarity or toward the ground.

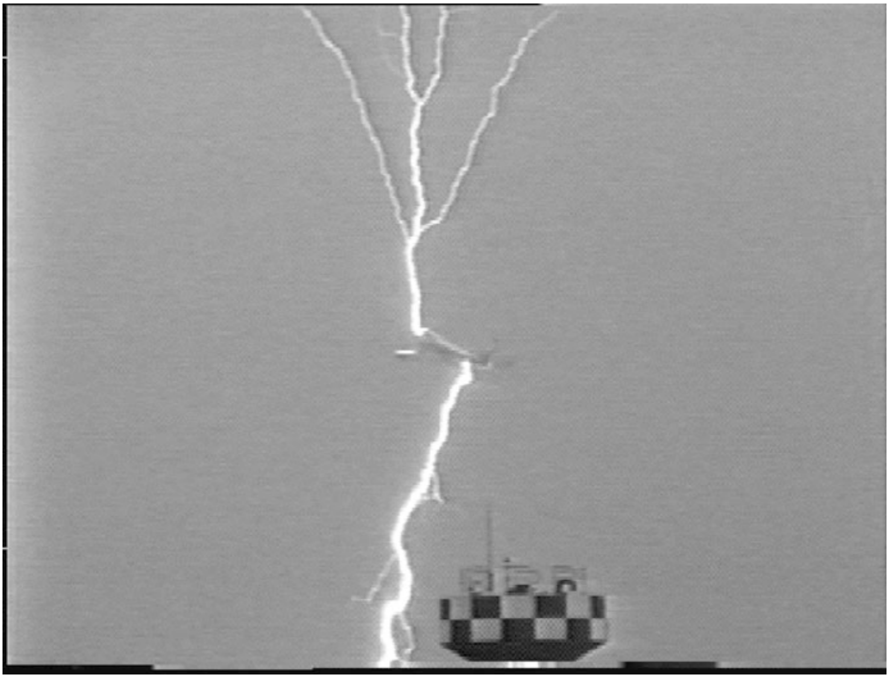


Fig. 15.11 Video frame of a lightning strike to an aircraft on takeoff from Kamatzu Air Force Base on coast of Sea of Japan during winter. Note that the branches of the upper part of the channel are directed upward, whereas the branches on the lower part of the channel are directed downward. This shows that a bidirectional leader started from the plane with one part propagating upward and the other downward (Courtesy Prof. Z.I. Kawasaki)

If one of the leaders ends on the ground, a ground flash results. If both leaders travel toward charge centers of opposite polarity, then the result is a cloud flash. In either case, the current flowing along the channel (including the return stroke currents in the case of a ground flash) is injected into the airplane at one of the leader initiation points, and this current leaves the airplane from the other leader inception point. The current flows along the metal skin of the airplane. Thus, the metal surface should not contain any gaps that could cause sparks during current flow. One of the most sensitive parts of an aircraft is the fuel system, and a lightning strike should not generate a spark in any part of the fuel system. Moreover, the metal skin of the airplane, especially the metal skin around the fuel tanks, should be thick enough to withstand a lightning current without puncture. In airplane lightning protection, possible lightning strike points are investigated, usually using scale models in the laboratory, and these points are strengthened so that they can take on the full lightning current without causing a puncture. Actually, airplanes are designed in such a way that they should be able to withstand the maximum current from a lightning flash. Figure 15.13 shows the lightning current test waveform that aircrafts should be able to withstand. This current represents one of the most severe lightning currents possible in nature.

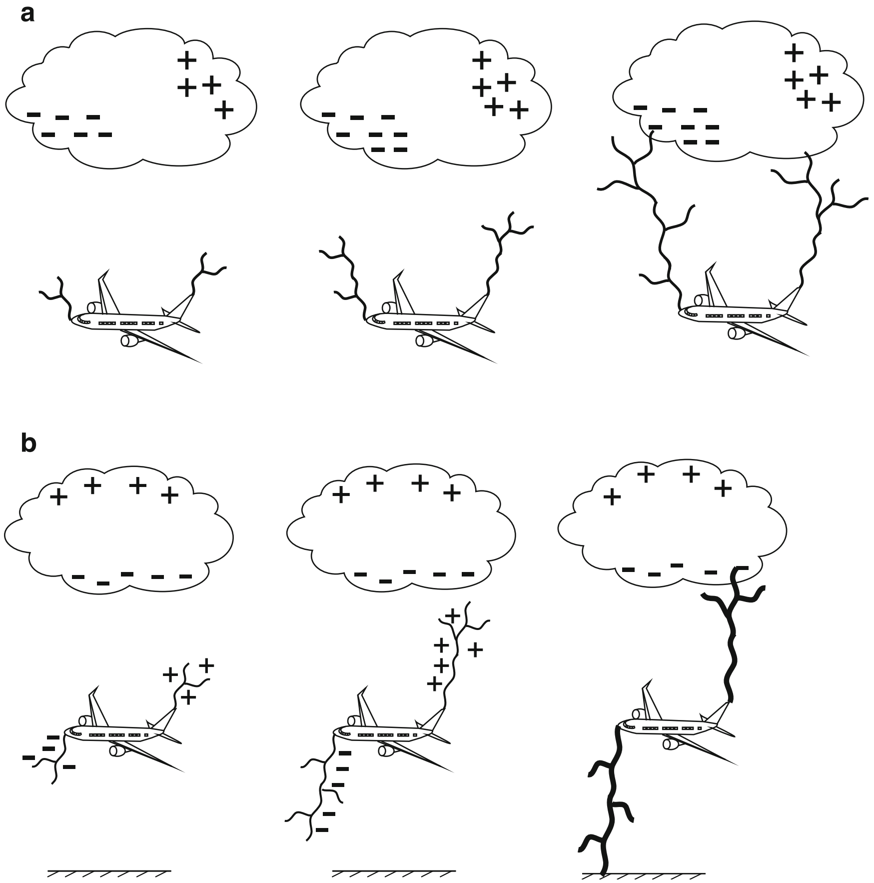


Fig. 15.12 (**a**) An airplane in the electric field of a thundercloud may give rise to leaders of opposite polarity moving away from the airplane from opposite locations (i.e., a bidirectional leader). If the two leader branches end up in opposite charge centers in the cloud as in (**a**), then a cloud flash results. If one of the leader branches travels to the ground as in (**b**), the result is a ground flash. In either case, the current flowing along the lightning channel passes through the body of the plane (Figure created by author based on information available in the literature)

The attachment process of a lightning flash to a moving airplane is slightly more complicated than in the case of a stationary grounded structure. Once a lightning flash becomes attached to an airplane, physical processes taking place at the points where the current enters the metal skin of the airplane attempt to keep the point of entrance of the current into the airplane the same throughout the duration of the lightning flash. However, as the plane moves forward, the arc channel is continually bent and stretched, and at a certain point in time it becomes favorable energetically for the current entrance point to move to a new location (Fig. 15.14). Thus, during a lightning strike to a moving airplane, the current entry point and exit point move

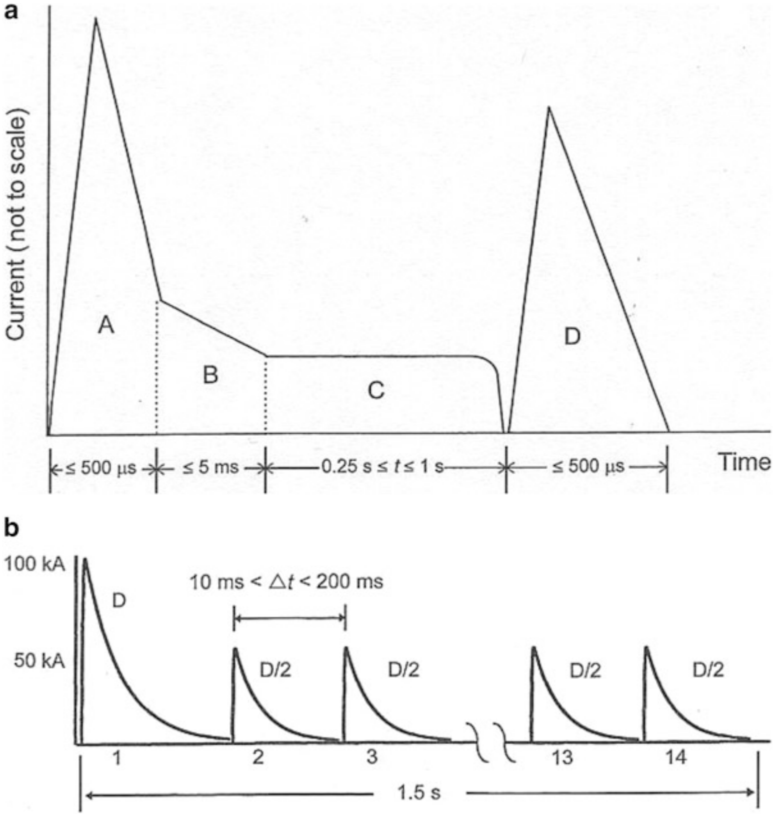


Fig. 15.13 (**a**) Test current waveform simulating first two strokes of a severe lightning flash to an aircraft. *Component A* (first return stroke): peak amplitude = 200 kA; action integral = 2×10^6 A^2s (in 500 µs); duration ≤ 500 µs. *Component B* (intermediate current): maximum charge transfer = 10 C; average amplitude = 2 kA; duration ≤ 5 ms. *Component C* (continuing current): amplitude = 200–800 A; charge transfer = 200 C; duration = 0.25–1 s. *Component D* (subsequent return stroke): peak amplitude = 100 kA; action integral = 0.25×10^6 A^2s (in 500 µs); duration ≤ 500 µs (Adapted from aircraft lightning protection standard SAE ARP5412). (**b**) Test current waveform simulating a severe multiple-stroke flash to an aircraft (Adapted from aircraft lightning protection standard SAE ARP5412)

along the body of the airplane (Fig. 15.15). Therefore, a lightning strike could create a series of strike points along the body of the airplane.

The passengers inside the airplane are usually safe from the lightning currents passing along the metal skin of the airplane because the current injected into a metal object flows along the surface of the object without penetrating into the object, i.e., the Faraday cage principle. However, not all parts of the airplane are made of metal. For example, to allow for the passage of radar beams, the front part of the airplane, called the radome, is made of nonmetallic material. This is the most vulnerable part of an airplane. However, protection procedures are usually put in place so that in the case of a lightning strike to the radome, the lightning current passes along the

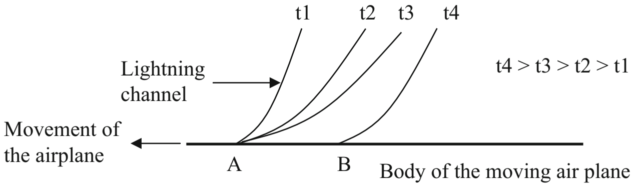


Fig. 15.14 As the airplane moves forward, the lightning channel is stretched, and at a certain time the strike point moves to the right (i.e., from *A* to *B*) (Figure created by author)

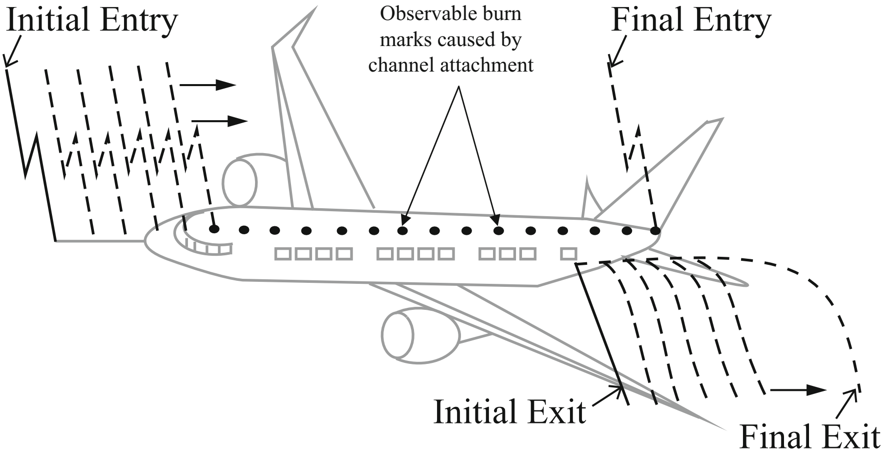


Fig. 15.15 As shown in Fig. 15.14, the movement of the airplane causes the current entry and exit points to move along the body of the airplane. The strike and entry points are observed as a series of spots with burnt paint on the body of the airplane (Figure created by author based on information available in the literature)

radome and enters the skin of the airplane without penetrating into the airplane. This is achieved by locating strips of conducting material on the radome in such a way that they do not obstruct the view of the radar while at the same time providing a safe path for the lightning current across the radome (Fig. 15.16).

During lightning strikes, electromagnetic fields can penetrate through nonconducting regions into the airplane. Moreover, depending on the thickness of the metal skin, even current flowing along the metal skin of the airplane can generate electric and magnetic fields inside the airplane as a result of the skin effect (Chap. 17). These fields, through electric and magnetic induction, can cause induced voltages in the electronic circuitry located inside the airplane. Thus, the sensitive electrical circuits in the airplane are protected using surge diverters (Chap. 17).

Before the 1960s several explosions involving airplanes were caused by lightning strikes. Today, however, accidents are rare, which shows that protection procedures currently in place are effective. In fact, 1967 was the last year a

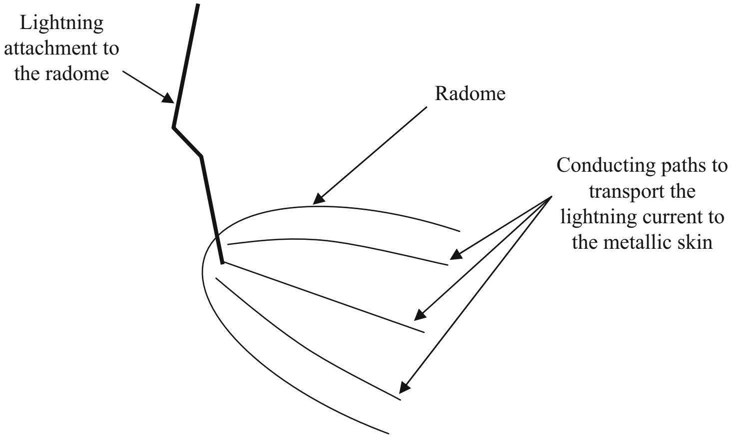


Fig. 15.16 The conductors located on the radome of an airplane to divert lightning currents away from the radome and into the metal skin of the airplane (Figure created by author based on information available in the literature)

lightning strike caused an airliner to crash in the United States. This was caused by an explosion in the fuel tank.

Today the use of composite materials in modern airplanes, like the Boeing 787, with a fuselage made predominantly of carbon fiber, has required additional design features. For example, composite material is made more resistant to lightning by an embedded layer of conducting fibers or a metal screen to conduct lightning currents.

15.11.4 Direct Strike to a Windmill

Alternative energy is the rallying cry of modern society, and wind power is the latest main source of alternative energy around the world. With increasing demand for wind power, the power-generating capacity of wind turbines has also increased over time [9]. However, the higher the power output of the wind turbine, the higher the required wind span of the turbine. A larger wingspan requires greater heights. Actually, the height of a wind turbine increases with increasing power output. Present-day wind turbines can reach heights of more than 100 m. Being rather tall, such wind turbines can initiate lightning flashes when exposed to thundercloud electric fields. Indeed, a wind mill could be a better initiator of lightning flashes than a stationary tower of similar height, for the following reason. In the presence of a background electric field, all pointed structures at ground level go into corona, and the tip of a tall tower is no exception (Fig. 15.17a). Corona discharges create a space charge region around the tip, and this space charge can screen the tip of the tower from an electric field. As the electric field produced by the thundercloud

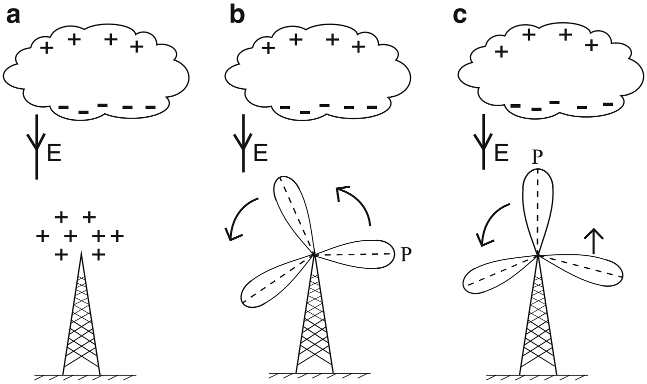


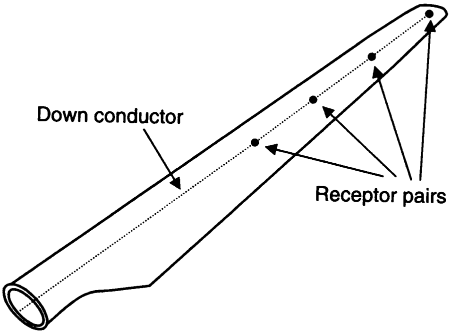
Fig. 15.17 Even though the background electric field remains constant, the electric field at the tip of a blade of a wind turbine changes from a low value to a high value as it rotates in a *vertical plane*. For example, the electric field at the tip of the blade located horizontally [marked *P* in (**b**)] increases as it rotates and reaches its maximum when the blade is vertical [marked *P* in (**c**)]. Thus, the electric field at the tip of the blade oscillates as the blade rotates in the background field

slowly increases, the corona discharge intensifies and continues to screen the tip from the increasing strength of the electric field. Thus, to create a connecting leader from the tip of the tower, the field must increase very rapidly to overcome the screening effects of the corona. In a slowly increasing field, the corona generated at the top will inhibit a tower from giving rise to a connecting leader. In the case of wind turbines, corona discharges are generated at the tips of the blades. But the space charge cannot accumulate at the tips because of its displacement resulting from the rotation of the blades. When a blade is located parallel to the ground, the electric field at its tip is rather low, and it increases rapidly as the blade turns up toward the cloud (Fig. 15.17b). The electric field is at its maximum when it is located perpendicular to and away from the ground (Fig. 15.17c). In other words, as the blade rotates, the electric field at its tip increases rapidly, and without a significant amount of corona space charge to screen the tip from the electric field, the conditions necessary for the launching of upward leaders is reached in the background electric field, which would not have generated upward leaders from stationary towers of similar heights.

Lightning can cause severe damage to blades (Fig. 15.18) [10]. Thus, the current in lightning flashes that strike wind turbines must not be allowed to flow along the surface of blades. This is achieved by placing lightning conductors inside the blades and connecting these conductors to the outer surface of the blades through metal receptors located flush with the blades (Fig. 15.19). However, there are cases where a lightning strike misses the receptor and enters the conductor by flashing over through the material of the blade, causing significant damage. Attempts to improve the lightning protection of wind turbines are ongoing in the lightning protection research community.

Fig. 15.18 Damage caused by lightning flash in wind turbine blade (adapted from [10])

Fig. 15.19 Metal receptors located on surface of blade. The metal receptors are connected to the lightning protection down conductors located inside the blade (adapted from [9])



15.11.5 *Effects of Lightning on Power Lines*

15.11.5.1 Direct Strike to a Power Line

Power lines are protected from direct strikes to phase conductors by a ground wire installed above the phase conductors. Usually, it is this ground wire that receives the lightning strike. However, there are instances where lightning strikes phase conductors directly. Even if lightning strikes a grounded wire, it can still create problems in the phase wire. The reason is as follows. The lightning current injected into the ground wire splits into two equal parts and travels outward along the ground wire (Fig. 15.20). The ground wire is grounded at the tower, and at this point the

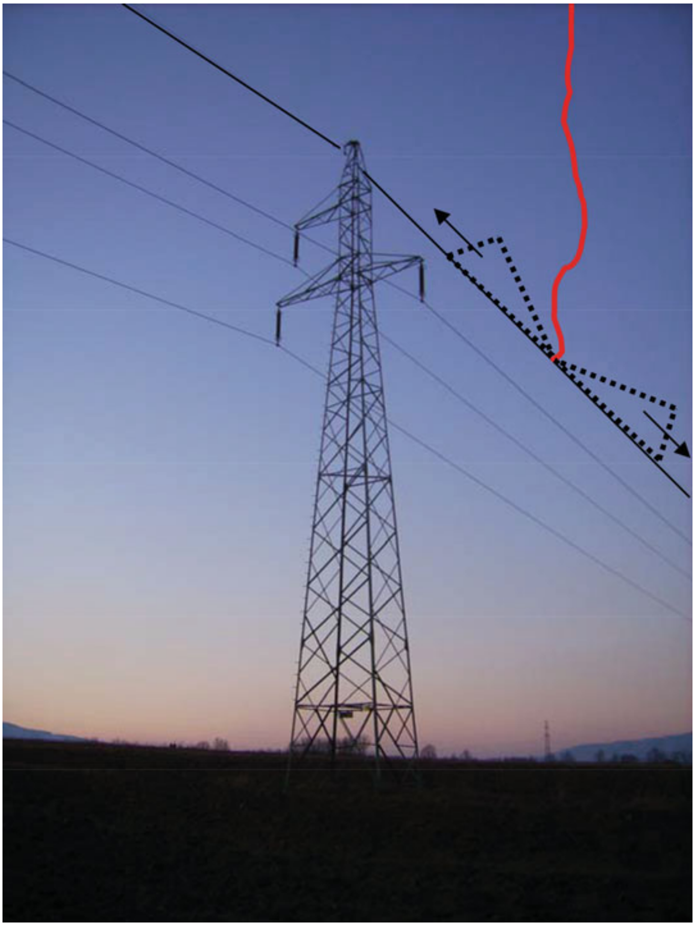


Fig. 15.20 When a lightning flash injects a current into a ground conductor, for example, the current splits into two equal parts and travels in the opposite direction at speed c. Once the current pulse reaches the grounded tower, it flows to the ground along the tower

current flows to the ground along the tower. If Z is the grounding impedance at the tower foot, the lightning current flowing through this impedance raises the tower to a potential of $Z\,i(t)$, where $i(t)$ is the current flowing down the tower. This gives rise to a voltage difference between the tower and the phase conductors, and if this voltage is greater than the value necessary to cause an electrical breakdown across the insulators, then a spark results connecting the ground wire and one of the phase conductors (Fig. 15.21). Once this spark is generated, part of the lightning current flows along this path into the phase conductor. Moreover, since an electric spark has a rather low resistance, it is not only the lightning current that passes through the spark channel but also a current driven by the voltage difference between the phase

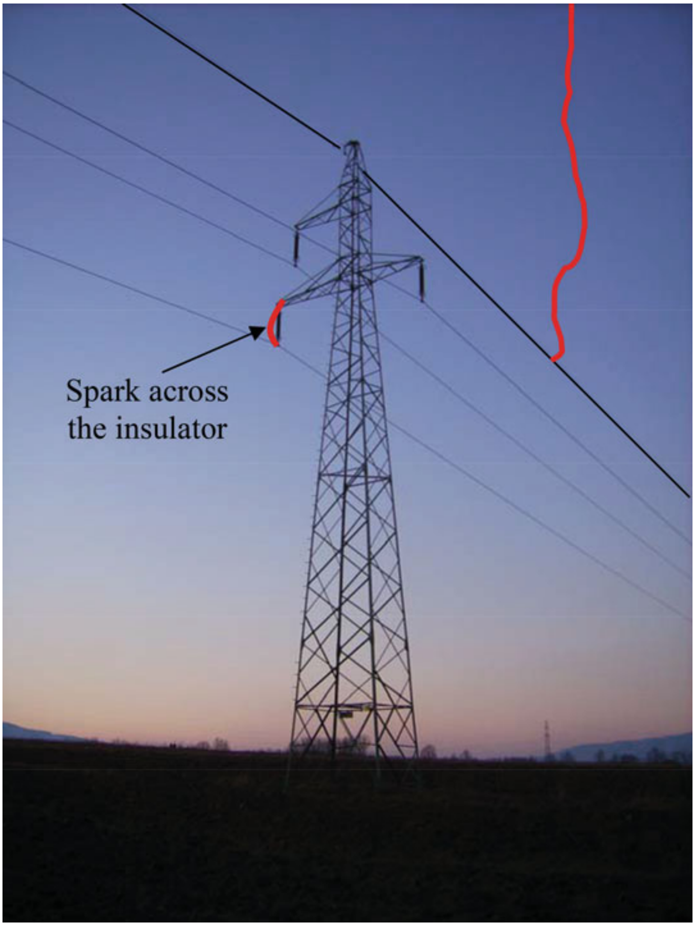


Fig. 15.21 As the current passes along the tower to the ground, the potential of the tower is raised because of ground impedance. For example, if the ground impedance is Z, then the tower is raised to a potential of $i(t)\ Z$ where $i(t)$ is the current. If this potential is sufficiently high, there could be an electrical breakdown between the tower and the phase conductors

conductor and the ground. This effect can have two consequences. First, part of the lightning current will penetrate into the phase conductors through the spark channel. These phase conductors are usually connected to a distribution transformer from where the electricity is distributed to the consumer. This lightning current, if not properly diverted to the ground before entering the transformer, can cause damage to the transformer windings, which could be very expensive to repair. Moreover, part of the lightning current could enter the consumer side after passing through the transformer, causing problems in the electronics at the consumer's end. The other undesired consequence is the following. Once a spark is created between a ground wire and a phase conductor, the voltage difference between the phase conductor and ground is large enough to maintain the spark. Thus, the current flowing along the phase conductor, which is meant for the consumer, starts to flow into the ground across the spark, cutting off the power supply to the consumer. This is called a *line fault*. The only way to correct the problem is to cut off the electric power to the line until the spark is extinguished. Devices that perform this task are called *circuit breakers*. Usually, after the power is cut off to a line to clear a fault, the power is reconnected to the line after enough time has passed to extinguish the spark by stopping its current flow. However, the subsequent return stroke that originated in the same channel at a later time could reignite the spark and the power to the line would have to be disconnected again. Depending on the number of subsequent strokes and the interval between them, the process may be repeated several times during a single lightning strike.

Insulators in power lines are designed to withstand the high voltage arising in ground wires as a result of lightning strikes. However, sometimes the insulation strength is weakened because of deterioration or growth of organic materials on the insulators, and the sparks that result between the ground wire and the phase conductor along the insulators can further damage the insulators.

15.11.5.2 Indirect Effects of Lightning on Power Lines

In the previous section, we described what happens when a power line is struck by lightning, causing direct current injection into either the ground wire or the phase conductors. However, since both magnetic and electric fields can generate voltages and currents in power lines, even a lightning flash that strikes in the vicinity of power lines can generate large voltages in the line that can cause transformer damage and line faults. Let us consider the basic principles used by scientists to investigate this effect [11, 12].

Transmission lines can transport currents and voltages along it. A transmission line need not be a standard power line to transport power. The cables that transport television signals are also transmission lines. They contain two conductors arranged in a specific manner. The simplest transmission line over ground can be represented as a single conductor located over a ground plane. The ground plane acts as the return conductor through which the current injected from the generator into the power line is returned back to the generator, completing the circuit.

Transmission lines are actually media that support the propagation of voltages and currents as waves. Consider any medium that supports wave propagation. One simple example is a stretched string. If the string is displaced at a given point, the displacement divide into two halves and propagate in opposite directions. Transmission lines behave in exactly the same way. Assume that a current is injected at any given point on a line. The injected current then divides into two equal parts and travels in opposite directions. Now, a current can be injected into a transmission line by connecting a generator to the line. This is what happens during a direct lightning strike. However, a current can also be injected into a transmission line in a more passive way. This is done by applying an electric field in a direction parallel to the conductors of the power line. Since the conductivity of a normal conductor is high, whenever an electric field is applied parallel to the line, free charges start to flow in an attempt to bring the electric field component parallel to the line to zero. Let us consider this problem mathematically. Consider a small section of a transmission line, say, dx. Now let us apply an electric field $E(x,t)$ parallel to the line at that point. This will generate a voltage of $E(x,t)dx$ across the element, resulting in a current $E(x,t)dx/Z$, where Z is the characteristic impedance of the line. The characteristic impedance of a single conductor transmission line located above the Earth is given by

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu_o}{\varepsilon_o}}\log\left[\frac{2h}{a}\right], \tag{15.17}$$

where h is the height of the conductor and a is its radius. Now, this current will separate into two equal parts and propagate in opposite directions. With this knowledge, it is possible to make a reasonable estimation of the voltages induced in a power line in many circumstances where the power line configuration is simple, i.e., a single conductor line. It can also be used to evaluate the order of magnitude of induced voltages in more complex configurations. The complexity arises because of the interaction of the electric and magnetic fields generated by the current flow in one conductor with other conductors of the line.

Let us illustrate how to apply the preceding concept using a simple example. Consider a single conductor transmission line of length L where both ends terminate at its characteristic impedance Z. It is important that the terminating resistance be equal to the characteristic impedance because whenever a voltage or a current wave propagating along a transmission line reaches a termination, both the current and the voltage waveforms are reflected. The polarity and the amount of reflected voltage depend on the difference between the characteristic impedance of the line and the impedance connected at the termination. If the impedance connected at the end of the line is equal to the characteristic impedance of the line, the waves are absorbed without any reflection. The preceding configuration, with terminating resistors equal to the characteristic impedance, therefore simplifies the analysis of the problem. On the other hand, if a wave reaches an open end of a transmission line where the impedance is infinite, the reflected voltage wave has the same sign and amplitude as the incident voltage, resulting in a doubling of the voltage. At the

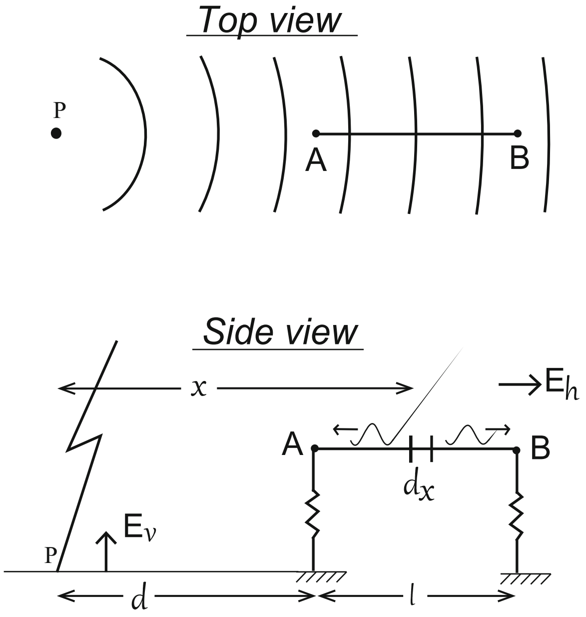


Fig. 15.22 *Top* and *side views* of geometry relevant to calculation of induced voltages in single conductor transmission *line* as a result of a nearby lightning strike. AB is the overhead conductor, $\mathbf{E}_v$ is the vertical electric field, and $\mathbf{E}_h$ is the horizontal electric field

same time, the reflected current waveform has the same amplitude and opposite polarity of the incident current, making the net current at the termination zero. The opposite takes place if the impedance is zero (i.e., short-circuited to the ground). In this case, the net voltage becomes zero at the termination and the current is doubled. To simplify the analysis, we will calculate the voltage induced in the terminations of a single conductor transmission line for the special case where the propagation direction of the electromagnetic field is along the line.

The side and top views of the geometry relevant to the problem under consideration are shown in Fig. 15.22. Points A and B are the locations of terminations of the single-conductor transmission line, and P is the strike point of the lightning flash. The impedances at the terminations are assumed to be equal to the characteristic impedance of the line, Z. The transmission line is assumed to be straight and horizontal, and the lightning channel is assumed to be straight and vertical. During the lightning strike the electromagnetic field propagates in a radial direction along the ground plane, and since the power line is located parallel to the radial direction, the direction of the propagation of the electromagnetic field is parallel to the direction of the line. In other words, the wave front of the electromagnetic field is perpendicular to the line (Fig. 15.22).

Let $t = 0$ be the time of occurrence of the lightning flash. Consider a small line element dx located at a distance x from the lightning channel. The electric field associated with the electromagnetic field generated by the lightning flash can be resolved into two parts, one parallel to the ground plane, $E_h(x, t)$ (i.e., in the positive x-direction), and the other perpendicular to the ground plane, $E_v(x, t)$ (i.e., in the positive z-direction). The polarity of the voltage at ground terminations is considered positive if it drives a positive current into the ground through the termination impedance. If the ground plane is perfectly conducting, the horizontal electric component is zero at ground level but it is not zero at points above the ground plane. The horizontal electric field induces a current of magnitude $E_h(x, t - x/c)dx/Z$ in the line element dx, and half of it propagates at the speed of light toward termination A and the other half propagates toward termination B. Let dI_B be the current generated by element dx reaching termination B. This is given by

$$dI_B = \frac{1}{2Z} E_h[x, t - x/c - (d + l - x)/c]dx. \tag{15.18}$$

Note that the field is incident on the line element at time x/c (its value is zero at times before that), and the current signal takes a time $(d+l-x)/c$ to reach the termination. Note that c is the speed of light, and this is the speed of propagation of current and voltage pulses along the line. Equation 15.18 can be written as

$$dI_B = \frac{1}{2Z} E_h(x, t - d/c - l/c)dx. \tag{15.19}$$

The total current reaching termination B due to the entire line is given by

$$I_B = \frac{1}{2Z} \int_{d}^{d+l} E_h(x, t - d/c - l/c)dx. \tag{15.20}$$

If the way in which the field changes with distance is known, this can be evaluated numerically. On the other hand, assume that the distance to line d from the lightning flash is much greater than the length of the line. In this case, the electric fields can be assumed to be of the same magnitude along the entire line (i.e., E_h is independent of x but is still a function of time), and in this case the current injected into termination B becomes

$$I_B = \frac{1}{2Z} E_h(t - d/c - l/c)l. \tag{15.21}$$

Since all this current is absorbed into the termination without any reflection, the voltage V_B induced in termination B as a result of the horizontal electric field associated with the lightning flash (note that this voltage is positive because the horizontal electric field is considered positive along the positive x-direction and it will drive positive charges through the termination into the ground) is

$$V_B = \frac{1}{2} \int_{0}^{l} E_h(x, t - d/c - l/c)dx. \tag{15.22}$$

Now, let us consider termination A. Let dI_A be the current generated by element dx reaching termination A. This is given by

$$dI_A = -\frac{1}{2Z} E_h(x, t + d/c - 2x/c)dx. \tag{15.23}$$

The total current reaching termination A due to the entire line is given by

$$I_A = -\frac{1}{2Z}\int_0^l E_h(x, t + d/c - 2x/c)dx. \tag{15.24}$$

The voltage V_A induced in termination A because of the horizontal electric field associated with the lightning flash is

$$V_A = -\frac{1}{2}\int_0^l E_h(x, t + d/c - 2x/c)dx. \tag{15.25}$$

If the temporal variation of the horizontal electric field as a function of x is known, this can be calculated numerically.

So far, we have considered only the voltage induced in the terminations of the line due to the horizontal electric field. The vertical field can induce voltages and currents in vertical conductors, and, as in the case of voltages induced by a horizontal electric field, they propagate in both directions along the line. Let us first consider termination A. The current induced by the vertical field on the vertical conductor at the termination is equal to $E_v(d, t - d/c)h/Z$. The polarity of this current is such that it transports positive charge in the positive direction of E_v. In writing this equation the whole vertical conductor was taken as one element. Half of this current is absorbed into the termination and the other half propagates along the line toward termination B (Fig. 15.23). The voltage generated by the current passing through termination A is $-E_v(d, t - d/c)h/2$. The current reaching termination B because of the vertical conductor at termination A is $E_v(d, t - d/c - l/c)h/2Z$. The voltage generated by this current across the impedance at termination B is $E_v(d, t - d/c - l/c)h/2$. Now, let us consider the vertical conductor at termination B. The current induced by the vertical electric field on the vertical conductor at termination B is equal to $E_v(d + l, t - d/c - l/c)h/Z$. Half of this current is absorbed into termination B and the other half propagates along the line toward termination A. The voltage generated across the termination impedance at B by this current is $-E_v(d + l, t - d/c - l/c)h/2$. The current reaching termination A because of the vertical conductor at termination B is $E_v(d + l, t - d/c - 2l/c)h/2Z$. The voltage resulting from this current at termination A is $E_v(d + l, t - d/c - 2l/c)h/2$. Now we are in a position to write down the expression for the total voltage appearing across terminations at A and B.

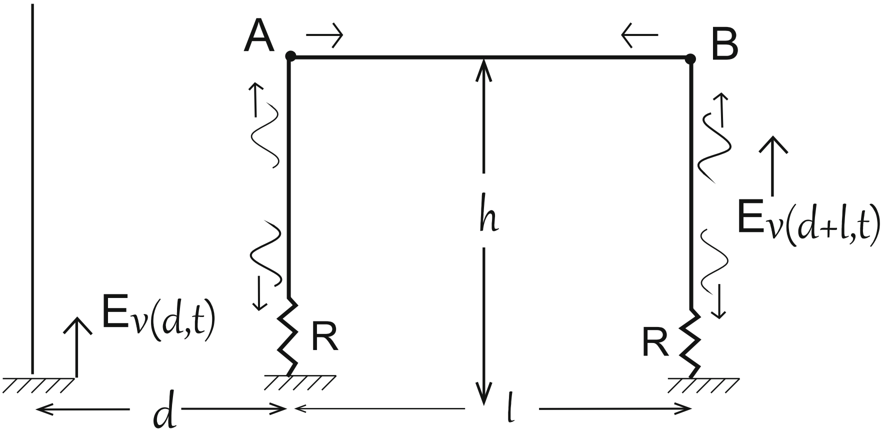


Fig. 15.23 Currents and voltages are induced in vertical conductors by a vertical electric field. Half of the current induced in the vertical conductor travels to the ground through the grounding impedance R and the other half enters the horizontal part of the conductor (i.e., AB)

The total voltage induced in termination *B* is given by

$$V_{B,\text{total}} = \frac{1}{2}\int_0^l E_h(x, t - d/c - l/c)dx - E_v(d + l, t - d/c - l/c)h/2 \\ + E_v(d, t - d/c - l/c)h/2. \tag{15.26}$$

The total voltage induced in termination *A* is given by

$$V_{A,\text{total}} = -\frac{1}{2}\int_0^l E_h(x, t + d/c - 2x/c)dx + E_v(d + l, t - d/c - 2l/c)h/2 \\ - E_v(d, t - d/c)h/2. \tag{15.27}$$

If both the vertical electric field and the horizontal electric field can be assumed to have the same amplitude and temporal wave shape along the line (i.e., when the distance from the lightning flash to the line is much greater than the length of the line), then the total induced voltage reduces to

$$V_{B,\text{total}} = \frac{1}{2} lE_h(t - d/c - l/c) - E_v(t - d/c - l/c)h/2 \\ + E_v(t - d/c - l/c)h/2 \tag{15.28}$$

and

$$V_{A,\text{total}} = -\frac{1}{2}\int_{0}^{l} E_h(t + d/c - 2x/c)dx + E_v(t - d/c - 2l/c)h/2$$
$$- E_v(d, t - d/c)h/2. \tag{15.29}$$

The same technique can be used to calculate the voltages induced in terminations of a power line when the position of the strike point is located in any arbitrary direction. In this case, it is necessary to keep track of the time of incidence of the electromagnetic field at different elements of the line. Moreover, the fact that the horizontal electric field is always radial to the strike point (and hence may make different angles with different line elements) should also be taken into account. Since currents are generated by the electric field component parallel to the line, it is necessary to consider only the component of the horizontal electric field parallel to the line elements in the analysis.

The foregoing analysis shows that knowledge of the horizontal electric field and the vertical electric field generated by a lightning flash makes it possible to estimate the voltages and currents induced in power lines using simple procedures. Of course, when the line configuration is complex, it is much more convenient to follow numerical procedures. But the foregoing analysis illustrates the basic principles involved in evaluating the voltages induced in power lines resulting from lightning flashes striking in their vicinity.

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