LIGHTNING AND LIGHTNING PROTECTION

Introduction

Lightning is defined as electrical discharges in the atmosphere and on the earth's surface, usually associated with thunderstorms. It is estimated that about 2000 thunderstorms are in progress somewhere around the world at any one time and that there are 30 to 100 flashes to ground every second. (Reference 1)

Each year lightning is responsible for the deaths of several hundred people in the U.S. and the injuries of several hundred more. It is also responsible for the deaths and injuries of hundreds of livestock and other animals. It causes an estimated 45 million dollars damage to buildings and sets some 10,000 forest, brush and grass fires. In addition, it damages communications equipment, power lines, etc. causing outages, disruptions and failures that are anything from annoying to catastrophic. It can effect electrical and electronic military systems as well as the oil, railway, power, communications and airlines industries. Although lightning has been studied for centuries, it was not until the 1750s that experiments conducted with kites by Franklin in the U.S. and others proved that lightning was electrical. Since then there has been a great deal written on the subject of lightning phenomenology and lightning protection. References 2 and 3 provide a history of lightning research.

Frequency of Occurrence of Thunderstorms

Until recent years, techniques for gathering statistics on lightning occurrence were rather crude. Today, new techniques for measuring lightning occurrence are being employed and better statistics on world-wide thunderstorm activities are becoming available from earth orbiting satellite data.

The use of modern computer techniques coupled with better data gathering capabilities is providing much better insights into the climatology of lightning incidence, including flash incidence, duration of thunderstorms, proportion of flashes going to ground, diurnal variations, influence of surface structure height, etc. Reference 4 provides more information on research in this area.

A rough idea of thunderstorm activity in the U.S. and the world is provided by figures 1 and 2. These are examples of isokeraunic maps provided by governmental weather bureaus which are prepared from data compiled by weather observers regarding the annual incidence of thunderstorm days. A thunderstorm day is any day during which thunder is heard at a specific location. These maps are typical of similar maps shown in books and reports on lightning. Although there are sometimes variations in such maps particularly for Florida which on some maps show up to 100 thunderstorm days per year, one can at least determine the degree to which lightning and lightning protection must be considered. For example, residents in Florida have a much higher probability of needing lightning protection than someone in Southern California. More exact calculations of lightning occurrence can be made using techniques given in Reference 4.

Types of Thunderstorms

Thunderstorms are usually classified as (1) local or convective storms or as (2) frontal or traveling organized storms. Local thunderstorms form independently and last up to an hour or two. They produce moderate lightning, winds, rain and sometimes hail. Organized storms are large and violent, and may last many hours. They are often associated with cold fronts and may line up along fronts for miles and travel with the fronts. They produce severe lightning, high winds, and sometimes hail stones over one inch in diameter. Storms of the convectional type account for the majority of thunderstorm days recorded annually in the United States. However, frontal storms account for most of the severe damage produced annually.

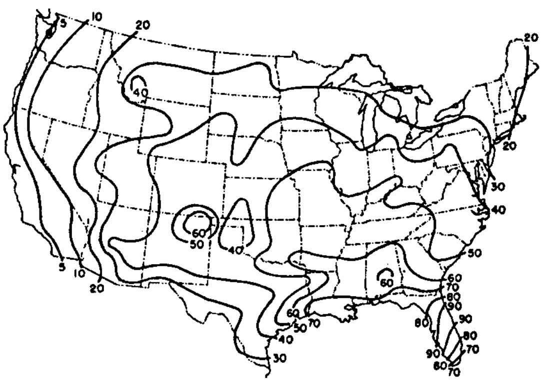

Figure 1. Average annual thunderstorm days (U.S.)

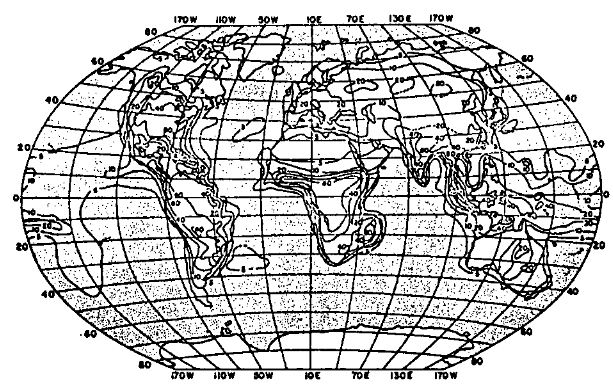

Figure 2. Average annual number of thunderstorm days (world).

Cloud-to-Ground Discharges

Most studies of lightning generation mechanisms have been devoted to cloud-to-ground discharges (see Figure 3). Briefly, the lightning flash of the cloud-to-ground variety begins in most cases at the base of the cloud in a region of dense electrical charge at an altitude of about five kilometers. This is the region of the cloud where water droplets freeze, a process that may be connected with the generation of electric charge.

The negatively charged part of the cloud can be at a potential of as much as 300 million volts with respect to the ground, but even that enormous potential is insufficient to support a spontaneous arc across five kilometers of air. The main discharge can begin only after the channel has been traced by a preliminary low-current discharge called the stepped leader. The stepped leader begins to form when electrons emitted by droplets in the cloud are accelerated by an intense electric field; the electrons collide with molecules in the air, freeing many more electrons and leaving a conductive path of partially ionized air. Such a cascade of accelerated electrons typically progresses only 50 to 100 meters, but with each step a portion of the cloud's charge is transferred downward, and the next step can begin from the tip of the advancing leader.

The course of the stepped leader is highly irregular and in its progress toward the ground it forms numerous branches. Each step is accomplished in less than a microsecond, but there is a pause of about 50 microseconds between steps. As the leader approaches the ground the potential gradient increases, and sparks are emitted from objects and structures on the ground, usually from the highest points first. When one of these sparks meets the downward-propagating leader, a conducting path between the cloud and the ground is completed. Since the potential difference across the path is a few hundred million volts, a surge of current immediately follows; this large current is called the first return stroke.

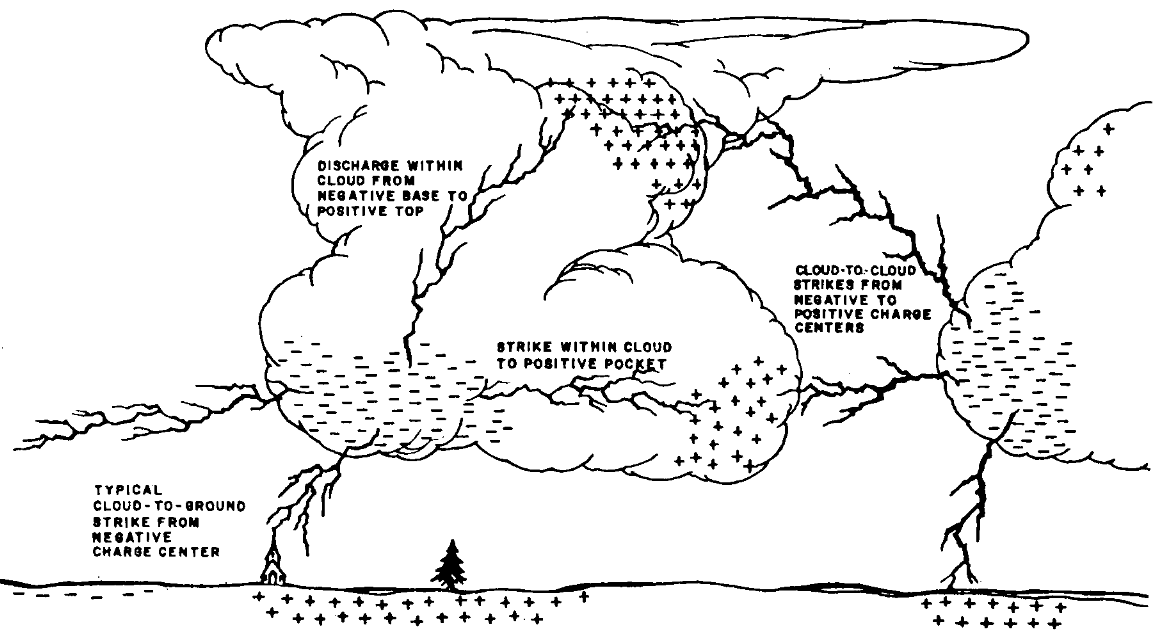

Figure 3. Various types of lightning discharges (Source: Reference 6)

The stepped leader may require 20 milliseconds to create the channel to the ground, but the return stroke is completed in a few tens of microseconds. In some cases, that is the end of the lightning flash; more commonly, however, the leader-and-stroke process is repeated in the same channel at intervals of tens to hundreds of milliseconds. The subsequent leaders, called dart leaders, progress faster and more smoothly than the stepped leader because the electrical resistance of the path they follow is lower than that of the surrounding air. As the dart leader progresses toward the ground, intracloud processes extend the channel within the cloud so that additional areas are discharged. The subsequent return strokes, however, are usually less energetic than the first one. A typical lightning flash has three or four leaders, each followed by a return stroke; one flash has been photographed that had 26 strokes.

Each surge of current in the flash, (including the steps in the stepped leader, the dart leaders and the return strokes) heats the gases in the lightning channel and thereby generates an acoustic signal we call thunder. Recent data on research in the area of thunder signal recording can be found in Reference 5.

Other Types of Lightning

Intra-Cloud Lightning Intra-cloud lightning, the most common type of discharge, occurs between oppositely-charged centers within the same cloud.

Cloud-to-Cloud Lightning As the name implies, the charge centers involved in this type of lightning are in two different clouds, and the discharge bridges the gap of clear air between them.

Cloud-to-Air Lightning The flash exits a cloud and terminates in clear air. This type is usually heavily branched, with each branch apparently ending in a region of space charge in the clear air. A special type of cloud-to-air discharge is the *bolt-from-the-blue*. In this case, the cloud responsible for the flash is out of the observer's sight.

Heat Lightning A general brightening of a cloud or group of clouds caused by either an intra-cloud flash or reflection by these clouds of the light from other lightning types.

Sheet Lightning Usually just a name given to an intra-cloud discharge producing a large diffuse illuminated area.

Ribbon Lightning Appears to the observer to be several closely-spaced lightning flashes following parallel congruent paths to ground. Together they look like a bright ribbon.

Bead Lightning A lightning flash in which the discharge channel appears to have alternate bright and faintly luminous, or nonluminous, sections. It, therefore, appears as a string of bright beads.

Ball Lightning This is possibly the most mysterious atmospheric electrical phenomenon. It appears as a luminous ball ranging in diameter from a few centimeters to a meter or so. Reports of its behavior vary considerably. Some experts now believe that it is as common as cloud-to-ground lightning and may, in fact, be caused by it.

St. Elmo's Fire This term, corona discharge, and point discharge are names given to the same physical process under different conditions. It is caused by the electric field intensifying in the vicinity of a more or less pointed object. St. Elmo's fire gets its name from the patron saint of sailors and was applied to the glow around mastheads during stormy conditions.

Lightning Interception and Prevention

Benjamin Franklin suggested the first principle of lightning protection, that of lightning interception or diversion through the use of a lightning rod. His first suggestion was that the rod would discharge the would-be source cloud by slowly draining away its electrical charge. He later modified this proposal to include the possibility of intercepting the stroke. Today, the use of a lightning rod to divert a stroke is a commonly accepted method of lightning protection and may be found installed on buildings and structures wherever there is a high level of thunderstorm activity.

The lightning rod serves primarily as a stroke diversion device, providing an easy path to ground for a stroke occurring in the area. As the stroke approaches the earth, a field induced spark originates on the rod which intercepts the stroke and diverts it to the rod where it continues to ground through the grounding system associated with the rod. The capability of the rod to divert the stroke depends on the nearness of the stroke to the rod and to the severity of the stroke. These factors lead to some disagreement as to the size of the volume protected by the rod from a direct stroke or "cone of protection". However, the generally accepted radius of the base of the cone about the rod, or combination of rod and support tower is two times the overall height of the rod and support. Fortunately, the larger the stroke the greater the effective volume of the cone and consequent protection.

Control of Lightning Induced Electrical Surges:

Where lightning strokes cannot be diverted to non-critical areas away from equipment being protected, additional efforts are required. These methods rely on the various lightning arresters available and on adequate grounding and bonding.

With the occurrence of a lightning stroke, the major damaging side effect is the power developed due to the passage of electrical currents of large amplitudes through electrical resistances. Where electrical conductors exist in the vicinity, these currents may be directly injected into the conductors, or they may induce secondary currents. Once in the conductor, these currents and the resultant conductor to ground potentials they develop, produce insulation breakdown and component failure. If a human becomes part of the surge circuit to ground by accidentally completing the path to electrical ground, serious injury including death may result.

The lightning arrester does nothing more than provide a controlled, easy path to ground for the surge energy, shorting it to ground before it is able to damage the equipment being protected. There are many varieties of lightning arresters; however, the necessity for the numerous types is primarily caused by the large number of different circuit applications.

Lightning Arresters and Their Applications

The two basic performance requirements imposed on lightning arresters form the background for the various designs in common use. The first requirement is that the arrester must divert the lightning-caused electrical surge away from the equipment or device being protected or limit its magnitude to an acceptable value. Secondarily, it must cause minimum interference with the ability of the circuit to peform its intended duty.

Considerations of the speed of response of the protector to a lightning caused surge, its ability to limit voltage levels to a specific value, and capability of diverting the expected surge current amplitudes and durations must be made as the first step in designing or selecting an arrester for a specific application. Concurrent with these considerations, an effort is required to assure that the arrester does not intefere with the normal transfer of power or signal during non-surge periods. Also following the operation of the arrester it must cease to conduct and allow the circuit to return to its pre-surge condition.

The arrester designer works with three basic type devices to provide the necessary spectrum of circuit protection. These are variable resistance devices or varisters, semiconductors such as diodes and selinium controlled rectifiers, and arc devices. Each device has its own area of application and the always present list of advantage and associated disadvantages. Other than for a few simple applications open to each type of basic device, most protectors are a combination of two or more of the same type or hybrid combinations of types.

Variable resistance devices such as the metal oxide and silicon carbide varisters are known as "soft" limiters in that they shunt the device with a variable resistance whose resistance is inversely proportional to the applied voltage. No critical voltage level of the surge is required to activate these protective devices as they are always in the circuit as a path to ground; thus the term "soft" limiters. Unless the level of voltage applied across the device rises, as during the occurrence of a surge, they remain at a relative high level of resistance. As the surge voltage rises, the varister lowers its resistance thus providing a low shunt impedance in parallel with the device being protected and consequently diverts the majority of the surge energy to ground. A major disadvantage of this type device on some circuits is its loading effect on the circuit during periods of steady state operation.

Although semiconductor devices such as the zener diode and the silicon controlled rectifier are the most recent additions to the field of surge protection, they are perhaps the best known. Although less "soft" than the varister, these devices have the ability to provide protection on voltage limiting down to the low voltage levels necessary to protect integrated circuits and other semiconduction devices. Their major drawback is their limited capability of handling significant surge energy.

Arc devices are perhaps the oldest form of lightning protector. Many versions exist; however, they all are based on an electrical breakdown between electrodes separated by various dielectrics. They are "hard" limiters in that the surge voltage must reach a critical level before the arc device begins to discharge the surge energy. Their major disadvantages are their inability to clamp surge voltages to a low level and their tendency to continue conduction once started on DC lines of significant voltage.

The combination of the various types of basic devices into hybrid arresters often provides the ability to overcome the disadvantages of each basic type. Where high AC power voltages are involved, some method must be provided to prevent losses across the arrester during periods when only the power voltage is on the line. Where arc type arresters are employed we also must find a method to limit the shunting of the power from the AC source to ground to as short a period as possible. Where a varister type device is used by itself, an undesirable steady state path to ground will result if the surge resistance of the device is chosen sufficiently low to provide adequate protection. Through the combination of these devices into a hybrid known as the valve arrester, a solution to this application may be devised. In this arrester the arc device (a spark gap) is placed in series with a varister element (the valve block) and as a consquence, the spark gap element provides high steady state insulation resistance while the varister element limits the power that flows through the spark gap from the AC source, or power follow currnt. This current occurs after ignition of the arc discharge by the lightning caused voltage surge, and flows until the spark gap element extinguishes on the first current zero at the half cycle point.

Table 1 lists several of the basic surge protection devices and their advantages and limitations.

Grounding and Bonding

Without the application of proper grounding and bonding techniques many lightning protection efforts are useless. As an illustration, figure 4 shows the effect on an installation having both an inadequate grounding and bonding system. It is assumed that lightning surge current enters a radio cabinet over the outer conductor of a coaxial line. An inductive voltage will develop in the grounding conductor between **a** and **b**. This voltage, V_L, also appears between the radio cabinet and an adjacent one.

Assuming an inductance L of 12.2 Henry, the maximum inductive voltage (V_L) that results from the rapid rate of change during the period of the current wavefront is as follows for a di/dt of 8000 amperes per microsecond.

$$V_L = L\frac{di}{dt} = 12.2 \text{ x } 10^{-6}\left(\frac{8000}{10^{-6}}\right) = 97.5\text{kv}$$

This is not an exceptionally high voltage for the type installation shown. Arc distances ranging from several inches to a few feet between equipment cabinets have been observed.

It is apparent from the foregoing illustration that the primary objective of the application of systemmatic grounding and bonding techniques is to establish an equipotential zone between equipment cabinets and throughout the installation being protected. This permits the minimum hazard to personnel and also provides a ground plane to which all other protection devices may be referenced. Where this equipotential zone can also be the local earth ground, a natural sink for lightning induced energy is provided. However, without a good earth ground, protection is still possible through the application of proper bonding techniques and the choice of supplemental lightning arresters and protectors. It should also be apparent that the illustration given is also applicable to the grounding and bonding of lightning rods and overhead ground wires. References 8 and 9 provide detailed discussions on various grounding and bonding techniques.

Verification of Protection

Due to the passive nature of all lightning protection devices, verification of protection is a major part of any lightning protection scheme. Following the choice of protection devices for any particular system, laboratory testing should be performed to assure protection to the maximum level of the surge expected on that system. For electrical devices, this type of testing is relatively straightforward using current injection methods. Capacitor discharge circuits are usually used having waveshapes following the expected stroke current waveshape at that point. Energy levels are raised until a predetermined upper limit is reached or circuit damage occurs. Where testing for direct lightning strokes is desired, testing is more difficult due to the inability to generate step leaders of the length found in nature. In this instance, a sacrifice in protection verification is necessary and lesser artificially produced strokes are used in combination with system models. Once equipment is installed in the field, periodic verification of the continuation of grounds and bonds is necessary to event deterioration of these critical connections.

The Future of Lightning Protection

As often happens, many technical improvements take place during periods of economic necessity. The field of lightning protection is presently undergoing such a period caused by the switch to circuits using low voltage level solid state devices. As the transistor has become widely used, the protection methods of the first half century have been found less adequate because of the lower level of protection necessary to protect the new semiconductor devices.

This article discussed the two basic approaches to lightning protection; the lightning rod and circuit protection devices. In the present urgency for better protection both areas are being pushed. Installations are being made which are intended to neutralize the cloud charge sufficiently to prevent a stroke from occurring in the nearby vicinity. These installations are designed to present a number of discharge points over a small area to provide sufficient point discharge current to neutralize the local cloud to ground field while providing a slow, neutralizing discharge to the cloud. This lightning prevention method relates to Benjamin Franklin's earliest conception of the operation of a lightning rod.

In conjunction with the lightning prevention effort, various combinations of the three basic protection components into hybrid designs providing protection down to less than ten volts are being used. As an example, assume protection down to a 5 volt level must be provided for a particular solid state data receiver input circuit. One solution might be to provide a two stage protector having a spark gap input circuit to short the majority of a lightning transient energy, followed by a second stage composed of a Zener Diode to clamp the residual low energy voltage spike. To prevent the Zener from attempting to shunt all the surge energy before the spark gap has an opportunity to discharge, a small inductance would be placed in series in the line between the spark gap and diode.

At present most circuits may be protected by the combination of the basic protection components. Effort is being made to extend the useful applications of the three basic protection components both through perfection of their design and through the development of circuits better able to draw from the advantages of each particular component.

This article was prepared for ITEM by William C. Hart and E. Wallace Malone. An expanded version of this article and bibliography is available at nominal cost by writing to Mr. Hart at 6137 Barrington Dr., Goleta, Ca. 93017.

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Comparative Values of Several Surge Protection Devices

Parameter	Spark Gaps	Varister Devices	Zener Diodes
Typical surge current capability (Amps)	10,000	1,000	500
Response Time (Sec)	10^{-8}	10^{8}	10^{-9}
Capacitance (fd)	10^{12}	10^{-10}	10^{-10}
Voltage Range (Volts)	90 and higher	40-700	2-300
Insulation Resistance	High (10^{9} ohm)	medium	medium
Bi-Polar Operation	Yes	Yes	No
Failure Mode	Short	Short	Short
Activated State	Short Circuit	Clamped	Clamped

Table 1

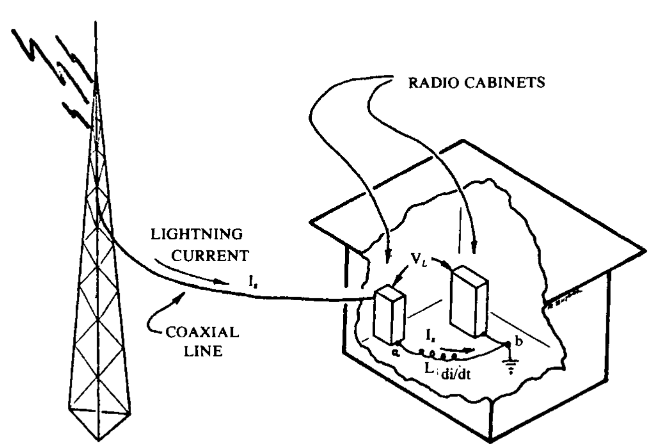

Figure 4. Typical considerations for grounding and bonding schemes.

See General Semiconductor Ind. on page 1 and GE on page 9.