ELECTRIC POWER RESEARCH INSTITUTE

PQ TechWatch

A product of the EPRI Power Quality Knowledge program

Understanding the Physics and

PQ Impacts of Lightning

June 2009

CONTENTS

SUMMARY

This PQ TechWatch explores lightning, its history as filtered through human experience, and current methods and technologies employed to protect transmission and distribution systems. Nearly as old as our planet, primordial lightning shaped our world. As a mystery to man, it spawned experiments from history's greatest minds, from Herodotus and Aristotle to Benjamin Franklin. This document discusses how these scientists and their findings contributed to our understanding of lightning.

Lightning is a complex meteorological phenomenon. The typical image of lighting is a stroke of brilliant light emanating from a cloud and striking the ground. However, other forms of lightning menace the transmission and distribution of electricity. Lightning also varies in frequency, depending on location. Therefore, while one utility in Florida must fight a constant—and expensive—battle to protect its assets from lightning strikes, another in California may employ more modest means of protection. Techniques for improving the reliability of transmission and distribution systems include enhancing grounding, modifying static wire locations, increasing insulator lengths, adding transmission line surge arresters, and modeling to aide in better designs of transmission and distribution systems.

About the EPRI Power Quality Knowledge Program

The EPRI Power Quality Knowledge Program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these resources are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility managers. The program's website, http://mypq.epri.com/, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 200 PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

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Aristotle is considered the founder of meteorology. In 350 BC, he wrote the book *Meteorology*, the standard in meteorology for 2,000 years.

EARLY AWARENESS AND UNDERSTANDING

The story of lightning is billions of years old. While lightning may have been a key factor in formation of the earth, we will begin by looking at lightning from the aspect of man's perception and understanding from early civilization to today.

Early humans regarded lightning in awe and terror and rendered these feelings and thoughts into myths, religion, and the mystical in an attempt to understand the world about them. The beginning of actually understanding lightning and the weather may be attributed to the early Greek philosophers Herodotus and Aristotle.

Aristotle (384–322 B.C.) may have been the first meteorologist when he attempted to explain the weather. He rationalized that the weather was due to changes in the two of the four basic physical elements of air, fire, water, and earth. The weather is attributed to the changes in fire and air, which lie between the heavens and earth. The changes in fire is caused by dry hot exhausts from the earth due to heating and movement, while rain, snow, and clouds are due to changes in the air from cool damp exhausts from water. It is very clear even with a basic knowledge of weather that Aristotle was not far off in his understanding of weather.

The basic understanding of lightning in some aspects can be attributed to Herodotus (484–425 B.C.) and Genghis Khan (1162–1227). Herodotus noted that tall objects are more susceptible to being hit by lightning than other objects. The conduction of lightning ground current by means of water channels and streams was observed by the early Mongolian tribes, to the extent that Genghis Khan forbade any Mongolian subject from washing clothes or bathing during a thunderstorm.

In more recent times, Leonardo de Vinci (1452–1519) provided a better understanding of updrafts associated with storm clouds. He observed, "When the movement of two contrary winds brings two clouds to strike together, these clouds then become incorporated in each other, and not being able either to expand or lower themselves because of the wind passing beneath them, these clouds extend in that direction in which their passage is least impeded, that is upwards." De Vinci as ingenious as he was did not provide any speculation about lightning. In fact, during the life of de Vinci, the basic understanding of electricity was not widespread and was merely limited to entertainment.

The Greek philosopher Thales (624–546 B.C.) was among the first to demonstrate static electricity around 600 B.C. Thales discovered that if a piece of amber was rubbed with a dry material, it would attract small pieces of straw or feathers. A Roman historian and philosopher, Pliny the Younger (62–115) repeated this experiment but did not offer an explanation as to why this phenomenon occurred. William Gilbert (1544–1603), a physician in the Royal Court of Queen Elizabeth, repeated the experiments of Thales and Pliny and named the study of this phenomenon *vis electrica* from the Greek word *electra*, from which the word *electricity* is derived.

THE BEGINNING OF UNDERSTANDING

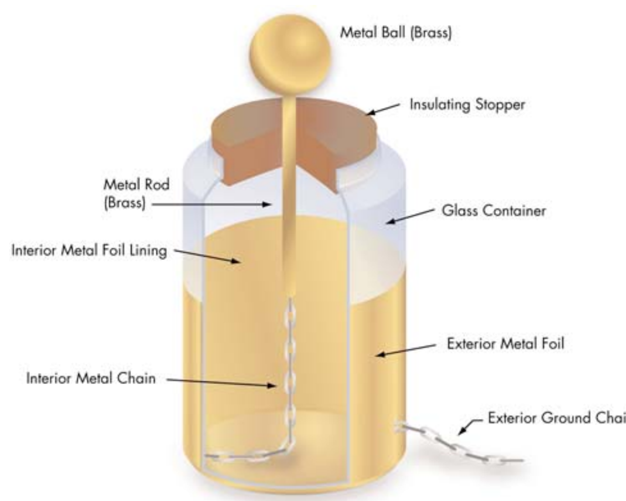
Otto von Guericke (1602–1686) was a famous German scientist who invented the vacuum pump in 1650 and established the physics of vacuums. Through his understanding of vacuums and pressures, he was one of the earliest scientists to demonstrate how to apply the barometer in the use of weather forecasting. Guericke later experimented with electricity and invented the first electrostatic generator called the *Elektrisiermaschine*, commonly known as a *friction generator*. Guericke's generator was constructed with a sulfur sphere as illustrated in Hubert-François Gravelot's engraving shown in Figure 1.

Figure 1. Elektrisiermaschine

Charles François de Cisternay DuFay (1698–1739), a French chemist, became interested in these early experiments and performed his own where he discovered what he called two types of electricity. He named them *vitreous*, known now as positive charges, and *resinous*, which is known as negative charges. Of importance is the fact that he distinguished the difference between conductors and insulators, calling them *electrics* and *non-electrics*. His observations on electricity were printed in Volume 38 of the *Philosophical Transactions of the Royal Society* in 1734.

The Leyden Jar, as illustrated in Figure 2, was invented by Pieter van Musschenbroek in 1745, which is basically a capacitor. It was able to store an electric charge. Musschenbroek used the friction generator invented by Otto von Guericke to charge the Leyden jar and demonstrated that electric charge can be stored, transported, and discharged at will. He found out that the Leyden jar could store an electric charge for some undetermined time when he accidentally shocked himself. He recorded his experience later, "…my whole body was shaken as by a thunderbolt…I thought it was all up with me." Since the announcement of the Leyden jar to the scientific community, it became an essential tool for research.

Figure 2. The Leyden Jar



Before the experiments of Benjamin Franklin, scientists assumed that there were two types of electricity. Franklin demonstrated one type with multiple states (positive and negative).

BENJAMIN FRANKLIN, KEY PLAYER

After the invention of the Leyden jar, there followed a frenzy of experiments performed by many notable scientist, chemist, philosophers, and the general intellectuals of the 1700s. However, one cannot discuss lightning without invoking Benjamin Franklin.

Benjamin Franklin was an extraordinary individual to say the least, due to his prosperous endeavors in printing. He had a considerable network of associates and friends in the British Colonies in America, where he lived, and in Europe. One associate was Dr. Spence of Scotland, who introduced Franklin to electrical experiments. Franklin was so impressed that he bought Dr. Spense's Lyden jar and static machine. Shortly thereafter, another close friend, Peter Collinson, a merchant in England, sent Franklin a glass tube that could hold a charge through rubbing. Franklin's interest was sparked to the point that he spent all of his available time devoted to electrical experiments.

Franklin wrote a letter to his friend Peter Collinson on the 11th of July in 1747, describing his experimental results. Of importance is the fact that Franklin stated that there was only one kind of electricity and not two. About the same time, Dr. William Watson of England had come to the same conclusion as Franklin and acknowledged that the theory had been independently derived at the same time by Franklin. This caused a lot of friction within the scientific community as many still clung to DuFay's concept that there were two types of electricity. What DuFay had called *vitreous electricity*, Franklin stated it as a surplus of charge and such bodies were positive charged. Bodies called *resinous*, according to Franklin, had a shortage of charge and were negatively charged. Therefore, electricity was one phenomenon with two types of states: positively charged and negatively charged. Franklin pointed out that charging an object merely transferred amounts of electricity from one object to another, leaving a loss in one and a gain in another. Also, the conservation of charge is maintained and the total quantity of electricity in an insulated system is maintained at a constant level and therefore can neither be created nor destroyed. Since Franklin defined vitreous electricity as positive and resinous negative, he stated that when the fluid moved, it flowed from plus to minus. Franklin had a 50% chance of getting it right, but unfortunately he chose wrong convention, and this has led to much confusion between electrical engineers and physicists because it was not until recent history that the electron was understood by two camps of teaching, one direction called *conventional flow* and the other convention called *electron flow*.

Until now, we have talked about Greek philosophers, inventors, and static electricity. Where does this stroll through the past lead us? It leads us to the development of the lightning rod and *key* experiments made by Benjamin Franklin. Franklin believed that clouds were clusters of electrical charges and that lightning was an electrical phenomenon. In 1749, Franklin wrote a letter to Dr. John Mitchell, a member of the English Royal Society, where he noted that lightning was attracted to towers, trees, spires, chimneys, and masts. Franklin also noted that small sparks made cracking noises and asked, "How loud must be the crack of 10,000 acres of electrified cloud?" This is the first observation known to explain that thunder was part of the electrical discharge from lightning.

In the same year, Franklin also wrote his friend Collinson and stated, "There is something, however, in the experiments of points, sending off or drawing on the electrical fire, which has not been fully explained.... I am of the opinion that

George Wilhelm Richmann, contemporary of Franklin, died by lightning strike in 1753.

houses, ships, and even towers and churches may be effectually secured from the stroke of lightning by their means.... There should be a rod of iron eight or ten feet in length, sharpen to a point like a needle, and gilt to prevent rusting, or divided into a number of points, which would be better....” Later in July of 1750, Franklin wrote his friend Collison and the Royal Society and again mentioned the use of the lightning rod, which included the use of a ground wire not previously mentioned in his letters. He also added instruction for protection of ships where a similar wire would be run from the lightning rod down one of the shrouds of the ship and down the side until it reached below the water line.

In the letter of 1750 to the Royal Society, Franklin also proposed an experiment to determine whether clouds were electrified. Franklin wrote, “On the top of some high tower or steeple place a kind of sentry box...big enough to contain a man and an electrical stand. From the middle of the stand let an iron rod rise and pass bending out of the door, and then upright twenty or thirty feet, pointed very sharp at the end.... If any danger to the man should be apprehended (though I think there would be none), let him stand on the floor of his box and now and then bring near to the rod a loop of wire that has one end fastened to the leads he is holding by a wax handle, so the sparks, if the rod is electrified, will strike from the rod to the wire and not affect him.” It is clear that Franklin did not recognize the power of lightning and the dangers in the instructions given in his letter. Professor George Wilhelm Richmann of St. Petersburg in 1752 performed several successful experiments, but the following year he was killed by a strike of lightning.

Figure 3. Franklin Flies a Kite

Benjamin Franklin had not heard of the experiments that were being conducted over in Europe based on his descriptions. Franklin, eager as ever, decided to proceed straightaway in pursuing his experiments in determining if clouds were electrified. He had planned on building the sentry box as he had described in his letter to the Royal Society, but instead he grew inpatient and conjured up the most practical way to perform his experiment—he would build a kite.

Franklin’s kite is reported to have been constructed of cedar sticks and silk cloth so it would not tear in the rain. The kite had a sharp pointed wire extending beyond the top, and Franklin placed a key at the end of the string followed by a couple inches of silk ribbon. He stood under the cover of a shed to prevent the ribbon of silk from getting wet. As the storm approached, he noticed that the string would start to bristle at the end of the knot joining the silk ribbon. As Franklin flew the kite higher, and longer, he was able to draw a discharge from the key to his hand. The higher he flew the kite, and the wetter the string had become, the discharge became more intense, as shown in Figure 3. For the final experiment, Franklin was able to store the charge in a Leyden jar and demonstrated the charge was similar to that would be made a friction machine, thus proving that clouds were electrified bodies and that lightning was caused by static electricity.

FORMATION OF THUNDERSTORMS

Thunderstorms form due to natural environmental effects and have a tertiary cycle, as shown in Figure 4. Temperature is the key to the formation of any cloud. Before sunrise, most land masses are about the same temperature, but by late morning, upward drafts will result due to temperature variations. These variations are caused by differences in geological makeup, such as minerals, shape, and color, which cause parts of the earth to heat at different rates. Due to the heating of the sun, most storms overland occur between 2:00 and 8:00 p.m.

During the first stage, referred to as the *cumulus stage*, the sun heats the earth during the day. As the surface warms so does the air around the surface. As the air warms, it begins to rise because warm air is lighter than cool air. This cycle will continue, and if the warm air has moisture in it, it will begin to condense and form a cumulus cloud, such as the one shown in Figure 5. This process will continue as long as the air beneath the cloud is warmer and continues to rise.

The second stage is known as the *thunderstorm stage*, or the *mature stage*. During the mature stage, the cloud is laden with moisture, and when the right temperature is reached, the moisture will begin to condensate, creating precipitation within the cloud. This precipitation may be carried at least 25,000 feet, but at times it may reach over 60,000 feet. Some of this moisture may form snow and/or may freeze directly into ice crystals. As this process continues, the snow and ice will collide into other ice crystals and freeze, forming multiple layers and creating hailstones. As the raindrops and hailstone increase in size, the upward draft cannot support their weight any longer, and they begin to fall. As the precipitation falls, cool air begins to enter the cloud and creates a downward draft, pushing the precipitation further down the cloud until it rains. At this point, the cloud is referred to as a *cumulonimbus cloud*, the classic thunderstorm cell having an updraft, downdraft, and rain, as shown in Figure 6.

The last stage begins within about half an hour of the typical one-hour cycle, and it is referred to as the *dissipating stage*. When enough cool air has entered the cloud and the downward drafts overcome the upwards

Figure 4. Storm Formation

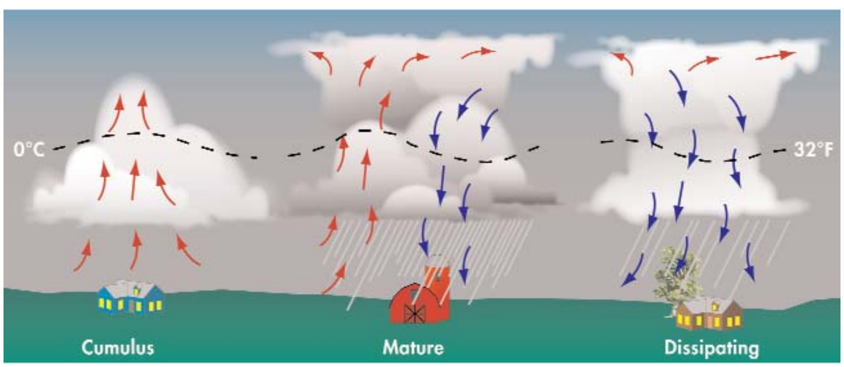


Figure 5. Cumulus Cloud

Figure 6. Cumulonimbus Cloud

Figure 7. Formation of Lightning

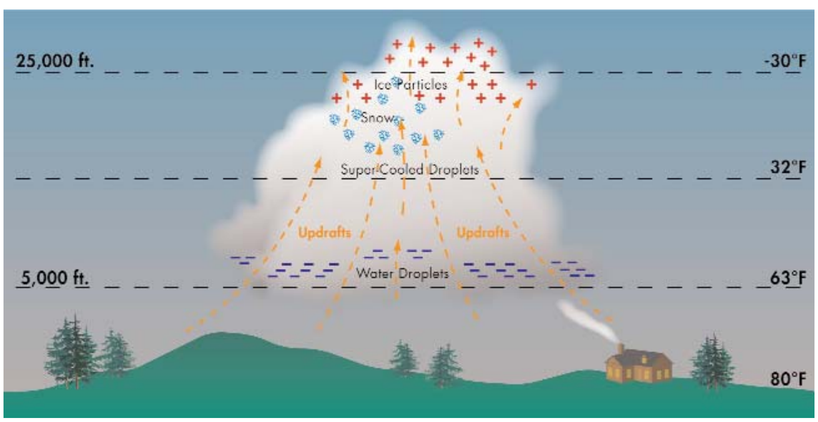
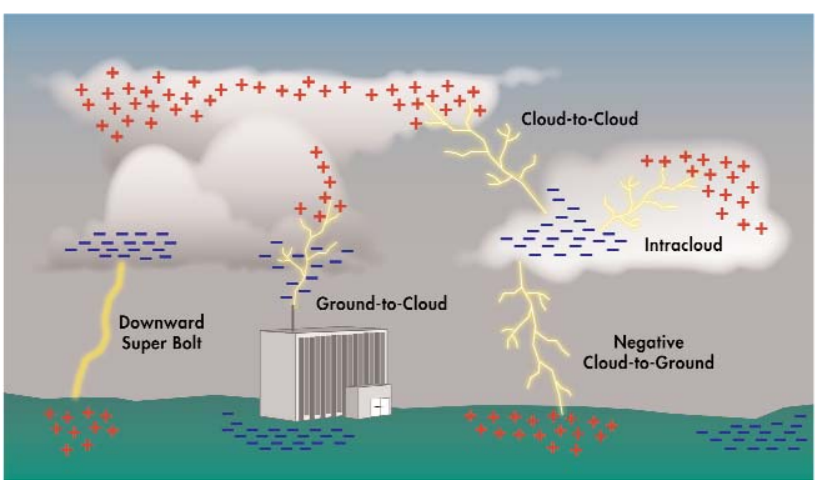


Figure 8. Lightning Illustration



draft, the warm moist air can no longer rise to cooler-temperature areas; precipitation slows until the condensation is no longer developed. During this stage, the storm dies out as the cloud more or less breaks up from the bottom up.

FORMATION OF LIGHTNING

The phenomenon of lightning usually occurs within a statically charged cumulonimbus cloud where falling droplets of ice and rain become electrically polarized as they fall through the atmosphere's natural electric field. The colliding ice particles become charged by electrostatic induction. The positively charged crystals tend to rise to the top, causing the cloud to build up a positive charge, and the negatively charged crystals and hailstones drop to the bottom layers, building up a negative charge.

The distribution of the electrical charge as the result of this formation is illustrated in Figure 7. The distribution of charges usually results in the negative-charge center being located near an altitude where the air temperature is about -20°C; the positive charge center is usually situated above the negative charge region in the upper levels of the cloud.

When the resulting electric field becomes large, a discharge occurs within the cloud or between the cloud and the ground or another cloud, as illustrated in Figure 8.

TYPES OF LIGHTNING

The most common lightning occurs within clouds or between clouds, called *intra-cloud* and *inter-cloud*, respectively, and is responsible for about 75% of all lightning. Intra-cloud lightning, as shown in Figure 9, occurs between oppositely charged centers within the same cloud. Inter-cloud lightning, as shown in Figure 10, occurs between charge centers in two different clouds with the discharge bridging a gap of clear air between them and is commonly called an *anvil crawler* and *sheet lightning*. Lightning discharges that occur between clouds and within clouds do not cause damage or disruption to the power system.

Figure 9. Intra-Cloud Lightning

Figure 10. Cloud-to-Cloud (Inter-Cloud) Lightning

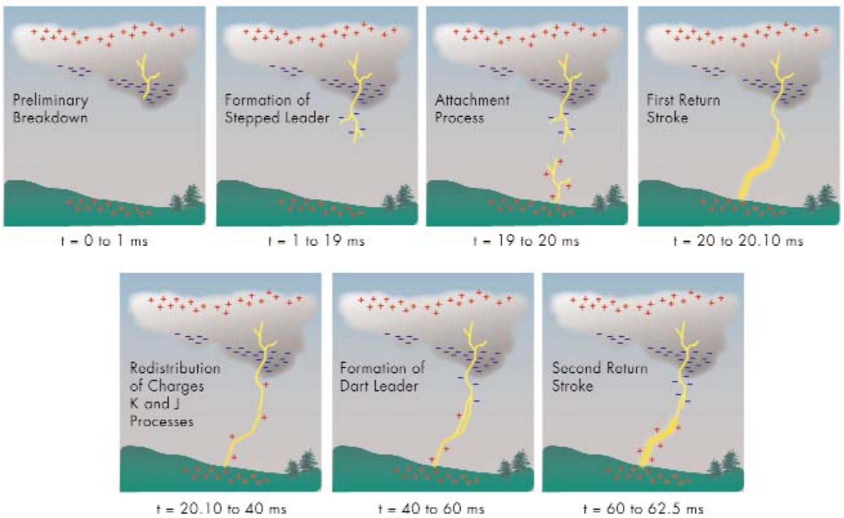
The second most occurring lightning event is the cloud-to-ground, as shown in Figure 11. This type makes up about 25% of all lightning events. It is the most dangerous and damaging form of lightning that can be encountered. However, it is beneficial to plant life because it introduces nitrogen into the ground during the process.

Figure 11. Cloud-to-Ground Lightning with Dart Leader

Since the cloud-to-ground lightning strike is the most dangerous and damaging, it is only appropriate that it is the most studied. The cloud-to-ground lightning strike begins with the electrical breakdown within the cloud, resulting in the creation of a charged column, t = 0, as shown in Figure 12 (refer to the timing sequence of the lightning discharge). This charged column is referred to as a *leader*. It travels downward towards the ground in a series of steps; often it is referred to as a *stepped-leader*, and several branches may be generated as it travels downward, an event that occurs from t = 1 to 16 ms after the creation of the charged column. The electric field at the ground increases as the leader approaches to within a few hundred meters and the attachment phase begins when upward streamers are generated from the ground, t = 19 to 20 ms. These streamers are generated from trees, buildings, towers, and shield and phase wires on distribution and transmission lines.

The object that is struck by lightning has the leader streamer that attaches first to the downward leader during this process.

Figure 12. Lightning Discharge



Cloud-to-ground lightning facilitates plant life by introducing nitrogen into the ground.

The upward leader that successfully attaches to the stepped leader determines which object will be struck by the lightning discharge, which is the first return stroke and occurs around t = 20 to 20.1 ms. Once this connection is made, a current of near-ground potential is transmitted along the lightning channel at approximately one-third the speed of light. When it connects, it generates a second return stroke. The discharge current of the return stroke typically peaks within a few microseconds and decays to half the peak value over a period of a few tens to hundreds of microseconds. At times, the current might continue to flow for hundreds of milliseconds and may be responsible for extensive burning and damage.

Often after the first return stroke, a second more rapidly moving downward leader may form along the partially ionized path of the first return stroke from t = 40 to 60 ms. This second leader is called a *dart leader*. The dart leader travels similarly to the original stepped leader and makes contact with the ground at the same point or near the original point of first strike.

When the dart leader contacts the ground, a second return stroke is initiated from t = 60 to 62.5 ms later, discharging the lightning channel. This process might repeat itself many times during a single lightning event. This process is called a *lightning strike*, and all of the strikes down the same path are jointly called a *lightning flash*. A typical lightning flash may last as long as a ½ second and can contain from 1 to 20 strokes.

Most of the lightning from cloud-to-ground is negatively charge, but occasionally a positively charged strike will occur as the storm is dissipating and occurs more frequently in the winter. Much less is known about positive lightning. Positive lightning flashes are composed of a single stroke followed by high current. The peak current and total charge transferred by positive lightning is much larger than negative strokes and is responsible for some of the largest recorded lightning currents ranging from 200 kA to 300 kA. Positive flashes probably originate from the upper positive charge region in the cloud. About 10 percent of cloud-to-ground lightning is positive flashes.

Another form of lightning is ground-to-cloud lightning, where upward lightning flashes can be initiated between the ground and a cumulonimbus cloud from an upward-moving leader stroke, as shown in Figure 13. Most ground-to-cloud lightning occurs when a leader is formed from the top of buildings, mountains, and towers. In this case, the main characteristic that differs from cloud-to-ground strikes is the fact that the leader is initiated from the top of the structure by the charge in the cloud and propagates upward and branches outward toward the cloud. Additional dart leaders propagate along the discharge channel and initiate return strokes. Many such lightning strikes have been recorded from tall buildings, including the Empire State Building in New York and the CN tower in Toronto.

Figure 13. Ground-to-Cloud Lightning Strike

The following is a list of twelve general characteristics of lightning. Notice that 1 through 3 are typical lightning current that is developed from a cloud-to-ground strike. This is of particular interest for surge protection. While most of the current is concentrated at the strike location, it does dissipate out, creating voltage potential differences that are responsible for most equipment damage, in particular systems that are distributed over some distance such as controls and sensors. As may be seen in item 12, currents can be as high as 200,000 amps and can cause facility-wide damage.

1. 10% of strikes exceed 80,000 amps.
2. 90% of strikes exceed 8,000 amps.
3. 99% of strikes exceed 3000 amps.
4. At any given moment, there may be 2,000 thunderstorms occurring and many as 44,000 a day.
5. Lightning occurs at least 8.5 million times a day.
6. The typical lightning channel is ½ inch to 1 inch wide.
7. The average length is three to four miles long.
8. Lightning occurs during sand and snow storms and above volcanoes.
9. Lightning may jump over 10 miles.
10. The air near a lightning strike is heated to 27,760 °C, hotter than the sun.
11. The voltage potential resulting in a cloud-to-ground strike is 100 million to 1 billion volts.
12. Induced ground current may range from 1000 to 200,000 amps.
13. Arcing may occur up to 20 meters from the point of attachment at the ground.
14. The length of strike from cloud-to-ground may range from 2000 to 16,000 feet.

WHY LIGHTNING STRIKES IN MORE AREAS THAN OTHERS

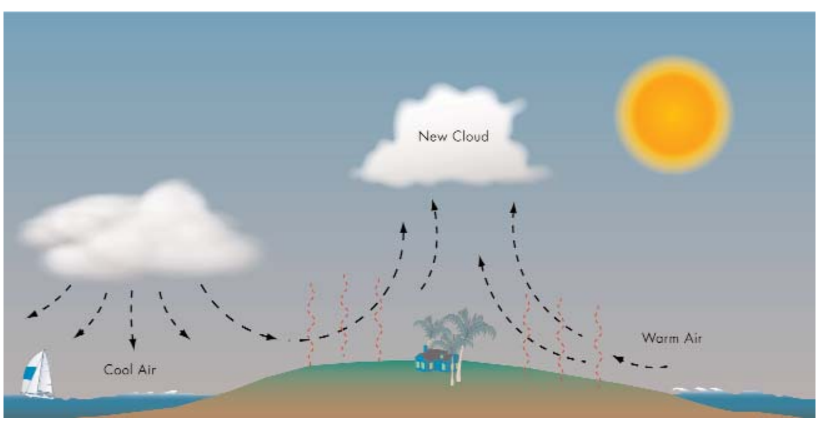
As previously described, temperature and moisture are key factors in the formation of the cumulonimbus cloud, which is responsible for the generation of lightning, but why does lightning occur more frequently in some areas and in others only once in ten years? Primarily it is due to the geography of the terrain, the atmospheric conditions, and global ocean currents and wind patterns.

The air near a lightning strike is heated to 27,760°C, hotter than the sun.

There are fewer thunderstorms developed over oceans because the temperatures are uniformly equal, as the oceans act as a large heat collector. But on the other hand, land masses such as islands, peninsulas, and mountains have rivers with bluffs, swamps, rugged terrain, and dry land, all which have drastic temperature contrasts, which contributes to updrafts. These updrafts are responsible for the formation of two types or classifications of storms, air-mass and frontal.

There are two types of air-mass storms known as *heat*, also called *convective* and *orographic* or *mountain* type. The heat storm grows in still air over land or water where differences in solar heating may occur, such as shady areas, vegetation, or the rising warm air from an island or peninsula next to cooler water or land features. This type of storm is common over Florida, islands, and in the tropics. Often only one or two days of hot weather are all that is needed to generate a storm, and they are usually scattered and not concentrated. (Figure 14).

Figure 14. Heat or Convective Storm Formation



The mountain storm is generated due to the heating of the slopes of the mountain, which has a higher temperature than the air around it. The heat given off the slope of the mountain heats the air adjacent to it, which drives the surface air upward. The right combination of temperature and humidity is required to form the cumulonimbus cloud; in many instances, only a small cumulus cloud will result if any (see Figure 15).

A good example would be the Andes Mountain range, which stretches 1,000 kilometers from Peru to northern Chile. Due to its height, at about 6,000 meters (20,000 feet), where most cumulonimbus clouds form their center, the moisture or rain does not reach over the mountain, resulting in the driest place on earth, the Atacama Desert, where it has never rained, while the costal side of the mountain is lush with vegetation.

Frontal storms do not depend on solar heating as much as convective storms, but they do require differentials in temperatures of air mass. The Midwestern United States experiences the majority of frontal storms. These storms are categorized into several different classes: cold front, warm front, stationary, and prefrontal known as a *squall line*. Frontal thunderstorms are created from moving air masses. When a collision of these air masses occurs, upward drafts are created, which may lead to the formation of a thunderstorm.

Figure 15. Formation of Orographic Storm and the Atacama Desert

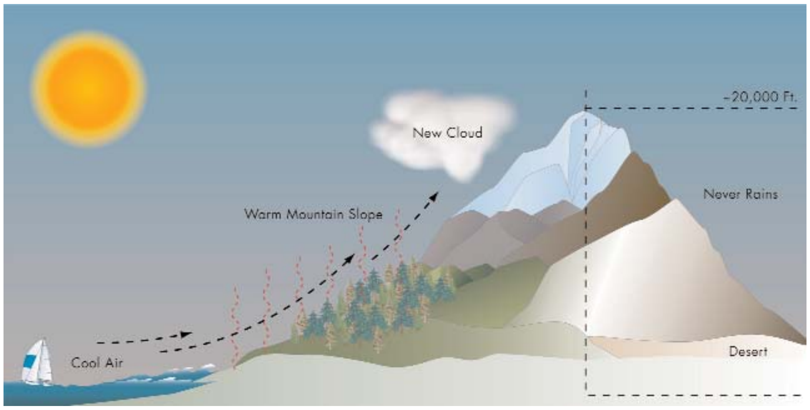


Figure 16. Cold Front Lifting Warm Air Mass

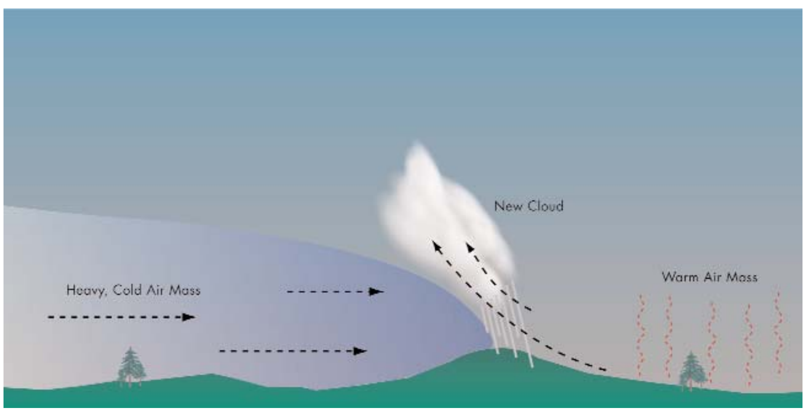
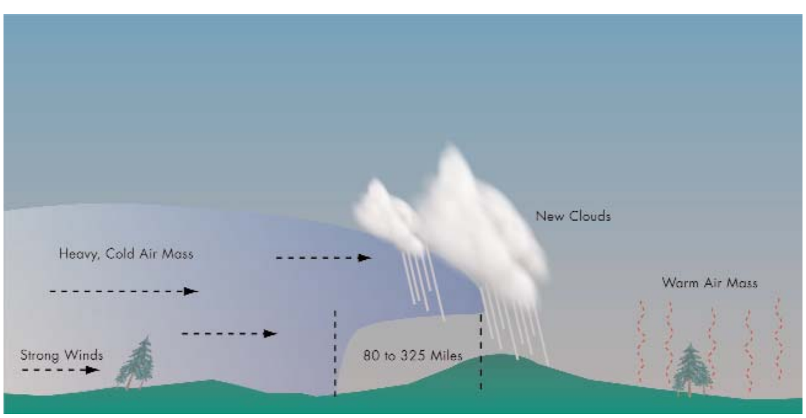


Figure 17. Overrunning Cold Front



Most cold frontal storms occur after a long period of warming with high humidity when a mass of cool air moves in and it slides under the warmer air, creating an upward draft, which in turn begins the process of generating a thunderstorm if the lifting is rapid and enough moisture is present (see Figure 16).

As illustrated in Figure 17, if the cold front is fast moving, it may overrun the warm air and create rain and thunderstorms from 80 to 325 miles ahead of the front where it touches the ground.

Warm fronts will produce thunder storms also, but in this case the warm air is lifted upward and over the cool air mass in front of it (see Figure 18). Spiral-like cirrus clouds are created high in the atmosphere and are signs of an approaching warm front. Most of the storms developed by warm fronts are scattered.

Colliding fronts and topographical features that generate updrafts do not always generate thunderstorms. The generation of a thunderstorm at any one time depends on a combination of events and circumstances leading to the unpredictable nature of the thunderstorm, including global influences.

Global air circulation influences storms and thunderstorms and affects the climate and weather conditions across the world. The global atmospheric circulation is influenced primarily by the sun and the earth’s rotation about it and the earth’s orbit around the sun. The thickness of the air around the earth is twice as thick at the equator due to warmer air and less gravity than as that at the north and south poles, where the air is much drier and cooler. With the tropical and subtropical regions of the earth being closer to the sun, the earth is heated around the equator and passes the heat through the earth, generating temperature differentials as the heat escapes from the poles, acting as a heat exchanger (see Figure 19).

Figure 18. Warm Front Overrunning Cool Air Mass

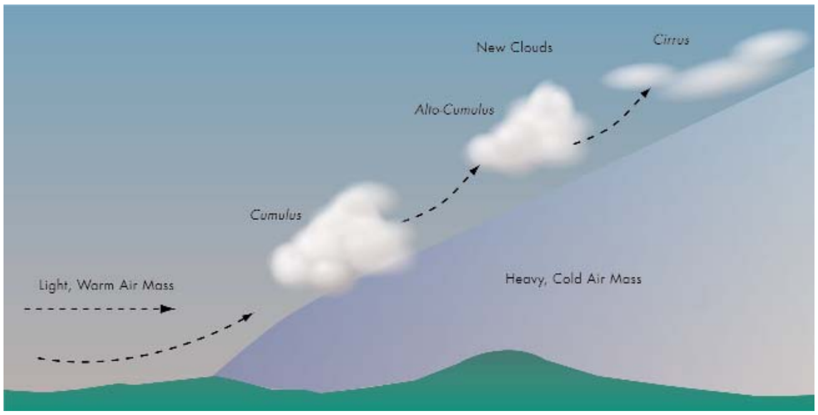
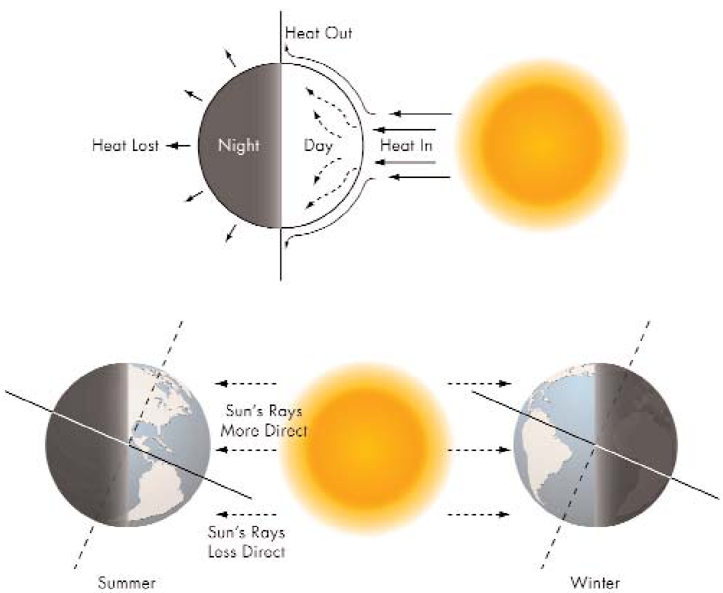


Figure 19. The Earth as a Heat Exchanger



The circulation of the air over the earth is due to differences in temperature, the rotation of the earth, and the tilt of the earth's axis, which lends to seasonal differences in storms. If the earth were smooth and made of one material, it would create an ideal circulation, but because the earth is not smooth, the ideal atmospheric circulation will not occur due to the different effects of the ocean and land masses. The circulations of the seas and oceans are blocked by land masses and assume a different course from that of the atmospheric circulation. Due to the fact that the earth is partially covered in clouds, the land masses will heat naturally with varying differentials in temperatures. These factors, along with seasonal changes, produce irregular circulation of the atmosphere.

As mentioned previously, the tropical regions of the earth have the highest temperatures and therefore the highest rates of lightning, with Africa having the most thunderstorm days than any other region on earth. It is primarily due to the weather pattern of Africa, where warm air from the Atlantic ocean collides with the mountains, which results in thunderstorms year-round. The area that has the most lightning activity on earth is located in the small village of Kifuka (elevation 3200 feet, 970 m) in the Democratic Republic of the Congo Mountains. In one year, 158 lightning strikes may occur over each square kilometer (10 city-blocks square) of the village. As can be seen in Figure 20, the black dot in the middle of Central Africa marks the location on the earth where the greatest lightning activity occurs. The second hottest spot on the earth is the Himalaya mountains, where the warm fronts from the Indian ocean converge with the cold air masses of the mountain. The ocean areas of the earth experience very little lightning because the ocean surface does not warm as fast the as the landmasses do during the day, because water has a naturally higher heat capacity. Heating of the surface air is crucial for storm formation; therefore, storms over the oceans do not occur often.

Figure 20. Worldwide Flash Density (Courtesy of NASA)

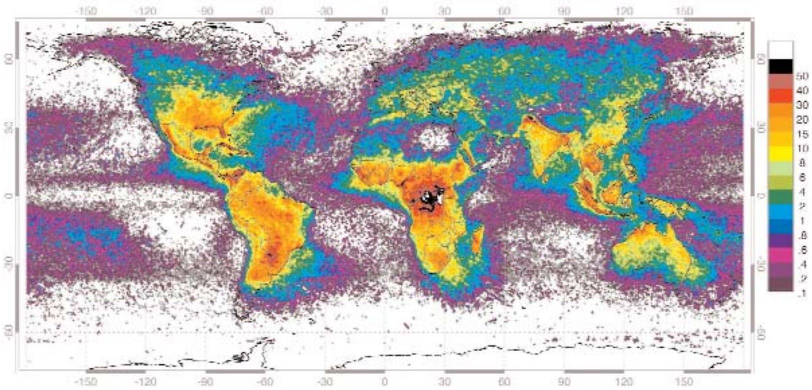


Figure 21. United States Flash Density Map

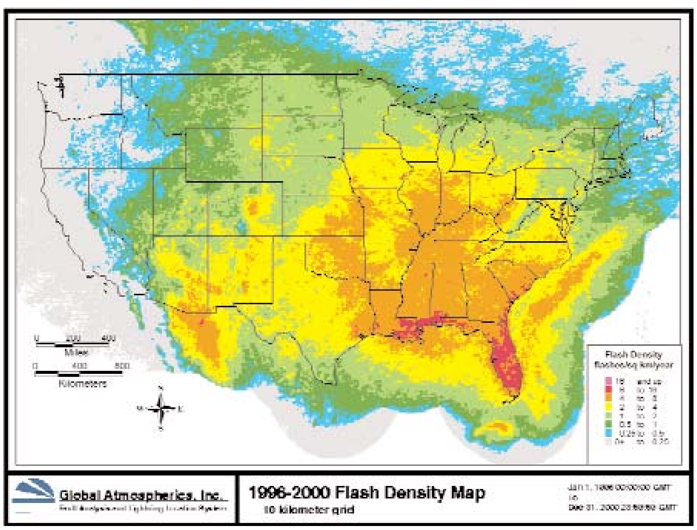
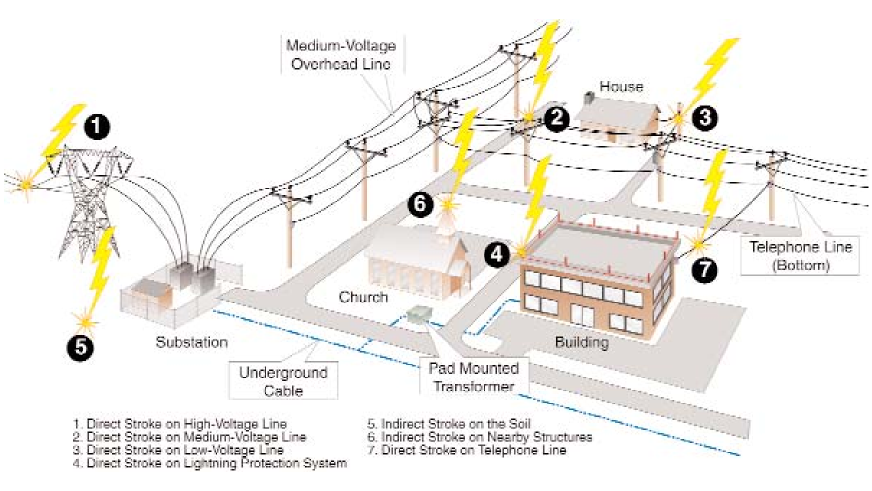


Figure 22. Lightning Impacts



Observing the poles, we see that there are hardly any thunderstorms occurring, especially at the South Pole. This is due to the drastic temperature differences that cause the moisture to be frozen long before any of it reaches overland. With the air and the surface at almost the same temperatures, cumulus clouds cannot be produced.

The most lightning-prone region in the United States is Florida, which has an average of 12 flashes of lightning per square kilometer each year (see Figure 21). Cool sea breezes from the Gulf of Mexico and the Atlantic ocean move inland from both sides of the peninsula, converging with the warm air over the landmass.

Lightning frequency generally decreases from the southeast to the northwest, and lightning occurs more often during the summer months in the United States. During the summer months, orographic or mountain storms are generated in the Rocky Mountains, where the topography causes thunderstorms to form repeatedly.

LIGHTNING IMPACTS

Lightning impacts everything that it comes into contact with and affects systems and components for miles. As shown in Figure 22, lightning impacts every aspect of an electrical system, possibly resulting in damage from transmission lines to residential homes.

Ben Franklin's lightning rod concept is the basis of preventing outages on power systems due to lightning by using shield wires. The practice of using overhead shield wires for lightning protection started during the beginning of the building of the electrical infrastructure. Shielding wires are found in the original design blueprints for the first power lines from Niagara Falls, illustrating mounting locations for overhead ground wires above each phase conductor. The utility industry quickly determined that a single wire, located several meters above the phases, acts as a horizontal lightning rod and provides adequate protection at a much lower cost.

Figure 23. Induced Traveling Wave on Distribution or Transmission Circuit from Nearby Cloud-to-Ground Strike

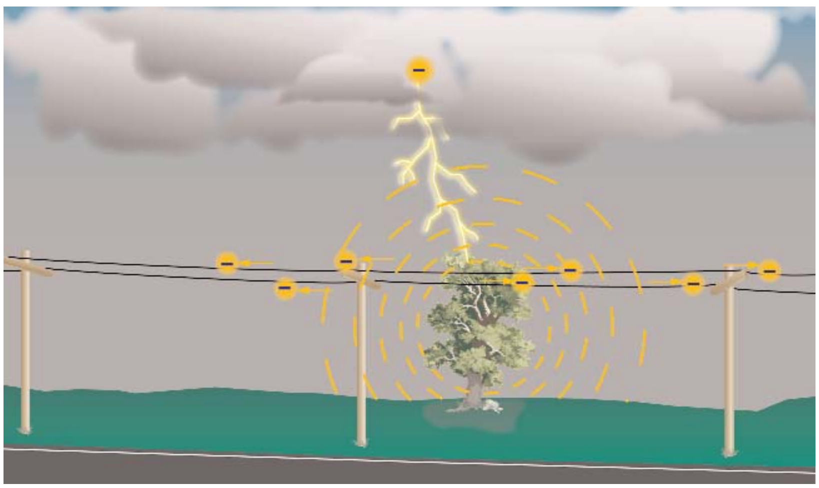
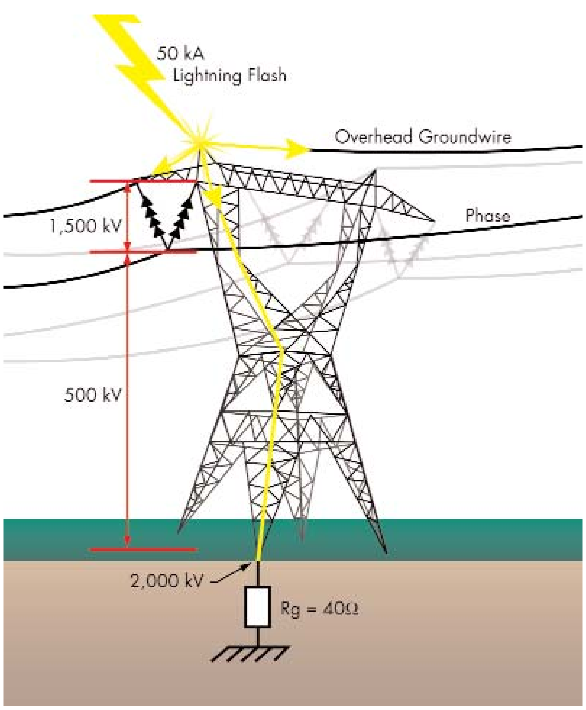


Figure 24. Single-Phase Transmission Line Lightning Strike



Even with the use of overhead wires and lightning protection surge arresters, lightning still remains the primary cause of transmission line outages, momentary interruptions, and reliability and maintenance problems. On a multi-circuit line, simultaneous flashover by lightning of two or more circuits can cause severe disruptions to service. Double-circuit tower flashovers may involve both circuits 50% of the time. A lightning strike can generate millions of volts across line insulators, leading to insulator carbon tracking and punctures. Once a flashover occurs, the resulting power frequency arc becomes the major source of melting, burning, and pitting of wires, corona shields, and supporting hardware. High-voltage transients injected or coupled onto phase conductors by tower flashovers or shielding failures can travel long distances and enter substations, presenting high stress levels to transformers, circuit breakers, and other components. The strong electromagnetic fields created by a flash to earth can induce enough voltage on a distribution or sub-transmission line to cause flash over to occur on the line, even though the flash does not contact the line directly (see Figure 23).

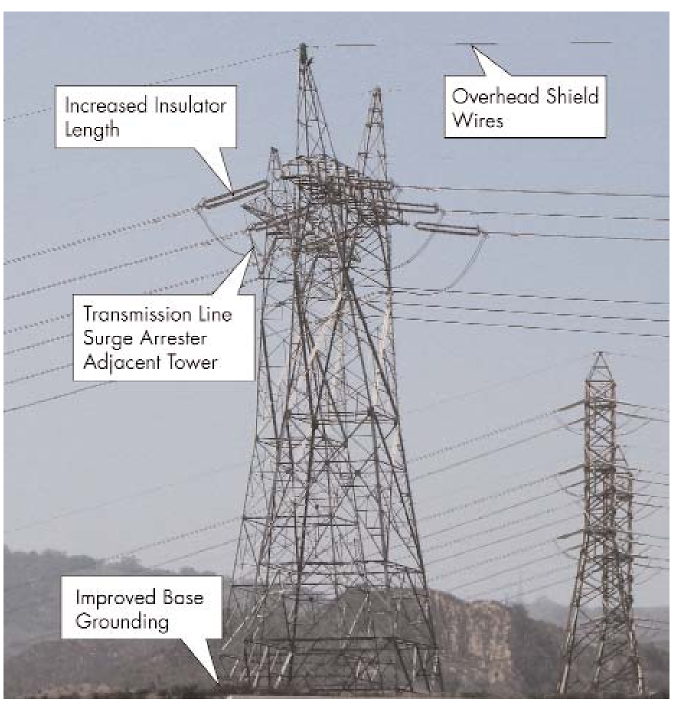
The generation of a flashover can be understood by the illustration in Figure 24, where a 50-kA lightning flash strikes a transmission tower with a 40-Ω footing resistance. The current generated from a single lightning strike could exceed 50 kA in areas where the flash density is high. The high surge impedance of the overhead shield wires will result in most of the lightning current flowing through the tower footing resistance to ground. Using basic calculations and ignoring complex variables in the following example, where 50 kA x 40 Ω = 2000 kV, the tower will float up to approximately this voltage, which will appear on the cross arm end of the insulator. The phase wire that is closest to the overhead shield wire will pick up about a quarter (500 kV) of the 2000-kV peak voltage that appears on the overhead shield wires. This voltage appears on the phase end of the insulator, creating a potential difference of 1500 kV, which will flash over an insulator length of nearly 3 m (10 ft).

In actual forensic examinations of lightning flashover damage in the field, insulator burns and/or structural damage usually leads to the conclusion that the support structure was associated with the lightning event. However, it is frequently the case that the structure with the observed damage is located one or more spans remote from the actual lightning strike location. A flashover at one tower can inject voltage on one or more phases, which will travel to adjacent towers in both directions, causing the towers to flash over also. The flashover closest to the generation will hold in and turn off the others. These are cascading flashovers, and they can occur as far as three spans or more beyond the strike location. Figure 25 shows various porcelain insulators that have flashed over. These types of burn marks on the top porcelain surface are not always visible after a flashover. The total heating effect of the flashover depends on the duration (number of cycles before breaker operation) and the magnitude of the fault current during the power-line-to-ground conduction.

Figure 25. Insulators with Burn Marks from Flashover

To improve reliability, the utility can initiate one or more of the following strategies: improving grounding, modifying static wire locations, increasing insulator lengths and/or adding transmission line surge arresters (TLSA), as shown in Figure 26.

Figure 26. Transmission Line Lightning-Protection Options



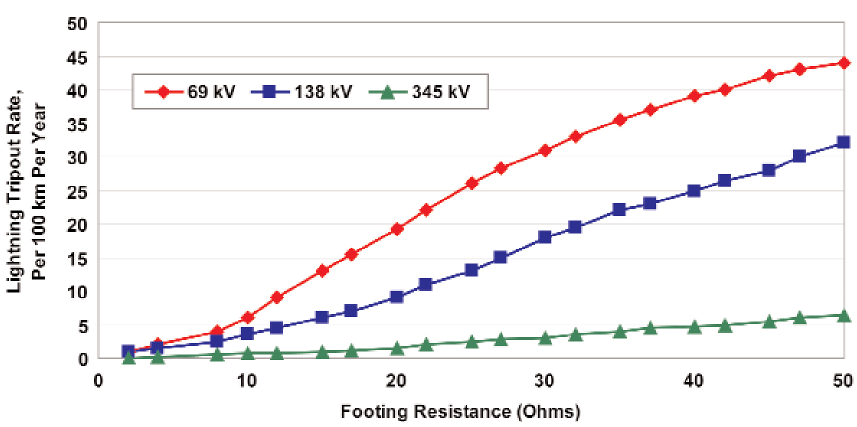
Grounding

Reducing the ground impedance of a tower will reduce the voltage developed on the structure when a lightning strike hits the structure or shield wire. The resulting lower cross arm voltage will reduce the insulation stress and reduce the number of back flashes for the line.

A counterpoise is sometimes used to obtain acceptable footing impedances where soil resistivities are high, such as with sand and rocky areas. Both continuous and radial counterpoises are commonly used. While the measured resistance of a continuous counterpoise may be near zero, the actual surge impedance during a lightning event is much higher. Transient currents travel much slower in conductors buried in the earth. During the first few microseconds of a transient lightning event, only a small segment of a continuous counterpoise will carry lightning current—while a given length of counterpoise with many radial sections attached to one tower will provide lower dynamic impedance during a lightning strike than the same total length of continuous counterpoise.

Reducing the footing resistance reduces the voltage that the insulator sees proportionally for a given strike current. With the lower resistance, it will take a higher strike current to flash the insulator. Figure 27 shows how the flashover rates for single-circuit 69-kV, 138-kV, and 345-kV transmission lines vary as the footing resistance is changed over a practical range of interest.

Figure 27. Back Flashover Rate as a Function of Footing Resistance [EPRI 1002021: Guide for Transmission Line Grounding]



On the other hand, a higher footing impedance will increase the cross arm voltage and result in more back flashovers. As the footing impedance is reduced, fewer and fewer back flashovers will occur until the footing impedance is approximately zero. Even with a near-zero footing impedance, back flashovers can still occur because of the cross arm voltage developed by the lightning stroke current flowing through the higher tower surge impedance.

Effects of Shielding

Adding and/or or moving shield wires are methods of improving the lightning performance of a transmission line. A poorly placed shield wire can allow an excessive number of lightning strikes to attach directly to the phase conductors and cause flashovers. Improved shielding will reduce the number of shielding failures and, reducing the resulting flashovers on a transmission line.

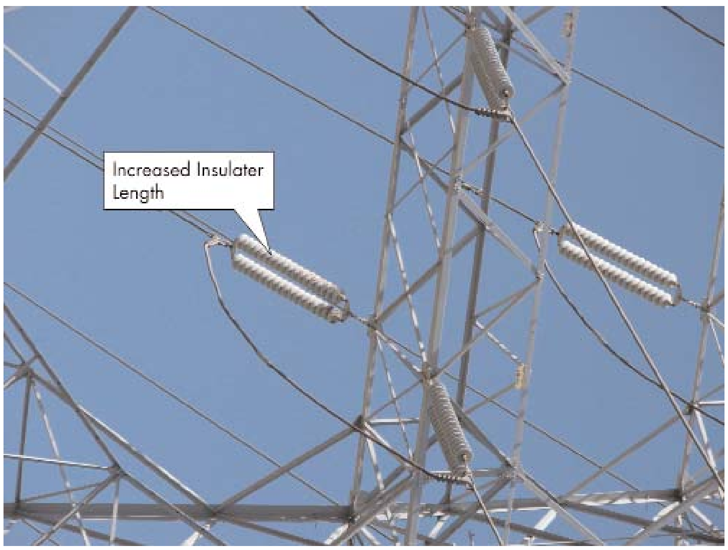
Overhead shield wires on power lines reduce the lightning voltage across the insulators by three different mechanisms:

1. By intercepting strikes that would otherwise hit the phase conductors.
2. By draining off part of the strike current that would otherwise flow through one tower's footing impedance.
3. By increasing the common-mode coupling of voltage surges on the shield wires to the phase conductors, causing insulator voltages to be reduced.

Insulator Lengths and Insulation

The one area where insulator critical flashover voltage, CFO, has a significant impact on lightning performance is on induced flashover. In general, changes in insulator length will have corresponding changes in line flashover performance. As an insulator length is increased, the CFO increases, which will require more lightning strike current to create sufficient voltage to cause an insulator flashover. This performance improvement applies to back flashovers, shielding failures, and induced flashovers. If a lower voltage line (insulation below 300 kV CFO) is experiencing an unacceptably large number of lightning outages, and if the line height is generally lower than the surrounding natural shielding, increasing the installation length to approximately 76.2 cm or more (CFO of 450 kV or more) will often produce a significant improvement in line lightning performance (see Figure 28).

Figure 28. Greater Than 76.2 cm Insulator Length



The impulse flashover strength of an insulator is roughly proportional to its length.

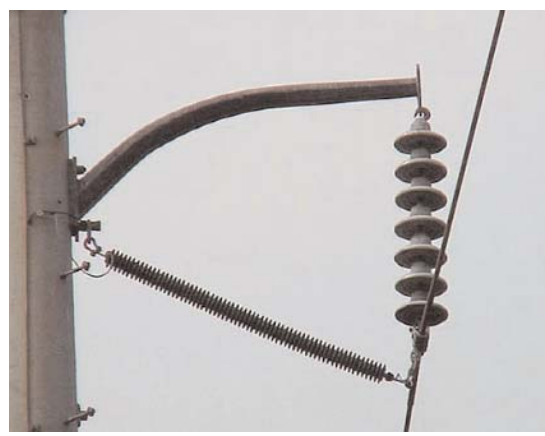
Power lines that are lower than other nearby objects will not receive many direct lightning strike and consequently will not have many shielding failures or back flashovers. Natural shielding around a line can include nearby trees, buildings, or other taller lines on the same right of way. If a line's lightning performance is poor, increasing the insulator CFO can have a significant positive impact on lightning performance.

The impulse flashover strength of an insulator is roughly proportional to its length. Usually, on an existing transmission line design, there is little room to significantly increase the insulator length. In such instances, small increases in length will have little impact on shielding failure flashovers, but the improved insulation might have a significant effect on induced flashovers.

Transmission Line Surge Arresters

Transmission line surge arresters (TLSAs), as shown in Figure 29 are, designed to restrict voltages seen between phase conductors and the tower structure in order to prevent insulation flashover. TLSAs will prevent lightning-induced flashovers in both high footing resistance areas and early shielded designs. Reducing the ground impedance on a transmission line that is experiencing shielding failures will not improve the lightning performance of that particular line. The only way to prevent shielding failure flashovers is by improving the shielding insulation distance or installing insulators with a higher CFO rating, but significant improvements are found by installing TLSAs.

Figure 29. A Transmission Line Surge Arrester [EPRI 1002019: *Handbook for Improving Overhead Transmission Line Lightning Performance*]



When a lightning transient reaches an impedance discontinuity on the conductor, part of the energy is reflected, causing the voltage to double at the point of the mismatch. Because of this doubling effect due to the impedance mismatch (such as by an open switch), most normally open transmission switches should be protected by a TLSA. The arrester will limit the voltage by directing a portion of the surge current to ground and preventing a flashover at the switch location.

TFLASH is a program that allows the user to model an entire transmission line or sections of a line quickly and easily for lightning studies.

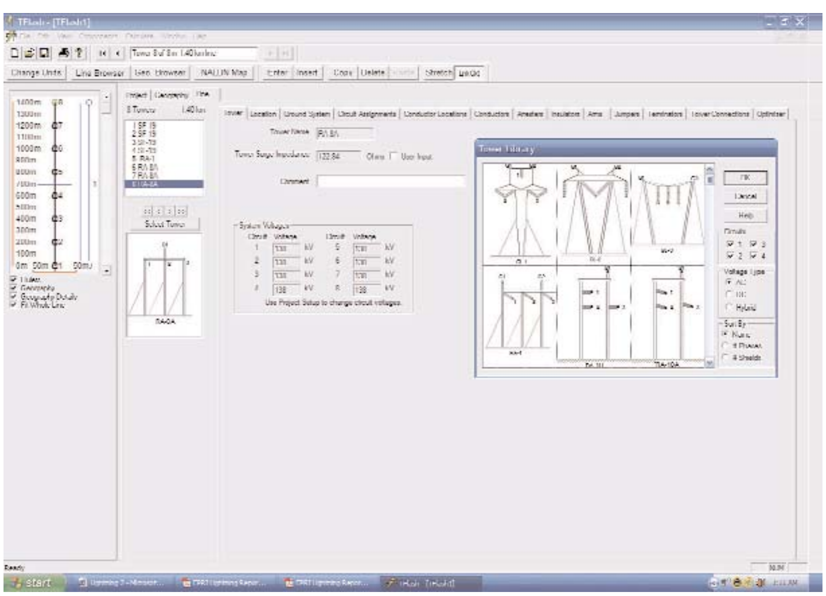
Lightning events, such as shielding failure or a back flashover, can inject severe transient voltages on a phase conductor that can travel for several kilometers and enter a substation and, at the same time, create a severe power frequency fault that must be cleared. The power frequency fault can create severe mechanical stresses from magnetic forces, particularly in transformers. The high-voltage transient arriving as an open breaker or disconnect switch tries to double as mentioned before; the resulting increased voltage can still exceed the substation insulation level, leading to a failure of insulation coordination. The distance from the lightning back flashover to the open terminal at the substation is a key element in the substation protection coordination. Surge arresters, located near the open terminals or on the transmission line entrance, can limit the transient voltage exposure.

Performance improvements—such as grounding, static wire locations, insulator lengths, CFO rating, tower geometry, terrain, and transmission line surge arresters—are often difficult to calculate and estimate but can be easily calculated by using EPRI's TFlash or a similar program.

TFLASH is a Windows™ based program that allows the user to model an entire transmission line or sections of a line quickly and easily on a PC. The line can have an arbitrary number of towers, and there are no restrictions on the number or order of unique towers that can be entered in the model other than the memory and computation capability of the computer used. Several other programs allow for a limited number of unique towers that can be repeated periodically.

TFLASH provides libraries of towers, as shown in Figure 30, and equipment to assist the user in building a model. Once the model is completed, the user can perform a number of different analyses.

Figure 30. TFLASH Tower Library Example



DISTRIBUTION PROTECTION

There are four basic approaches that utilities use for protection of distribution lines:

1. Shield wires — A good shield wire design can achieve high performance if high insulation levels and good grounds are established (less than 10 ohms preferably).
2. Arresters — Arresters can be used on the top phase like a shield wire and requires good grounding and insulation on the unprotected phases, or arresters may be used on all three phases, which require good insulation and grounding (see Figure 31). For significant fault-rate improvement, utilities may use arresters on every pole or every other pole in areas highly populated with sensitive loads and have high exposure levels such as that found in high flash density areas.

3. Shield wire and arresters — Using both shield wires and arresters can provide exceptional performance. The shield wire provides a path to direct most of the lightning energy, and the arresters protect against back flashover.

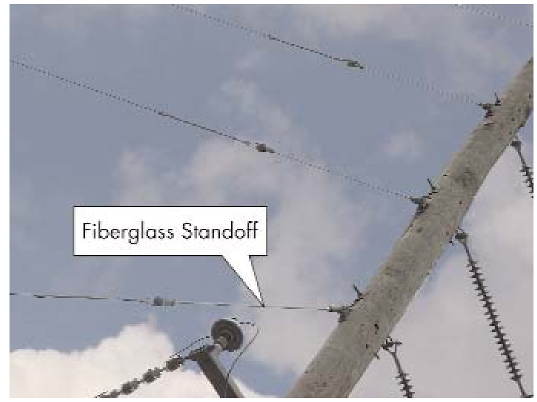
Figure 31. Surge Arresters on Three Phases

4. Grounding — Utilities may reduce the ground impedance by using multiple ground rod configurations, and grounding every pole leading into a facility will help reduce rises in voltage potential. Poor grounding can increase lightning surges that enter into customer facilities (both residential and commercial). Poor grounding may also force more surge current into telephone and cable television systems.

Reducing the grounding impedance helps to reduce voltage potential caused by lightning.

In order to achieve good relative protection, hardware and construction techniques should provide critical flashover voltage (CFO) ratings greater than 300 kV; ratings less than 100 kV result in poor performance. To achieve a high CFO rating, there should be at least 2.5 feet of wood along all possible flashover paths. Guy wires should use fiberglass strain insulators (see Figure 32).

Figure 32. Fiberglass Insulated Down Guys



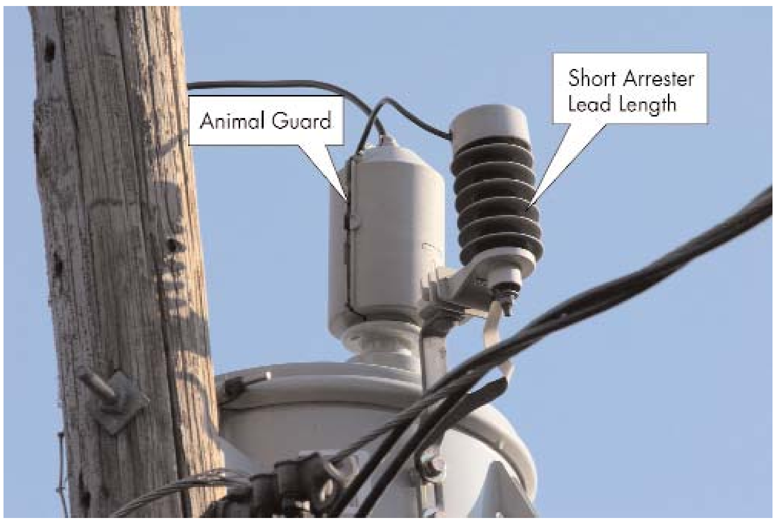
Fuse cutouts can be arranged so that the attachment bracket is mounted on the pole away from any grounds, including guy wires (see Figure 33). In addition, the utility may install arresters on long exposed distribution lines at a minimum of one arrester for every six poles. Reduced spacing will help protect against induced voltages and will help reduce equipment failures, but it will not help reduce direct-strike flashovers.

Figure 33. Fuse Cutout on Backside

To help protect utility equipment and customer sites, arresters may be installed at all equipment poles, transformers, riser poles, capacitors, reclosers, and regulators. The lead lengths should be minimized because they add about 8 kV per foot of electrical length, and not 1.6 kV per foot as older standards state. In addition, animal-protection guards should be used on all arresters (see Figure 34).

Advances in lightning surge-protection arresters have led to better performance. While old arresters had a failure rate of 1%, new arrester designs have about a 0.15% failure rate in an area with a GFD=1 fl/km^2/yr.

Figure 34. Customer Protection with Animal Guard



CONCLUSION

Lightning is a unique weather-related phenomenon that has sparked man's interest from the earliest times, inspiring both fear and fascination. Today, lightning is a well understood science through the use of statistics and advances in all sciences from meteorology to rocket science. While direct threats cannot be eliminated, potential damage may be reduced by the use of the low-tech Franklin Rod and advanced materials and construction techniques.

The utility company has several options and tools in its repertoire for mitigation and advanced software for modeling. These tools assist the utility engineer in selecting the most cost-effective construction and protection equipment to be used in new construction and for improvements in existing transmission and distribution infrastructure for the protection of the utility assets and its customers.

STANDARDS AND DESIGN GUIDES

The following is a partial list of standards and guides available for reference in assessing lightning performance of power systems:

EPRI TR 1002019, *Handbook for Improving Overhead Transmission Line Lightning Performance*

EPRI TR 1012313, *Outline of Guide for Application of Transmission Line Surge Arresters—42 to 765 kV*

The Nature of Lightning and How to Protect Yourself from It—The Lightning Book, Peter E. Viemeister, The MIT Press, Cambridge, Massachusetts and London, England, April 1972

ANSI C63.12-1987, *American National Standard for Recommended Practice for Electromagnetic Compatibility Limits*

ANSI C63.13-1991, *American National Standard Guide on the Application and Evaluation of EMI Power Line Filters for Commercial Use*

IEEE Std 1243-1997, *IEEE Guide for Improving the Lightning Performance of Transmission Lines*

IEEE Std 1410-1997, *IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines*

IEEE Std 998-1996, *IEEE Guide for Direct Lightning Stroke Shielding of Substations*

IEEE Std 299-1997, *IEEE Standard for Measuring the Effectiveness of the Electromagnetic Shielding Enclosure*

IEEE Std C37.90.2-1995, *IEEE Standard Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers*

IEEE Std 81-1983, IEEE *Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System (Part 1)*

IEEE Std 81.2-1991, *IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems (Part 2)*

IEEE Std 1143-1994 (R1999), *IEEE Guide on Shielding Practice for Low Voltage Cables*

IEEE Std 1185-1994, *IEEE Guide for Installation Methods for Generating Station Cables*

IEEE Std 1299/C62.22.1-1996, *IEEE Guide for the Connection of Surge Arresters to Protect Insulated, Shielded Electric Power Cable Systems*

IEEE Std 655-1995, *IEEE Guide for Generating Station Grounding*

IEEE Std 666-1991 (R1996), *IEEE Design Guide for Electric Power Service Systems for Generating Stations*

IEEE Std 1046-1991 (R1996), *IEEE Application Guide for Distributed Digital Control and Monitoring for Power Plants*

IEEE Std 1050-1996 (R1998), *IEEE Guide for Instrumentation and Control Grounding in Generating Stations*

IEEE Std 367-1996, *IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage From a Power Fault*

IEEE Std 837-1989 (R1996), *IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding*

IEEE Std 80-1986 (R1991), *IEEE Guide for Safety in AC Substation Grounding*

IEEE Std 1299/C62.22.1-1996, *IEEE Guide for the Connection of Surge Arresters to Protect Insulated Shielded Electric Power Cable Systems*

IEEE Std C62.11-1999, *IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits (>1 kV)*

IEEE Std C62.22-1997, *IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating Current Systems*

IEEE Std C62.23-1995, *IEEE Application Guide for Surge Protection of Electric Generating Plants*

IEEE Std C62.31-1987 (R1998), *IEEE Standard Test Specifications for Gas-Tube Surge-Protective Devices*

IEEE Std C62.32-1981 (R1998), *IEEE Standard Test Specifications for Low-Voltage Air Gap Surge Protective Devices*

IEEE Std C62.33-1982 (R1994), *IEEE Standard Test Specifications for Varistor Surge-Protective Devices*

IEEE Std C62.34-1996, *IEEE Standard for Performance of Low-Voltage Surge-Protective Devices (Secondary Arresters)*

IEEE Std C62.35-1987 (R1993), *IEEE Standard Test Specifications for Avalanche Junction Semiconductor Surge Protective Devices*

IEEE Std C62.43-1999, IEEE *Guide for the Application of Surge Protectors Used in Low Voltage (Less than or Equal to 1000 V RMS or 1200V DC) Data, Communication and/or Signaling Circuit Applications*

IEEE Std C62.45-1992 (R1998), *IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits*

IEEE Std 1250-1995, *IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances*

IEEE Std C62.23-1995, *IEEE Application Guide for Surge Protection of Electric Generating Plants, June 1995*

Transmission Line Reference Book-345 kV and Above, Second Edition. EPRI, Palo Alto, CA: 1982. EL-2500-R1

AC Transmission Line Reference Book, 200 kV and Above, Third Edition. EPRI, Palo Alto, CA: 2004. 1008742