Chapter 1
Introduction to Lightning and Lightning Protection

Abstract In this chapter we introduce the entire subject of the book from both engineering and physics perspectives. A brief presentation of the general nature of lightning flashes is followed by describing, with simple models, the two main parts of the lightning flash. Namely, the leader stroke and the return stroke. The electromagnetic phenomena related to lightning is also presented. First the electromagnetic waves along the lightning channel are analyzed considering the lightning channel as an electric plasma channel with free electric charge particles moving in it; We study the electric parameters of the lightning channel, including its electric conductivity. Models of the lightning flash are briefly presented. Lightning protection is summarized in this chapter considering aircraft interaction with lightning and aircraft protection zones, and protection of electric power systems. In addition, the protection of electronic systems and devices is also considered.

1.1 The Lightning Flash: General Characteristics and Damage Caused

Lightning engineering is an increasingly important discipline due to the increase in lightning damage to electronic and microelectronic systems that are operated at very low voltage and current levels. The electronic systems include computers, communication systems, medical equipment, security and safety equipment, military systems, and monitoring devices. Relatively small lightning induced voltage surges and slightly increased current flows can damage and disrupt the function of these sensitive systems used in navigation, military technology, biomedical systems and many other transport, business and service systems and smart homes applications in ground and airborne systems and devices. Furthermore, since electrical power and communication, and command and control systems are interconnected and cover a large space, the entire system is simultaneously exposed to lightning-caused electric voltage and current threats. When large machinery to handheld devices are electronically monitored and operated, the entire interconnected system hardware is exposed to instability and damage if the microelectronic systems should be interfered with

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or burnt by lightning flash voltage impulses. Present and future smart cities are particularly vulnerable to lightning-caused malfunction and damage.

As much as thirty percent of damage in electrical power and electronic systems is caused by over-voltages due to switching and lightning flashes. The remaining seventy percent of damage is due to water, human error, fire, sundries, theft and storms. Damage due to lightning surges far exceeds that due to switching surges. Lightning damage is caused by direct lightning strikes to installations and structures, as well as by indirect effects of lightning where the electromagnetic pulse radiated by lightning (lightning electromagnetic pulse, LEMP) induces surge voltages and currents in distant, electrically unconnected electric power lines and electronic systems. The effects of LEMP are similar to those due to nuclear electromagnetic pulses (NEMP). The ratio of the number of direct lightning strike surges to indirect lightning surges is about 1: 600, but the ratio of damage caused is about 1: 2 since direct strikes are far more severe than the surges induced by indirect effects of LEMP. In other words, say there are 100 direct lightning strike surges in a system of a city each year. Then the indirect lightning effect caused surges will be about 600,000. However, if the number of damages caused by direct lightning strike to the telecommunication installations of the city is 50,000, then the damage caused by indirect effects will number 100,000. The cost of lightning-caused damage to electrical and electronic systems and devices runs into tens of millions each year for a moderately sized, technologically advanced country. Insurance payout due to lightning has reached such high proportions that insurers only pay for damages to hardware, and even that only if it is a first event. After the first damage, they expect the customer to improve lightning protection to prevent further damage.

Consider first a few examples of lightning-caused damage to hazardous areas. Outdoor or underground (e.g. diesel station) Storage tank flammable material is susceptible to catch fire when lightning strikes the tank or the ground nearby. In 1965 a solid petrol tank roof was struck by lightning. Once the petrol tank roof voltage was elevated above the lightning flash voltage of a million volts, the large volt drops between the tank and the wires of the measuring cable, which was at earth potential, resulted in an electric arc flashover between the roof and the cable. The electric arc which is at a very high temperature fired the explosive mixture. The whole tank exploded and was burnt. In Netherlands, in 1975, a lightning flash to a tree close to a kerosene tank resulted in a flashover between the roots of the tree and the underground earthing system of the tank. Once the earthing conductor voltage increased to millions of volts, there was a flashover between the earth conductor and the line running from the thermostat measuring the temperature inside the tank. The flashover ignited the kerosene-air mixture inside, which resulted in an explosion and a fire. In 1984 in Herne, the potential of the measuring cable entering the tank was raised due to lightning flashes, and the potential drop between the measuring line and the ground conductor caused an arcing flashover inside the alcohol chemical plant resulting in a fire. In 1995, an Indonesian oil refinery tank was hit, and the tank caught fire. Due to poor grounding of the earthing system this fire resulted from a lightning-produced arc. Neighboring tanks also caught fire causing a major oil crisis in the country. In 1996, a lightning strike to a petrol tank in USA set fire to multiple

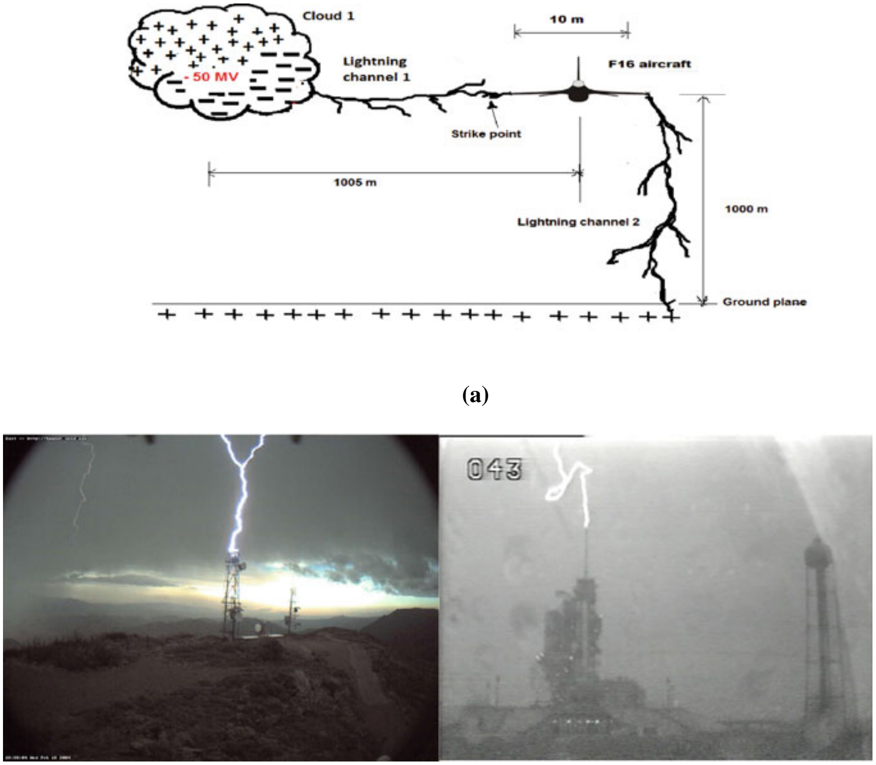
Fig. 1.1 Multiple lightning flashes over a built-up city *Credit* NOAA_NSSL With permission

tanks. The basic reason for these damages to explosive installations is the potential drop of about one million volts that develops between the enclosing Faraday cage like tank and the single cable coming into the tank, where the cable is connected to monitoring and measuring devices inside the tank.

Figure 1.1 shows multiple lightning flashes from the cloud to ground (CG). The downward, that is cloud to ground, direction of the initial electric breakdown (the leader stroke) is indicated by the downward pointing branches of the lightning flash. As cities move towards greater use of Internet of Things (IoTs) and smart cities, the threat of lightning induced impulses poses a greater threat to microelectronic system based transport, safety, security, communication, navigation, and commercial systems. If the thunderstorm is in the vicinity of an airport, any aircraft that are landing or taking off may be struck by lightning, as well as aircraft parked outside the hangars. A lightning strike to a commercial aircraft taking off from the Tokyo airport showed one part of the lightning channel to originate from the radome of the aircraft and move up towards the thundercloud. With the branches of the lightning segment pointing upward, the indication is that the aircraft imitated the lightning flash due to large accumulation of electric charges at the radome resulting in an electric field greater than the breakdown electric field for air, which is about 30 kV/cm (or 3 MV/m) at ground level (for dry air but lower in wet or moist conditions). Moreover, the second portion of the lightning channel extended from the fin of the aircraft down towards the ground and had branches pointing downwards. This indicates that the second part of the lightning flash also originated from the aircraft, specifically from the aircraft tail, and moved towards the ground. When connections with the thundercloud above the aircraft and the ground below are completed, then the high-current return stroke (e.g. 300,000 Amperes, with rise times of the order of one microsecond) which radiates intense light, is initiated. The aircraft structure, as well as the internal power, electronic, control, navigation, and information technology systems and equipment need to be well protected against adverse effects of aircraft-lightning electrodynamics. In 1987, in Rundschau, lightning struck a Boeing 747 aircraft with 225 passengers, when it entered into a thunderstorm zone close to Newark, New Jersey airport. The four lightning strikes to the aircraft within a few minutes damaged the autopilot, radio communication to the airport and the weather radar. The captain and the co-pilot had to exercise immense effort to keep the aircraft flying because the elevator control was also damaged. Air to air communication with a nearby British Airways aircraft was used to safely land the aircraft. Landing gear brakes had to be used since the braking thrust reversals of the four engines were also damaged by the lightning strikes. About the structure of the aircraft, parts of the tail fins were missing, and hundreds of fire damages to the aircraft shell and wings were also found, where lightning had attached itself to the aircraft, or was burnt by the dragging of the lightning stroke over the surface of the structure.

In 1985 a lightning-caused fire accident of the Perishing II rocket in Germany killed three army personnel and injured nine others. The fire was caused by electrostatic sparks produced by the thundercloud electric fields in the propelling charge of the motor. Apollo 12 rocket and the Saturn V rocket were struck by lightning in 1964, 36 s after lift-off. The Saturn V was struck by lightning when it was 2000 m above ground, with a connecting strike to the ground platform. In 1987 lightning struck the 78-million-dollar Atlas Centaur rocket 51 s after take-off, sending it out of control. Lightning struck the nose of the rocket. Both the rocket and the 83 million Pentagon satellite payload it was carrying had to be destroyed over the Atlantic Ocean. The lightning strike which penetrated the rocket, by making a 5 cm hole on its nose, disrupted the main computer which gave false commands to the driving engineer resulting in a failed trajectory. In 1987, lightning struck three small research rockets at the NASA base in Wallops, tripping the ignition mechanism. The three rockets had a common earthing system. After lifting off after the ignition was switched on by the lightning induced currents, the three rockets fell into the Atlantic Ocean. The normal practice is not to trigger the take off of a satellite launch vehicles when there is thunderstorm activity in the vicinity, just as aircraft are usually prevented from taking off or flying under thunderclouds.

Lightning also strikes small passenger planes and control towers. In Fig. 1.2a is shown a lightning strike path through a military aircraft flying at striking distance from the thundercloud. More frequently lightning strikes commercial aircraft when it takes off or landing, and under the thundercloud. In 1995 the radar control station at Changi Airport, Singapore was directly hit by lightning, and it took four hours to start up the system with the backup system. In 1993 in France, an Airbus was struck when taking off, the nose was broken, and the radar was affected, and the aircraft had to be landed in emergency. In 1992, the almost impregnable lightning protection system with 32 lightning arresters in the airport control tower was bypassed by a lightning strike knocking out the control tower for two hours. The fire control system was also set on fire. In 1996 lightning strike to the German meteorological measuring system



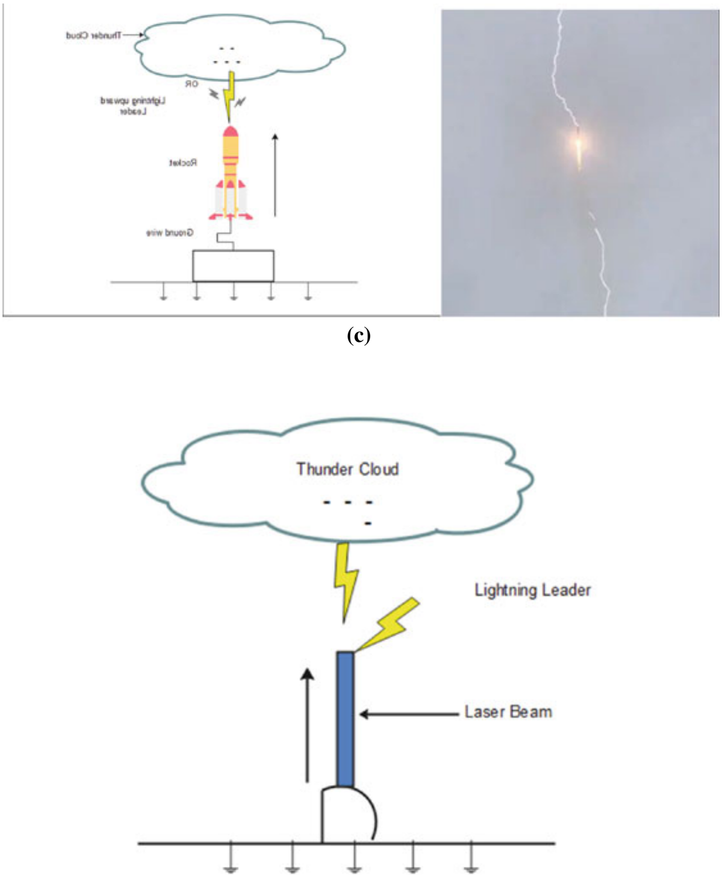
(a)

(b)

Fig. 1.2 Lightning flash to **a** Lightning strike to an aircraft; the lightning channel connects the thundercloud and ground through the aircraft. **b** Lightning strike to an elevated structure, such a electric power towers and buildings. *Credit* NOAA_NSSL, USA. With permission. Endeavor space shuttle pad hit by lightning *Credit* NASA, USA). **c** Lightning flash triggered by a rocket fired towards a thundercloud. Photograph of a space vehicle struck by lightning (*Credit* NASA, USA). **d** Lightning flash triggered by a laser beam fired towards the thundercloud, An experimental system set up in Switzerland

at Dusseldorf made it malfunction, resulting in a temporary shutdown of the airport to flights.

Figure 1.2b shows a lightning strike to an object elevated from the ground. Here the forked lightning channel is seen above the tower, such as a telecommunication tower. Lightning strikes electric power line towers as well as the bare power lines held up by the towers which run for several hundreds of kilometers. Multiple lightning channels from the strike point to a power line indicate that there is not only one flash, but following the first stroke, are subsequent strokes to the same point on the power line through the now ionized channels, imitating a multiple number of destructive high voltage transient pulses that will travel along the line in both directions, that is,



(c)

(d)

Fig. 1.2 (continued)

towards the power generating station at one end and towards the power substation at the other end, at which the transmission voltage is stepped down to lower voltages for electric power distribution. In Fig. 1.2c is shown an artificially triggered lightning strike. A rocket which has a light, flexible, grounded conducting wire connected to it, is fired towards a thundercloud. The rocket, thereby, takes the ground potential close to the thundercloud, thus increasing the electric field at the tip of the rocket at ground potential to make it become very large until it launches a leader stroke towards the thundercloud. Then the first return strike occurs through the wire and the rocket, melting or destroying both with its heat. In Fig. 1.2d, instead of a rocket attached to a ground conductor wire, a laser beam is shot towards the thundercloud, which takes the ground potential closer to the thundercloud. Here the first return stroke occurs through the conducting laser beam. These artificially triggered lightning strikes are used to make measurements on lightning at a controlled, instrumented, fixed point on earth.

About thirty percent of electric power failures in the USA are due to lightning flashes. The damage caused can exceed five billion dollars. Lightning-caused electric power failure and damage to both the power apparatus and the consumer installations connected to the power grid are much higher in poorly protected electric grids in developing countries. In 1977 a 345 kV power line close to New York was struck by lightning. With the whole city plunged into an electric power cut, it took one day to restore electric power, with a loss of 350 million dollars to the city. Two 345 kV power lines in Minnesota went out of service due to lightning and subsequent overheating of power lines sagging down to touch trees, caused further electric short circuits and failures. For over nineteen hours, the chain reaction at other interconnected state power grids resulted in eight states plunging into loss of electricity. In technically developed countries, such as France, close to five percent of all insurance claims in a year is lightning related. In the telecommunication industry this can be close to ten percent of all insurance payments. In the USA about 50% of the annual 200,000 forest fires are due to lightning. In the summer of 1999 about 2000 forest fires were caused by lightning flashes resulting in 400 million dollars of property damage. With the increase in renewable energy sources used for the generation of electricity, lightning protection of both wind power stations and solar power installations becomes more important. In 1988 a particularly severe thunderstorm in Sweden triggered 1400 alarms, and the police radio and telephone exchange was disrupted. The 130 kV power system failed, and the emergency generators were not started up because the control computers were damaged. The low voltage mains distribution, the control room, and computer terminals were damaged. In 1993 the rotor wings of the large wind generator in Helgoland, Germany, were destroyed, causing damage with up to DM 800,000 spent on repair. Although the annual number of lightning flashes over the ocean is much lower than the annual number of lightning flashes over land, offshore oil platforms need lightning protection because of the tall structures and the special type of material handled.

Figure 1.3a shows a heavily branched cloud-to-ground lightning flash. The branches of the lightning flash point downwards, giving it the appearance of an inverted tree. The downward pointing branches indicate that the leader stroke of the flash traveled from cloud towards ground, and the intense return stroke traveled from the ground towards the cloud. The return stroke not only runs towards the thunder cloud, but also along the branches thus neutralizing the electric charges deposited in the branches of the leader stroke. Such lightning flashes are called cloud-to-ground (CG) lightning flashes. This is the most common type of lightning flash to ground. The upward going leader, from tall earth structures or aircraft radome (or nose) for instance, is called a ground to cloud (GC) flash. In GC flashes, the branches point upward towards the cloud. In Fig. 1.3b is shown a ground to cloud (GC) lightning flash, with the branches pointing upward. Such upward GC flashes are produced by tall buildings and towers. Lightning protection of the structure of buildings and its surrounding environment is important. Moreover, the electrical and information

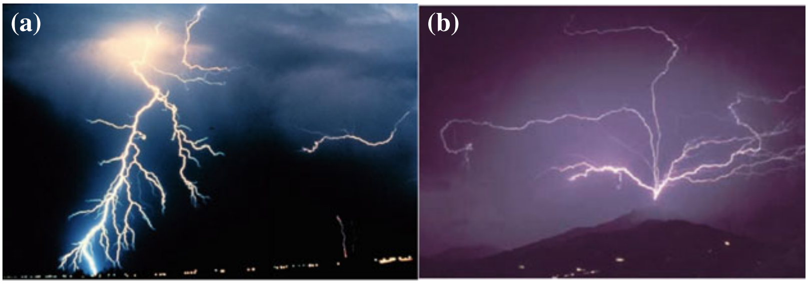


Fig. 1.3 **a** A heavily branched lightning strike to ground. A simultaneous, horizontal cloud to air flash well above ground, like an inverted tree. A cloud-to-ground (CG) lightning flash. *Credit* NOAA_NSSL With permission. **b** An upward lightning stroke, where the branches point upwards, like an upright tree. A ground to cloud (GC) lightning flash. *Credit* DEHN. With permission

technology (IT) equipment inside the buildings needs to be protected from the lightning currents and voltage impulses, as well as from radiated electromagnetic pulses (LEMP) produced by the lightning flash.

Figure 1.4 shows long lightning flashes stretching across the sky. One such cloud flash in Oklahoma terrain stretched to a distance of 350 km. Such flashes could be between electric charge centers within a single cloud, between the thundercloud and air or lightning flashes between two large thunderclouds. It is expected that unusually intense lightning flashes, as well as long flashes that may last for several seconds (instead of the conventional one second flash) will increase with climate change, especially with the warming up of the earth's surface. Much research into lightning strikes and lightning strike parameter prediction for severe lightning flashes with climate change is an urgent need for the protection and preservation of electrical, power, telecommunication and emergency electronic systems (e.g. medical surgery and intense care unit electronic/computer systems), as well as for human safety.

The microphysical and thermodynamics-based nonlinear processes of the atmospheric disturbances and anthropogenic enhancements of heat emission play a crucial

Fig. 1.4 Lightning flashes within a thundercloud (the intracloud or IC flash) or cloud to air flash (cloud to air or cloud to cloud or CC flash). *Credit* NOAA_NSSL, USA. With permission

role in the cloud-to-ground electrification. Evidence has shown that surface temperature rise from heat generated through anthropogenic activities is a key factor in driving lightning activities. Such evidence points to an inevitable risk of cloud-to-ground (CG) flashes that have been observed over major cities around the world. The risk is heightened further as a result of unprecedented weather patterns due the effects of climate change. There is strong interactions between climate change and the electrical processes of the earth's atmosphere (i.e. the troposphere, extending from the earth's surface to a height of 14 km) and beyond (notably, the ionosphere, the layer that stretches from 90 to 400 km above the earth). Moreover, it is conventional to link climate change with all extreme weather events including high frequencies and intensities of lightning flashes. Lightning inception criterion is still a subject of debate and research. Lightning activity is more continental than oceanic, with continental updrafts at 50 m/s producing thunderclouds compared to the 10 m/s updrafts over the ocean. Intense lightning activity is seen to prefer dry climates (e.g. Africa) rather than wet climates (e.g. South America), although both regions may be close to the earth's equator. Thus, lightning flash, especially the CG flash, induced voltage and current transients pose serious threats to ground and airborne vehicles, structures, and systems. The need for mitigation of lightning's direct and indirect effects continues to drive the protection systems to structures, their contents and systems to a higher level.

There are, to date, no devices or methods capable of modifying the natural weather phenomena to the extent that they can prevent lightning discharges. Lightning flashes are hazardous to people, to the structures (buildings, towers, aircrafts, etc.) and their contents and installations. This is the overarching reason why protection measures in aircraft, structures and systems become vital against both the direct and indirect effects of lightning. The need for protection, the economic benefits of installing protection measures, and the selection of adequate protection measures should be determined in terms of risk management.

Lightning interaction with structures is categorized as direct effects and indirect effects. The direct effects of the lightning stroke (or flash) comprise high return currents. The current peak magnitudes are of the order of several tens of kilo amperes. A value of 200 kA and up to 500 kA has been reported. The four specific effects of lightning current due to direct effects that are considered to be of high severity in producing damage are: (1) the peak current, which is the high-current pulse flowing through a conducting surface. It is responsible for the voltage induced on the conducting surface of magnitude $v = iR$, where i is the current pulse, and R is the resistance of the surface; (2) The maximum rate of change of current. This is dependent on the current steepness which gives rise to an electromagnetically induced voltage $v = M\frac{di}{dt}$, where M is the mutual inductance of the loop of conductors; (3) The integral of the current over time, $Q = \int i dt$, which is the electric charge transferred and is responsible for the mechanical force and the heating effects; and (4) The integral of the current squared over time $\frac{W}{R} = \int i^2 dt$, where W is the energy dissipated into a 1 Ω resistor (R) which is referred to as the specific energy or the action integral. The resistance R is the temperature-dependent D.C resistance of the conductor and *R/W* is the specific energy which is responsible for the melting effects.

The indirect effects of lightning threats are due to the radio frequency interferences and lightning electromagnetic pulses (LEMPs). The LEMPs can induce disruptive voltages ($v = Ldi/dt$) and currents ($i = Cdv/dt$) that can adversely impact electrical and electronics systems through resistive and/or electromagnetic couplings. The advent of digital electronic technology in electrical/electronic systems and the evolution of Internet of Things (IoT) through radio frequency identification devices, barcodes, smart phones, and the convergence of smart technologies in smart homes, smart industries, smart cities, smart environment, and smart ecosystem in smart people with micro-chips implanted forming the smart planet by integrating modern communication and information technologies will all heighten the requirements for a professional approach to lightning protection. LEMPs threats can have serious damaging effects. The electrical and electronics systems are susceptible to LEMPs at frequencies between 1 and 500 MHz and produce internal field strengths of 5 to 200 V/m or even greater. Internal field strengths greater than 200 V/m of pulse widths less than 10 μs can absorb lightning-induced voltages and currents ranging from several tens to thousands of voltages, say from 50 V and 20 A to over 3000 V and 5000 A. Susceptibility of electrical/electronic system to LEMPs has been suspect as the cause of “nuisance disconnects,” “hardovers,” and “upsets” in electronic systems. Generally, such malfunctions in digital electronics systems occur at lower levels of EM field strength than that which could cause component failures, if no proper shielding or protection system is utilized.

Because of the lack of detailed knowledge of the lightning strokes, little theoretical work has been done. Where the physics of the leader stroke or return stroke is taken into consideration, the underlying theories frequently contradict even some of the known, measured behavior of the strokes. The bulk of the work on the leader stroke has been to determine the velocity of the leader—each school of thought assuming different processes to dominate. We examined the leader stroke theories, to gain an understanding of the path over which the return stroke travels. Work on the return stroke was examined, to learn from the ideas found therein and their limitations, examining why no satisfactory solution or agreement regarding the physics of the return stroke has been found to date. A common weakness has been to prescribe unreasonably large, stored energy in the leader in order to obtain observed return stroke velocities of the order of 10^8 m/s, close to a third of the velocity of light in free space. The lightning flash is a challenging problem in physics and engineering, but it is not easy to tackle to full satisfaction any one of the many distinct stages which make up the majestic flash, from thundercloud formation, to lightning initiation, to the leader stroke and return stroke, or the subsequent dart leader and return strokes. That each stage plays an important role in discharging the thundercloud, thus balancing the electrical changes which take place during fair-weather conditions, is clear.

1.2 The Leader Stroke

The fair-weather volt drop of 250 kV between the upper atmosphere and the earth may be represented by a battery. Shown in Fig. 1.5 is also the electric circuit model of the fair-weather electric circuit: voltage source represented by a DC battery connected through the thundercloud resistance R to the fair-weather atmospheric resistor R_f (200 Ω), which in turn is connected to the ground through the fair-weather capacitance Ci (0.7 F). The fair-weather CR time constant is 2 min. This is the time taken for the 250 kV electric potential difference between the earth and the upper atmosphere to charge the fair-weather capacitor Ci. The charging current Ic is about 1250 A. When the thundercloud replaces the fair-weather environment, the large, approximately 50–100 million volt drop (50–100 MV) between the thundercloud and the earth generates electric breakdown (at about 30 kV/cm electric field stress, sometimes as low as 18 kV/cm) and the leader stroke moves between the earth and the thundercloud to create a short circuit. The short circuit results in the intense, destructive return stroke current wave.

The nature of the leader is represented by an RC circuit (Fig. 1.5) triggered by a constant voltage source, for which

$$RI(t) + \frac{1}{C}\int I(t)dt = V(t) \tag{1.1}$$

which on differentiation gives

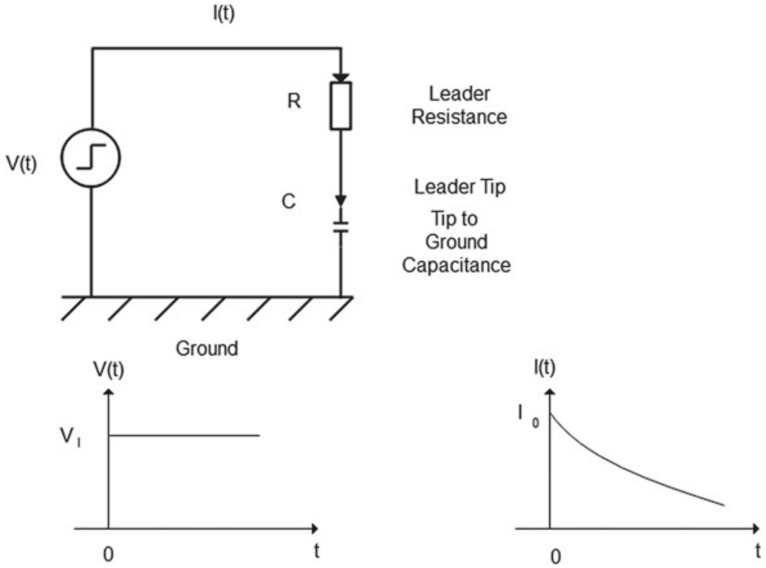


Fig. 1.5 A crude circuit model for the leader stroke

$$I(t) = e^{\left(-\frac{t}{RC}\right)}\left[\int \frac{1}{R} e^{\left(\frac{t}{RC}\right)} \frac{dV}{dt} dt + I_o]\right]. \ \mathrm{orI(t)} \ = \mathrm{I_o e^{(-\ t/RC)}} \qquad (1.2)$$

After the initial rise of V, we have dV/dt = 0. Thus the current is simply Io exp(-t/RC) and is sketched as in Fig. 1.5b.

The fair-weather electric field between the upper ionosphere and the earth at a height z may be given as

$$\mathrm{E(z)} \ = \ -\left(-93.8 \ \mathrm{e}^{(-4.5278\mathrm{z})} + 44.4 \ \mathrm{e}^{(-0.121\mathrm{z})}\right)\mathrm{V/m}$$

for height z less than 60 km. At ground level, with $z = 0$, E is about 150 V/m. At $z = 10$ km, E is 4.5 V/m and at 30 km it drops to 0.3 V/m and to 1 μV/m at very high altitudes close to 60 km. Under the thundercloud, with its lower region at a height of 1 km from ground, the electric field at ground level could rise to about 50 MV/km, yielding 50 kV/m. The high electric field produces the lightning leader stroke which results in the high-current lightning return stroke. The energy in a return stroke is in the region of 10^9 to 10^{10} J. Can this lightning energy be used to provide electricity to homes? Consider a 100 W bulb burning for one month. The energy it requires is $100 \times 3600 \times 24 \times 30 = 0.26 \times 10^6$ J. This means just to light up a 100 W electric bulb, it will take about 10^4 years of lightning energy to light that electric bulb for one month. The reason for this is that although electric power in lightning is high, the electric energy is very low, since it lasts for only about half a minute. Moreover, since much of the lightning energy is dissipated into heating in the lightning leader channel, the energy delivered to earth is much lower.

The electric charges in the lower part of the thundercloud determining the electric charge polarity of the lightning flash varies from country to country and season to season. A positive electric charge concentration in the lower part results in a positive lightning flash, with positive electric charges lowered to the ground by the return stroke. When the lower part of the thundercloud has a surplus of negative electric charges, this results in a negative flash with the return stroke lowering negative electric charges from the thundercloud to the ground. In the USA, for instance, monthly positive lightning flashes are about 90, whereas the negative flashes per month are about 50. In summertime, there are more negative flashes (20 per month) than positive flashes (15 per month). In Japan the number of monthly positive flashes (66 per month) is much higher than negative flashes (29 per month). In France on average there are 81 positive flashes each month and 34 negative flashes each month.

There are two difficulties facing the theoretician studying lightning and laboratory spark leader strokes: (1) There is scant knowledge of transport, ionization and recombination coefficients and of thermal and electrical conductivities of the processes involving kinetic energy dissipation by chemical, thermal and radiative means; (2) Theoretical calculations of unknown parameters such as the electron temperature, calculations that are based on mere assumptions. The problem still remains intractable. In the extensive work on leader channels using the time invariant fluid equations for electric plasmas, some of the assumptions made are quite drastic—for example, it is assumed that there are no conduction, convection, or displacement currents flowing in and around the leader; however, current peaks of 1kA and average currents of 100–300A have been reported for leaders. Further it is assumed that the diameter of the leader is over 5 m, hence postulating that the leader motion is due to electrostatic forces between the cloud and the tip. However, such a shock wave theory, in addition to the unacceptable assumptions made above, is difficult to defend for the following three reasons:

(1) In a sphere—plane electrode system the electric field will exponentially drop, as the observer moves from the sphere to the electrode. In such a situation the energy for the progress of the streamer to a short distance from the thundercloud may be provided by the cloud. But the major part of the gap must be governed by the streamer using stored potential energy in the pocket of charges accumulated at the tip, which is constantly refurbished by conduction currents flowing down from the cloud;

(2) The theory does not properly explain the progress of a positive streamer. In order for a positive streamer to exist, the electron pressure must pass through a sharp maximum in the positive streamer wave front such that the electron diffusion process allows the electrons to move against the electric field. Such a high temperature it is claimed is achieved by electron–electron collision, which is rather doubtful since this would require very large electron density and collision frequency. Even if electrons could be heated to high temperatures, the question of how much energy is used for velocity reversal and how much lost to the electric field has to be addressed; and

(3) The shock wave theory of the leader requires a leader radius larger than 5 m. However, the leader radius for long laboratory sparks is 1–5 mm, with a thinly ionized region surrounding it. Generally, the thin corona streamer develops into a highly conducting leader in about 75 μs, during which time both current and the temperature changes are observed as the channel expands from 1 mm to say 2 mm.

The leader tip is preceded by quite complex processes. Some choose to ignore these discharge processes which precede the leader. The view that there is a pilot leader preceding the main leader appears to be correct; the pilot leader must be made up of corona and glow phenomena. Collisions between accelerated free electrons and atoms generate more free electrons, which result in the highly ionized, electric plasma environment around the leader tip. Electron acceleration depends on the electric field at the tip of the leader. As to how a 1 m diameter corona region first collapses into a glow region and then into a thin leader channel is not clear. This transition is observed to occur with the arrival of a rekindling wave. There is not a sufficient amount of data on long DC sparks, these being very difficult to generate, and hence we assume that some of the observations made on leaders with impulsive voltages are also applicable to DC sparks. We take it that the lightning leader diameter is about 5 mm, with high conductivity which is invariant once having fully developed. In the return stroke considerations, we are not interested in the initial expanding stage of the leader.

Various relationships between the leader velocity and leader current have been claimed. One such relationship suggested for a 16 m long spark at about 2.5 MV is v $= \mathbf{I} + 0.95$ cm/μs where v and **I** are average velocities and currents, respectively. The leader currents observed for laboratory sparks are of the order of 1 A, giving a velocity of about 2 cm/μs. This velocity for the positive spark is about an order smaller if the current is taken to be 200 A and compared to a negative leader step velocity of 0.5 m/μs or dart leader velocity of about 0.06 m/s (0.2 m/μs from triggered lightning measurements). A fundamental difference which must determine the higher currents and velocity in the lightning case, compared to the long DC laboratory spark, must be the very high potential of the thundercloud, leading to restrikes which are associated with intense ionization and large current pulses.

When downward leaders in cloud-to-ground flashes approach a tall object or structure, it rapidly changes direction and strikes largely the tip of the tall object. In such lightning flashes one can observe a sharp kink, or change of direction as the lightning leader sharply turns towards the tall, grounded structure. The current-striking distance is related to the stepped leader charge Q (Coulombs). The relationship between the peak return strikes current I (kA) to the electric charge transferred is empirically defined by $I = 10.6\ Q^{0.7}$. The relationship between the striking distance d (meters) and the peak current I (kA) is $d = 10\ I^{0.65}$. The upward leader that rises from the tip of the tall structure to encounter the downward leader heading towards it could be 20–100 m long. In rare cases where there are two tall structures that launch upward leaders towards the down coming main leader, there will be two different stepped leaders producing two different return strikes, giving rise to a forked lightning.

Upward leaders in ground to cloud flashes are initiated from very tall earth structures, and structures or trees in the mountaintops or artificially initiated lightning where a rocket with a ground conductor attached to it is fired towards a thundercloud. The 3×10^5 m/s upward leader first initiates a dart leader that travels down to ground initiating a first return stroke going from ground to cloud, which largely looks like a subsequent return stroke of a cloud-to-ground flash. In rare cases, the upward going leader may initiate a first return stroke that travels from cloud to ground. When the upward going leader enters into a thundercloud, there are strong intracloud flashes that lower 30 C–300 C electric charges into the dart leader that carries it towards the ground. Fast introduction of conductors, including an aircraft, rocket, nuclear explosion produced conductive matter, or plumes of water that sprout from an ocean bomb blast, can also initiate an upward leader that travels towards the cloud. When rockets with ground wires trailing behind them are fired towards a thundercloud, the rocket height H meters at which the upward leader is launched depends on the electric field E kV/m at ground before the rocket is launched. The relationship between E and H is roughly, $H = 3900\, E^{-1.33}$. The velocity of the rocket and the type of the ground wire attached to it does not appear to have a major effect on the lightning flash properties. However, the presence of melted conductor inside the lightning plasma channel and the very good grounding provided at the earth end give rise to sharply rising wavefronts in rocket initiated lightning flashes compared to natural lightning flashes.

1.3 The Return Stroke

1.3.1 General Description

The lightning leader strokes are largely generated at the thundercloud electric charge center and move downwards towards the ground, and at the leader channel terminations at ground are generated the return strokes of a cloud-to-ground (CG) flash. Figure 1.3 shows both CG and GC lightning flashes, where the return stroke travels from ground to cloud (CG, Fig. 1.3a) and from the thundercloud to ground (GC flash, Fig. 1.3b). Figure 1.6 shows the intracloud (IC) flash, where there are multiple lightning flashes from the electric charge centers, e.g. negative charge centers) from one part of a thundercloud to the electric charge centers (e.g. positive electric charge centers) of opposite polarity in another part of the thundercloud. Here in Fig. 1.6 multiple, spidery shaped multiple bright flashes that are seen in Fig. 1.6, namely, multiple return strokes, travel from one electric charge center towards another.

The lightning return stroke therefore originates at the point at which the leader stroke contacts the ground (CG flash) and moves upwards along the ionized leader stroke channel. However, when a tower or ground object of 150 m height is under the thundercloud, about 23% of the lightning leader strokes originate at the upper tip of the ground object or tower, and these move upward towards the thundercloud. In this case, the lightning flash is called a ground to cloud (CG) flash. This return stroke

Fig. 1.6 An Intracloud (IC) lightning flash between multiple electric charge centers inside the thundercloud. Simultaneous clod to ground flash *Credit* NASA, USA

originates at the cloud electric charge center (or at the round?) and moves downward towards the ground (or upward towards the cloud?). When the object is 200 m tall, 50% of the leader strokes originate at the earth object or tower. The percentage of ground to cloud flash increases to 80% of flashes when the height is 300 m to 91% when the object is 400 m tall, and to 98% when the height is 500 m.

Once the first return stroke has completed traveling from ground to cloud in a cloud-to-ground (CG) flash ionized channel, there could be a subsequent leader and a subsequent return stroke occurring. In between the first return stroke and the subsequent leader, smaller electric voltage pulses called the M-components may travel from the cloud-to-ground transporting electric charges from the thundercloud to ground.

During the electrically intense return stroke strong electromagnetic pulses called the lightning electromagnetic pulses(LEMP) are radiated out from the return stroke ionized channel. These LEMP may induce large electric voltage pulses on distant electric lines and circuits. Up to 5 MHz the strength of LEMP is inversely proportional to the frequency (f). In the range of 100 MHz–1 GHz the strength of LEMP is inversely proportional to f^2.

1.3.2 The Empirical Model

Both the lightning leader stroke and the return stroke are columns of ionized gas, in which when the free electrons are subject to an electric potential (such as the thundercloud voltage), the electrons collectively move in one direction, resulting in the flow of electric current. Matter exists in four states. These are, namely, solid, liquid, gas, and plasma. Plasma in electrical science, is ionized gas. The thundercloud produced electric breakdown results in electrons freed from oxygen and water molecules, producing leader strokes, and subsequent return strokes. In nuclear fusion technology, electric plasma is produced and the free ionized particles are confined to the plasma region by strong magnetic fields externally produced in parallel to the plasma column. Nuclear fusion plasma immersed in an external magnetic field is called magnetized plasma. But the lightning channel is an unmagnetized plasma channel, where at high pressure the channel particles may in a high-pressure internal explosion be thrust out of the ionized column. That expulsion as a shock wave is heard as thunder. The return stroke currents flow along the electric plasma channel of the leader. The ionized gas channel (i.e. the plasma channel) acts like a conductor for the lightning return stroke current.

We may identify two different approaches to the modeling of the return stroke. The first approach is to specify the current-time and current-height characteristics. Parameters such as the peak current, the time constants, and the velocity of the return stroke may be obtained from ground measurements of currents and/or the LEMP. The double exponential empirical description of the return stroke current is the most widely used, because it is simple and easily generated in a high voltage laboratory.

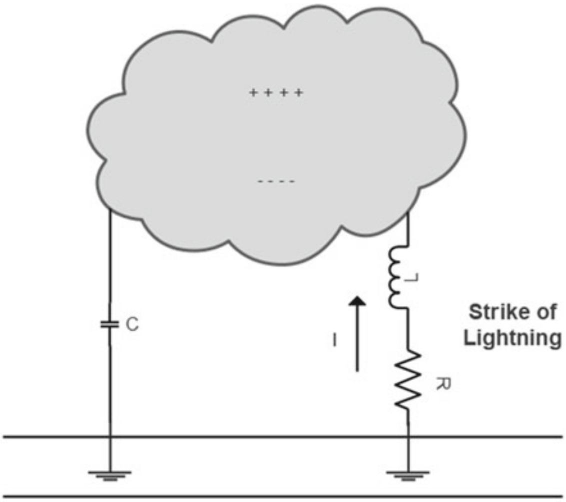


Fig. 1.7 A simple circuit model for the return stroke

However, it is open to question whether such models are true to the physical processes and whether they may rightly be called models of the return stroke.

We may best illustrate this lumped LCR circuit model by a very crude, intuitive model of the return stroke, as shown in Fig. 1.7.

In the case of the return stroke, for the simple model shown in Fig. 1.7 (a), we assume that all the cloud charge is transferred to the leader as the leader is connected to the ground. For the lumped circuit shown in Fig. 1.7a, Kirchhoff's law gives

$$L\frac{dI}{dt} + RI + \frac{1}{C}\int I dt = 0. \tag{1.3}$$

Differentiating (1.3) gives

$$L\frac{d^2 I}{dt^2} + R\frac{dI}{dt} + \frac{I}{C} = 0 \tag{1.4}$$

which has the solution form

$$I(t) = Ae^{\left(\frac{-R-K}{2L}\right)t} + Be^{\left(\frac{-R+K}{2L}\right)t}, \tag{1.5}$$

where

$$K = \sqrt{\frac{R^2 - 4L}{C}}. \tag{1.6}$$

Using, the initial condition I(t) = 0 when t = 0 we obtain

$$I(t) = V_o\left[e^{\left(\frac{-R-K}{2L}\right)t} - e^{\left(\frac{-R+K}{2L}\right)t}\right] \tag{1.7}$$

The form of (1.7) resembles the empirical Bruce-Golde lightning return stroke model and is sketched in Fig. 1.7b.

Differentiating (1.7) and setting di/dt = 0, we have the rise time given by

$$t_T = \frac{L}{K}\log B\left(\frac{R+K}{R-K}\right)\sec s \tag{1.8}$$

which is a strong function of L/R, for $R^2 >> 4L/C$ and K ~ R. We note that the important parameter t_T depends on the careful estimation of L/R. Some LCR circuit models for the return stroke set L/R = 0.0 so that such distributed LCR models are unreliable for rise time estimation. In the case of erroneous setting of parameters, for instance, ignoring the L parameter at ground level, singularity points appear in the calculations. In computation it is important to keep the time step Δt << L/R, and the accuracy is easily checked by ensuring that there are computed points on the wavefront.

Return stroke velocity. The velocity with which the lightning return stroke current and voltage surges travel from ground to cloud, in a cloud-to-ground lightning flash, is about 10^8 m/s. The value is less than the velocity of light (3×10^8 m/s). The velocity of a surge traveling along a lossless electric conductor is equal to the velocity of light. The return stroke current I = dq/dt, where q is the electric charge collapsing along the lightning return stroke channel as it is rapidly lowered to ground by the return stroke traveling upwards in a cloud to ground flash. The velocity of the return stroke wave is v = d*l*/dt. where *l* is the length traveled by the return stroke. With q being the electric charge deposited along a channel of length dl, current I = qv. Unit mismatch. I becomes C m/s Hence for velocity $v = 10^8$, and $q = 10^{-3}$ C/m check unit, we get I = 100 kA, the return stroke current. We have assumed that the velocity v is constant from ground to cloud. But in lightning flashes, the velocity v of the rerun stroke decreases with height.

There are two factors that affect the velocity of the return stroke. (I) First, the longitudinal resistance of the lightning channel, which is not zero. The lightning plasma channel, or the ionized channel, is not lossless, but a lossy conductor with a finite value of R of about 1 Ω/km. The maximum electric field along the lightning channel, or the longitudinal electric field, falls from about 100 kV/m in the first few microseconds. But as the lightning channel diameter expands the electric field falls to a value of about 10 kV/m. The resistance of the channel may increase to about 30 Ω/km in 20 to 30 μs after the return stroke first reaches a point along the channel. (II) Secondly, there is a further reason why the lightning return stroke velocity is less than the velocity of light. When considering the lightning return stroke channel, at the center it is very narrow, a highly conductive core the diameter of which is a few mm to a cm. This inner core is surrounded by a larger region of dispersed, conductive ionized particles. This sheath therefore has a conductance. The outer sheath conducting region further adds to the surge impedance, which from free space values of 300 Ω could increase to 500 Ω. This outer corona sheath could further impede the propagation of the return stroke and reduce its velocity.

1.3.3 Lightning Return Stroke Models

Although a variety of lightning models have been discussed in the literature, the two most important models from an engineering perspective are the following two. (1) The curve fitting model obtained from electromagnetic field measurements and then trying to guess what the electric current that is generated should look like, by a curve fitting technique. The curve fitting method is used extensively by lightning researchers in USA and Sweden. The method is to construct the lightning current pulse by a curve fitting method to get the shapes of lightning electromagnetic pulses (LEMP) measured at ground level. This is an indirect, curve fitting method, that is not strictly based on the physics of the lightning flash. (2) The other, the most important model in our view, is the distributed transmission line model. The lightning flash was initially modeled as a lumped circuit as described in Sect. 1.3.2. Taking the lumped circuit model a step further, the return stroke is modeled by the distributed LCR transmission line model. For the model to have self-consistency, it is necessary to ascertain that it is scientifically valid to represent the return stroke by a transmission line, and if there is a satisfactory case for such a model, with the elements of the line to be determined from basic principles. The models, unless carefully calculated L, C, and R parameters are used, may yield erroneous solutions for a CR network instead of an LCR network. The CR network is a diffusion model and not a fast electromagnetic wave model. In Chap. 5 is presented a self consistent LCR model of the lightning return, which is solved using the finite difference time domain method (FDTD).

There have been suggestions that it is important to include resistances which vary with frequency or time t, as the channel expands. Braginskii's model of a hot plasma channel is used to obtain radius r (proportional to $t^{1/2}$). Moreover, a curve fit is used to obtain conductivity σ following Plooster. Discussion on the lightning leader models using shock wave-like phenomena and their shortcomings also apply to using the Braginskii's and Plooster's works. The degree of freedom in estimating r–t and σ–t characteristics are larger. $R = 1/6\pi r^2$, where R, σ, r are the per unit resistance, conductivity and the radius of the channel, respectively. The distributed LCR electric circuit model to represent the lightning return stroke wave as an electromagnetic wave yields, as shown in Chap. 5, results that adequately match all known measurements, including the convex wave front of the return stroke, without going into additional frequency or time domain calculations of channel radius and conductivity.

Now in the case of the lightning channel where high currents repeatedly flow through the channel, both during the leader and the return stroke phases over a considerable length of time, the channel would have reached a saturation level in terms of its conductivity. During the leader phase itself the discharge carries average currents of the order of 300 A for a negative leader, and above 1000 A for a positive leader. It is reasonable to assume that the high-current leader resembles a high-pressure arc in its final stage, with the current mainly determined by the external circuit. The idea is further supported by the fact that the estimated temperature of the leader is 20,000° K, and for the return stroke the peak temperature is about 25,000° K (the average is about 20,000° K). It is therefore reasonable to expect a negligible amount of change in the lightning channel conductivity during the return stroke phase.

The general picture of return stroke modeling work is that there has been a trend to put in lots of details which may not be significant in reality but are characterized by a serious lack of agreement with fundamentals. The questionable models include postulating a conducting shell around the return stroke channel, and equating the energy dissipated to establish a laboratory arc to the energy used in establishing the lightning return stroke. Fluid equations for electrons in a laboratory leader have been extended to the return stroke. A standing wave for the return stroke has been assumed without any discussion of how the wave is formed in the first place. Data from laboratory sparks has been used to model the lightning return stroke without considering the different processes taking place, and in putting in details that may lead to drawing wrong conclusions from computer procedures which are questionable (e.g. in the time step used which may allow the fast moving wave to spill over to the next spatial increment before a single time step is over.) Large capacitances have been prescribed to obtain low velocities for high frequency signals along transmission lines. Others have prescribed electromagnetic models of the return stroke, as described above, using a curve fitting technique to project back from measured return stroke radiated electric and magnetic fields.

1.4 Lightning Radiated Electromagnetic Pulses (LEMP)

1.4.1 Computation of Radiated Electromagnetic Pulses

The most severe lightning flashes have return strokes of the order of 200 kA, with an electric charge of the order of 100 C and $T_1/T_2 = 10/350$ μs where T_1 and T_2 are the front time and half fall-off time. The action integral, that is the specific energy, is about 10 MJ. The return stroke front time to half fall-off time ratio values is given by $T_1/T_2 = 10/350$ μs. Subsequent return strokes of severe lightning strikes have a maximum value of 50 kA, rate of rise of 200 kA/μs and T_1/T_2 of 0.25/350 μs. The very short rise times of 0.25 μs give rise to high values for dI/dt. This results in large radiated electromagnetic fields or LEMP. These radiated LEMP may couple to loops to induce destructive voltage and currents in electric power systems to microelectronic circuits. Thus, one needs to try to avoid loops in electric circuits. Continuing currents lower electric charges up to 200 C over a duration of 0.5 s. The total flash charge is of the order of 300 C. The voltage induced in a voltage loop of area A by a magnetic field B radiated by the lightning return stroke is given by $V = A\, dB/dt$. A current I flowing along the lightning channel produces a magnetic flux density $B = \mu_o I/(2\pi r)$, at a distance-r from the flash channel, with $\mu_o = 4\pi x 10^{-7}$. Let us do a simple calculation on induced voltage. At a distance of 10 m from the flash, $B(t) = 2 \times 10^{-8} I(t)$. For $dI/dt = 10^{11}$ A/s, the voltage induced in a 10 cm × 10 cm square loop of area $A = 10^{-2}$ m^2, is $V = (\mu_o A/2\pi r)\, dI/dt = 2 \times 10^{-8}\, dI/dt = 2 \times 10^3 = 2$ kV, which is relatively large. In addition to the electromagnetic pulses radiated by the lightning leader and return strokes, there are also smaller radiations of electromagnetic pulses called the M and K pulses. The K pulses are produced by electric processes that take place between two return strokes, that is during the inter-stroke period or the dark period after the ground flash is over. The M pulses occur mostly during the luminous, 200 A or so continuing current that immediately flows after the, say 100 kA, return stroke. The M and K changes are non-threatening, and similar to each other. The M process radiate more frequent submicrosecond pulses than the K process. These processes are of some interest in radio noise studies.

Calculation of the electric and magnetic fields radiated from the lightning return stroke are important for two main reasons: (1) any new return stroke (and leader) models must be tested to verify that the fields determined from such models are consistent with the general radiated electromagnetic pulses (LEMP) measured on ground. (2) To be able to determine the LEMP at any height above the ground and distance from the lightning flash. Although the current-time characteristics at different heights of the lightning channel postulated from field measurements do not give a valid return stroke model, a self- consistent return stroke model ought to give LEMP which generally resembles the observed, ground LEMP. Such a return stroke model may be used to determine the LEMP at any point in space surrounding the return stroke model, including points at which an aircraft which is landing or taking off may be located in space, points that are inaccessible for measurements.

The methods of LEMP calculations may be classified into four different classes.

(i) The old dipole moment method. This method has been widely used to determine fields far from the lightning channel.

(ii) The method based on integral equations for electric and magnetic fields. The integral formulation is most suitable when the field at a limited number of points is required. A widely used approach, it formulates the integral expression of magnetic and electric fields radiated from the entire length of the channel. What is unfortunate about this method is that it is difficult to visualize the contribution to LEMP fields made by the distance-R dependent electrostatic term (dependent on the electric charge, and decays as $1/R^3$ where R is the distance from the channel), the induction or intermediate term (dependent on current, and decays as $1/R^2$) and the radiation term (dependent on the rate of change of current, and decays as 1/R). Furthermore, there appears to be a fundamental error in the expressions as they stand. The constants of integrations do not result from the return stroke. This constant may be arbitrarily taken to be 3100 A. The leader charge has not been accounted for in the calculations reported.

The leader has an electric charge distribution of the order of 0.3 mC/m, for a total charge of say 1 C distributed along the leader trunk of 3 km length. The average charge lowered by a subsequent stroke (without branches) is about 1.4 C. Ignoring this charge in LEMP calculations will give higher field values close to the flash; in particular, for positive flashes where the charges involved are higher, the appearance of bipolar fields (+ve field changing to −ve, or vice versa) near the flash will be suppressed. In physical terms, ignoring the charge deposited along the leader amounts to not considering the return stroke discharging the charged leader channel. In order to rectify this error, an effort is made to place point charges at the tips of the elements of a discretized leader channel, whence adding a new term to the former expression. The magnitudes of these charges are determined by considering the difference in currents between two adjacent segments to reside in a sphere and integrating it over time. Such an assumption is difficult to defend, and it should be remembered that the charge is distributed over the whole length of the channel and does not reside in globules.

(iii) The integral technique reported in this book, the best and most scientifically accurate method reported to date, includes accurate integral method LEMP calculations linked to the currents and distributed electric charges along the lightning channel calculated using the distributed LCR model of the return stroke electromagnetic wave. The channel is discretized, during the LCR model for return stroke current calculations, made up of many segments of specified length (e.g. 100 m segments for a 1000 m lightning channel) to solve the LEMP by numerical integration. This book, moreover, includes the technique for the calculation of electrostatic fields before a lightning strike, with or without an aircraft present in the vicinity. This allows the lightning currents, electric charges, voltages and LEMP to be calculated with external bodies or structures, such as aircraft and buildings or towers present in the vicinity, and become attached to the lightning leader-return stroke phases. Thus, it provides a self-consistent, low memory, fast and accurate computer-based testbed for lightning simulation and lightning interaction and testing.

(iv) A fourth method for determining fields is numerically to solve the differential formulation of the problem using the finite element method. It is best used when fields over the whole space around the lightning channel are required, and external objects such as an aircraft are present in the vicinity. But it is an expensive method if LEMP fields at only a few points are required. The generality of the differential formulation makes it difficult to identify the contribution of the different field terms. The finite element method is a promising tool for three-dimensional and transient field calculations on aircraft.

1.4.2 Calculating Rate of Rise of Currents from Measured Electric Fields

With a notable increase in electric field measurements in the late 1970s and 1980s, there have been attempts at the calculation of the rate of rise of return stroke current using measured electric fields E, from the expressions for E and B given in the well-known forms:

$$E_Z = \frac{\mu_0}{2\pi} D \int \frac{di}{dt} dz. \tag{1.9}$$

The electric field at ground level is approximately expressed as

$$E_Z = \frac{\mu_o}{2\pi D}\left[Iv - \int i\frac{di}{dt}dz \approx \frac{\mu_o}{2\pi D} Iv \right] \tag{1.10}$$

at ground, where v is the return stroke velocity (assumed constant along the channel) and I the current (also assumed constant). With the knowledge of dE_Z/dt at the wave front, dI/dt has been determined—giving very high values for dI/dt, even as high as 280 kA/µs. The average measured value of dI/dt for negative subsequent strokes is 40 kA/µs, for first strokes it is 12 kA/µs. Since wave front of E_Z measured at far distances (e.g. 100 km) will be significantly modified by the earth, trees, buildings, etc. fields measured close to the lightning strike point, at say 1 km were considered. However, only radiation field component was assumed to contribute to the wave front, and thus normalized it to 100 km by using 1/R decay. The contribution of the near (electrostatic) and intermediate fields to the overall electric fields measured was ignored. Hence the erroneous. large dI/dt values obtained using near field values, and then they were normalized to distant field values for the computation of dI/dt from measured dE/dt.

Three further points to note are (a) (1.10) only applies for a return stroke wave front with a constant dI/dt. In actual fact E_Z is proportional to dI/dt.v in agreement with (1.10). However, measured LEMP electric field E wave fronts have a sharp rise for only about 90 ns, giving rise to the calculated value of 280 kA/s which is an overestimate, since it has been assumed that the whole E_Z wave front has a 45 v/m/µs rate of rise. (b) The second note is a word of caution in interpreting measured electromagnetic fields. If the value 45 V/m/µs was obtained from measurements made near to the flash, the 19 V/m/µs contribution of leader has to be deducted. Furthermore, the near and intermediate components of the fields contribute about 20 per cent or more of the fields. If the fields were measured at distances of about 30 km, the 9 V/m/µs contribution of cloud pulses has to be deducted. (c) Without proper velocity measurements, the validity of the use of (1.10) is limited by the fact that it is velocity dependent. The return stroke velocity ranges from 50 m/µs to 150 m/µs. Very few correlated measurements exist. We have also noted that there is a large discrepancy in the rate of rise of ground electric fields reported. And inaccuracies in field measurements need careful consideration.

1.5 Electromagnetic Waves

The four Maxwell equations that form the basic mathematical foundation to electromagnetic fields yield the electromagnetic wave equation in conducting medium,

$$\nabla^2 E \frac{1}{\varepsilon \nabla \rho} = \mu\varepsilon \frac{d^2 E}{dt^2} + \mu \frac{dJ}{dt}, \tag{1.11}$$

where E is the electric field, ρ was the volume electric charge density, J is the electric current density, ε the permittivity of the material, and μ the permeability of the material.

Using (1.11) and rearranging we obtain

$$\nabla^2 E - \mu\sigma \frac{dE}{dt} - \mu\varepsilon \frac{d^2 E}{dt^2} = \frac{1}{\varepsilon \nabla \rho}. \tag{1.12}$$

We assume that E(r,t) = Eexp(j(ωt-k.r)) and also remember that the electromagnetic wave is a transverse wave $k.E = o$ where k is unit vector in the direction of travel; thus (1.12) reduces to

$$k^2 E = k_o^2 \left(1 + \frac{\sigma}{i\omega\varepsilon_o}\right) E. \tag{1.13}$$

where k is wave number and $k_0 = (\omega^2/c^2)^{1/2}$ and $c = 1/\mu_0\varepsilon_0$ the velocity of light. E on left and right in (1.13) will cancel, yielding,

$$k^2 = k_o^2 \left(1 + \frac{\sigma}{i\omega\varepsilon_o}\right), \tag{1.14}$$

where k is complex. But when $\sigma/\omega\varepsilon_0 >> 1$, k^2 is predominantly imaginary. In this case the attenuation distance, the distance over which the amplitude decreases by 1/e and is roughly given by the usual formula for the skin effect,

$$d = \left(\frac{2}{\mu_o \sigma \omega}\right)^{\frac{1}{2}} \tag{1.15}$$

for $\sigma = 4000\ \Omega^{-1}\ m^{-1}$, f = 1 MHz say, d = 8 mm and d = 25 cm for f = 1 kHz with k = 1/d + j 1/d. In a poor conductor, $\sigma/\omega\varepsilon_0 << 1$, k = ω/v where wave velocity $v = 1/(\mu\varepsilon_0)^{1/2}$.

In the discussion above the magnetic force exerted on an electron is ignored in comparison to the force exerted by the electric field; the ratio magnetic force/electric force = v/c << l, when the electron velocity v is much less than the velocity of light, c. The term "fully ionized gas" is somewhat loosely used for the lightning channel where there is about 10 per cent ionization. For an electron density of about 10^{24} /m^3, with the density of gas molecules for air at standard temperature, pressure is $2.5 \times 10^{25}\ m^{-3}$, it is appropriate to point out the implications of taking the lightning channel to be a fully ionized gas.

For a weakly ionized gas, the number densities of electrons and positive ions are considerably less than the number of the neutral particles. The electronic motion is modified by collisions with the neutral particles. For this Lorentz gas, the Langevin equation ignoring the effect of the magnetic field of the electromagnetic wave,

$$M_e \frac{dv}{dt} + M_e \gamma_{em} v = -eE \tag{1.16}$$

$$v = -\frac{e}{Me}\frac{1}{(\gamma_{em} - i\omega)}E. \tag{1.17}$$

Now the electron current density

$$J = \sigma E - N_e e v. \tag{1.18}$$

And hence from (1.18) and (1.17) the conductivity is given by

$$\sigma = \frac{N_e^2}{M_e}\frac{1}{(\gamma_{em} - i\omega)}. \tag{1.19}$$

The conductivity has a real and an imaginary part. The DC value of conductivity is $N_e e^2/M_e\gamma_{em}$.

If we substitute (1.19) in (1.14) and extract the real and imaginary parts,

$$k^2 = k_o^2\left[\left(\frac{1-\omega_p^2}{\gamma^2+\omega^2}\right) - \frac{1\omega_p^2\gamma}{\omega(\gamma^2+\omega^2)}\right]. \tag{1.20}$$

Dropping the subscript for the collision frequency and remembering that the plasma frequency is given by $\omega_p{}^2 = N_e e^2/M_e\varepsilon_0$ when $\gamma = 0$, we have the familiar dispersion relation

$$k^2 = k_0^2\left(\frac{1-\omega_p^2}{\omega^2}\right), \tag{1.21}$$

where no dissipation takes place in the plasma. The situation given by (1.19) and (1.21) is important if the lightning channel is a very poor conductor, in which case the channel is like a dielectric rod, or, if the electron temperature is very high. The latter situation would arise if there is a very high electric field (about 1 MV/m) to be associated with return stroke, in which case there will be electron run away with the electrons moving quite independently of other particles so that $\gamma = 0$. The possibility of this cold plasma type of motion occurring in lightning needs further discussion.

The first case of dielectric line plasma is more to be associated with low current discharges, as in corona or glow discharges. In this case low frequencies cannot propagate along the column, the actual dispersion curve depending on the ratio γ / ω, according to (1.20). In lightning leader and return strokes, the low frequency signals dominate, whereas the high frequency signals are not very significant. The dielectric analogy where electrons are like bound charges, each being associated with a positive ion to form an electric dipole, is probably true for lightning initiation and inter-stroke processes; it is these processes which will radiate in the frequencies above 1 MHz. For the return stroke the static conductivity may be employed without appreciable error, well into infrared frequencies if necessary.

In a fully ionized isothermal gas, the collision frequency assumes another meaning from that in the Lorentz gas. First, when electrons and ions are the only constituents, $\gamma_{\text{eí}}$ ($>\gamma_{\text{em}}$) is the predominant frequency, so that conductivity σ is smaller than when neutrals are present. Secondly, the presence of large numbers of electric charges requires that the frequent distant encounters must be included. It is this conductivity in which we shall be interested. The boundary between weakly and strongly ionized gases depends on collision cross section area and gas temperature.

Considering a temperature of 20,000° K, with a gas density of about 10^{25} /m^3, the electron-ion collision frequency is about 10^{15} s^{-1}. At such a high electron-ion collision frequency we may take $N_e/N_n > 10^{-2}$ to be for a strongly ionized gas. A useful test for local thermodynamic equilibrium is

$$N_e(cm^{-3}) > 1.75 \times 10^{14}(T_e(ev))^{\frac{1}{2}}(E_i^{z-l}) \tag{1.22}$$

from which it is reasonable to take for a discharge column in air, mainly consisting of N_2 ($V_i = 15.5$ V) and O_2 ($V_i = 12$ V), and a fair measure of oxygen atoms ($V_i = 13.5$ V), and NO ($V_i = 12$ V), at $N_e = 10^{18}$ cm^{-3} and $T_e = 20.000°$ K (1.7 eV) to be at local thermodynamic equilibrium. In this situation the population of excited states is mainly determined by collision with free electrons.

The electron density of 0.5 to 1 × 10^{18} cm^{-3} is taken to be a good estimate, since this was calculated from Stark profiles of Ballmer series of hydrogen-hydrogen due to decomposition of water vapor—which is primarily dependent upon charged particle number densities and only slightly dependent upon particle energies. The values obtained using Saha's equation at temperatures determined by line intensities for nitrogen plasma show good agreement.

1.6 Lightning Protection: An Introduction

Over the past decade there has been an increasing interest in lightning and lightning protection for several reasons, including the proliferation of microelectronic equipment and IT systems in mission critical systems as well as in everyday use in banks, industries to homes. Both high voltage power systems and low voltage networks need lightning protection. Personal protection of people is also highly critical in thunderstorm environment and from electrocution by lightning currents flowing through the ground, electric conductors and water systems. Lightning strikes to power lines produce large, fast transient voltage and current surges which trickle down to IT systems, military command and control systems as well as to several other microelectronic equipment and control systems. Moreover, aircraft may be struck by lightning when it is parked on ground, landing and taking off or in military operations where the aircraft has to keep close to ground and when the atmosphere is electrified by a thundercloud. Unusual phenomena have been recently observed which includes a lightning flash which stretched to over 350 km over Oklahoma, USA, and in 2016 about 300 reindeer in Norway were killed by a single lightning strike to ground. Severe thunderstorms may soon become more common if the temperature signature of the earth surface with climate change continues as at present. Whereas a single lightning phenomenon was expected to last only for one second, it has been recently observed that a single lightning event may last as long as seven seconds, packing in an immense amount of energy and repeated strikes at one location or to one object. The energy and intensity of lightning may continue to increase causing damage and electronic rust, as well as increasing threat to human life. We explore here the protection of electronic equipment, structures and in house systems from lightning. We will also consider lightning related Electrostatic Discharge (ESD) threat to aerospace vehicles and microelectronic systems. This is especially so with the increased use of non-metallic, composite material for the aircraft body. Moreover, we will summarize the important lightning techniques used in the protection of electric power systems and houses.

1.6.1 Lightning Effects

Lightning can initiate forest fires, endanger life, destroy electric equipment and cause power line faults. It plays a vital role in atmospheric chemistry. It was found that during the summer months lightning activities increase NO_X by 90% and ozone by more than 30% in the free troposphere.

The damage caused by lightning mostly occurs at some point where a cloud-to-ground leader stroke terminates on a tree, a structure such as buildings, or a conductor situated on an elevated position like high rise wiring systems. Electric control systems malfunction and fail, and expensive microelectronic equipment to super high voltage

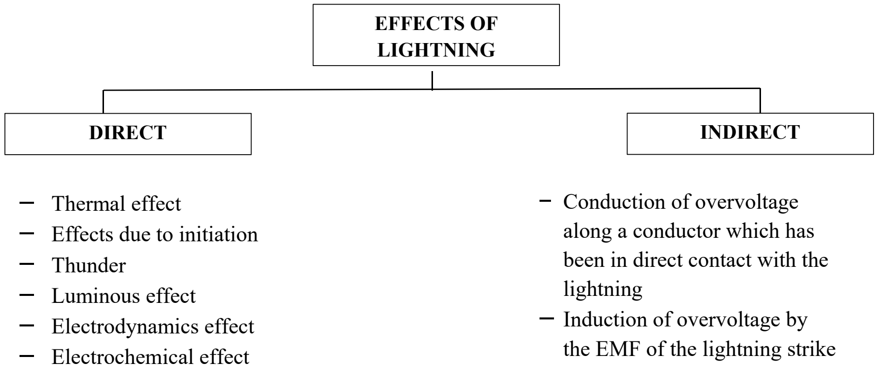


Fig. 1.8 The direct and indirect effects of lightning

(SHV) apparatus are destroyed by lightning strikes. But the lightning strike also results in other kinds of after-effects that impact living things (Fig. 1.8):

- Visual effect (lightning flash)
- Acoustic effect
- Thermal effect
- Electrodynamic effect
- Biological effect

Generally, these lightning effects are classified into two types of accidents or disasters which are a direct lightning strike accident which relates to all the effects mentioned above when lightning directly strikes upon an object or a being. The second classification is due to indirect lightning effects where the after effect of the lightning strikes causes problems to any nearby object or being which is due to (i) electric induction, (ii) conduction, and (iii) magnetic coupling of lightning currents and voltages in the ground to other grounded electric conductors and systems. Consider first the direct effects.

Visual effect: this effect is due to the extremely high brightness emitted by the lightning strikes which can injure any person or damage visual measuring devices such as a light sensor. With a close enough distance from the striking zone, this will cause a short-term blindness in eyesight. In certain instances, a fatal permanent eye blindness may occur. Other than the eye, electronics also may be affected where a light sensor can be burnt due to overdose of light received from the lightning strike. Hence, any devices with light sensors such as a camera may suffer malfunction.

Acoustic effect: this is normally caused by thunder emanating from the expanding lightning channel during the return stroke, where the sudden shock wave from the overheated lightning channel causes a rapid release of pressure (2–3 times atmospheric pressure) which breaks the sound barrier and creates a sonic boom. Exposure to the sonic boom from thunder may lead to a short-term loss of hearing or in the worst case, damaging the ear drums. Other organs such as the heart and lung too may be affected by the pressure wave. Fracture of glass and disruption of microphone and transducers are also caused by thunder.

Thermal effect: since lightning strike emits extremely high heat (higher than the heat emitted by the sun), it results in melting holes of varying sizes on high resistant materials that are attached to the lightning channel. On other materials with low conductivity or high insulation (e.g. trees), the large amount electrical energy released by the lightning strike is instantly converted to heat energy. This quick transformation of heat can burn any materials, sometimes causing flammable liquid or gases to be ignited and turning water into steam at high pressure in a short amount of time, which can result in an explosion of the container with flammable material.

Electrodynamic effect: lightning currents through the magnetic fields produced may become strongly coupled to other current carrying conductors. In this situation, the effects of the interactions between conductors and other equipment occur due to large magnetic fields produced by a lightning strike's current. This in turn causes a considerable amount of mechanical forces which may be attractive or repulsive. The mechanical forces are stronger when the distance between the conductors is smaller and the current flowing through them is higher.

Consider now the indirect effect of lightning strikes. The indirect effects have become more important due to the increasing use of highly sensitive microelectronics. These microelectronic devices are vulnerable to the transient overvoltage caused by lightning. The overvoltage can either be atmospheric in origin (such as lightning) or of industrial origin (from man-made equipment such as electric motors). The atmospheric (e.g. lightning) overvoltage is more harmful than industrial overvoltage. The indirect effects of lightning are categorized as follows:

(1) Conduction: this is from an overvoltage that flows along a conductor or apparatus which has been directly hit by a lightning strike. This sudden rush of electricity may have a very destructive effect on other systems, apparatuses, and humans at a distance since most of the lightning energy will spread through the entire power system network or grid causing threats to all the other devices or systems the strike point is connected to.

(2) Induction: this is caused by the radiation of the electromagnetic field (LEMP) produced by the lightning strike. The return stroke currents flowing along the lightning channel resemble a transmitting wire antenna carrying currents. The LEMP radiated may be picked up by other conductors that act like a receiver antenna. Therefore, under the effect of the sudden fluctuation in current, the wiring cables, air ducts which act as aerials, and antennae may receive through induction a large portion of the lightning destructive overvoltage and energy. This is also the reason that putting the network and power system underground does not guarantee full protection from a lightning strike, since LEMP can penetrate the ground or be generated by lightning currents flowing inside the ground.

(3) Lightning effects transferred through the ground: this happens when a lightning strike hits the ground, upon which an overvoltage and current can rise up from

> the ground in order to find a more preferable path (in other words, more conductive path) to flow. This may cause a sudden overvoltage in a nearby grounding conductor. It can lead to a backflow of currents from earthling conductors and shields into the tanks, electric and electronic devices, and apparatuses, posing a threat. Moreover, the large voltage drop caused in the ground, with the voltage rapidly dropping from the point of lightning contact with ground, causes circulation of currents through the legs of creatures such as cows, as well as across differently grounded electrical installations, which is fatal.

With the disastrous effects, direct or indirect, of lightning strikes on living beings and material things (such as electronics, power grids, trees, and man-made structures), the importance of lightning protection is obvious and it must address the control, avoidance or diversion of high currents, high voltages, high temperatures, and high-pressure waves that are associated with lightning flashes.. Loss of the impacted equipment will be costly for the utility or user. If the lightning protection system is weak or poorly maintained and not upgraded, loss of lives, massive loss of revenues, crimes, and social disruption are frequent short-term effects. In addition we have long-term damage to electrical and electronic equipment and systems which is unavoidable.

According to Ohm's Law.

$$V = I.R \tag{1.23}$$

V = Voltage Drop, in V.
I = Peak current of lightning strike, in A.
R = Earth Resistance, in Ω.

Assuming that the resistance of the object struck (e.g. ground) is constant, the voltage at the point of strike follows the time domain pattern of the lightning current. Other than current and voltage, the charge Q of the lightning current is also an important element in the characteristics of a lightning strike. The charge of the lightning current plays a role in energy conversion where the energy W (electrical energy) will be converted into another form of energy (mostly heat energy) at impact point. The formula for Q and W can be seen below.

$$Q = \int i dt \tag{1.24}$$

$$W = Q.V \tag{1.25}$$

Q = Charge of lightning current, in C.
i = current of lightning strike, in A.
W = energy conserved in a lightning strike, in J.
V = voltage drop of the lightning strike near the impact zone, in V.

Therefore, the electric charges and the energy conversion at the lightning strike point result in extremely high heat which will cause the impact point to melt or burn.

However, the efficiency of energy conversion from electrical to heat largely depends on the resistance at the impact point. This energy conversion is given by

$$\frac{W}{R} = \int i^2 dt \tag{1.26}$$

$$W = R.\int i^2 dt = R.\frac{W}{R} \tag{1.27}$$

R = resistance of conductor (temperature dependant), in Ω.
$\frac{W}{R}$ = specific energy, or action integral.

The calculation implies that all the heat generated by the conversion of energy is dissipated in the ohmic resistance of the impact point. Furthermore, it is also expected that there is no perceptible heat exchange with the surrounding due to the extremely short duration of the conversion process. Table 1.1 shows the temperature rises of different materials that are used in lightning protection as well as their cross-sections as a function of specified energy.

Apart from specific energy, the electrodynamic forces F generated by the current *I* in the conductor that was struck by the lightning on a long, parallel conductor of length *l*, at a distance *d*, can be estimated by using the formula:

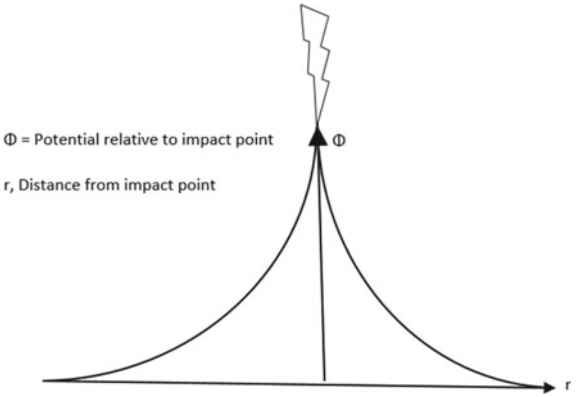
$$F(t) = \frac{\mu_0}{2\pi}.i^2(t).\frac{l}{d} \tag{1.28}$$

F(t) = Electrodynamic force, in N.
i = current within a conductor, in A.
μ_0 = Magnetic field constant in air, (in $4\pi.10^{-7}$ H/m).

Table 1.1 Temperature rise ΔT in K of different conductor materials

Cross section (mm^2)			4	10	16	25	50	100
Material	Aluminum W/R (MJ/Ω)	2.5	–	564	146	52	12	3
		5.6	–	–	454	132	28	7
		10	–	–	–	283	52	12
	Iron W/R (MJ/Ω)	2.5	–	–	1120	211	37	9
		5.6	–	–	–	913	96	20
		10	–	–	–	–	211	37
	Copper W/R (MJ/Ω)	2.5	–	169	56	22	5	1
		5.6	–	542	143	51	12	3
		10	–	–	309	98	22	5
	Stainless Steel W/R (MJ/Ω)	2.5	–	–	–	940	190	45
		5.6	–	–	–	–	460	100
		10	–	–	–	–	940	190

Fig. 1.9 Representation of Potential Gradient Area



l = conductor length, in m.
d = distance between two parallel conductors, in m.

The force between two conductors can be attractive if the two currents flow in the same direction and repulsive if the two currents flow in the opposite directions. The force is proportional to the magnitude of current and inversely proportional to the distance between the conductors. Thus, the specific energy dissipated by the lightning strike will cause stresses upon the impacted conductor to cause deformation.

When a lightning strike hits the ground, large amounts of current flow through the ground, neutralizing them. However, this action also causes the conductive surface of the impact area to form a potential gradient area, as shown in Fig. 1.9. If a living being (either human or animal) is inside the potential gradient area, an upwards voltage is formed and can cause an electric shock towards that being which could potentially kill it or cause other negative effects which can be referred to the effects of lightning strikes section. But, this risk can be reduced if the ground's conductivity is higher which then, flattens the potential gradient area making the victim less likely to get electrocuted.

Most lightning properties are beyond normal human comprehension. The cloud-to-ground discharge has an enormous magnitude of voltage that is tens of millions of volts or more. The maximum discharge of currents in each strike may vary from several thousand Amperes to 200,000 Amperes or even more. The current increase to this high magnitude lasts for a short time of about few millionths of a second (microsecond), and the primary part which usually has the highest possible value of current on each strike usually lasts even less than a thousandth of a second.

1.6.2 *Effects of Lightning on Aircraft*

Both commercial and military aircraft in flight are subject to many atmospheric disturbances of which lightning is no exception. As commercial aircraft are scheduled to fly fixed routes, it is often difficult to avoid thunderstorm formation along their paths. It is statistically reported that on average, every commercial aircraft is struck by lightning once every year. The flight path is an influential factor that increases the probability of lightning strike rate on an aircraft. That is, a lightning strike to an aircraft is a function of both the aircraft flight path and altitude, and the thunderstorm formation altitudes. Aircraft at a low altitude either in ascending or descending phases have an increased probability of being struck by lightning.

As the aerospace industry expands into both manned and unmanned commercial and military vehicles, preventing electric field enhanced aircraft initiated lightning strikes and protections against serious damage and accidents become a major concern to the aerospace industry. When an aircraft flies into the environment of an electrified cloud, it enters into an enhanced electric field region surrounding the cloud, which in most cases has a large negative charge center in its lower region. The electric fields will induce an electric dipole charge over the body of the aircraft, with positive electric charges on the top surface of the aircraft and negative electric charges on the underbelly of the aircraft, resulting in an electric dipole charge structure. These can be sufficiently enhanced to result in electric discharges, for instance, resulting in positive leaders emanating from the radome of the aircraft. With this, at another extremity of the aircraft, that in the tail part, a negative leader may develop from electrostatic discharges occurring at another electric field enhanced part of the aircraft body. The negative leader will move towards the ground or another nearby thundercloud or electric charge center in the air. It is important to determine the electric field enhanced areas of the aircraft in order to design preemptive measures to reduce lightning strike risks, even to design and to maintain the aircraft to reduce electric field enhancements in these high-risk areas. A knowledge of the electric charges induced on the aircraft body and the electric field distribution is also essential to decide on the safe placement of sensitive microelectronic systems associated with aircraft measurement and navigational systems.

For an aircraft to be air worthy, the aircraft manufacturers need to provide the overall assurance for adequate lightning protections. This process requires certification plans for tests done on components or systems of components such as the airframes, power and electrical wirings and components, fuel systems and components, avionics and communication systems such as the radar, and other control and automation components. The certification plans for the tests are done either within the aircraft manufacturers' laboratories or the component suppliers' laboratories. In a nutshell, the protection of aircraft against lightning strike can be summarized in the following steps (i) determine lightning attachment zone; (ii) determine systems and components which are likely damaged by lightning; (iii) set lightning protection standards for systems and components; and (iv) confirm the rationality of the protection design by the use of tests. The following parts of the aircraft experience electric fields that have potential to cause electrostatic discharge or electronic circuit flashovers: the radome, the wing tip, the wing surface, and the stabilizer tip.

In future aircraft the metal body surfaces will have their body materials increasingly replaced by composite materials, and fiber glass. Determining the lightning strike effect zones using prestrike electric field stress, becomes more critical to these non-electric shield materials. The most susceptible return stroke zones, the first strike zones, are the extremities of the aircraft. All the areas of the aircraft surfaces where a first return stroke are likely during lightning channel attachment with a low expectation of flash hang on, that is the lightning flash remains than being attached to the aircraft as the aircraft moves. The current at these zones of attachments may exceed 200 kA. Zone 2 are the aircraft surfaces where a subsequent return stroke is likely to be swept with a low expectation of flash hang on. The current in Zone 2 can exceed 100 kA. Zone 3 includes those surfaces not in Zones 1 and 2, where any attachment of the lightning channel is unlikely, and those portions of the aircraft that lie beneath or between the other zones and/or conduct substantial amount of electrical current between direct or swept stroke attachment points.

1.6.3 Lightning Effects on Electric Power Systems Network

Electric power transmission and distribution grids are routed for miles in open fields. Thus, they are prone to lightning strike. A lightning strike on structures such as a high voltage overhead transmission line can induce voltage and current surges whose amplitudes far exceeding the peak values of the nominal operating levels. The amplitudes are in the order of 1000 kV and 100 kA or more in the transmission line. The values of the peak rate of rise can reach measured and modeled values of 100 kA/μs. An overhead earth wire provides protection against direct lightning strikes in diverting the current and or voltage pulses to ground through the tower footing resistance. The tower footing resistance should be as low as 10 Ω or even less for more negative reflection from the tower base to reduce the chance of a voltage flashover at the top of the tower.

However, in the event of shielding failures, back flashover, and or an induced voltage on a transmission line when lightning strikes a nearby object, high current and voltage pulses will reach the terminal equipment such as a transformer at substations. (That is, the cloud charge induces a charge on the line which is attracted to a point closest to the cloud, and when the cloud charge flashes to a nearby object, the charge on the line is released from the Coulomb forces holding it and runs in both directions). In such cases, surge protection devices (SPD) are required to divert the major part of the energy of the surge to ground via surge diverters or absorbers, or by modifying the waveform to make it less severe via surge modifiers. Fuses which depend on exploding wires, or melting wires, are too slow to act for the high speed lightning surges that travel along conductors. Surge diverters (or lightning arrestors) generally consist of one or more spark gaps in series, together with one or more nonlinear resistors in series. Silicon Carbide (SiC) was the material most often used in these nonlinear resistor surge diverters. However, Zinc Oxide (ZnO) is being used in most modern day surge diverters on account of its superior volt-ampere characteristic. An ideal lightning arrester should: (i) conduct electric current at a certain voltage above the rated voltage; (ii) hold the voltage with little change for the duration of overvoltage; and (iii) substantially cease conduction at very nearly the same voltage at which conduction started. Figure 1.10 gives an illustration of lightning protection system with placements of shield wire, SPDs, circuit breakers, grounding systems, and the air terminals.

An absorber is in series with the line, such as a conducting PbO. As the surge runs through it, the property of PbO changes with heat, it becomes a nonconductor and kills the surge. A divertor is connected from the line to the ground like a spark plug. The surge makes the gap break down and diverts it to the ground. It is reusable. But an absorber is not reusable, because its composition changes.

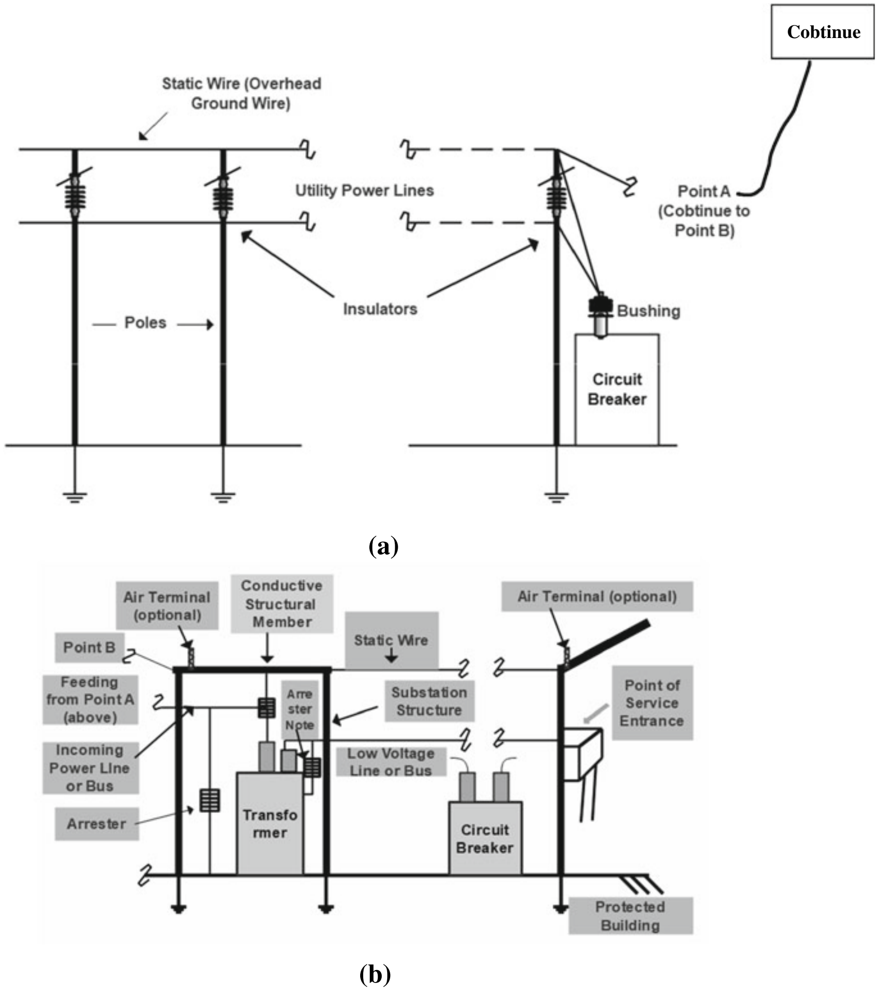


Fig. 1.10 Illustrations of power network protection **a** Transmission line and **b** substation protection systems *Credit* Adapted from DEHN

1.6.4 Substation Protection Systems

Substations accommodate some of the most expensive equipment such as the power transformers, current transformers, voltage transformers, and relays. Protection systems using arresters, absorbers, and breakers only protect the equipment from traveling waves induced by lightning. Protection against a direct lightning strike requires masts and shielding wires, as shown in Fig. 1.10a. The lightning protection of a substation utilizes three methods: using masts, using shielding or static wires, and/or using both masts and shielding wires. However, breakage of shielding wires (due to lightning current or poor maintenance) can cause catastrophic faults in substations when it snaps off. Further, another disadvantage of using shielding wires is high cost in comparison with the using of masts. Moreover, a mast attracts lightning flashes more easily than the shielding wire when the tip is made small. Thus, the application of a mast in substations is preferred to shielding wires for lightning protection for substations. A general arrangement for a power substation protection is shown in Fig. 1.10b. The requirements for the two different lightning protection mechanisms are discussed below (i) A shield wire lightning protection system will be generally used in smaller substations of lower voltage class, where the number of bays is fewer, the area of the substation is small and the height of the main structures is of normal height. The major disadvantage of shield wire type lightning protection is that it causes a short circuit in the substation or may even damage the costly equipment in case of its failure (i.e. snapping off); (ii) A lightning mast: this type of protection is generally used in large, extra high voltage substations where the number of bays is more. It has the following advantages, (a) It reduces the height of the main structures, as peaks for shield wire are not required, and (b) It removes the possibility of any back flashover with the nearby equipment or structure during discharge of lightning strokes.

Further, electrical substations require an earth mat for good grounding. Grounding high frequency signals or currents of the lightning currents require special care in order to keep the high frequency grounding resistance small enough. Vertical grounding rods that conduct lightning currents carry currents at frequencies up to 100 MHz, compared to the low 50 Hz or 60 Hz electric power frequency. At higher frequencies the currents flow only over the outer surface (determined by the frequency dependent skin depth) of the vertical rod, thus increasing the grounding impedance because of the reduced surface area over which the currents flow at high frequencies. The earthing system provides a low resistance return path for earth faults within the plant, which protects both personnel and equipment. The earthing system provides a reference potential for electronic circuits and helps reduce electrical noise for electronic, instrumentation, and communication systems. The earthing system also provides a low resistance path (relative to remote earth) for voltage transients such as lightning and surges/over-voltages. Another requirement for substation earthing is to provide for equipotential bonding which helps prevent electrostatic build up and discharge, which can cause sparks with enough energy to ignite flammable atmospheres. Special consideration must be given to the protection of the increasing amount of electronic systems, such as the distribution static compensator (D-SATCOM), that form the critical systems of the electric power grid.

1.6.5 Rolling Sphere Method Applied in Substation Protections

The application of the rolling sphere method involves rolling an imaginary sphere of radius S over the surface of a substation. The sphere rolls up and over (and is supported by) lightning masts, shield wires, substation fences, and other grounded metallic objects that can provide lightning shielding. A piece of equipment is said to be protected from a direct stroke if it remains below the curved surface of the sphere by virtue of the sphere being elevated by shield wires or other devices. An equipment that touches the sphere or penetrates its surface is not protected. The basic concept is illustrated in Fig. 1.11 based on IEEE Standard 998–2012, "IEEE Guide for Direct Lightning Stroke Shielding of Substations."

The calculation for the rolling sphere method is based on the electro-geometrical model. It is summarized in the following equations based on a 69 kV substation. The striking distance, S with respect to lightning strike peak current, I_s is calculated by using Eq. (1.28).

$$S = 10 \cdot I_S^{0.65}, \tag{1.28}$$

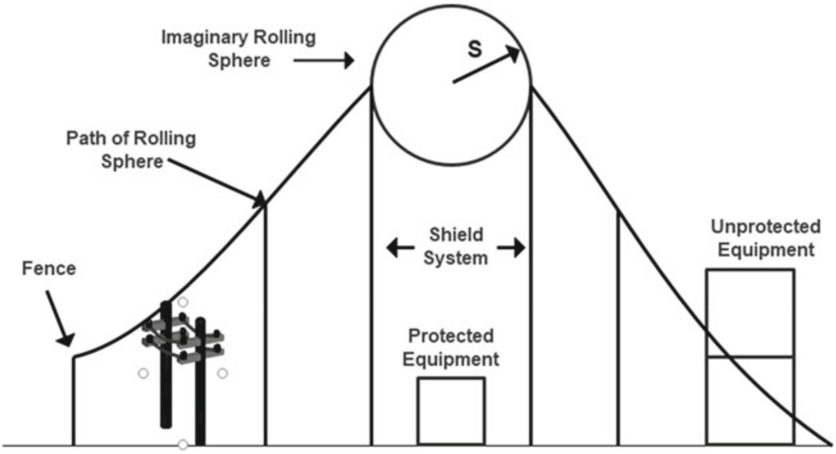


Fig. 1.11 Illustration of rolling sphere protection method. *Credit* Adapted from DEHN

where I_S is a function of the surge impedance (Z_s) and the basic impulse level (BIL). For a 69 kV system for which an assumed $Z_s = 300\ \Omega$ and BIL: = 350 kV. Then

$$I_S = 2.2 \cdot \frac{BIL}{Z_s} \tag{1.29}$$

from which we get a value of I_S of 2.567 kA. Using the calculated current stroke value, the radius of the sphere can be computed which is 18.45 m. This is the length of the last leader as it strikes the mast. It is also the length of the upward leader from the mast tip as it meets the downward leader from the cloud at the stroke point.

1.6.6 Lightning Protection Methods for Buildings and Infrastructures

The lightning protection system of buildings and infrastructures is categorized into three as illustrated in Fig. 1.12. It covers (i) protection for buildings and installations against direct strike by lightning; (ii) protection systems against overvoltage on incoming conductors and conductor systems; and (iii) protection systems against the electromagnetic pulse induced by lightning striking a nearby object as an indirect effect.

The protection against direct lightning strike requires air-termination rods with good bonding to ground through down conductors via metallic structures on the external building structures as specified by grounding standards. Figure 1.11 gives and illustration of the rolling sphere requirements for buildings with areas indicated as shown that need air terminals to shield the building from direct lightning strike. Further, a good bonding to ground is necessary to provide an equipotential ground plane for all components within the building for single integrated earth termination systems for structures, combining lightning protection, power and telecommunication systems. Figure 1.13 gives an illustration of the equipotential bonding of an installation and the application of SPD in protection of building components (Fig. 1.14).

Figure 1.14 shows the complete protection system zones within a building. Air-termination methods in protection of building structures requires the electro-geometrical method of rolling sphere to determine the safe zones from lightning strikes. The air-termination method requires the use of rods spanned by wires or cable, and mesh conductors. Further, the air terminal requires the electro-geometrical method of a rolling sphere to determine the safe zones from lightning strikes.

The protection systems cover both external protection devices using air terminals, and down conductors to ground. This protects the building from both direct and induced voltages and currents from lightning striking the nearby objects. The interior protection requires the necessary grounding of the building circuits and utility piping. The SPD devices are also used indoors for the protection of lightning induced LEMPs on appliances.

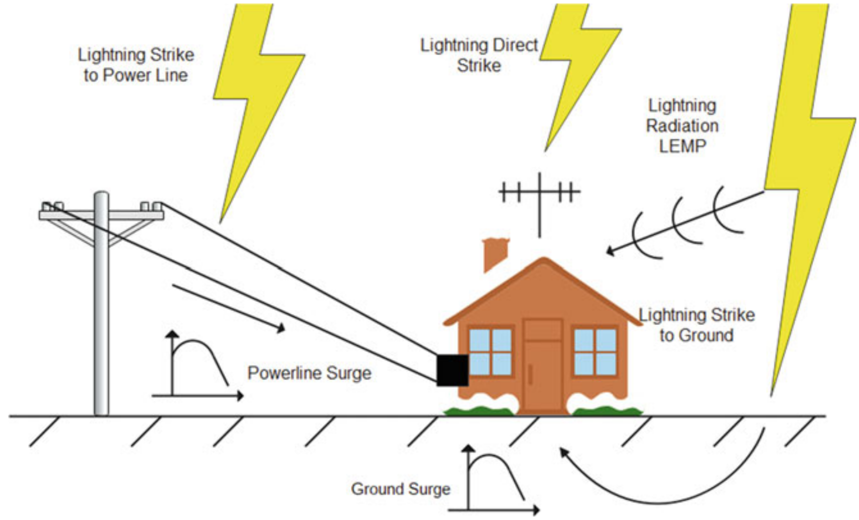


Fig. 1.12 Illustration of lightning strike through direct hit, through incoming conductor, and induced through objects nearby

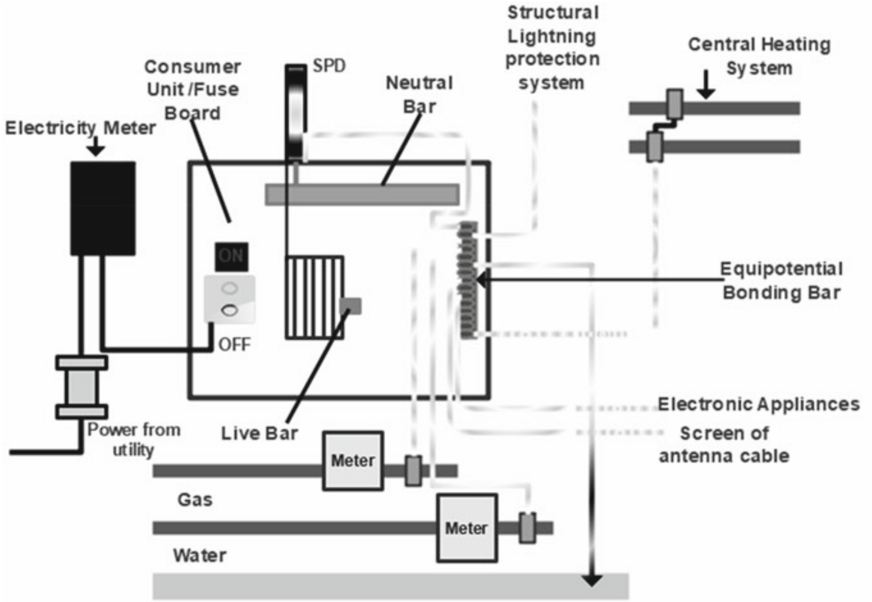


Fig. 1.13 Equipotential bonding of building components (*Credit* Adapted from DEHN)

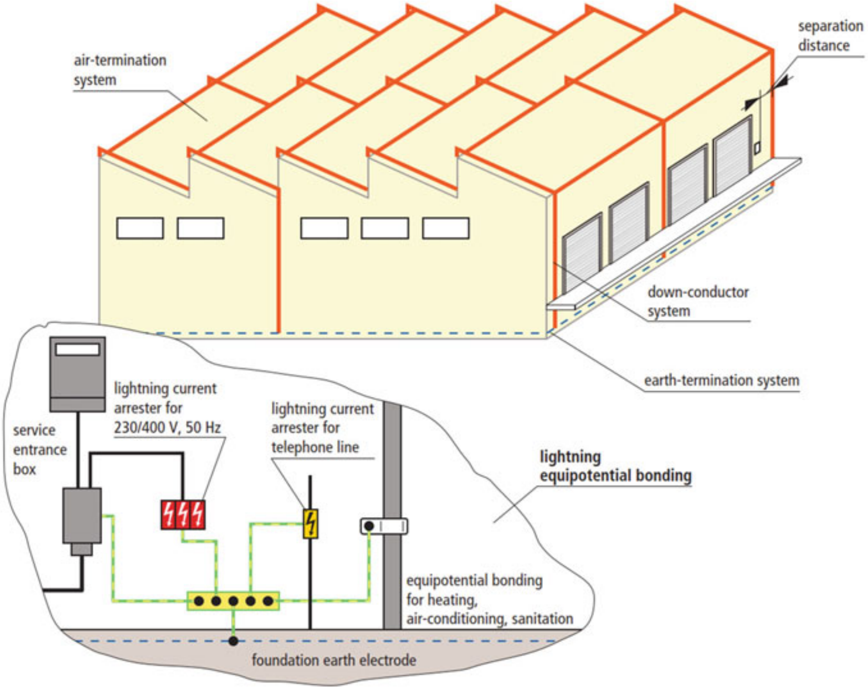


Fig. 1.14 Lightning protection system. (*Credit* From DEHN, with permission)

1.7 Lightning, Climate, Upper ionosphere, and Other Planets

Lightning is a good indicator of the intensity of atmospheric convection. Hence lightning can be related to the earth's atmosphere where there is the greatest instability. This atmospheric instability occurs either due to the heating of the boundary layer by solar radiation or by mixing of air of different densities. There is an organized pattern to form the unstable regions which is originally driven by the heating pattern of the earth's surface by the sun. Therefore, if the climate system is changed, the regions of convection will be changed ultimately changing the lightning patterns around the globe. Meteorological Measuring Systems are used to globally monitor lightning activity, which is also a direct measurement of climate change. Monitoring is carried through all three stages of the thunderstorm life cycle, namely, the developing stage, the maturing stage and the dissipating stage. Over the developing stage the towering cumulus cloud builds up and there may be occasional lightning activity. It is during the maturing stage that we get heavy rain, strong wind, hail, frequent lightning and tornadoes. During the heavy rainfall of the dissipating stage lightning activity may drop, but it continues even after rainfall ceases.

Due to solar heating there will be rising temperature around the globe with maximum occurring in tropical regions. The region of rising air along the thermal equator is known as the Inter Tropical Convergence Zone (ITCZ). The thermal equator is not a constant as is the geographical equator. The thermal equator moves to the northern and southern hemisphere with the seasonal changes. As the land to ocean ratios are different in the two hemispheres and as the heat capacities are also different, the width of the ITCZ will also change.

The tropical monsoons consist of moist oceanic air, which results in heavy rainfall with low rates of lightning. Intense lightning can be observed in a dry environment. That is why more intense lightning activities can be observed in the African continent. Lightning activity in the North Pole has dramatically increased in recent times, as well as the annual number of lightning flashes over many countries, including the USA. Increase in the number of electrically severe thunderclouds results in increasing number of severe tornadoes produced by such super thunderclouds. The greater the air mass density difference, the greater the atmospheric instability which will result in a greater intensity in these storms.

1.7.1 Effect of Temperature on Lightning

By using different time scales (diurnal, daily variations, intra-seasonal, semiannual variations, annual variations, etc.) it was observed that there is a positive relationship between temperature and lightning with lightning activity increasing for every degree the surface warms up. The daily, regional, averaged surface temperature over Africa when compared with the regional lightning activity, showed that lightning activity increases with surface temperature. For tropical lightning surface temperature is a key factor determining daily lightning activity, while no relationship was observed in the long term over the last 50 years.

Water vapor absorbs infrared radiations emitted from the earth's surface and it is the primary natural greenhouse gas influencing the climate. The earth's climate is more sensitive to the changes of water vapor in the upper troposphere which naturally has a low level of water vapor. Recently it was found out that thunderstorms deposit a large amount of water vapor in the upper troposphere. Lightning activity over Africa was seen to vary with the specific humidity of the upper troposphere. It may be stated that lightning can be used to monitor the intensity of the deep convection. Water vapor, cloud cover, ice water content, and ice particle size have different impacts on earth's radiation balance and many studies have proved lightning activity has a direct correlation with the above.

1.7.2 Effect of Lightning on Troposphere

Lightning activity will produce nitrogen oxides and ozone, which is another greenhouse gas. Recent studies show concentrated NO_X in thunderstorm anvils and concentrated ozone in downwind. Taking exact measurements of the concentration of these gases and building a relationship with lightning parameters is a difficult task. But lightning is the main source of NO_X and these gases play a vital role in earth's climate.

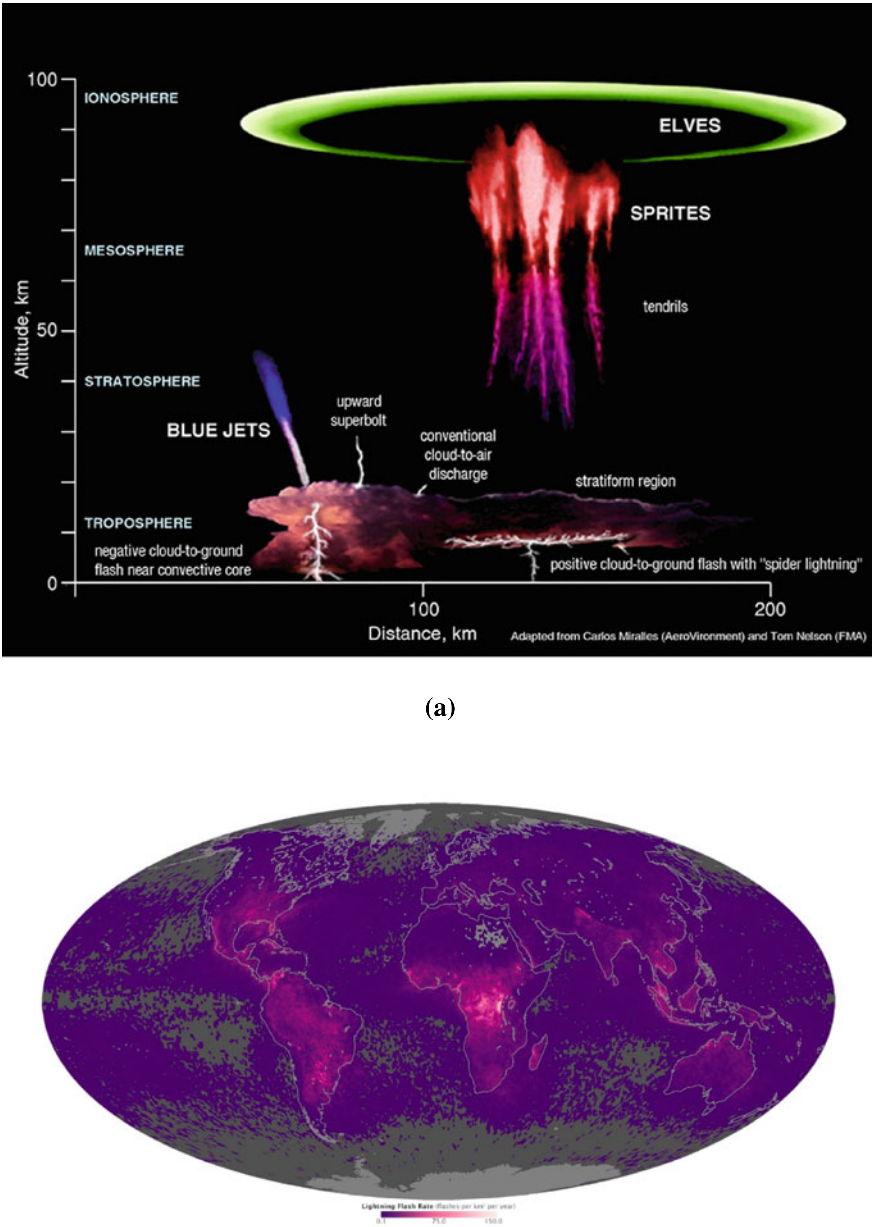
It is evident that global temperatures are increasing and the cause is the increase of greenhouse gases. The modeling of future lightning activities showed that the greatest warming due to greenhouse gases will occur on the equatorial upper troposphere and not on the surface, and moisten the upper troposphere due to the deep convection. But a paradox occurs as the upper atmosphere warms up, and atmospheric lapse rate becomes more stable tending to inhibit future convection which will reduce the amount of thunderstorms. But many climate model stimulations conclude that lightning activities will increase in a warmer climate with 10% increase in lightning activity globally for every 1 °C warming. It is shown that in a doubled CO_2 climate, the updraft strengthens, and drying in a warmer climate reduces the frequency of the thunderstorms but those that do occur are very intense.

Global temperature in recent times has increased by about 2–5 °C depending on the region of the planet earth. The annual increase in temperature on average is 0.25 °C per decade. Nitrogen oxides NOx (NO and NO_2) break into Nitrogen and Oxygen molecules through electron impact and very high temperatures in the lightning channel. About 10 eV energy electrons inside lightning channels are able to break N_2. Electrons at energy higher than 5 eV are able to break O_2. In a region with 10^8 ions in a 0.5 mm radius streamer, electron collisions can produce about 5×10^{11} NO molecules. Moreover, high temperatures of the order of 25,000 °K inside the lightning channels also result in the formation of NO molecules, through the reactions of $O + N_2 = NO + N$ and $N + O_2 + NO + O$. However, NO can be destroyed by thermal collisions too: $NO + N = N_2 + O$, $NO + O = N + O_2$ and $NO + NO = N_2O + O$. In general, a total of about 10^{25} NO_x molecules may be found in a 10 km long lightning channel. This production of NO_x occurs not so much during the return stroke phenomena, but during the production of streamers, corona and M-components.

Lightning activity over ship routes are expected to double due to particles emitted from ships. In cities lightning flashes to earth are expected to increase in the range of 45–80% during summer. This is partially due to an increase in urban cloud condensation nuclei concentration. A fourfold increase in summertime lightning activity is expected. Over growing cities, due to convergence of surface winds due to the heat island effect and high air pollution, may increase lightning flash density from 1 per km^2 to 4 per km^2. In some cities, lightning activity over cities has increased by 60–70% over the built-up areas of a city. A decrease in positive lightning flashes by 7–8% has been observed over such cities. Due to increase in pollution particles over the city, cloud-to-ground flashes were seen to increase by about 50%. Lightning is a major cause of damage to trees and forests through direct hits or by setting forests on fire. In the Western USA 40% of forest fires over an area of 0.4 ha are due to lightning, with 76% in Alaska, with an area larger than 200 ha. Over the years between 1973 and 2013, with climate change, it was found that there was a global mean of fire season increased in duration by 18.7%, with an increase of 10.8% in burnable areas. With the increase of wind turbines in 90 countries from a capacity of 514 GW to 5476 GW in 2050, damage to the rotor, burns, punctures, tip damage and edge debonding of blades is expected significantly to increase with the increased number of wind turbine installations and increase in atmospheric temperature and frequency of severe lightning strikes. It is known that the rotor blades of the wind turbines initiate lightning at 3 s intervals over periods of hours. The rotating blades increase lightning strike vulnerability.

The most destructive type of lightning is the cloud-to-ground discharges. Since they might discharge large currents to the earth through buildings, living beings, etc., only about 25% of global lightning events are cloud-to-ground lightning. There are several types of cloud-to-ground discharges. They are negative downward, negative upward, positive downward, positive upward lightning flashes and bipolar lightning flashes. From these about 90% of lightning flashes are downward negative lightning flashes which transport negative charges in the downward direction of the cloud. Figure 1.15 shows lightning and electric discharges in the upper atmosphere above the thundercloud. Lightning cloud discharges paint beautiful pictures in the sky. They do not make contact with the ground. They can be either an inter-cloud discharge, intracloud discharge or an air discharge. Out of these three categories intracloud discharges are more frequent. Cloud discharges are less destructive to human life and animals since they do not make contact with the earth. But cloud discharges can be destructive to aircrafts, space crafts and complex electronic devices. Lightning mapping arrays are used to study lightning. These are three-dimensional arrays which are used to map lightning. Red sprites, blue jets and elves are three types of transient luminous events which are associated with cloud discharges to the higher atmosphere. These are rarely observable to the naked eye. Red sprites are not very bright. They are red in color and the period of red sprites are is just a few seconds. Blue jets have been witnessed by pilots and the period of blue jets is less than a fraction of a second. Elves occur in the ionosphere, during the occurrence of a cloud-to-ground discharge. The period of elves is less than a thousandth of a second. Elves are of an expanding disk shape, as shown in Fig. 1.15a. In Fig. 1.15b is shown the global lightning activity, showing very little activity over the sea (say, 5 lightning flashes/km^2/year) and as many as 150 to 250 lightning flashes/km^2/year in some countries close to the equator. The highest number of flashes are found in Africa and South America. In some regions such as North India, lightning activity peaks around the monsoon rain season (in May, for instance), whereas in other countries lightning activity is uniform throughout the year.

Sprites. Consider now the upper ionosphere of earth. The troposphere extends from 10 km altitude to 15 km. Lightning flashes occur from the top of a thundercloud to the upper atmosphere. There are further lightning like activities in the upper ionosphere. First, there are the Sprites which are jelly fish shaped, as shown in Fig. 1.15. They



(a)

(b)

Fig. 1.15 **a** Types of Lightning (*Credit* NOAA_NSSL, USA. With permission. https://www.nssl.noaa.gov/education/svrwx101/lightning/types/) **b** Global Lightning activity, with as many as 150 lightning flashes per square kilometer per year in the light pink areas (*Credit* NASA, USA) have an oval shaped body with numerous tendril-like electric discharge channels. The Sprites occur at altitudes of 70 to 90 km. The main electric discharge body is reddish in color, and the tendrils tend to be bluish in color. The total length of Sprites is 5 to 30 km with the individual tendrils being 10 m in diameter. The entire volume is about 10,000 km^2. It lasts for about 10 to 100 ms. The Sprites are thought to be produced by lightning activity in the earth's lower atmosphere. The upper atmosphere is a good conductor. The upper region of a thundercloud produces a strong electric field in the upper atmosphere, which move the free electrons in the upper atmosphere. The thundercloud electric charge builds up slowly, so that the movement of the electrons is slow. However, when the lightning flash suddenly depletes the thundercloud of electric charges, the electric field in the upper atmosphere suddenly collapses. This results in a fast, sudden collapse of electrons producing rapid ionization, that appears as sprites. Inside the upper region of a thundercloud, at an altitude of 10 km, the total electric charge could be about 100 C.

Blue Jets. In addition to Sprites, there are also blue jets and gigantic jets that appear in the upper atmosphere. These travel up from the upper region of the thundercloud, originating from 15 to 18 km and moving up towards the upper atmosphere to heights of about 40 km. The blue jets are conical shaped, and travel at about 10^5 m/s, with a cone angle of 15° and last for 200 to 300 ms. When lightning flash rate is high, gigantic blue jets are produced which travel from the top of the thundercloud at 15 km to all the way up to the ionosphere at 70 km. They travel at a velocity of 10^5 m/s. Blue jets are largely positive discharges.

Elves. When electromagnetic waves (electric field E and magnetic flux density B) impinge on the ionosphere, they produce the Lorentz force $F = q\ (E + v \times B)$ on free electric charges q inside the ionosphere moving at velocity v. These electric charges moving along the upper layer of the ionosphere produce a current that moves out in ring shape. These currents radiate visible electromagnetic fields when the moving electrons collide with N_2 and O_2 with the excited atoms radiating light. These ring shape red light radiations are called elves and last for about 1 ms. There are other non-visible energetic radiations also associated with lightning, including X ray and antimatter from within thunderclouds. These radiations occur due to very large electric fields inside the thunderclouds which accelerate electrons to run away speeds. These electrons, which are at energy levels of 100 meV, radiate X-rays and γ-rays. These strong electric fields are generated at points where positive and negative streamer tips meet.

1.8 Summary

Direct and indirect lightning effects on a power systems network, and building and system structures have become serious threats. The effects of climate change coupled with the anthropogenic enhancements of heat emission play a crucial role in the cloud-to-ground electrification which is experienced in major cities today. The threats can be contained through proper protection measures such as the SPDs, and proper shielding and grounding practices as defined in various standards on lightning protections highlighted. Future changes in lightning activities and severity with climate change may force a reevaluation of current lightning protection standards and techniques. However, with the probabilistic nature of lightning phenomena, the protection measures many not provide 100% protection in shielding the direct and indirect effects of lightning flashes. Thus, new measures in protections and standards will have to drive protection to a higher level for the mitigation of lightning threats.

The need to harden aircraft, power systems, structures, electronics, computers, electronics devices and other information communication systems against severe electric storm has been highlighted in this chapter. Among the many things highlighted is that electric storms remain a complex phenomenon that cannot be controlled and or be prevented. Undoubtedly, it remains a serious threat to aircraft, power systems, electronics, and communications systems. As an aircraft in flight near ground can become a path of the electric storm discharge circuit either through a triggering mechanism process or through interception, the direct and indirect effects pose severe threats to flight safety. These threats are heightened further with aircraft industries continually modifying and or adopting new designs into the aircraft such as the CFC in airframe design and the latest in the state-of-the-art digital control, command, and communication systems. As climate change may result in lightning flashes with more electric voltage and current pulses, and electric power transmission is pushed to higher voltages and taller towers, the number and severity of lightning strikes to electric power systems and surges that trickle down to low voltage commercial, industrial and smart city installations will increase. Microelectronic circuits and systems that operate at very low battery voltage ARE??? more vulnerable to small voltage and current spikes due to the lightning radiated electromagnetic pulses (LEMP).

Bibliography

Airbus A380, Aircraft Characteristics Airport and Maintenance Planning, Airbus Technical Data and Support and Services (2014)

Aircraft Lightning Environment and Related Test Waveforms, SAE ARP 5412 Committee Report, April (2012)

A Antonescue S Stefan 2011 The urban effect on the cloud-to-ground lightning activity in the Bucharest area Rromania, Romanian Reports Phys. 63 2 535 542

Barry, J.D.: Ball Lightning and bead Lightning, Plenum (1980)

Bazelyan, E.M., Raizer, Y.P.: Lightning Physics and Lightning Protection, IOP Publishing (2000)

Car, S.K., Liou, Y.A.: Analysis of cloud-to-ground lightning and its relation with surface pollutants over Taipei, Taiwan, Annales Geophysicae, Vol.32, pp. 1085–1092 (2014)

Catlin, X.L.: GAPS Guidelines, A Publication of Global Asset Protection Services LLC, A Publication of Global Asset Protection Services LLC, [Online], Available: http://xlcatlin.com/~/media/gaps/522_0.pdf (2015)

Chalmers, J.A.: Atmospheric Electricity, Pergamon, 2nd Edn (1984)

Cooray, V.: An Introduction to Lightning. Springer (2015)

Cooray V. (Ed.): The Lightning Flash, IET (2003)

Cooray, V. (Ed.): Lightning Protection (2010)

Cooray (Ed.), Lightning Electromagnetics (2012)

DEHN + SÖHNE, "Lightning Protection Guide," 3rd updated edition December (2014)

Dung, L.V., Petcharaks, K.: Lightning protection systems design for substations by using masts and MATLAB. World Acad. Sci. Eng. Technol. Int. J. Math. Comput. Phys. Electr. Comput. Eng. **4**(5), (2010)

Dong, Z.Y., Luwen, C.: Climate lightning activity and its correlations with meteorological parameters in South China, XV International Conference on Atmospheric Electricity, pp. 1–14, June (2014)

EHV AC Substations, Layout, Equipment, Bus arrangements. http://srldc.in/var/NRC/PSTI%20course/vol2_PS%20Operation/2EHV%20susbattions_psjg_apr11.doc

Farias, W.R.G., Pinto, W.O., Naccarato, K.P., Pinto, I.R.C.A.: Anomalous lightning activity over the Metropolitan Region of São Paulo due to urban effects," Journal of Atmospheric Research Vol. 91, pp. 485–490, Lightning Physics and Lightning Protection, IOP Press (2009)

Fisher, F.A., Plumer, J.A., Perala, R.A.: Lightning Protection of Aircraft", Lightning Technologies Inc., second edition (1999)

Fisher, J.J., Hoole, P.R.P., Pirapaharan, K., Thirukumaran, S., Hoole, S.R.H.: Cloud to ground and ground to cloud flashes in lightning protection: and future severe lig htning and climate change. International Conference on Lightning Protection (ICLP), pp. 440–445, IEEE Xplore Digital Library (2014)

Fisher, J., Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.: Applying a 3D dipole model for lightning electrodynamics of low-flying aircraft. IETE J. Res. **61**(2), 91–98 (2015)

Fisher, J., Hikma, S., Hoole, P.R.P., Sharip, M.A.R.M., Pirapaharan, K., Al-Khalid Hj Othman, Julai, N., Harikrishnan, R., Hoole, S.R.H.: Observations on the electrostatic discharge threats to aircraft body and to aerospace electronics. J. Telecommun. Electr. Comput. Eng. (JTEC) (2017)

Fisher, J., Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.: Applying a 3D dipole model for lightning electrodynamics of low-flying aircraft. IETE J. Res., 1–8 (2015)

Fisher, J., Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.: Parameters of cloud to cloud and intra-cloud lightning strikes to CFC and metallic aircraft structures. Proceedings International Symposium on Fundamentals of Engineering, IEEE Xplore Digital Library (2017)

Fisher, J., Hoole, P.R.P., Pirapaharan, K., Thirukumaran, S., Hoole, S.R.H.: Cloud to ground and ground to cloud flashes in lightning protection: and future severe lightning and climate change, Lightning Protection (ICLP), International Conference pp. 440–445. IEEEXplore Library (2014)

Fisher, J., Hoole, P.R.P., Pirapaharan, K., Thirukumaran, S., Hoole, S.R.H.: Three dimensional electric dipole model for lightning-aircraft electrodynamics and its application to low flying aircraft, Lightning Protection (ICLP), International Conference, pp. 435–439, IEEEXplore Library (2014)

Gamerota, W.R., Elismé, J.O., Uman, M.A., Rakov, V.A.: Current waveforms for lightning simulations. IEEE Trans. Electromag. Comp. **54**(4), 880–888 (2012)

Golde, R.H.: Lightning Protection, Arnold (1971)

Golde, R.H. (Ed.):Lightning, Vol 1: Physics of Lightning, Academic Press (1977)

Golde, R.H.: Lightning, Vol. 2: Engineering Applications, Academic Press (1977)

Hasse, P.: Overvoltage Protection for Low Voltage Systems, IET (2000)

Heidler, J.F., Flisowski, Z., Zischank, W.: Ch. Bouquegneau, Mazzetti, C.: Parameters of lightning current given in IEC 62305-background, experience and outlook. 29th International Conference on Lightning Protection, Uppsala, Sweden, 23–26 June (2008)

Hess, R.: The electromagnetic environment. The Avionics Handbook, CRC Press LLG (2001)

Hoole, P.R.P., Coowar, F.: Statistics on tropical lightning and its interaction with power systems. Electr. Power Syst. Res., 63–77 (1989)

Hoole, P.R.P., Pirapaharan, K., Kavi, M., Fisher, J., Aziz, N.F., Hoole, S.R.H.: Intelligent localisation of signals using the signal wavefronts: a review. Lightning Protection (ICLP), International Conference, pp. 474–479 IEEE Xplore Library (2014)

Hoole, P.R.P.: Simulation of Lightning attachment to open ground, tall towers and aircraft IEEE Trans. Power Delivery 8 2 732 738 (1993)

Hoole, P.R.P.: Modeling the lightning earth flash return stroke for studying its effects on engineering systems IEEE Trans. Magn. 29 1839 1844 (1993)

Hoole, P.R.P., Hoole, S.R.H.: Guided waves along an un-magnetized lightning plasma channel IEEE Trans. Magn. 24 6 3165 3167 (1988)

Hoole, P.R.P., Hoole, S.R.H.: Simulation of lightning attachment to open ground, tall towers and IEEE. Trans. Power Delivery **8**(22), 732–740, Institute of Electrical and Electronics Engineers (1993)

Hoole, P.R.P., Hoole, S.R.H.: Charge simulation method for the calculation of electromagnetic fields radiated from lightning. JJ Conner CA Brebbia Eds Boundary Element Technology Computational Mechanics Publications Southampton 153 169 (1986)

Hoole, P.R.P., Hoole, S.R.h.: finite element computation of magnetic fields from lightning return strokes. In: Cendes, Z.J. (Ed.), Computational Electromagnetics, North Holland, pp. 229–237 (1986)

Hoole, P.R.P., Pearmain, A.J.: A review of the finite-difference method for multidielectric electric field calculations. J. Electr. Power Syst. Res. **24**(11), 19–30. Elsevier (1992)

Hoole, P.R.P., Thirukumaran, S., Hoole, S.R.H., Harikrishnan, R., Jievan, K.: Ground to cloud lightning flash currents and electric fields: interaction with aircraft and production of ionospheric sprites. Proceedings The 28th International Review of Progress in Applied Computational Electromagnetics, 6 p., Michigan, USA (2012)

Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.: Waveguide and circuit EM models of lightning return stroke currents. J. Japan Soc. Appl. Electromagn. Mech. Japan **19**, S167–S170 (2011)

Hoole, P.R.P., Hoole, S.R.H.: A distributed transmission line model of cloud-to-ground lightning return stroke: Model verification, return stroke velocity, unmeasured currents and radiated fields Int. J. Phys. Sci. UK 6 3851 3866 (2011)

Hoole, P.R.P., Thirukumaran, S., Ramiah, H., Kanesan, J., Hoole, S.R.H.: Ground to cloud lightning flash and electric fields: Inter., action with aircraft and production of ionospheric sprites. J. Comput. Eng., Article ID 869452. https://doi.org/10.1155/2014/869452 (2014)

Hoole, P.R.P., Thirukumaran S., Hoole, S.R.H.: A software testbed for electrodynamics of direct cloud to ground and ground to cloud lightning flashes to aircraft. Int. J. Appl. Electromagn. Mech. **47**(4), 911–925 Japan (2014)

Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.:An electromagnetic field based signal processor for mobile communication position-velocity estimation and digital beam-forming: an overview J. Japan Soc. Appl. Electromagn. Mech. Japan 19 S33 S36 (2011)

Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.: Waveguide and circuit EM models of lightning return stroke currents J. Japan Soc. Appl. Electromag. Mech. Japan 19 S167 S170 (2011)

Hoole, P.R.P., Fisher, J., Pirapaharan, K., Al K. H. Othman, Julai, N., Aravind, C.V., Senthilkumar, K.S., Hoole, S.R.H.: Determining safe electrical zones for placing aircraft navigation. Measur. Microelectron. Syst. Static Thunderstorm Environ. Int. J. Control Theory Appl. **10**(16) (2017)

Hoole P.R.P., Hoole, S.R.H.: Computing transient electromagnetic fields radiated from lightning. J. Appl. Phys. **61**(8), 3473–3475 (1987)

Hoole, P.R.P., Balasuriya, B.A.A.P.: Lightning radiated electromagnetic fields and high voltage test specifications. IEEE Trans. Magn. **29**(2), 1845–1848 (1993)

Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.: Waveguide and circuit EM models of lightning return stroke currents J. Japan Soc. Appl. Electromag. Mech. Japan 19 S167 S170 (2011)

Hoole, P.R.P., Hoole, S.R.H.: Computer aided identification and location of discharge sources. J. App. Phys. **61** (1987)

Hoole, P.R.P., Hoole, S.R.H.: Computing Transient Electromagnetic fields from lightning. J. Appl. Phys. **61**, 3473 (1988)

Hoole, P.R.P., Hoole, S.R.H: Stability and accuracy of the finite difference time domain (FDTD) method to determine transmission line traveling wave voltages and currents. J. Eng. Technol. Res. (2011)

Hoole, P.R.P.: Smart Antennas and Electromagnetic Signal processing for Advanced Wireless Technology: with Artificial Intelligence and Codes, River Publisher (2020)

Hoole, P.R.P., Pirapaharan, K., Hoole, S.R.H.: Electromagnetics Engineering Handbook WIT Press UK (2013)

Hoole, P.R.P.: Smart Antennas and Signal Processing for Communication, Medical and Radar Systems, WIT Press, UK, 2001. (See IEE review of this book close to the end of this document)

Hoole, P.R.P.: Electromagnetic Imaging in Science and Medicine WIT Press UK (2000)

Hoole, S.R.H., Hoole, P.R.P.: A Modern Short Course in Engineering Electromagnetics, Oxford University Press, USA (1996)

IEC, Protection against Lightning Vol. 1: General Principles

IEC Protection against Lightning Vol. 2: Risk Management

IEC Protection against Lightning Vol. 3, Physical damage to Structures and Life Hazard

IEC Protection against Lightning Vol. 4: Electrical and Electronic Systems within Structures

IEC Protection against Lightning Vol. 5: Services

IEEE Guide to Direct Lightning Stroke Shielding of Substations, IEEE Std. 998–1996 (1996)

Industry Document to Support Aircraft Lightning Protection Certifications, U.S. Department of Transport Federal Aviation Administration Advisory Circular, AC No: 20–155A (2013)

IEEE Guide, How to Protection Your House and Its Content From Lightning, IEEE Guide for Surge Protection of Equipment Connected to AC Power Communication Circuits. http://lightningsafety.com/nlsi_lhm/IEEE_Guide.pdf

IEC, Protection Against Lightning – Part 1 General Principles, IEC International Standard, IEC 62305–1, Edition 2 (2010–2012)

Kendall, C., Black, E., Larsen, W.E., Rasch, N.O.: Aircraft generated electromagnetic interference on future electronic systems. Federal Aviation Administration Report No: DOT/FAA/CT-83/49, December (1983)

Kramer, J.: Lightning: Nature in Action, Lerner (1992)

Lightning Protection Standards, BS EN/IEC 62305 Standard for Lightning Protection (2006). http://www-public.tnb.com/eel/docs/furse/BS_EN_IEC_62305_standard_series.pdf

Morgan, D., Hardwick, C.J., Haigh, S.J., Meakins, A.J.: The interaction of lightning with aircraft and the challenges of lightning testing Aerospace Lab J. 5 ALO5-11 1 10 (2012)

Naccarato, K.P., Campos, D.R., Meireles, V.H.P.: Lightning urban effect over major large cities in Brazil. XV International Conference on Atmospheric Electricity, Norman, Oklahoma, U.S.A, 15–20 June 2014

NSSL: Severe Weather 101: Lightning, https://www.nssl.noaa.gov/education/svrwx101/lightning/

NPFA, Standard for the Installation of Lightning Protection System, NPFA-780 (2020)

Petrov, N.I., Haddad, A., Petrova, H., Griffiths, H., Walters, R.T.: Study of effects of lightning strikes on aircraft. Recent Advances in Aircraft Technology, Dr. Ramesh Agrawal (Ed.), ISBN978–953–51–0150–5, InTech, pp. 523–544 (2012)

Pinto, O., Pinto, I.R.C.A.: About sensitivity of cloud-to-ground lightning activity to surface air temperature changes at different time scales in the city of Sao Paulo, Brazil. 20th International Lightning Detection Conference and 2nd International Lightning Meteorology Conference, Tucson U. S. A, April (2008)

Poelman, D.R.: On the science of lightning: an overview. Royal Meteorological Institute of Belgium, Publication Scientifique et Technique, No. 56 (2010)

Price, C.: Thunderstorm, lightning and climate change, 29th Internation Conference on Lightning Protection Conference, Uppsala, Sweden, June (2008).

Rakov, V.A.: Lightning phenomenology and parameters important for lightning protection. IX International Symposium on Lightning Protection, 26th–30th November, Brazil (2007)

Rakov, V.A.: Lightning discharge and fundamentals of lightning protection. J. Lightning Res. **4**(Suppl. 1: M2), pp. 3–11 (2012)

MH Rawoot MFAR Satarkar 2014 Some critical study of lightning impulses on electrical transmission line system Int. J. Curr. Eng. Technol. Spec. Issue 3 217 221

Rakov, V.A., Uman, M.A.: Lightning: Physics and Effects, CUP (2003)

Rakov, V.A.: Fundamentals of Lightning, CUP (2016)

Severson, V., Murray, P., Heeter, J.: Establishing cause and effect relationships between lightning flash data and airplane lightning strike damage, 23rd International Lightning Detection Conference and 5th International Lightning Meteorology Conference, Tucson U. S. A (2014)

Shah, G.S., Bhasme, N.R.: Design of earthing system for HV/EHV AC substation: a case study of 400 kV substation at Aurangabad, India. Int. J. Adv. Eng. Technol. **6**(6), 2597–2605 (2014)

Teng, X., Liu, G., Yu, Z., Zhuang, X., Zhao, Y.: Research on initial lightning attachment zone for aircraft. 3rd International Conference on Electric and Electronics, Hong Kong, December (2013)

Thirukumaran, S., Hoole, P.R.P., Ramiah, H., Kanesan, J., Pirapaharan, K., Hoole, S.R.H.: A new electric dipole model for lightning-aircraft electrodynamics. COMPEL: Int. J. Comput. Math. Electr. Electron. Eng. (COMPEL) **33**(1/2), 540–555 (2014)

Uman, M.A.: All About Lightning, Dover (1986)

Uman, M.A.: The Lightning Discharge, Academic Press (1987)

Uman, M.A.: The Art and Science of Lightning Protection, CUP (2008)

Uman, M.A., Rakov, R.A.: The interaction of lightning with aerospace vehicles. Progress in Aerospace Sciences, Vol. 39, Elsevier Sciences Ltd, pp. 61–81 (2003)

Yadee, Y., Premrudeepreechacharn, S.: nalysis of tower footing resistance effected back flashover across insulator in a transmission system. International Conference on Power Systems Transients, Lyon, France on June 4–7 (2007)

Yahaya, N.Z., Daud, M.A.: Study of lightning safety distance using rolling sphere method. J. Scient. Res. Energy Power Eng. **5**, 266–273 (2013)

Zhang, Y., Ma, M., Weitao, L., Tao, S.: Review on climate characteristics of lightning activity. Acta Meteor. Sinica **24**(2), 137–149 (2010)