Lecture # 8

ESD

ESD stands for Electrostatic Discharge. The concept of electricity originates from electric charge. Charges at rest are the static charges and are covered in the subject of static electricity whereas; charges in motion constitute electric current and are the subject of dynamic or current electricity. Most form of ESD events that are experienced in daily life are in the form of spark that can cause minor discomfort to people, severe damage to electronic equipment, and fires and explosions if the air contains combustible gases or particles. However, many electrostatic discharges are small enough to occur without a visible or audible spark. One form of ESD is lightning discharge, commonly known as lightning discharge. All physical objects are made up of atoms that are electrically neutral, because they have an equal number of positive and negative charges. Therefore, all things are composed of charges. Opposite charges attract each other and like charges repel each other. The phenomenon of static electricity therefore requires a separation of positive and negative charges. When two materials are brought in contact with each other, electrons may move from one material to the other, which leaves an excess of positive charge or deficiency of electrons in one material, and an equal increase of negative charge and therefore excess of electrons on the other. When the materials are separated they will retain this charge imbalance. The various methods by which different materials acquire charge are discussed in following sections.

Contact-induced Charge Separation (triboelectricity)

Rubbing two materials together produces static electricity through a phenomenon known as triboelectricity (or the triboelectric effect). The triboelectric effect is the main cause of static electricity as observed in everyday life. A balloon rubbed against the hair becomes negatively charged and when on a wall, the charged balloon is attracted to positively charged particles on the wall, which can cling thus appearing to be suspended against gravity. Thus if we put two different materials in contact, and one attracts electrons more than the other, it is possible for electrons to be pulled from one of the materials to the other. When we separate the materials, the electrons effectively jump to the material that attracts them most strongly. As a result, one of the materials gains extra electrons, becoming negatively charged while the other material loses electrons become positively charged. When we rub things together again and again, we increase the chances that more atoms will take part in this electron-exchange, and a static charge builds up.

Pressure-induced Charge Separation (Piezoelectric Effect)

Applied mechanical stress produces charge separation in certain types of crystals and ceramics, known as piezoelectric effect, and materials exhibiting this effect are called piezoelectric materials. Piezoelectric effect is the appearance of an electrical potential across the sides of a crystal when subjected to compressive mechanical stress. Normally, piezoelectric crystals are electrically neutral; the atoms may not be symmetrically arranged, but their electrical charges are perfectly balanced; a positive charge in one place cancels out a negative charge nearby. However, if a mechanical stress (compressive or tensile) is applied to a piezoelectric crystal, deformation of the structure results in pushing some of the atoms closer together or further apart, thereby upsetting the balance of positive and negative centers, and causing net electrical charges to appear. Some naturally piezoelectric occurring materials include Berlinite (structurally identical to quartz), cane sugar, quartz, Rochelle salt, topaz, tourmaline, and bone.

Heat-induced Charge Separation (Pyroelectric Effect)

Heating produces a charge separation in the atoms or molecules of certain materials, known as pyroelectric effect or pyroelectricity. Pyroelectric effect is exhibited only in crystallized non-conducting substances having at least one axis of polar symmetry. Development of opposite electrical charges on different parts of a crystal is subject to temperature change. When energy in the form of heat is applied to a pyroelectric material generate an electrical charge in response. The shifting of charges by temperature difference causes them to separate and forms charge centers. Portions of the crystal with the same symmetry will develop like-charges. Changes in temperature produce opposite charges at the same point that is if a crystal develops a positive charge on one face during heating, it will develop a negative charge there during cooling.

Accumulators and Non-accumulators

Accumulators are substances that collect and accumulate charges for a longer time in contrast to non-accumulators which decay any charges build-up quickly. This all depends on conductivity with a separating line defined by a value of 50pS/m. Substances that have electrical conductivity below 50pS/m are called accumulators, and those having conductivities above 50pS/m are called non-accumulators. An important concept for insulating fluids is the static relaxation time T_0. This is similar to the time constant of a circuit. For insulating materials, it is the ratio of the static dielectric constant ε_r divided by the electrical conductivity σ (S/m) of the material. That is:

$$T_0 = \frac{\varepsilon}{\sigma} = \frac{\varepsilon_0 \varepsilon_r}{\sigma} \qquad 1$$

For insulating hydrocarbon fluids, such as transformer oil with relative permittivity of 2.2, the static relaxation time is approximated through dividing the electrical conductivity of the fluid, which is about 1pS/m. Thus a transformer fluid that has an electrical conductivity of 1pS/m has an estimated relaxation time of about 20 seconds. On the other hand Kerosene has conductivity somewhat near to 1pS/m and is therefore strong accumulator. The conductivity is inverse function of the charge accumulation and retention by a substance.

Example 1: Calculate the relaxation time for polystyrene having conductivity of 1200µS/cm and relative permittivity of 3.

Solution:

Given that σ = 1200μS/cm or 0.12 pS/m and ε_r = 3.

Using:

$$T_0 = \frac{\varepsilon_0 \varepsilon_r}{\sigma} = \frac{3 \times 8.85 \times 10^{-12}}{0.12 \times 10^{-12}} = \mathbf{221.25\ sec\ or\ 3\ min,\ 41\ sec}$$

This relaxation time is quite large, so it would seem that polystyrene has a property of being an accumulator as its conductivity is below 50pS/m.

Energy in ESD

Since ESD occurs through the medium between two charged objects creating a potential difference, the system behaves as a capacitor and the ESD can be viewed as discharge of the capacitor. The energy ξ (in joules) can be calculated from the capacitance C of the object and the static potential V in volts by the relationship:

$$\xi = \frac{1}{2} C V^2 \qquad 2$$

The energy released in ESD may vary over a wide range. The energy stored due to static charge on an object varies, which depends on the size of the object and its capacitance, the voltage to which it is charged, and the dielectric constant of the surrounding medium. Low relative humidity increases the charge buildup; walking on vinyl floor at 15% relative humidity causes buildup of voltage up to 12 kV, while at 80% humidity the voltage is only 1.5 kV. As little as 0.2 mJ may present an ignition hazard; such low spark energy is often below the threshold of human visual and auditory perception. Removing or preventing a buildup of static charge can be as simple as opening a window or using a humidifier to increase the moisture content of the air, making the atmosphere more conductive. Earthing or grounding is the usual methods by which charge build-up can be prevented.

As a simplified model, the effect of static discharge on sensitive electronic devices by human being is represented as a capacitor of 400 pF, which is say, charged to a voltage of 4 kV to 35 kV. When touching an object the energy is discharged in less than a microsecond. While the total energy is small, on the order of milli-Joules, remembering that the energy needed to damage most electronic devices is between 2 and 1000 nJ..

Example 2: Calculate the possible ESD energy delivered by a leaky automobile spark plug cord to a mechanic when the voltage at the spark plug is 25kV. If the discharge time of energy is 10ms, find the power of the discharge.

Solution:

Given that: V = 25kV and capacitance of human body is 400pC.

Using:

$$\xi = \frac{1}{2} C V^2 = \frac{1}{2} \times 400 \times 10^{-12} \times (25000)^2 = \mathbf{0.125\ J\ or\ 125mJ}$$

For a discharge time t = 10ms, the power P of the discharge is:

$$P = \frac{\xi}{t} = \frac{125}{10} = \mathbf{12.5W}$$

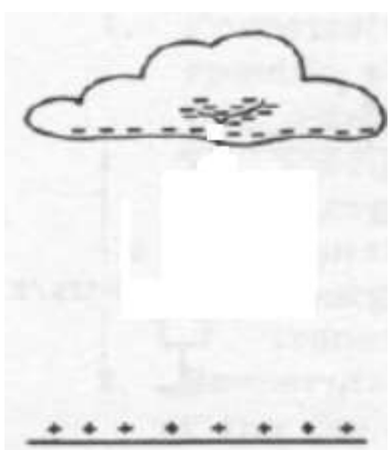
Mechanism of Cloud Charging

Atmospheric lightning is form of ESD, which emanates from the charge centers in the clouds but the mechanism by which the clouds in the upper atmosphere accumulate charges is uncertain. Much is thought to be due to the effects of wind, which moves one cloud (grapul; soft mixture of ice and water droplets) from the other. Difference between the temperature densities of two clouds, friction of wind with the moisture in clouds, and action of rain droplets on clouds etc are a few ways by which clouds in the upper atmosphere acquire charge. Charge separation requires updraft winds that carry water droplets upward, super-cooling them between –10ºC and –40°C.

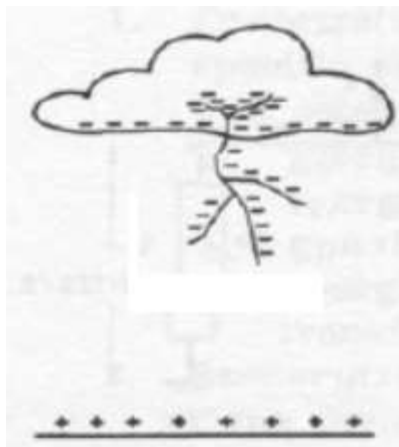
Mechanism of Lightning Discharge

Lightning is a natural way of neutralizing the charge centers formed in the clouds and on the ground objects when a strong electric field created by charge centers that produces millions of volts potential difference between the cloud and Earth resulting in an ionized channel. The lightning discharge heats up the surrounding air causing a bright flash, accompanied by shock waves, producing thundering sound. The possible mechanism of lightning discharge, widely recognized can be explained as illustrated with accompanying figures in sequence as follows:

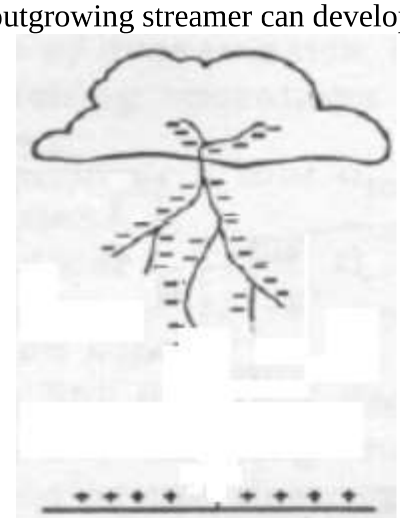
1. As a thundercloud moves over the Earth’s surface, an equal but opposite charge is induced on the underlying Earth’s surface and objects by the process of electrostatic induction. The induced ground charge follows the movement of the cloud, remaining underneath it.



2. When the electrical field in the vicinity approaches approximately 10kV/cm in the presence of water droplets, it ionizes the air in the vicinity of the base of the cloud causing the formation of corona. An initial bipolar discharge, or path of ionized air, starts from the corona region of mixed water and ice in the thundercloud in the form of zigzag channels known as stepped leaders. The formation of zigzag pattern discharge channels are due to difference in air density near the base of the cloud in the upper atmosphere. The negatively charged stepped leader proceeds downward with a speed of about 10^5 to 2×10^5 m/s in a number succession of quick jumps (steps). Majority of the leaders exceed 45 meters in length, with most in the order of 50 to 100 meters.

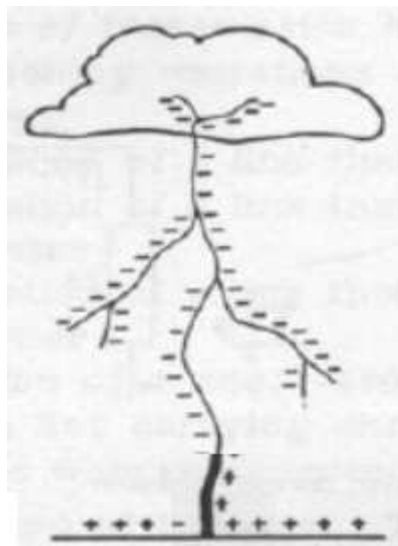


3. As it continues to descend towards the ground, the stepped leader branches into a number of streamers. As the stepped leaders approach the ground, the presence of opposite charges on the ground objects enhances the strength of the electric field. These objects, specially pointed and tall (trees, poles, electrical pylons, cellular phone towers and tall buildings) start responding to the strong electric field by generating streamers (tiny luminous discharge channels) appearing is the form of purplish color. If the electric field is strong enough, a conductive discharge referred to as a positive outgrowing streamer can develop from these points.

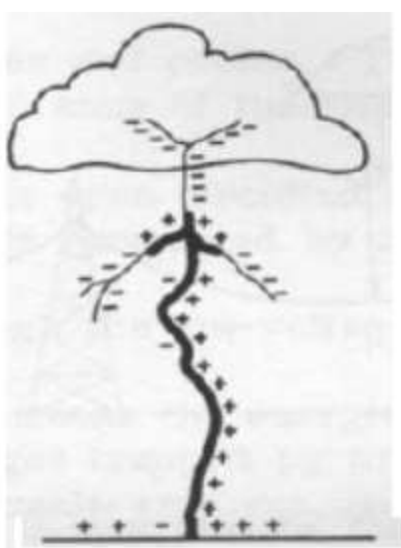


Actually anything on the surface of the Earth has the potential to send a streamer. The human body also can, and does produce such positive streamers when subjected to a strong electric field such as that of a storm-cloud.

4. The streamers thus wait patiently (like riot police waiting for the mob), stretching upward as the stepped leaders approaches. It is also possible for many streamers to develop from many different objects simultaneously, with only one streamer, closest to the tip of maximum extended approaching leader, forming a return stroke traveling with a speed of 10^8m/s or speeds almost approaching that of light.



5. The return streamers grow toward the incoming leader and thus bridge the gap. It is very common for lightning to strike the ground even though there is a tree or a light pole or any other tall object in the vicinity. This is probably the reason that the stepped-leader does not necessarily take the path of a straight line for discharge to occur.



6. Once a channel of ionized air is established between the cloud and ground this becomes a path of least resistance and allows for a much greater current to propagate from the Earth towards the leader in the form of return stroke.
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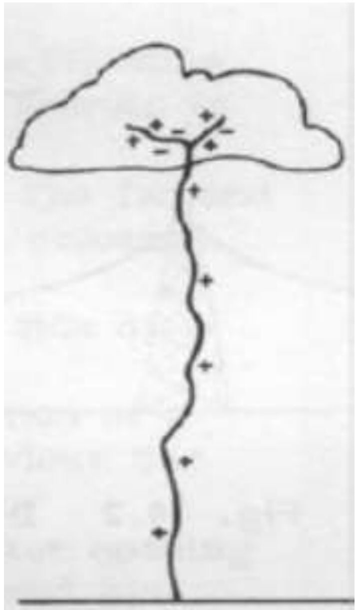

This is the return stroke and it is the most luminous and noticeable part of the lightning discharge. When a leader and a streamer meet and the current flows (the strike), the air around the strike becomes extremely hot. After the stepped-leader and the streamer meet, the ionized air (plasma) has completed a round-trip, it leaves a conductive path. This discharge of current is natural way of neutralizing the charge-separation. Return strokes constitutes current in the range of 1 to 200kA or even higher lasting for about 100μs. The return streamer and the incoming leader thus form the main discharge path.

7. With the potential of the portion of the charged cloud from where the discharge originated is not fully neutralized, a high potential develops between the original charge center and another charge center in the clouds, the charge of the other charge center is first transferred to the first one, and then it passes to the Earth through the ionized channel formed by the first discharge. Thus at the end of the first discharge with a delay of about 40 μs and due to sufficient remnant charges in the path, allows a subsequent stroke known as a dart leader. The dart leader is much faster in speed and unlike stepped leader has no branches.

Multiple Stokes

The most important part of the lightning stroke is the return streamer, which completes the development of a single lightning stroke, forming an ionized channel that bridges the gap between the charged cloud and the Earth object. The lightning discharge may not neutralize all the charges and remnant charges in the cloud and on Earth objects can make conditions favorable for a second and subsequent return strokes resulting in multiple strokes in a single lightning discharge. Similarly, the other charges are discharged to the Earth in the form of multiple dart leaders and return strokes along the same ionized channel. Lightning strokes with any discharge are therefore known as multiple or repetitive strokes. The sequence of development of a return streamer for a single stroke is shown in Figure (1).

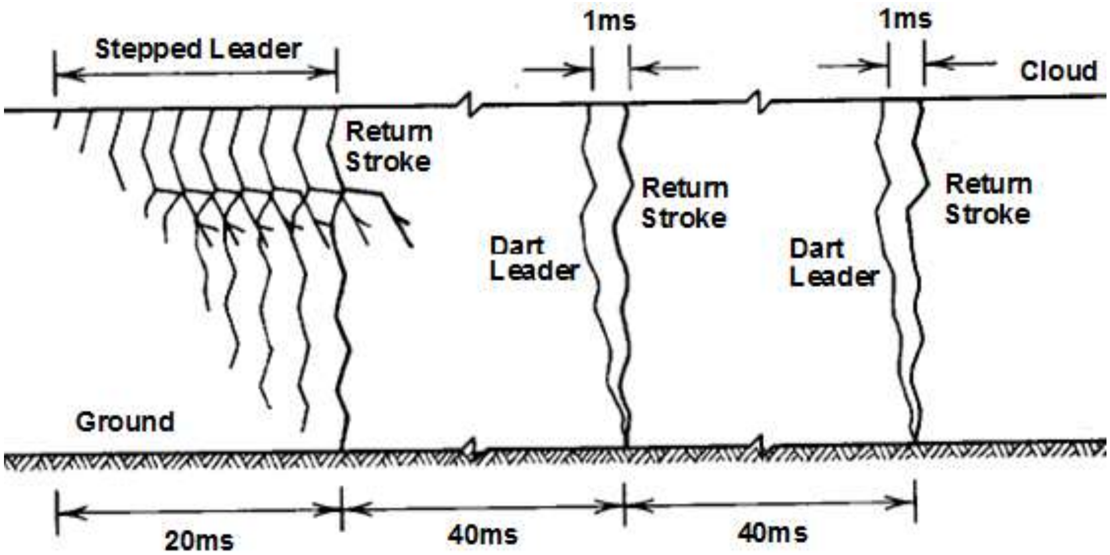

Figure (1)

Once the ionized channel between cloud and ground is complete, a conducting path is established, short-circuiting the charge centers. The return stroke constituting the main current can flow to neutralize the charge imbalance. Lightning discharges comprise of multiple strokes noticed as one persistent image with the initial leader stroke and main return stroke followed by subsequent leaders and return strokes in rapid succession. A typical strike is made of several single strokes, with the possibility of as many as 40; each follows the initial leader track unless heavy winds or other disturbances can move the channel.

The stroke usually re-uses the discharge channel formed by the previous stroke. The variations in successive discharges are the result of smaller regions of charge within the cloud being depleted by successive strokes. The sound of thunder from a lightning strike is prolonged by successive strokes. The majority of strokes occur inside a cloud so we do not usually see most of the lightning activity during a thunderstorm.

Example 3: Estimate the number of strokes in a lightning discharge that persist before our eyes for one second, assuming that multiple strokes are separated in time-frame of 40ms.

Solution:

Given that: time between each successive stroke is t = 40ms, and let T is the time of persistent before human eye. Therefore, the numbers of strokes n in one second are:

$$n = \frac{T}{t} = \frac{1}{40 \times 10^{-3}} = 25 \text{ strokes}$$

Lightning Features

1. An average stroke of negative lightning carries an electric current of between 10 to 200kA or higher, and transfers about 15 Coulombs to 350 Coulomb of electric charge with 500 MJ of energy.

2. For a typical return stroke current of constituting current of 100 kA with voltage gradient of 10kV/cm will result in a peak power of (10 kV/cm x 100 kA) 1GW/cm. The average peak power output of a single lightning stroke is estimated to about one trillion watts or 1Terawatt (10^{12} W), and a single stroke lasts for about 30 millionths of a second or 30 μs.

3. In addition, lightning rapidly heats the air in its immediate vicinity to about 15,000°F to 60,000°F, which is about three times the temperature of the surface of the sun.

4. Lightning discharge is accompanied by production of Terrestrial Gamma-ray Flashes (TGF) with energy amounting to 20MeV.

5. It is well-known that the movement of electrical charges in a conductor produces a magnetic field. In a similar way, intense currents of a lightning discharge create Lightning-Induced Remnant Magnetism (LIRM).

Keraunic Level

Knowledge of the number of lightning strokes within a selected area is essential to set standards for safe design of electrical systems in structures connected to the local power substation and for insulation coordination. A parameter called the keraunic level, also known as keraunic number denoted by K_L is helpful to determine lightning activity. Keraunic number describes lightning activity in an area based upon the average number of thunderstorm-days per year. On the basis of considerable observational data, it is estimated that the number of lightning strokes N_S is given by:

$$N_s = 0.04 K_L^{1.25} \qquad 3$$

However, a keraunic number does not distinguish between forms of lightning, such as cloud-to-cloud, or cloud-to-ground, and is limited by the requirement for the thunder to be audibly detected. For these reasons, the keraunic number has been replaced by more accurate Ground Flash Density (GFD), which is defined as the average number of strokes per unit area per unit time at a particular location. It is usually assumed that the GFD to Earth, a substation, or a transmission line is roughly proportional to the keraunic level at the locality.

$$N_K = 0.12K_L \qquad 4$$

Where: N_K are the number of flashes to Earth per kilometer square per year. The average annual keraunic level for locations can be determined by referring to keraunic maps which contains plots contours of equal keraunic number on a map of the country.

Example 4: A region has a keraunic level of 55 thunder storm-days/year. Estimate the likely number of lighting discharges per year and the ground flash density.

Solution:

Given that: K_L = 55 thunder storm-days/year.

Using:

$$N_S = 0.04K_L^{1.25}$$

Or

$$N_S = 0.04(55)^{1.25} = \textbf{6 lightning discharge/year}$$

The GFD is:

$$N_K = 0.12K_L = 0.12 \times 55 = 6.6 \text{ or } \textbf{7 flashes/km}^2\textbf{/year}$$

Protection against Lightning

Lightning is an impulsive, random and unpredictable event, with characteristics include; current levels, sometimes in excess of 300 kA, temperatures over at-least 15,000ºF, and speeds approaching one-third the speed of light. Lightning discharges require millions of volts. Natural objects, such as; trees and boulders can also promote point discharges, particularly in mountainous areas where physical elevation further intensifies the field. These objects are essentially conductors, short-circuiting part of the vertical field and hence producing an intense field at the tip. As a result upward streamers are generated from some of these objects. These discharges themselves are of no great magnitude and are thus relatively harmless, but they serve as a timely reminder that true lightning discharges may be imminent.

Lightning prevention and protection in absolute term is not possible. A reduction of its consequences, together with incremental safety improvements, can be accomplished by the use of metal device known as lightning rod, lightning conductor, lightning electrodes, also known as air terminal. Lightning conductor may be in the form of a single rod/electrode or may be equipped with a spark-over device or multiple electrodes in the form of "spikes" which creates electric field enhancement at the tip. A typical lightning conductor with multiple electrodes is shown in Figure (2).

The proper installation of lightning conductor on building can save immeasurable amounts of monetary as well as re-channeling of the energy of a direct stroke. The idea behind a lightning conductor is that it serves as the highest object around and so it intercepts the stepped-leader on its way to the ground. A sharp tip on the lightning conductor facilitates the rise of a streamer and increases its effectiveness. Lightning conductor design may alter streamer behavior. Different designs of lightning conductors may be employed according to different protection requirements. In equivalent electric fields, a blunt pointed rod is seen to behave differently than a sharp pointed rod.

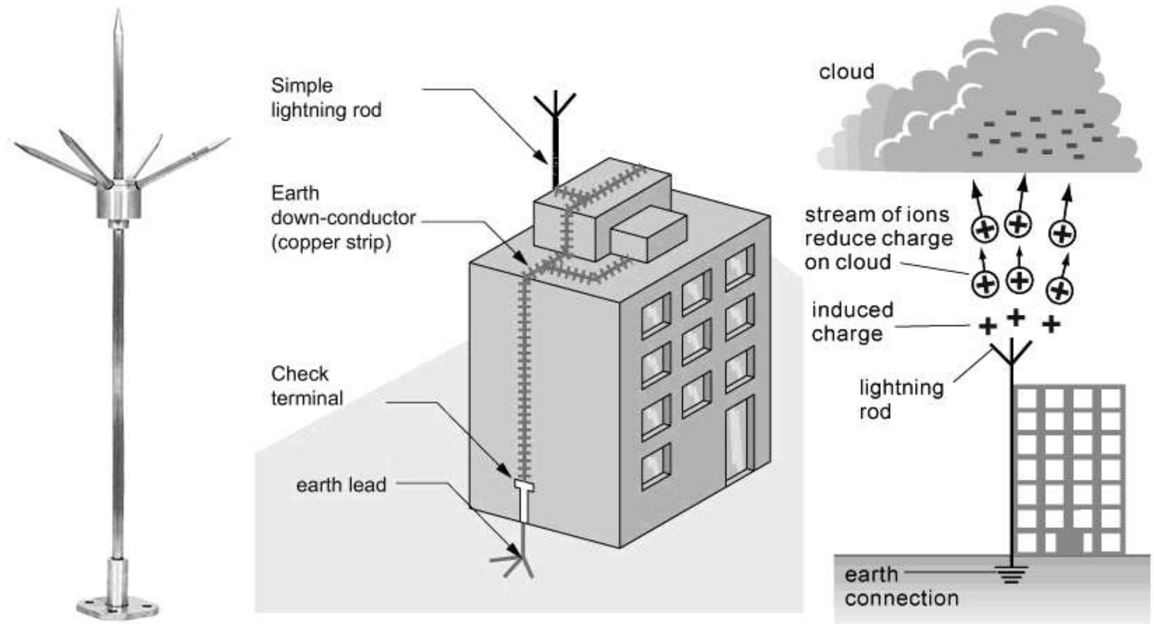

Figure (2)

Lightning conductor is installed at the highest portion of the building; an overhead water tank often attached to a post as shown in Figure (2) with down-conductor bonded at the other end to an earth electrode or counterpoise. Down-conductors should be installed in a safe manner through a known route, outside of the structure. They should not be painted, since this will increase impedance. Gradual bends should be adopted to avoid flashover problems. Connector bonding should be thermal (welded), not mechanical. Mechanical bonds are subject to corrosion and physical damage. Frequent inspection and electrical resistance measuring of compression and mechanical connectors is recommended. In the event of thunderstorm, charges build-up in the cloud that can produce leaders are neutralized by electric field enhancement at the tip of the lightning conductor start generating streamers.

Most of the charge is neutralized without causing concern of lightning strike. Lightning conductor will generally protect a zone within a 45º angle defining a protection zone, hypothetical cone beneath the lightning conductor as illustrated in Figure (3). Consider a cone with an apex angle of α and a point A at a height of h from the circular base. Then the radius of the circular base is:

$$OC = h \tan \alpha .$$

Thus the protection zone (perimeter of the base of the cone) will be:

$$A_Z = 2\pi(h \tan \alpha) \qquad 5$$

For a shield angle of 45º, the protection zone (perimeter) is then:

$$A_Z = 2\pi h$$

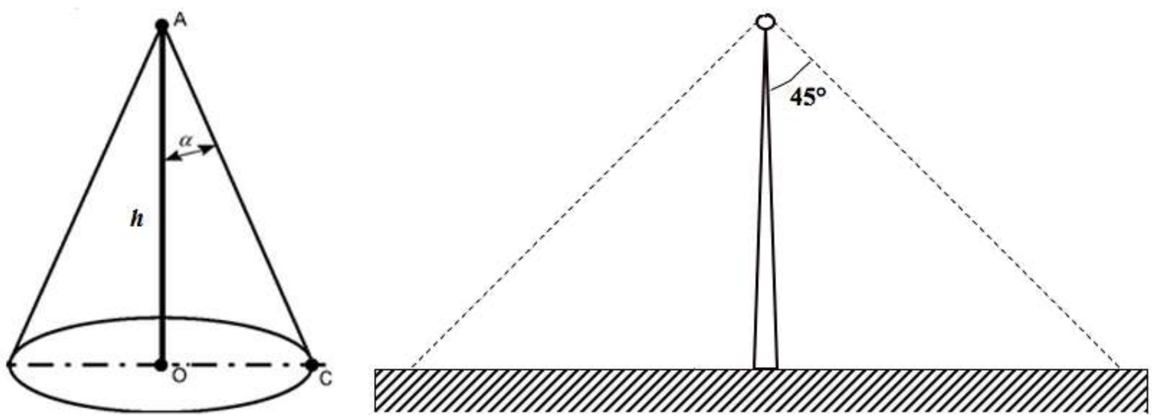

Figure (3)

For large structures, several lightning conductors may be needed to insure complete protection, or perhaps a network of overhead ground wires. For example, the utility industry prefers overhead shielding wires for electrical substations. Shielding is an additional line of defense against induced effects. It prevents the higher frequency electromagnetic noise from interfering with the desired signal. It is accomplished by isolation of the signal wires from the source of noise. In some cases, no use whatsoever of lightning conductors is appropriate, for example; ammunition bunkers. Lightning conductors, however, do not provide for safety to modern electronic appliances; such as television sets and computers within structures. In such cases an additional protection through the use of surge protection device is essential.

Example 5: A building with a roof area of 10 x 20m having an overall height of 25m is to be protected by lightning conductor. Estimate the height and number of the lightning conductors for protection.

Solution:

Given that: roof area: 10 x 20m = 200m^2

In this case a scheme of providing several lightning conductors of suitable height can accomplish the purpose of protecting the building. For example, if we use lightning conductor of 5m length, then the hypothetical cone of protection at angle of 45º will be:

$$A_Z = 2\pi h = 2\pi \times 5 = \text{ 31.4m of cone base perimeter.}$$

If we can manage to fit a square within the base of the cone, the square will have sides measuring $\sqrt{2}$ (radius of the base of the cone) = $\sqrt{2}\, h$ for apex angle of 45º, so that each side will be: 7.07m and its area will be: 50m^2. Thus the lightning conductors of 5m length required are: $\frac{200}{50} = \mathbf{4}$