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LIGHTNING AND ITS EFFECTS ON RAILROAD SIGNAL CIRCUITS

F. Ross Holmstrom

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16. Abstract

This study discusses the occurrence of lightning, its effects on railroad signal equipment, and protection of such equipment from lightning damage, with special attention to known protective techniques which are employed in a variety of situations in the power, communications, and railroad industries. A brief review is offered of the causes of lightning and other surges, followed by an extensive treatment of the means by which lightning and power-line transients induce surges and over-voltages in signalling circuits. Specific topics include the effects of the direct stroke current, the collapsing electric field when the stroke occurs, inductive coupling, and the effects of ground currents in the earth. A survey of protective devices and techniques currently in use for specific types of equipment is presented, including categorization of arrestors by type and application. Preferred lightning protection practices in railroad signalling are examined and related to practices in other fields. The problem of lightning protection is addressed from an overall systems viewpoint, encompassing development and testing of protective systems and design of systems, so that they can more easily be protected. Recommendations for future research are made.

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PREFACE

Preparation of a report on lightning and its effects is complicated by the many different factors that are involved--gaseous discharge phenomena; electromagnetic phenomena on a grand scale; the electrical behavior of metals, insulators, and the earth; and the characteristics of many types of electrical devices. This report is, of necessity, written for a reader with an electrical engineering background. Some familiarity with lightning protection practices is helpful as well.

In this report, the author has attempted to present information drawn from a variety of sources on current lightning protection practices in a unified and coherent manner, to provide a foundation document for present-day system applications and to assist in formulation of research and development plans in this area. Although the treatment deals with railroad signal systems in general, the impetus for the study, and a primary application area, is the impact of lightning protection considerations upon grade crossing motorist-warning systems. This arises from both the high degree of public funding of such systems and the extensive use of solid state electronic circuits in them--far greater than is true for other railroad signal system field installations.

The author has had valuable help from a number of individuals. Dr. John B. Hopkins of the U. S. Department of Transportation, Transportation Systems Center, has provided information

on the framework within which this work should be carried out, as related to the Federal Railroad Administration's overall program in grade crossing safety. Mr. Lennart Long of DOT-TSC provided useful information concerning DOT's overall interest in lightning protection, and plans for future activities in that field. Mr. Ronald L. Pike of Safetran Systems Corporation provided technical information on the operating characteristics of his company's lightning protection products. Mr. Emil Kraus of the Union Pacific Railroad was a source of statistics on actual lightning damage costs, and a source of first-hand experience of the effects of lightning on railroad signal systems. The author would like to express special thanks to Mr. Fred A. Kahl of Joslyn Electronic Systems, Joslyn Mfg. Co., who provided valuable technical information on the design, characteristics, testing, and evaluation of lightning protection equipment for diverse electrical applications, including railroad signalling.

This work has been carried out under Contract No. DOT-TSC-589, funded by the Office of Research and Development, Federal Railroad Administration, as part of its program in rail safety in general and grade crossing protection in particular.

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1. INTRODUCTION

Lightning causes damage and destruction of millions of dollars of railroad signalling equipment yearly in the United States. This has been the case since the inception of electrical signalling and control systems on the nation's railroads. Over the years, protective devices and techniques have been developed that greatly alleviate the problem of damage to electrical signalling equipment by lightning but do not completely eliminate it. It is felt by many persons in the railroad industry that the standard devices and techniques that have been developed and used for many years have been generally cost-effective in limiting lightning damage. Cost-effectiveness here implies that the price of protective devices and techniques has been more than returned by savings in equipment replacement costs and maintenance manpower costs. Conversely, it has been felt that spending a great deal more money for more sophisticated protection techniques would not have resulted in a worthwhile additional savings, and therefore would not have been cost-effective.

Much has happened recently to alter the picture of lightning damage, damage prevention, and repair from what it has been over the few past decades. One factor that has changed drastically is the price of labor. Another factor has been the introduction of modern solid-state electronic components and systems, either to replace older electromechanical relay systems or to perform signal and control functions that were never possible with electromechanical relay systems. For certain types of signalling operations, solid-state electronic systems offer the potential of far less routine maintenance than older electromechanical systems because of the absence of moving parts. A good example of this is seen in comparison of maintenance requirements of equipment for railroad-highway grade crossings where it is required that train speed be measured to provide nearly constant warning time to motorists. Timing blocks and electric motor-driven clock relays have been used in the past to sense train speed and to control the circuits for gates and flashing lights. These high-maintenance items are now being supplanted by sophisticated solid-state systems with no moving parts, such as the Marquardt Grade Crossing Predictor®. These solid-state systems require far less in the way of routine maintenance and therefore offer potential savings in maintenance costs. However, the solid-state components in these systems are inherently far more susceptible to lightning damage than the electromechanical components that they replace. Similarly, the widespread use of audio frequency overlay track circuits at grade crossings depends upon use of solid-state electronics.

Thus, the potential for more effective and reliable operation at lower overall cost offered by modern solid-state systems will only be met as new techniques are implemented for protecting these systems from lightning in the railroad environment. In addition, there has been steady increase in the price of labor for maintaining and repairing older electromechanical systems that have been damaged by lightning. This fact probably increases the cost-effectiveness of more sophisticated forms of lightning protection for older systems as well.

It is the purpose of this report to review the subject of lightning, its effects on railroad signalling equipment, and protection of equipment from lightning damage, with special attention to known protective techniques that are employed in a variety of situations in the power, communications, and railroad industries. A brief review is offered of the causes of lightning and other surges. A more extensive treatment is given to the means by which lightning and powerline transients induce surges and over-voltages in signalling circuits. A survey of protective devices and techniques currently in use for specific types of equipment is presented. The problem of lightning protection is discussed from an overall systems viewpoint, encompassing development and testing of protective systems and design of systems so that they can more easily be protected.

2. THE CAUSES AND CHARACTERISTICS OF LIGHTNING

The treatment offered here for the causes and characteristics of lightning is brief and a number of the more subtile points have been eliminated. However, the central principles of lightning generation are presented. For more detailed treatments, the reader is referred to detailed texts on the subject.

At certain times of the year in many locations, the sun heats the ground and moist lower layers of the atmosphere near the ground to a temperature sufficient to cause the moist air near the ground to thermally expand, become less dense than cold upper air, and start to rise just as a hot-air balloon would rise. As the air from near the ground rises, it cools--partly from adiabatic expansion and partly from becoming mixed with already cold air aloft. Water vapor then condenses out and forms droplets as the air cools below the dew point. The droplets grow in size and frequently freeze to form ice particles or snow.

Negative and positive ions always present in air have a differing affinity for water droplets and for ice particles. In addition, a falling water droplet that breaks up releases negative ions to the air, leaving the smaller droplets that then result with a greater net positive charge. If the droplets fall as rain, this charge is carried to earth. If the droplets are carried upward to the top of the cloud, net positive charge is transferred from the bottom of the cloud to the top of the cloud.

The net end result of the rather complex physical process going on within the atmosphere and within the cloud is that a tremendous degree of charge separation occurs, with the bottom of the cloud taking on a net negative charge, and the top of the cloud and the surface of the ground underneath taking on a net positive charge, as shown in Figure 1. In addition to the net positive charge taken on by the ground underneath the cloud due to the positively charged falling rain, the ground has induced on it an additional charge distribution due to the dipole field of the cloud above. The dipole field contribution of induced charge on the ground will be positive directly under the cloud, but farther away from the cloud, the dipole field contribution of induced charge on the ground can in fact be negative. Here, the total ground charge density can be either positive or negative, depending on the particular balance of various factors.

The net positive charge on the ground under the cloud can achieve a value in the range of +100 coulombs, and the net negative charge within the cloud above can achieve a value in the range of -100 coulombs, distributed in many cellular regions of space that are isolated from each other and spread throughout the volume of the cloud. The existence of these multiple cells of negative charge, which are discharged by individual lightning strokes, is the reason why multiple lightning strokes occur, each stroke discharging a single negative cell by conducting on the order of a few coulombs of charge each from ground to cloud.

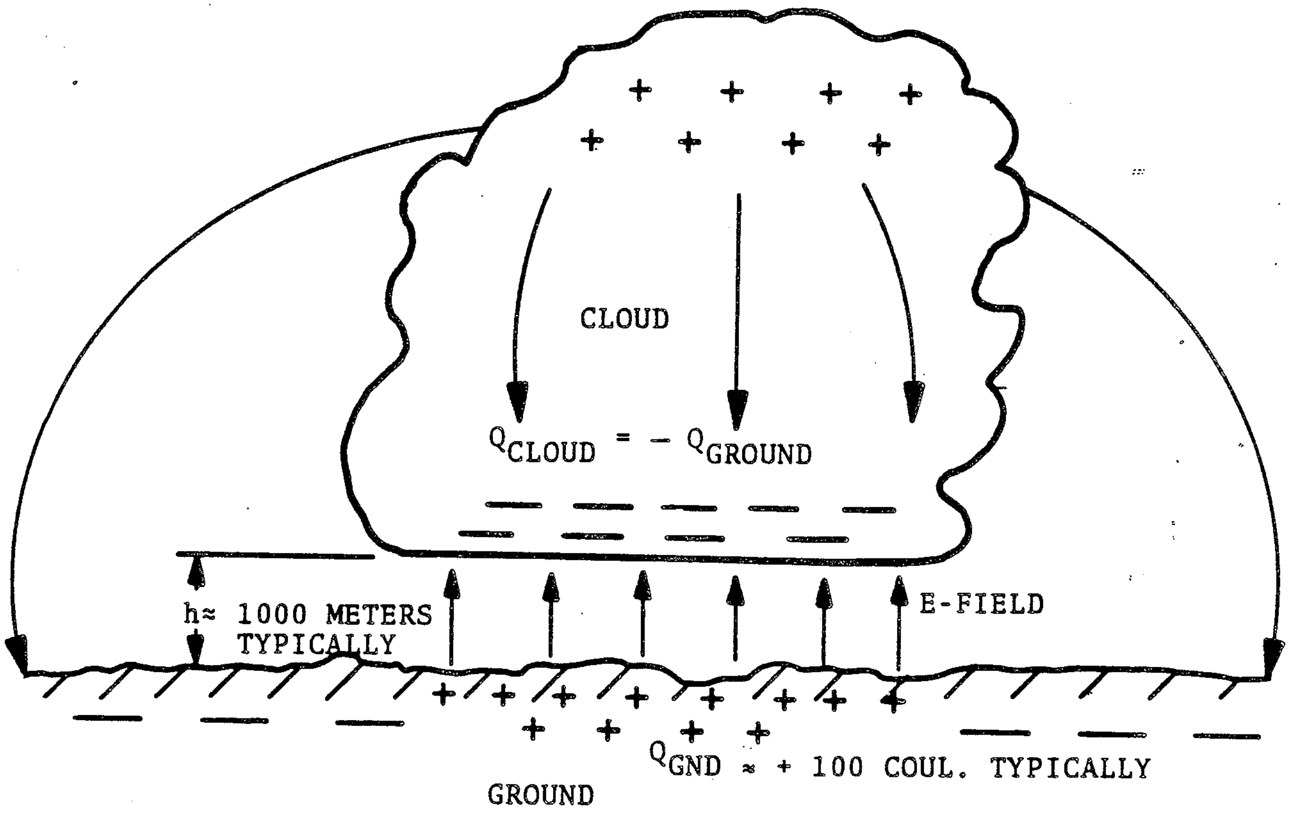


Figure 1. Simplified schematic diagram of the charge distribution in a lightning cloud. Note that because of the dipole nature of the cloud, the ground charge immediately under the cloud can be positive while that farther away can be negative.

Various estimates exist for representative cloud-to-ground voltages, charges, and stroke currents. The numbers presented here are representative of values given by a number of sources. A typical ground-to-cloud height is on the order of h = 1,000 meters, and a single large cloud could have an area of 10 km x 10 km, or $A = 10^8$ m^2. The resulting ground capacitance is

$$C = \varepsilon_o A/h = 1 \text{ microfarad}$$

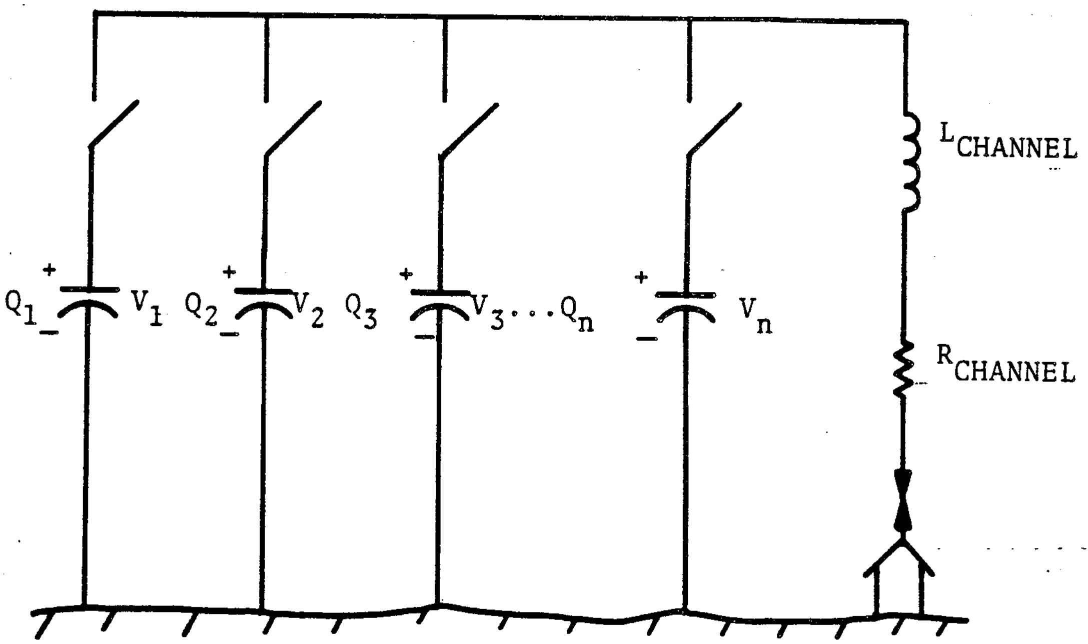
where the dielectric permitivity of free space is

$$\varepsilon_o = (36\pi \times 10^9)^{-1} \text{ farads/meter.}$$

At breakdown, the cloud-to-ground average electric field is typically $E = 10^5$ volts/meter, yielding a total voltage of $V = E \times h = 10^8$ volts, and a total charge on the ground, balanced by total opposite charge in the cloud of $Q = C \times V =$ 100 coulombs. The intense electric field causes a corona-type discharge to initiate at the cloud, and propagate along a continually lengthening channel toward the ground. This is called the "leader," and it takes on the order of 20 milliseconds for the leader to propagate to a point sufficiently near the ground so that the total cloud-to-ground voltage is now impressed across a very short remaining gap on the order of 10 to 100 meters long. The tremendous electric field in this short gap causes an arc discharge to occur across the gap to the high-conductivity ionized channel of the leader, after which the circuit is closed for the massive main stroke called the "return stroke."

When we speak of a lightning "stroke" it is usually the return stroke we mean, for it is during the return stroke that massive current flows along the conductive channel from ground to cloud, partly neutralizing the collected charge on ground and cloud. Strokes very seldom occur singly. In a single discharge of lightning, there generally occurs a series of strokes usually from 3 to 4 in number, but sometimes as many as 25 in number, following each other at 3 to 100 microsecond intervals, with typical time between strokes in the 40 microsecond range. These strokes are obviously spaced in time by intervals shorter than the minimum resolution time of the eye and are seen by the observer as a single "flash." Thus, we see lightning flashes, each comprised of a number of strokes. The occurrence of multiple strokes is believed to be related to the existence of numerous charge cells in the lightning cloud, all of which do not discharge simultaneously. After the first stroke, an ionized high-conductivity path exists from ground to cloud across which the voltage is much lower than before. Thus, voltage gradient is transferred to regions within the cloud, causing successive ionization channels to form within the cloud which connect with the original channel to ground, and along which additional current flows neutralizing successive cells of charge.

The equivalent circuit of lightning stroke current production is shown in Figure 2. The current waveform during



TOTAL C $\simeq$ 1 μf TYPICALLY

ALL Q'S < 0.

Figure 2. The equivalent circuit for charge storage and lightning discharge. The switches close successively, causing individual current pulses to flow through the channel to ground. Note that all the Q's are negative in polarity, the (+) and (-) signs indicating the algebraic definition of polarity.

a single return stroke can be thought of as being determined by the cloud-to-ground capacitance C, the resistance R of the conducting channel, and the inductance L of the conducting channel. Thus, the electrical circuit is a damped LRC circuit, and we can expect the current pulse to take the form of a damped oscillatory burst at a frequency $f = 1/2\pi\sqrt{LC}$, or to take the form of a single pulse, depending on the relative magnitudes of L, R, and C. It is believed that oscillatory current waveforms have in fact been observed. However, the more usual current waveform is one in which the current rapidly rises to a peak value, in a time of 1 to 30 microseconds with a normally observed time in the 3 microsecond range, and then the current falls at a lower rate approximating exponential decay, with a time interval for decreasing to half the peak value that is approximately 10 times the time taken to reach peak value. This type of behavior, with a ratio of 10 between time to fall to half of peak value and time to reach peak value, is characteristic of a heavily damped LRC circuit in which the RC time constant governing rate of fall and the L/R time constant governing rate of rise are in the ratio 60 to 1. That is,

$$\frac{RC}{(L/R)} = \frac{\tau_f}{\tau_r} = 60.$$

If one compares time between strokes and stroke durations, one finds that they are comparable. Thus, current in a lightning flash typically has an irregular pulse-shaped waveform due to contributions of several closely-spaced individual pulses, as seen in Figure 3. Overall maximum current at the peak of a single stroke can be as large as 100,000 amps, with 10,000 amps a typical approximate value. Typical charge transferred during a single stroke is on the order of 3 coulombs, and about 10 times that for an entire flash. Typical values for total energy released during a lightning flash are in the range of 10^8 to 10^9 joules, or 1,700 to 17,000 kWh per flash.

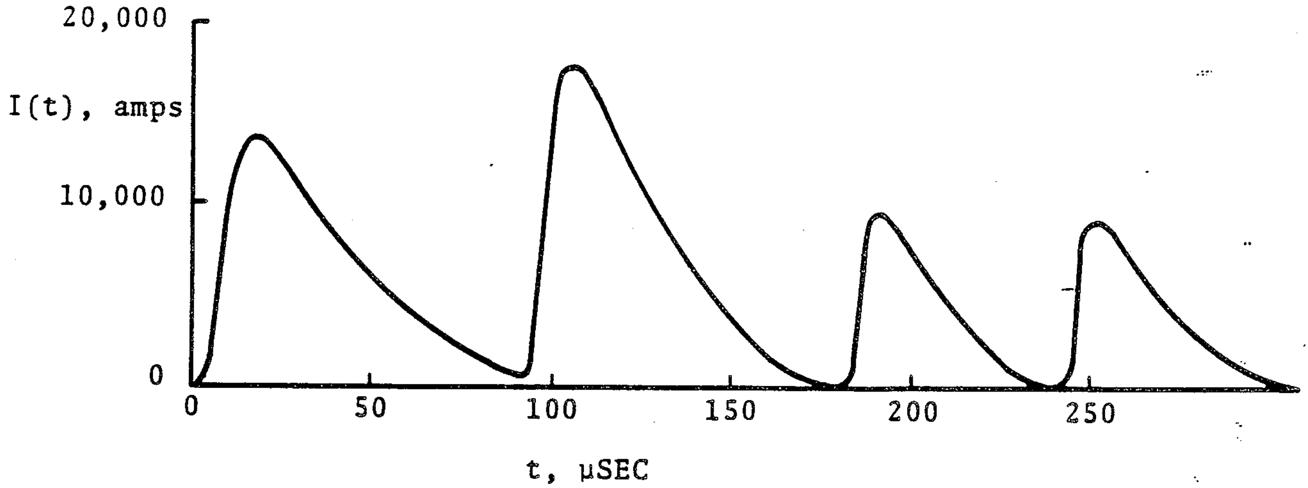


Figure 3. Resulting typical waveform for a lightning flash comprised of a number of strokes. Note that I(t) as shown is the current that flows upward from ground to cloud.

3. LOCATIONAL AND GEOGRAPHIC FACTORS ASSOCIATED WITH LIGHTNING

From examining the fundamental causes of lightning storm activity, it is obvious that not all regions of the United States or the world are equally active lightning areas, and it is obvious that not all times of year are equally favorable for lightning storm activity. What it takes to produce lightning storms is moist air at low altitudes near the ground and warm sunshine. Thus, those areas that experience the most lightning activity are the areas that combine the highest humidities and the highest rates of solar heating. The Isokeraunic Map for the United States is shown in Figure 4. The contour lines shown on the map are contours of equal numbers of days per year on which lightning activity occurs. Note that the Florida peninsula with a combination of tropical sun and high humidity leads the nation, with lightning activity occurring on over 100 days per year in the central area. On the other hand, the extreme western fringe of the continental United States along the Pacific Ocean has lightning activity on an average of only 5 days per year. Besides having a more northerly latitude than Florida, the weather in this region is dominated by the cool winds that blow off the Pacific Ocean year-round. Because of their low temperature, these winds cannot carry much moisture in absolute terms--and what they do carry mostly falls as rain on the first range of mountains a few miles inland.

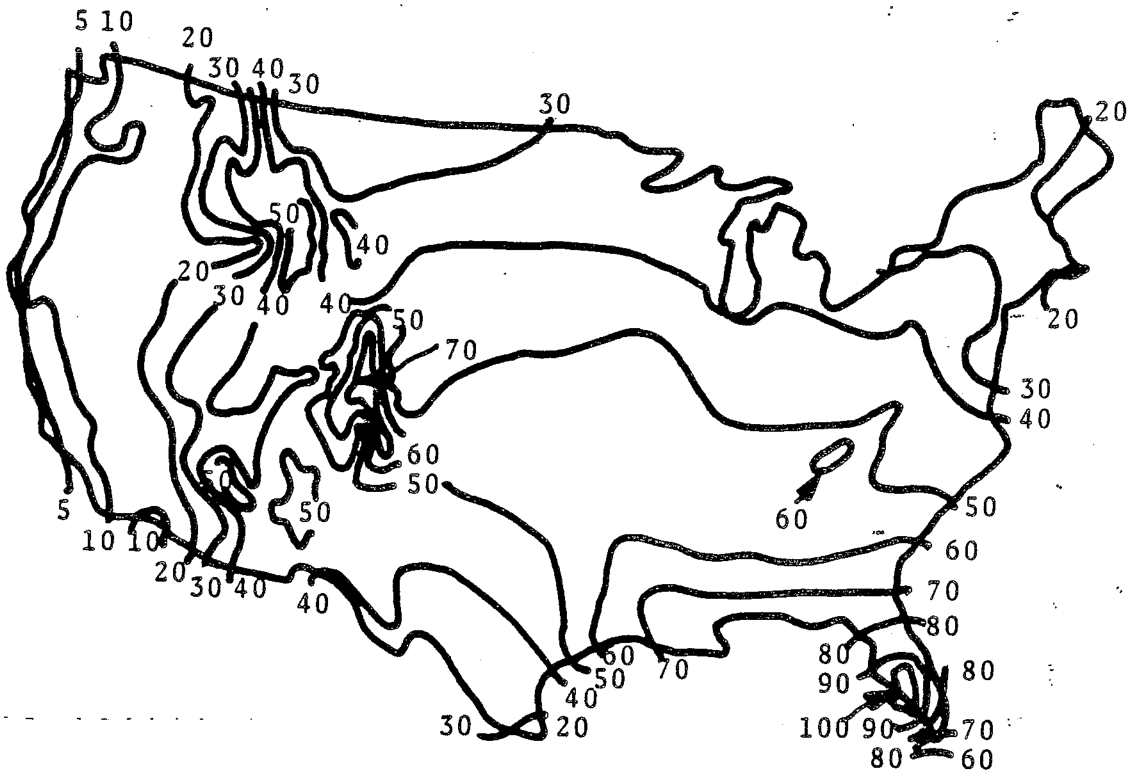


Figure 4. The Isokeraunic map of the Continental United States. Contours are lines of equal thunderstorm activity, and give the number of days per year on which a trained observer in a given locality hears thunder or sees lightning flashes.

The nationwide variations in lightning activity are of profound importance as far as yearly costs of lightning damage are concerned. These variations also affect the economics of providing lightning protection, as will be discussed later in this report.

Even within small geographical regions, local factors often play an important role in determining where and how often lightning strikes. It has been fairly well established that in a certain geographical region, each area of a few square miles or a few square km will experience the same number of lightning flashes per year as each adjacent region of equal area. However, within such an area, points of higher elevation, tall structures, isolated trees, and other solitary objects rising above the surrounding terrain can "attract" the lightning strokes that would otherwise strike the ground in a more uniformly distributed manner. Thus, an elevated object can be thought of as providing a "protective cone" within which adjacent objects are much less susceptible to lightning strikes than would otherwise be the case. A generally accepted rule of thumb is that the radius of the circular region on the ground that is thus protected is equal to the height of the elevated object, as is seen in Figure 5. Note that locations within this cone are not wholly immune from lightning strikes, since where lightning strikes is dependent on a great number of statistical factors, but the probability is greatly reduced. Also note that hills have to be very steep and precipitous in order to provide a protective cone at all.

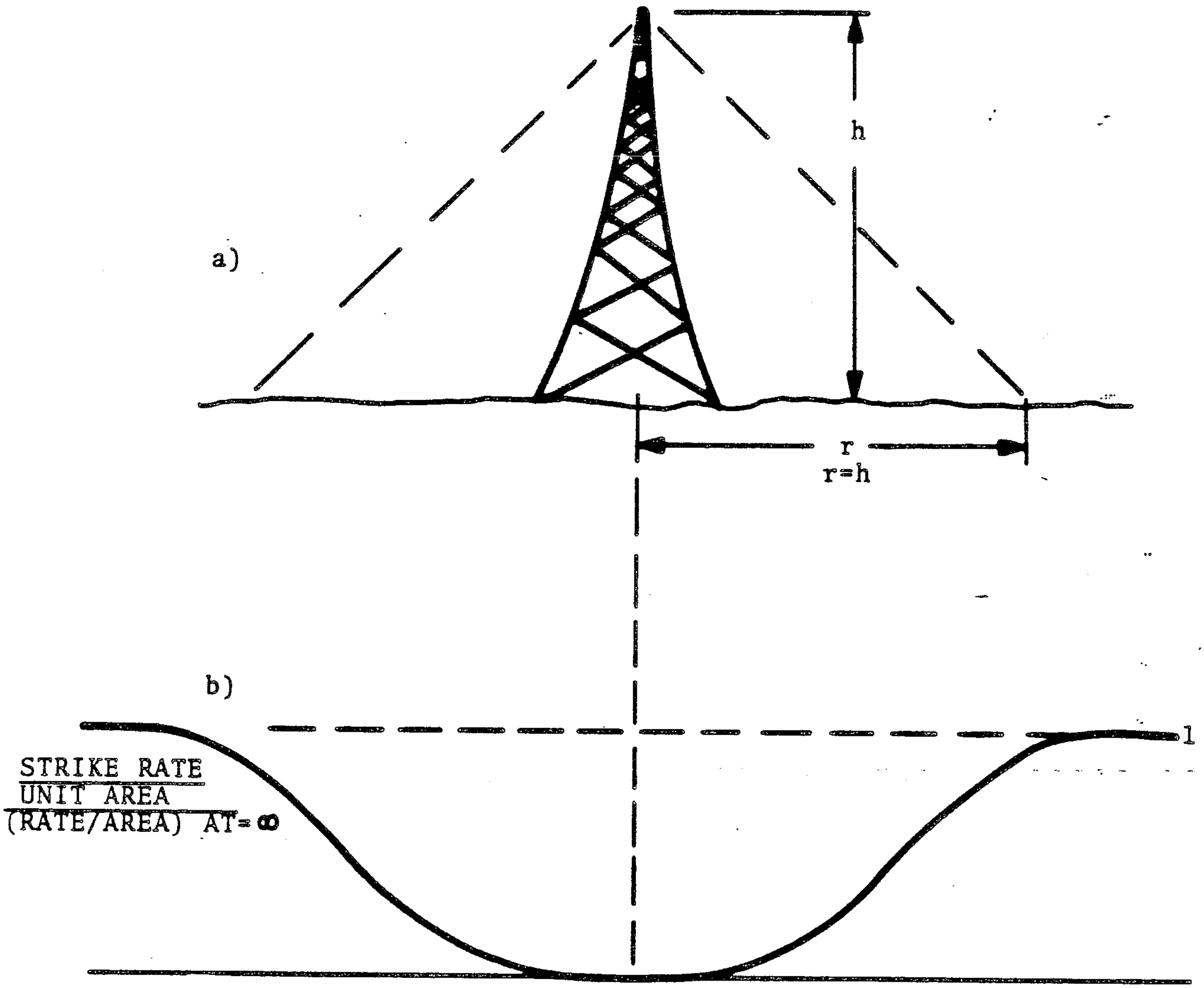


Figure 5. Schematic illustration of the Protective Cone effect.
a) The Protective Cone.
b) Approximate graph of the strike rate per unit area near a protective object compared to the strike rate per unit area far away from the object. Lightning strokes are drawn away from the ground near the tower and strike the tower instead.

A commonly used statistical rule for predicting frequency of lightning strikes on any object is to multiply the area of the base of the "protective cone" or "protective tent" in the case of overhead lines, expressed in square miles, by 1/2 times the isokeraunic index, to determine the average number of lightning strikes of the object per year. As an example, a 500-foot high tower in the northeast, where the isokeraunic index is 20, will be struck on the average of once every 3-1/2 years. The same tower in central Florida would be struck on the average of once every 8-1/2 months.

Proper installation of lightning rods and lightning towers can greatly reduce damage rates from direct strikes by lightning within protected areas. However, an ironic fact is that protecting an installation's electrical and electronic equipment from damage due to direct strikes by installing lightning towers or lightning rods nearby can even cause an <u>increase</u> in lightning-induced surges, since more lightning strokes can be expected to the nearby tower. Thus, providing lightning rods and lightning towers reduces damage from direct strikes; however, provision for protection from the effects of lightning-induced surges must be maintained or increased in any event. In actuality, many types of electronic equipment, including railroad signalling equipment, suffer greater overall damage every year from induced surges than they do from direct strikes. This fact is discussed in greater detail later in the report.

There is one possible means by which the occurrence of lightning strikes can be eliminated entirely within certain areas. This means appears to have been successfully employed in a number of specific cases. The method of protection in question is the provision of a mechanism for "bleeding off" surface charge on the earth in a gradual and continuous manner as it collects during development of a lightning storm. Lightning Elimination Associates, of Downey, California, has reported success in completely eliminating lightning strikes from specific protected areas using this technique. "Dissipation Arrays" fabricated from metal sheet and containing a large number of very sharp metal points are typically mounted on towers within the area to be protected, with the points pointing upward. A typical array can be approximately five feet square and contain 1500 sharp points spaced approximately 1.5 inches apart. As an example of a typical installation, the company mounted 15 such arrays at the tops of 15 towers 90 feet in height to protect a 3-acre area at the Atlantic-Richfield refinery in Wilmington, California. There are a total of 22,700 points in the protected area.

The high electric field strength associated with lightning cloud proximity is greatly increased in value at the tip of each point, giving rise to field ionization or corona formation directly at the point, and a current flow from the point into the air above the point. This current flow is quite erratic for any one point, but contributions from many points in an entire panel exhibit a fairly steady dc current that rises and falls with passage of a cloud overhead. At the ARCO site, it was found that a peak current of 8 amperes dc was measured using an ammeter on a single tower guy wire. It is estimated that total dc current from ground to space could exceed 200 amperes. This mechanism thus provides for current flow from ground to cloud at cloud-to-ground potentials that are far less than that required for lightning stroke initiation; therefore, since charge is continuously bled off, potentials never reach dangerous level and lightning strikes are completely eliminated.

Overhead lines are protected in a similar manner by replacing the overhead ground wire strung above power or communication lines with strands of "Dissipation Wire" that is barbed with in excess of 10,000 active point sets per mile of line--a density of barbs slightly greater than the usual barbed wire used for fencing. It is essential in the case of either wire arrays or panel arrays to provide grounding of high quality--usually provided by buried cable arrays at bases of towers or buried ground cable underneath transmission lines, with heavy conductors connecting the dissipation arrays or cables with the ground system.

Whereas the economic practicality of such techniques has been demonstrated in a number of specific instances, more work is needed to prove this method of lightning protection as an economically viable one for installations such as railroad systems that are greatly extended in space. At some time in the future, however, techniques such as these just may greatly alleviate all aspects of the lightning problem.

4. LIGHTNING SURGES IN CIRCUITS--DIRECT AND INDUCED

It is fairly evident that when a lightning stroke hits an object on the ground, be it a building, tree, transmission line, railroad track, or other object, that the object struck will be forced to conduct the stroke current. It is not immediately obvious, but can be seen from a relatively simple analysis, that induced voltages and currents created by lightning strokes striking nearby are also a hazard to electrical equipment, property, and life. Four main causes of voltage and current surges are discussed below. They are the effects of the direct lightning stroke itself, voltages developed by stroke current flowing in structures and the ground, voltage surges in overhead lines induced by collapsing cloud-to-ground potential, and magnetically induced surges due to circuits inductively coupling to the lightning stroke current itself.

4.1 The Direct Stroke Current

As has been discussed, lightning strokes occur in the form of extremely large pulses of current emanating from sources with millions of volts of internal source potential, with pulse current waveforms being determined in large measure by the impedance characteristics of the cloud-to-ground conduction channel. In terms of electrical circuit theory, the lightning stroke is for all intents and purposes a nearly ideal current generator and--in any circuit routinely constructed by man--voltages will reach any level necessary for the stroke current to flow--and flow it will. It can be channeled but not stopped. The equivalent circuit for lightning stroke current generation, shown in Figure 2, shows that current is determined by the impedance of the stroke channel--not by any object on the ground.

The electrical energy dissipated in any object through which the lightning stroke current passes is directly proportional to the resistive component of voltage developed by the current pulse. The total electrical energy dissipated in any object can be thought of as W = (current)x(resistive voltage)x(pulse duration), or more accurately as

$$W = \int_{t_1}^{\infty} \left(i_{surge} \right) \times \left(v_{surge} \right) dt \ .$$

Thus, the damage done to a physical object will in general be directly related to how much resistance that object provides to the flow of the surge current through it.

4.2 Heating Effects of Direct Stroke Currents in Conductors--Generally Negligible

Since lightning strokes are pulses of relatively short duration, high-frequency techniques must be used in analyzing the electromagnetic effects of lightning. As far as calculating resistance heating of wire due to lightning surge currents is concerned, account must be taken of the skin-effect decrease in effective cross-sectional area of the wire that occurs at high frequencies. This will be done here in a manner that errs on the side of slightly overestimating the increase of resistance, just to show that even with a worst-case estimate of skin-effect consequences, damage to conductors of at least moderate size due to direct stroke currents is generally negligible.

Consider a "typical" lightning stroke conducting 10,000 amperes peak with a time between half-maximum-current points of 40 microseconds. The time of 40 microseconds is one half-period of a 12,500 Hz sinusoidal signal. For currents of this frequency, the resistance per meter of copper wire, which will be defined here as the "lightning surge resistance," and is based on inclusion of the skin effect, is calculated to be

$$R = \frac{4.17 \times 10^{-6} f^{1/2}}{a_{cm}} = \frac{4.66 \times 10^{-4}}{a_{cm}} \text{ ohms per meter,}$$

where a_{cm} is the wire diameter in centimeters. As an example of electrical effects, consider a current pulse which will be assumed to be of square shape with 10,000 amperes current and 40 microseconds total duration flowing in #12 AWG copper wire with the above effective resistance behavior. Number 12 wire is approximately 0.1 cm in radius, and thus has surge resistance $R = 4.66 \times 10^{-3}$ ohms per meter. The total electric energy dissipated in a one-meter length of #12 wire will be

$$W = i^2Rt = (10^4)^2(.00466)(4\times10^{-5}) = 18.65 \text{ watt-sec.} = 18.65 \text{ joules.}$$

The mass of copper in the 3.1 cm^2 volume of one meter of wire is m = 20 grams, and the specific heat of copper is c_p = 5.85 gcal/gm-°C = 24.5 joules/gm-°C. Therefore, the temperature rise in the copper conductor will be

$$\Delta T = \frac{W}{mc_p} = 0.03°C \ .$$

This amount of temperature rise is truly negligible.

Next, consider a strand of #18 wire with half the radius of #12 wire and therefore, twice the lightning surge resistance and one-quarter the cross sectional area and volume; and allow this wire to conduct a 40 μsec pulse of 100,000 amperes. The temperature rise in this case will be 800 times the temperature rise in the #12 wire, or 24°C (43°F). This temperature rise is still not enough to even damage the insulation on wire, let alone the conductor itself.

The estimates used above for lightning surge resistance overestimate this parameter to some degree and therefore, overestimate the amount of lightning-induced heating of the conductors. The above calculations do indicate that it is not the current in a lightning surge itself that is responsible for destroying <u>conductors</u>, even small conductors. Rather, it is the effects of not providing a low-resistance path for the current to flow in. This leads to voltages being reached that are whatever is required for the current to flow, which leads in turn to arcing between conductors or between conducting objects at high voltage levels with tremendously increased energy release in the vicinity of the conductors.

4.3 Mechanical Forces on Conductors Due to Surges

Next, consider the electromechanical forces acting on conductors carrying surge currents, as shown in Figure 6. A straight current-carrying conductor gives rise to magnetic field strength circling itself of magnitude

$$B\phi = \mu_o \frac{I}{2\pi r} \text{ webers/m}^2\text{, where } \mu_o = 4\pi \times 10^{-7} \text{ henries/meter.}$$

Another conductor carrying current I' parallel to the first conductor and of length L will experience a force

$$F = BI'L\text{, or in vector terms, } \overline{F} = I'\overline{B}\times\overline{L}\ .$$

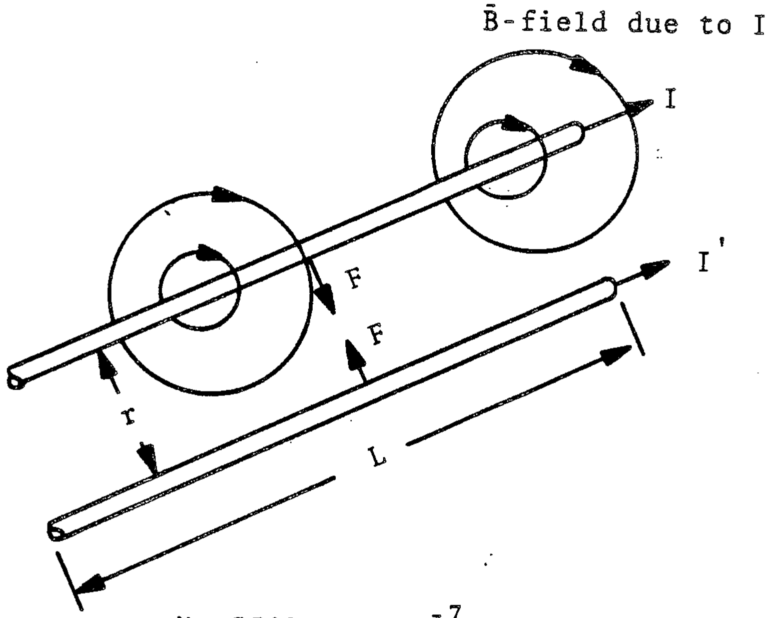
This force in fact acts mutually on both conductors and is attractive if the current flows in the same direction, and is repulsive if current flow is in opposite directions. If both conductors carry the same current, the force experienced by each is

$$F = \mu_o \frac{I^2 L}{2\pi r}$$ where r is the distance separating the wires. The forces acting on each of two parallel wires one meter long, separated by 10 cm (4 inches), and conducting typical peak lightning surge current of 10,000 amperes is

$$F = \frac{(4\pi x 10^{-7})(10^4)^2(1)}{(2\pi)(.1)} = 200 \text{ newtons} =$$

20.4 kg = 45 lb force.

It must be realized that conductors carrying high-frequency or pulsed currents will induce currents of similar



$$F = \frac{\mu_o\, II'L}{2\pi r} = \frac{2\text{x}10^{-7} II'}{r} \text{ NEWTONS}$$

WHERE I,I' ARE IN AMPS
AND r IS IN METERS

$$F = \frac{1.8\ II'}{r} \text{ lb. force}$$

WHERE I,I' ARE IN KILOAMPS
AND r IS IN INCHES

Figure 6. Magnetic forces between straight current-carrying conductors.

magnitude in nearby conductors, whether the nearby conductors be wires, sheet metal, or metal structural framework. These currents in turn will cause their own B-fields, which interact with the original current-carrying conductor. Thus, a single conductor carrying lightning stroke current will experience forces of the above magnitude if it passes near other metal objects or conductors. It is easy, therefore, to see how the current conduction effects of direct lightning stroke currents can easily destroy or damage conductors through electromechanical forces. It is therefore obvious that those conductors that <u>will</u> conduct lightning stroke currents, as well as those conductors that are <u>nearby</u>, must be of sufficient gage and must be adequately mechanically supported if they are to escape physical damage.

Whereas a single straight conductor produces a magnetic field that exerts no self-force on the conductor, large self-forces do result when conductors with bends conduct surge currents. In this case, every single straight segment of wire can be thought of as a single conductor generating its own magnetic field, and the forces exerted on the other segments will be of the same magnitude as the forces exerted between separate conductors. Therefore, it is imperative to provide more adequate support for ground leads with bends in them than is necessary for straight ground leads passing near only nonmetallic objects. In addition to increases in reactance due to the presence of bends, the bends add to potentiality for physical damage as well.

4.4 Effects of Surge Currents on Other Objects and Devices

As has been discussed, the heating effects of lightning stroke currents are directly proportional to the current times the voltage times the duration of the surge. If an arc discharge occurs between metal objects in an air atmosphere due to voltage breakdown, most of the voltage drop of the resulting arc discharge occurs across very short distances near each end of the arc. These voltage drop regions have voltages across them on the order of up to 10 volts for materials such as copper, steel, or carbon, when currents range in the thousands of amperes. Thus, a typical amount of energy released in a small region of space very near conducting objects might be on the order of

$$W = (10{,}000 \text{ amps})(2\text{x}10 \text{ volts})(4\text{x}10^{-5} \text{ sec}) = 80 \text{ joules.}$$

This much energy would not set fire to anything under most circumstances, unless a potential arc region had been placed immediately adjacent to a pile of tinder. We must keep in mind that lightning stroke currents of 10 times average current and 10 times average duration will occasionally occur, however. Therefore, on rare occasion, direct lightning surges will dissipate 800 joules; on rarer occasion still, 8,000 joules will be dissipated. So once in a very long time, in a location that has frequent enough lightning activity to begin with, an energy discharge of 800 joules, or 13 watt-minutes of power will be dissipated practically instantaneously in a very small region of space due to a lightning stroke being conducted across an arc, and combustible material such as wood, plastic, or insulation material can be directly set on fire.

Electrical devices, such as electromechanical relays, are therefore susceptable to damage due to failure of interterminal insulation and damage of insulation on wires. In addition, any electrical device having inductive coils or windings, such as a relay or motor, can suffer extreme mechanical damage due to the intense magnetic forces generated by interaction of stroke current with current-induced magnetic field.

It is informative to consider the total energy released in standard types of lightning arrestors and surge suppressors due to conduction of a typical direct lightning current stroke. The arc voltage drop across a carbon-block primary arrestor is approximately 200 volts, giving a total dissipated energy from a typical stroke of W = (10,000 amps)(200 volts)(40 μsec) = 80 joules. This will be sufficient to form a very hot spark of short duration that will vaporize some electrode material and will create a loud "pop." The arc voltage drop across a low-voltage rare-gas-filled arrestor is typically in the 50-volt range, yielding a total energy release of 20 joules from a typical current stroke. Energies of this magnitude are survivable by either of these arrestors. However, it must be remembered once again that on rare occasions energy releases of 10 or even 100 times these levels will occasionally occur due to strokes of greater than average peak current or greater than average duration, or both.

Of course, any communications-type semiconductor device or even a small power semiconductor device will be immediately destroyed by internal breakdown and heating if any sizeable portion of direct surge current is allowed to flow in it. The extremely small volumes of "active region" of semiconductor devices cause energy dumped into these devices in electrical impulses all to be concentrated in microscopic volumes, which then are heated beyond the failure point. Therefore, ultra-short current pulses have effects more severe by far than do current pulses of smaller amplitude but longer time duration that dissipate equal total energy in the semiconductor device.

Explosive effects of direct lightning surge currents frequently occur when a lightning arc discharge channel forms in the interior of a nonconducting object, such as a tree or stone or masonry wall. Under these circumstances, the gases formed in the vaporized arc channel cannot expand as they are heated and thus rise in pressure. The arc resistance of high-pressure arc columns increases rapidly as pressure increases, and the increased resistance leads to a greater rate of energy dissipation due to increased arc voltage gradient. The result can be arc voltage drops of thousands of volts, instantaneous energy release of hundreds of thousands of watts, and tens of thousands of joules of total energy released in an extremely small arc volume in a very short time, causing a small explosion that can crack a wall or splinter a tree.

When considering the effects of conduction of direct lightning stroke currents in the above, no consideration has been made of the effects of "power-follow" that can occur when power transmission systems are struck by lightning. Once an arc is struck, due to high-voltage breakdown caused by the lightning stroke, it is possible frequently for the arc to be maintained at voltages that are less than the system operating voltage for relatively long periods of time, leading to greatly increased energy dissipation--the energy now being supplied by the power system rather than by the lightning stroke. The design of lightning arresters to minimize the effects of power follow will be discussed in the section on lightning arresters. At this point, it will simply be noted that properly designed lightning arresting systems use lightning arresters that are wired into the circuits being protected in such a way that arcs occur mainly in the arresters themselves, limiting surge voltages in the circuits to levels below which arcs can be maintained anywhere else in the system; and the arresters have conduction and power handling characteristics that make them immune to the effects of power follow.

4.5 Electrostatically Induced Lightning Surges

Consider an overhead line that is at an elevation of $h = 5$ meters (16 ft.), with conductor size that gives a surge impedance or characteristic impedance for wave transmission of $Z_o = 500$ ohms, corresponding to #12 wire at that elevation, according to the relationship $Z_o = 60 \ln\left(\frac{2h}{a}\right)$ where $a = 0.1$ cm for #12 wire, and assume that this line is several kilometers in length. Next assume that a lightning cloud passes overhead, causing induced positive charge on the ground underneath the line. There will be some finite level of leakage resistance between line and ground, which will allow the line to charge to ground potential. The surge impedance Z_o of the line, its inductance per meter L, and its capacitance per meter C, and its wave propagation velocity are related by the equations

$$c = 3\text{x}10^8 \text{ meters/sec} = 1/(LC)^{1/2}, \; Z = (L/C)^{1/2}.$$

Therefore, this typical line will have a capacitance per meter with respect to the ground plane of

$$C = (LC)^{1/2}(C/L)^{1/2} = 1/(Z_oc) =$$
$$6.67\text{x}10^{-12} \text{ farads per meter.}$$

Even a total shunt resistance to ground of 1000 megohms every kilometer of line will give a circuit RC time constant of

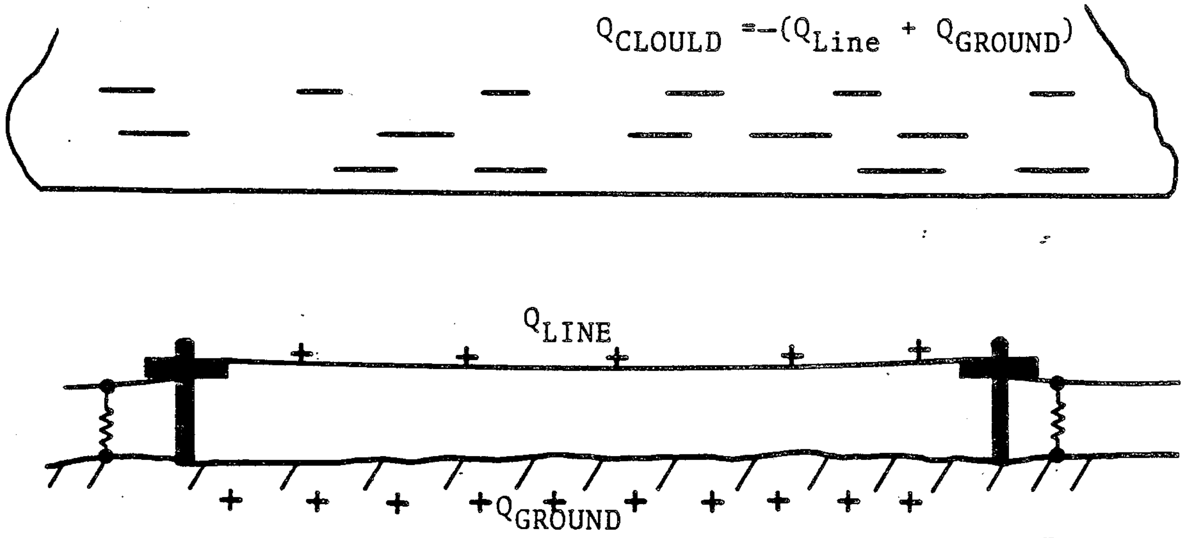
$(6.67\times10^{-12}\times1000\times10^{9} = 6.7$ seconds, and therefore, in the minutes it takes for a thunder cloud to pass overhead, the overhead line will remain quite constantly at ground potential. Charges will be induced on the line by the overhead cloud; and the amount of induced charge on the line will be exactly the amount required to cancel the voltage drop that would occur in the distance from the line elevation to ground if the line were not there. If the average cloud-to-ground electric field is near the critical level for lightning strokes of approximately $E = 10^{5}$ volts per meter, the charge induced on the line will be

$$Q = CV = CEh = 6.67 \times 10^{-12}\times5\times10^{5} =$$
$$3.33\times10^{-6} \text{ coul/meter.}$$

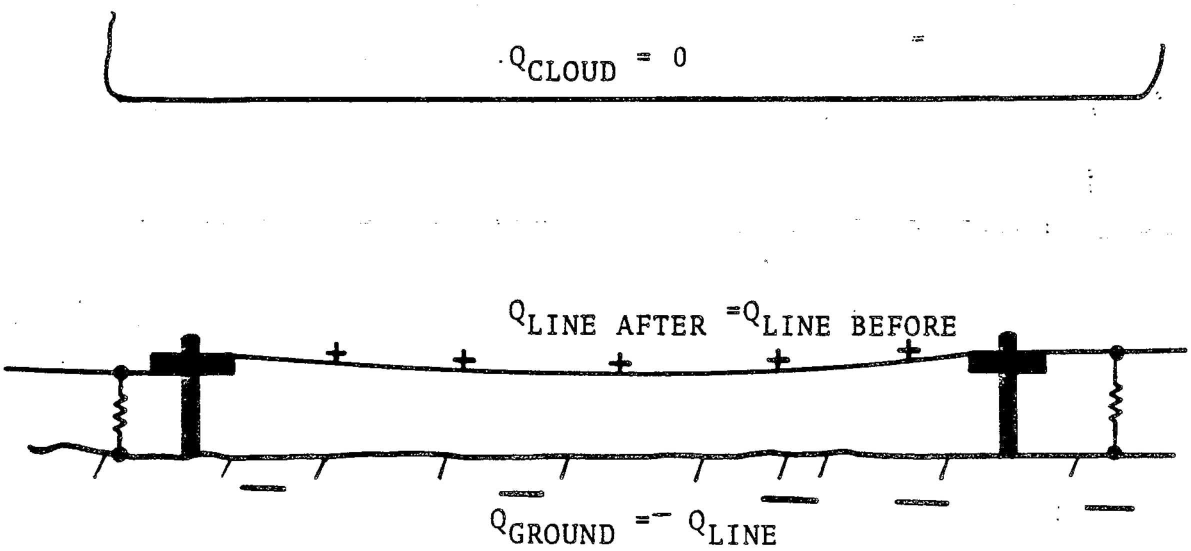
Now allow a lightning flash to occur in the region near the overhead line, and assume that the stroke currents that flow during the flash completely neutralize the opposite charges on cloud and ground. Flashes occur in extremely short times--times that are too short for the charge induced on the line to leak back to the ground. Therefore, immediately after the flash, the induced charge on the line is still there, and now produces an electric field between line and ground of opposite polarity to the original cloud-to-ground electric field; and the resulting line-to-ground voltage will be $V = Eh = +5 \times 10^{5}$ volts. This mechanism is pictured in Figure 7.

The total stored energy in a kilometer of line will be

$$W = \ell CV^{2}/2 = (1000)(6.67\times10^{-12})(2.5\times10^{11})/2 = 830 \text{ joules.}$$



a) BEFORE FLASH.



b) AFTER FLASH.

Figure 7. Charge distribution on cloud, overhead line, and ground, a) immediately before, and b) immediately after lightning stroke in vicinity. After the stroke, half of Q_{line} will immediately start travelling in each direction at approximately the speed of light, producing a moving surge on the line.

This quantity of stored electrostatic energy is rather large and is obviously capable of doing severe damage to electrical equipment. Further, it represents a grave safety hazard. In high-voltage power transmission systems, the insulators from which overhead lines are suspended might often be capable of withstanding the extremely high voltages found in the above analysis. However, communications lines supported by glass or ceramic one-piece insulators will not maintain these large voltages for any considerable time, since arcing will occur across the insulators to the poles carrying the lines, and the line voltage will be lowered to approximately the 35,000 volt range in a matter of microseconds, this figure representing an approximate withstand voltage of typical communications line insulators. After this lower voltage level is reached, there remains stored electrostatic energy in one kilometer of line of approximately

$$W = \ell CV^2/2 = (1000)(6.67\text{x}10^{-12})(35{,}000)^2/2 = 4 \text{ joules.}$$

This remaining stored energy is not sufficient to cause damage to electromechanical components that are minimally protected with any type of arrester or surge suppressor. The remaining stored energy is sufficient to destroy semiconductor equipment that is not adequately protected, and it does represent a very severe safety hazard to humans.

In order to understand what happens to the induced charge on the line and the stored energy on the line after voltages have reached a level along the line that can be withstood by the low-voltage insulators used for support, one must use transmission line theory. Half of the induced charge will start flowing one way, and half the other way on the line at almost the speed of light. The travelling current and voltage surges will be partly reflected, partly attenuated, and partly transmitted forward every time a resistive path to ground is encountered, unless a resistance to ground is encountered that exactly matches the characteristic impedance of the line Z_o, at the end of the line. Even a gap-type lightning arrester or even a dead short to ground will not cause the surge to be immediately dissipated. Rather, partial or nearly complete reflection of the surge will occur, with the wave then travelling in the other direction down the line. Thus, actual voltage surge waveforms and current surge waveforms can appear quite complicated in any given overhead line, with overall time-varying behavior depending on many factors.

The important fact to remember about surges that are electrostatically induced in overhead lines is that they do carry enough voltage and energy to damage unprotected equipment and to injure or kill humans. Since these surges can result from lightning strokes in the general vicinity of the overhead lines--direct strikes not being necessary--current and voltage surges of dangerous and damaging magnitude will be observed far more frequently in overhead lines than one would expect just on the basis of probability of direct lightning strikes.

4.6 Magnetically Induced Lightning Surges

A good rule of thumb for calculating the induced surge current or voltage in a line due to a surge in an adjacent line when no shielding is provided between the lines and when the lines are located closer to each other than they are to ground, is to assume that the surge induced in the second circuit will be equal in magnitude to the primary surge in the original circuit. One can calculate the mutual inductance between adjacent conductors to any degree of accuracy, but for a worst-case analysis, it turns out that two conductors spaced very closely with only their insulation separating them have mutual inductance nearly equal to the self-inductance of either conductor. Therefore, the mutual inductance between two conductors can be approximately calculated by calculating the self-inductance of one conductor over the length of the adjacent region. In a situation where conductors cannot be magnetically shielded from each other, each conductor therefore must be equipped with lightning arrester protection equivalent to the other for the protection of connected electrical equipment and for the protection of persons.

As an extreme case of magnetic coupling effects, consider the magnetic coupling that can occur to an overhead line due to a nearby lightning stroke. Figure 8 shows a lightning stroke striking the ground at a distance of 100 meters from the end of a 1-km long overhead line that is 5 meters above ground. If it is assumed that the current in the lightning stroke rises linearly to a peak value of 10,000 amperes in a time of 4 microseconds, then the sum of voltages induced across devices connected to the ends of the line is

$$V = \frac{d\Phi}{dt} = \mu_o h I_{max} \ln(1100/100)/\tau_{rise} = 6000 \text{ volts.}$$

This voltage is much smaller than other voltages induced by other effects, but it is still of dangerous magnitude. The above calculation serves to demonstrate potential magnitudes of magnetically induced surges caused by the very large stroke current surges even when these are a great distance from another circuit.

4.7 Lightning Surges Induced by Impedance Effects

When analyzing the currents and voltages caused by lightning, one must keep in mind that at the massive current levels of lightning strokes and in the very short time intervals it takes for currents to rise and decay, every single object through which stroke current flows, including the ground itself, must be regarded as an impedance. Wet dirt has a resistivity

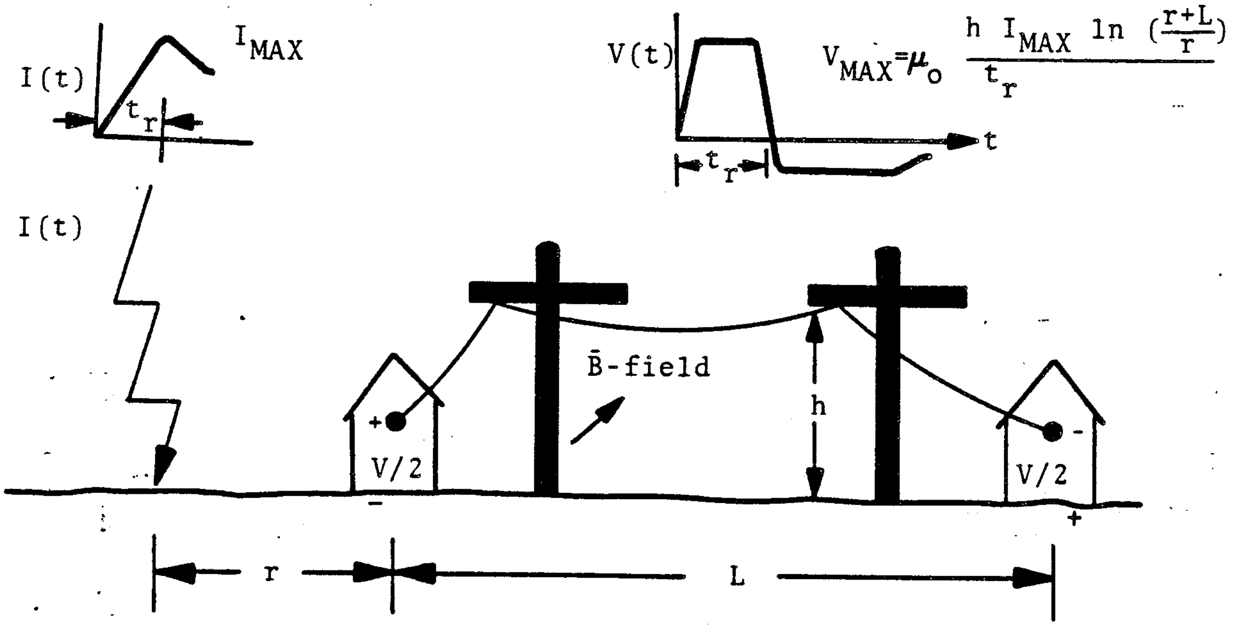


Figure 8. Schematic diagram showing direct inductive coupling from lightning stroke current to an overhead line.

of approximately $\rho = 100$ ohm-meters, and very dry dirt or rock can have a resistivity in the vicinity of $\rho = 10^6$ ohm-meters. Thus, lightning stroke currents passing through the ground can give rise to enormous point-to-point voltages along the surface of the ground. These voltages produce one of the greatest hazards to people and livestock outdoors during a lightning storm. In addition, these voltages appear in circuits of large spatial extent that are in close proximity to ground.

In analyzing the voltages that result from lightning stroke currents flowing in the ground, we must calculate the electric fields that result from currents passing through bulk resistive material. Under dc conditions, current injected into the ground at a point will spread radially outward from the point of injection, and downward as well. Since the current flows through concentric hemispherical surfaces of radius r and area $A = 2\pi r^2$, we can calculate electric fields along the surface of the ground by the relation

$$E = I\rho/A = I\rho/2\pi r^2 \text{ volts/meter.}$$

Under pulsed conditions, account must be taken of the ac skin effect exhibited by conductors in the presence of rapidly varying electromagnetic fields. The currents do not penetrate infinitely deep into a conductor; rather they are concentrated in a region near the surface of "skin depth" δ, where

$$\delta = \sqrt{\rho/\pi f \mu} \, .$$

In the above relation, f is the frequency at which the electromagnetic field varies, and μ is the magnetic permeability of the conducting material. If we assume that a lightning stroke has an approximate "frequency" of 10,000 Hz, and we assume that earth has magnetic permeability little different from free space, then the skin depth is given by

$$\delta = (\rho/\pi \times 4\pi \times 10^{-7} \times 10^{4})^{1/2} = \sqrt{1{,}000\rho}/2\pi \ .$$

The current due to a lightning stroke can now be assumed to flow outward across a cylindrical surface of area $A = 2\pi r\delta$, producing an electric field along the surface of the ground of magnitude

$$E = I\rho/A = I(10^{-3}\rho)^{1/2}/r \ .$$

Figure 9 shows the behavior of current flow in the ground due to a lightning stroke. The electric field gradient as a function of r along the surface of the ground is approximately

$$E(r) = \begin{cases} I\rho/2\pi r^{2}, & \text{for } r < 5\rho^{1/2} \\ I(10^{-3}\rho)^{1/2}/r, & \text{for } r > 5\rho^{1/2} \end{cases} \ .$$

Under conditions where the ground resistivity has a typical value of approximately 1000 ohm-meters, the critical value of r in the above equation is approximately 150 meters.

As an example of voltages that can arise in a circuit, assume that a wire extends 100 meters from an instrument case at one end to an instrument case at the other end, and each instrument case is "grounded." Then assume that a lightning

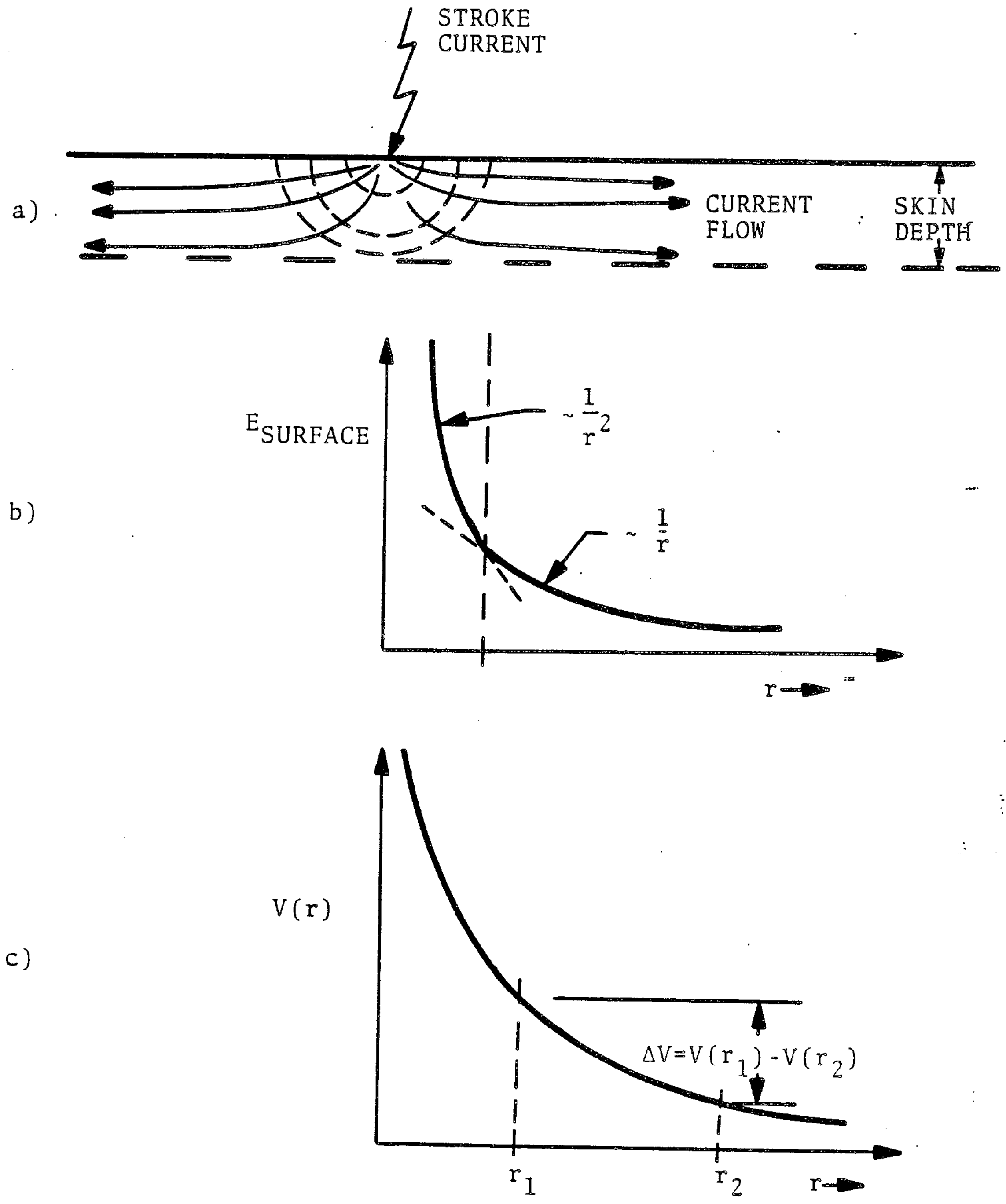


Figure 9.
- a) Approximate current flux distribution due to lightning stroke hitting resistive earth, including skin effect.
- b) Resulting radial electric field at the surface of the ground.
- c) Resulting voltage gradient at the surface of the ground.

stroke hits the ground 50 meters from one end of the wire and 150 meters from the other end. The instrument cases then have a total potential difference

$$-V = \int_{r_1}^{r_2} E(r)dr = (I\rho/2\pi)\left[\frac{1}{r_1} - \frac{1}{r_2}\right] = 2\text{x}10^{-3}\ I\rho \text{ volts.}$$

If I has peak value of 10,000 amperes, and ρ = 1000 ohm-meters, the total of voltage drops between the ends of the wires and the instrument cases into which the wires run will have a maximum value of V_{max} = 20,000 volts.

Using the same figures for resistivity and current, the voltage drop between two rails of a railroad track when lightning strikes 10 meters away is also calculated to be

$$V_{max} = \frac{10^4 \text{ x } 10^3}{2\pi}\left[\frac{1}{10} - \frac{1}{11.44}\right] = 20{,}000 \text{ volts.}$$

The question immediately arises, If these very large voltages appear to arise in spatially extended circuits when different points are tied to local ground, would it not be better to isolate them from ground? The answer is that one would have to put the entire system on gigantic standoff insulating supports and surround it with a Faraday cage if he were to take this approach--signal wires, tracks, relay racks, bungalows, and all. It simply is not practical. The next best approach is to provide an extensive interconnection system in the form of a grounding system to tie all portions of relay racks and bungalows at one location together, and then use lightning arrestors to limit line voltage excursions away from local ground potential to safe levels. Incoming lines must be routed and lightning arrestors must be placed so that the surge currents that flow in incoming lines due to induced ground potentials can be conducted safely to ground.

Inductive reactance also plays a role in induced surges one line or wire conducting a surge will have on inductive voltage drop along its length. Voltage can be raised thousands of volts above the potential of adjacent lines tied to ground a distance away, and arcing can then occur between conductors. When the overhead ground wire protecting overhead lines from direct lightning strikes is hit, local ground voltage at the pole tops nearest the lightning strike can be raised sufficiently above distant ground level due to ground resistance and ground lead inductance in the grounding wire fastened to the pole to cause "back flashovers" to the protected lines. The same phenomenon can occur in instrument housings, and is the reason why ground wires must be as heavy, short, and straight as possible.

4.8 Conclusions

The total surge current and voltage waveforms resulting in an electrical system due to a single lightning stroke or a series of lightning strokes in one flash must be viewed as resulting from a combination of effects. Direct stroke currents can release tremendous energy in an electrical system that is not adequately protected. In addition to direct lightning strikes, induced surges are of equal importance, and perhaps because of their greater probability of occurrence, of greater importance in estimating overall potential hazards to circuits from lightning. The problems of protecting against induced surges are more complex than those of protecting against damage from direct lightning strokes. For the latter, it suffices to install as many lightning rods and ground conductors as are required to do the job, but for protection against the former, great care must be taken in circuit design, layout, employment of shielding for conductors, and placement of protective devices--even after the hazards of direct stroke currents have been completely eliminated.

To conclude this section of the report, the reader is reminded once again that all of the sample calculations that were performed above in which maximum surge currents of 10,000 amperes, and current rise and fall times of 4 and 40 microseconds respectively, only give <u>typical</u> results of lightning strokes. Stroke currents of greater than 100,000 amperes and stroke durations of 400 microseconds or even longer will occur some proportion of the time, and must be protected against.

5. DEVICES AND TECHNIQUES USED TO PROTECT ELECTRICAL CIRCUITS FROM LIGHTNING SURGE EFFECTS

Devices used to protect electrical circuits from surges caused by lightning operate in a number of ways. Voltage-limiting devices such as spark-gap arresters and zener diodes provide low-impedance paths for conducting surge currents to ground while voltages are maintained below levels that are presumably safe for equipment. Reactive devices such as series inductors and shunt capacitors are used to "slow down" and "flatten out" the residual portions of surges that get past voltage-limiting devices, so that voltage rises and current amplitudes will be further attenuated, and so that following voltage-limiting devices will have time to work. Reactive elements can be thought of as providing low-pass filtering to block the high-speed surge transients while allowing normal circuit operation at very low frequencies or dc. A large number of types of devices and combinations of devices are described below. Equivalent circuits for these devices are shown in Figure 10.

5.1 Gap-type Arresters

One of the first types of protective devices to be used in electrical circuits for shunting lightning surges to ground was the gap-type arrester (Figure 10a). Depending on the specific shape of the gap electrodes--pointed vs. flat--and

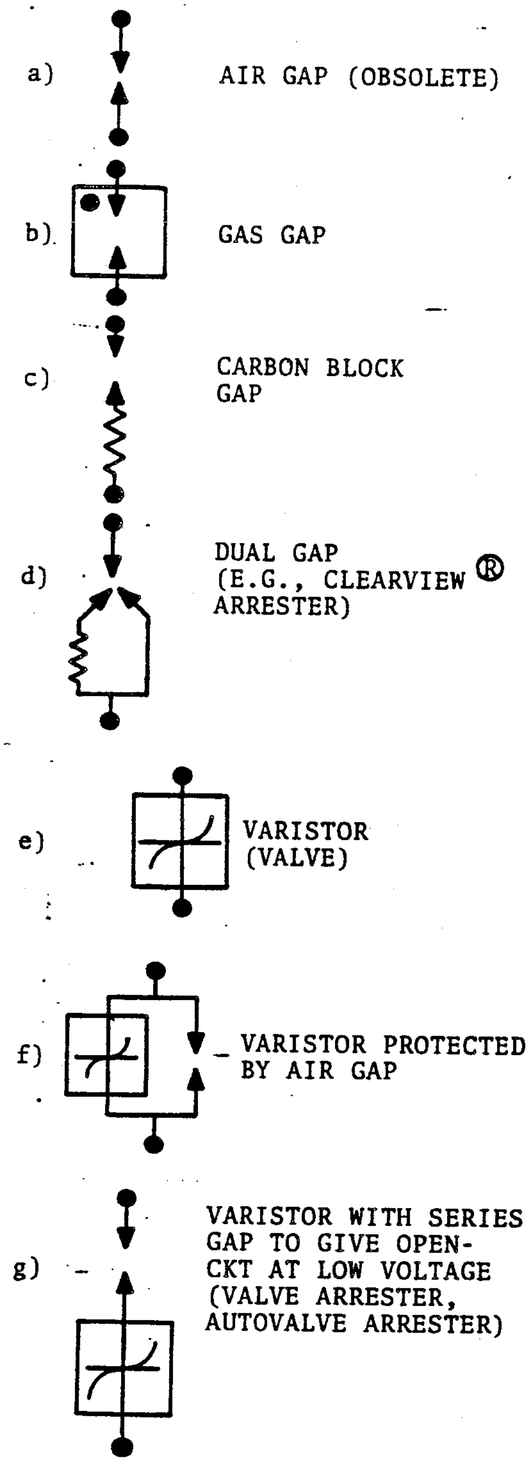
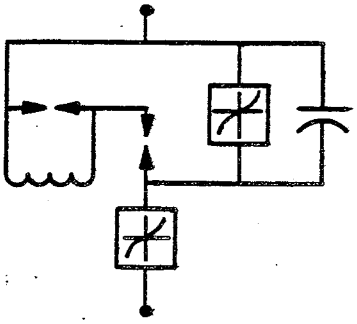


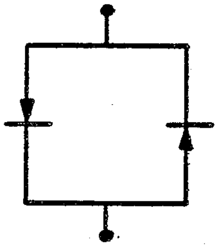
Figure 10. Circuit diagrams and symbols for various types of lightning arresters and surge protective devices.

h)



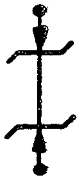
CURRENT-LIMITING GAP (MAGNE-VALVE)

i)



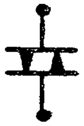
BACK-TO-BACK DIODES (V_{MAX} < 1 VOLT)

j)



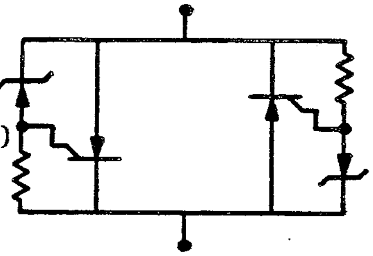
REVERSE-BREAKDOWN DIODES (SELENIUM OR SILICON ZENER DIODES)

k)



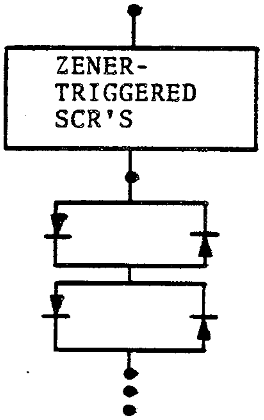
BIDIRECTIONAL BREAKDOWN DIODE (FOR AC USE ONLY)

l)



ZENER-TRIGG ERED SCR'S (EX: SAFETRAN SOLID-STATE ARRESTER) (FOR AC USE ONLY)

m)



DIODE STACK ADDED TO GIVE SELF-CLEARING ON LOW-VOLTAGE DC CIRCUITS (EX: SAFETRAN SOLID-STATE ARRESTER BOOSTER)

Figure 10, continued

depending on the electrode material and the spacing of electrodes, it is possible to construct an air-gap device with electrode spacings on the order of a fraction of a millimeter that will electrically break down forming an arc discharge when dc gap voltages reach approximately 300 to 3,000 volts. Generally, pointed electrodes give lower breakdown voltages, and smoothly polished electrodes give higher breakdown voltages. As the gap spacing widens, breakdown voltage increases, but the relationship is not a linear one. As a practical matter, there are difficulties in using simple air-gap arresters for protecting power circuits, since after an arc discharge is struck by a high-voltage surge, a much smaller dc or 60 Hz ac voltage is sufficient to sustain the arc. Figure 11 illustrates the current-voltage characteristics of arc discharges. If the normally present system voltage and source impedance are such as to produce a load-line that does not intercept the arc current curve, the arc will extinguish itself after the surge passes. If the system voltage and impedance characteristics are such as to sustain the arc once struck, a permanent fault results. In high-voltage power transmission systems relying on gap-type arresters, series circuit breakers are used to interrupt circuits long enough to extinguish arcs and clear faults. These brief interruptions of power are what frequently cause the lights to flicker or blink during a lightning storm.

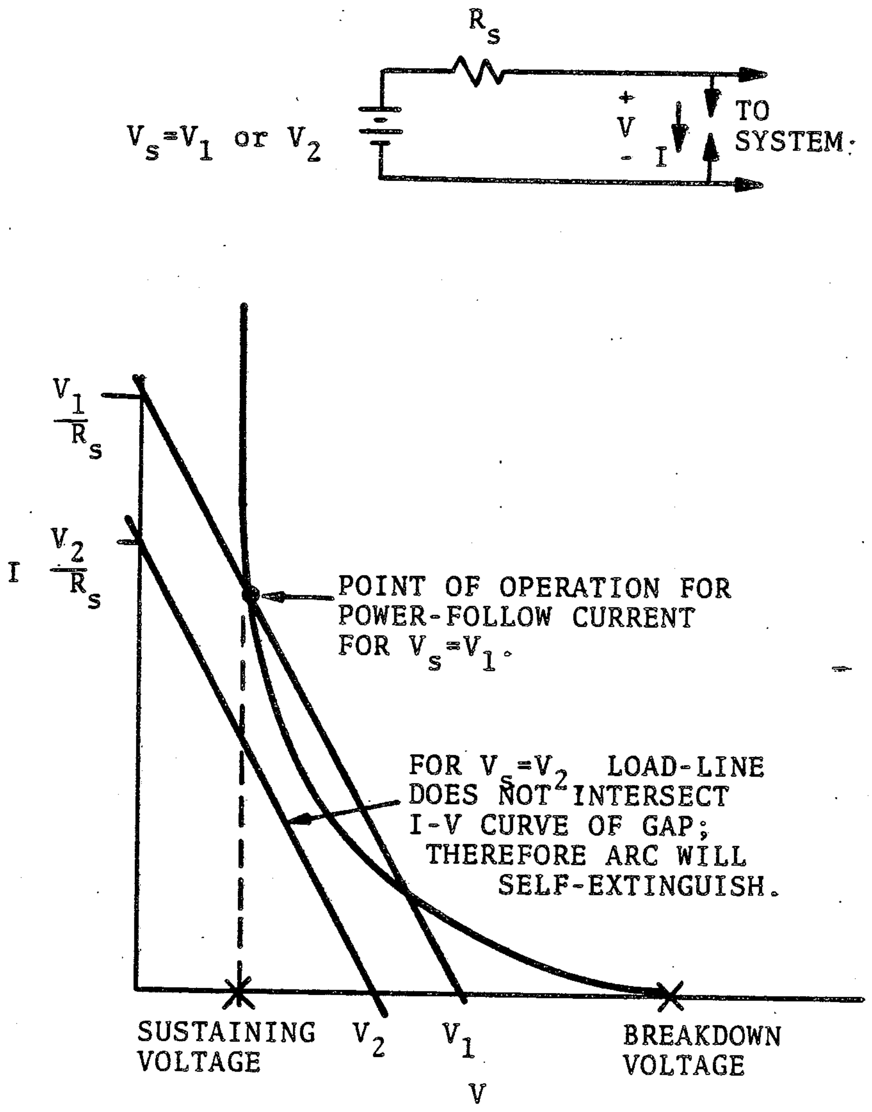


Figure 11. Load line diagram for predicting whether or not power-follow current will flow.

One critical difficulty in employing air gap-type arresters is that the initiation of the arc discharge depends on avalanche breakdown of the air in the gap, and the time required after a voltage surge is impressed to establish the arc discharge and lower the voltage is statistical in nature and is frequently too long on the average to provide adequate protection to sensitive circuits. The response speed of a given gap-type arrester is generally stated by recording the ratio of sparkover voltage upon application of rising voltage ramps of different speeds to the sparkover voltage under dc conditions. For instance, an air-gap arrester that has a dc rating of 500 volts may not break down until a surge rising at 10,000 volts/microsecond reaches 1,500 to 2,000 volts. Faster rising surges will go higher before breakdown is reached. In addition, after breakdown is reached, some time is taken for the arc to establish itself and for the voltage to drop to the sustaining voltage level. The result is that the air-gap arrester passes a residual surge that must further be dealt with. Heavy electromechanical railroad relays are generally immune from normally encountered residual surges. Solid-state equipment is not.

Gas-filled gap-type arresters (Figure 10b) have been used increasingly in recent years, and offer a number of advantages over air-gap arresters. Mixtures of rare gases at a total pressure of approximately one atmosphere are typically used.

The breakdown characteristics of the gas allow wider gap spacing for equal breakdown voltages, and the wider spacing makes possible maintenance of more accurate tolerances on breakdown voltage, and thus allows for use of devices having lower nominal breakdown levels. In addition, they are generally faster in operation. Some gas-filled arresters incorporate a radioactive source to enhance operating speed. A potential disadvantage of gas-filled arresters is that since the arc volume is completely enclosed in an insulating envelope, unrelieved pressures can be reached during high-power surges that can rupture and destroy the devices.

Gap-type arresters are seldom employed alone but are generally used as one element in an overall protective system. One modification that has been used in air-gap arresters to improve their operating characteristics is to include a carbon-block resistor in series with the air gap (Figure 10c). This produces an overall current-voltage characteristic that will cause the arc to self-extinguish in low-power circuits. Inclusion of the resistor offers the disadvantage that it causes additional voltage and additional power consumption and heating during high-current surges.

One air-gap type arrester that is widely used in railroad applications employs closely-spaced gap electrodes in series with a carbon resistor, in conjunction with an added electrode with wider spacing that has no resistor in series (Figure 10d). In operation, the narrow gap breaks down first, but rising current causes IR voltage drop across the resistor that makes the longer gap the lower-impedance path for current. Ionization from the narrow gap initiates the arc discharge across the wider gap, which in turn limits the current through the resistor. Figure 12 compares this device's I-V characteristics to the previously mentioned devices. This device offers the turn-on characteristics of a narrow-gap arrester, and the turn-off characteristics of a wide-gap arrester, and thus offers superior protection in conjunction with greater immunity from the effects of power-follow in low-power circuits. A typical device of this design will self-clear in circuits where dc voltages are 50 volts or less, or where ac voltages are 175 volts or less, while providing breakdown voltage of 700 to 1000 volts.

5.2 Varistor Devices (Valve or Thyrite Devices)

If protective levels below approximately 300 volts are desired in electrical circuits, air-gap or gas-gap devices are generally unuseable. Manufacturing tolerances do not allow the required dimensional accuracy in the very narrow spacing needed at lower voltages. For voltage limitation to lower levels under surge conditions, the nonlinear current-voltage characteristics of "Thyrite" materials are typically used. (Thyrite is General

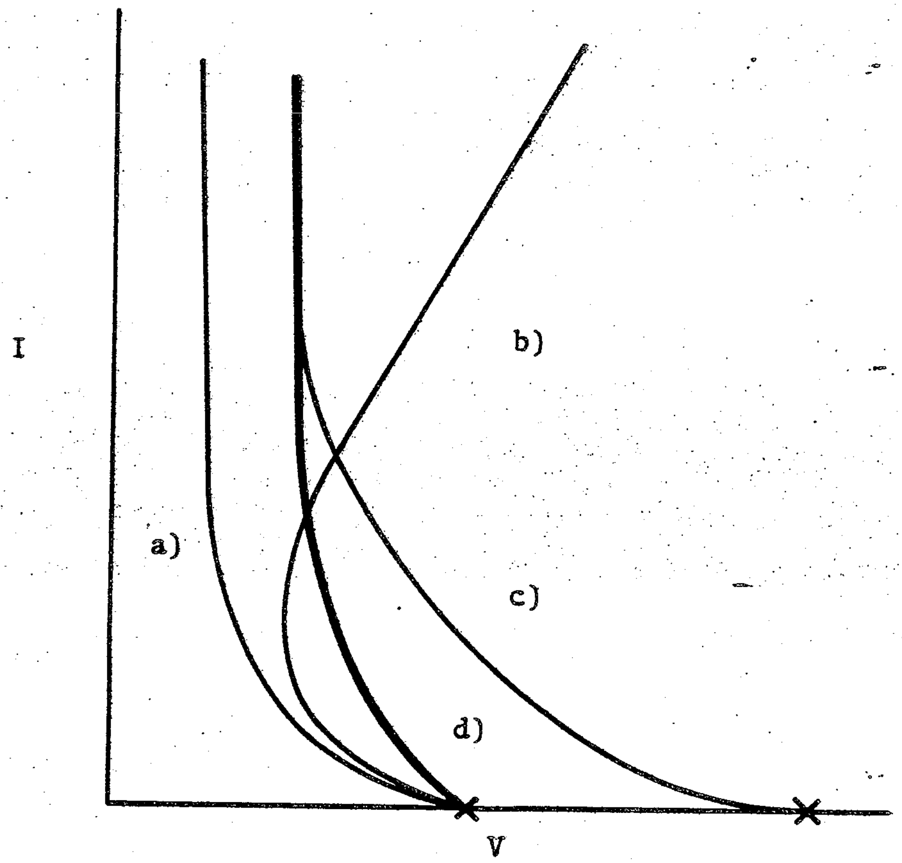


Figure 12. Current vs. Voltage Behavior for a) Low-voltage air gap, b) low-voltage air gap in series with a resistance, c) high-voltage air gap, and d) device of type (b) shunted with device of type (c).

Electric's registered trade name.) Thyrite devices, also referred to as varistor or valve devices (Figure 10e), are basically composed of bulk silicon carbide with portions of other materials added that is finely ground and then compressed and sintered. The conductivity characteristics of a solid device made from such material result in current vs. voltage behavior that over many orders of current magnitude can be approximated by the relation

$$I = kV^n \ , \quad \text{or} \quad V = (I/k)^{1/n}$$

where n is typically approximately 3 to 5. These devices are generally spoken of as having decreasing resistance with increasing current, or a negative current coefficient of resistance. The value of k will depend on the dimensions and exact composition of the material used, and the value of n will depend on composition.

In operation, a device having $k = 10^{-6}$ and $n = 4$ will pass .01 amps at V = 10 volts, and 100 amps at V = 100 volts. A 10,000 ampere surge will result in a peak voltage of 300 volts, at which time the ratio of voltage to current will be (V/I) = 0.03 ohms.

General Electric has recently introduced varistors fabricated from metal oxide material for which their trade name is GE-MOV. This new material produces varistors with n as high as 25, thus providing exceptional voltage limitation during high-current surges.

In signal circuits, varistor devices are typically employed when it is desired to provide surge voltage limitation at values from a few tens of volts up to the range where air gaps become practical. In addition, they are employed in power circuits at all voltage levels because they are immune to power-follow effects. In signal circuits where the primary danger is from power-line transients and other surges not as severe as lightning surges, varistors are often used by themselves, with voltage and power handling capability being chosen as a function of specific application. For applications in higher power systems or in more severe environments, varistors are used in conjunction with spark gaps to provide the required current-voltage behavior and to provide the required energy handling capacity.

Since varistors are frequently used to limit surge voltage differences between conductor pairs in balanced signalling circuits or across signal lamp filaments, they are called "equalizers." When used in other applications, they are called "discharge resistors." For heavy-duty applications, a spark gap is provided to shunt extremely high current surges around the varistor, thereby controlling the maximum energy dissipated in the varistor (Figure 10f). These devices are also referred to as "heavy-duty equalizers" and "shunt-type arresters." Heavy-duty equalizers have been designed for ac power circuit applications to protect power transformers. In such an application, a number of low-voltage shunt-type devices are connected in series to establish a higher voltage rating. Surges of lower current are passed directly by the varistor elements. Higher current surges will cause the air gaps to arc, but the arcs will self-extinguish in an ac circuit after the surge has passed, due to cooling during the current zero-crossings. Extinguishing of the arc is aided by the varistor, which can be thought of as "robbing current" from the arc at higher voltages. Initial arcing voltage levels can be maintained at a relatively high level, since power transformers are relatively rugged devices.

Frequently, varistors are used in series with air gaps (Figure 10g). In this configuration, a completely open circuit results at lower voltages. Voltage surges will break down the air gap, but the overall current-voltage characteristics of gap plus varistor will enhance self-clearing. Series combinations of varistors and air gaps are called "autovalve arresters" or "autovalve blocks." Lower-voltage units are stacked in series and packaged for outdoor use for protecting high-voltage power lines. Autovalve arresters can be designed to offer adequate lightning protection to ac power transmission lines and at the same time have overall current-voltage characteristics that will provide for self-clearing of faults in ac systems.

5.3 Arresters Incorporating Magnetic Arc Control

For providing a high degree of reliable surge protection and elimination of power-follow problems in either dc or ac power circuits, devices using magnetic arc control are employed (Figure 10h). In these devices, a fraction of the surge current is passed through magnetic coils, and a magnetic field is generated at a right angle to the majority of surge current that is conducted across an arc gap. The $\bar{I} \times \bar{B}$ force causes the arc to move sideways, stretching it, increasing its voltage, and cooling it, thus causing it to self-extinguish after the surge has passed. In one such device, called the "Magne-Valve," spark-gap bypass is provided around the magnetic coil to protect it from damage from very large surges, and a series varistor is included to assist in elimination of power-follow. Individual magne-valve units are stacked in series for protection of high-voltage power lines, with one unit added for each 6 kv of line voltage. When used in series strings, each magne-valve unit incorporates a very high-resistance varistor and a small capacitor shunting the main arc gap to assure uniform voltages and breakdown conditions along the string during fast rising surges. Magne-valve arresters can be designed to adequately protect high-voltage dc power transmission lines, and self-clear to prevent power-follow. When used on ac power lines, they offer greater effectiveness and reliability than autovalve arresters.

In some arresters designed for even low-voltage systems, magnetic coils or permanent magnets are employed to produce magnetic fields that continuously move the arc in a spark gap, thus preventing overheating of any one spot on the cathode electrode. This design feature leads to greater power handling capability and longer lifetime.

In some very sophisticated lightning arresters, pulse transformer igniting circuits or piezoelectric igniting circuits are used to speed initial arc formation. Magnetic arc control devices frequently use arc chambers filled with rare gas.

5.4 Solid-state Devices Used for Surge Suppression

No solid-state semiconductor device used for surge suppression can really be spoken of as being a "lightning arrestor" but a variety of semiconductor devices are routinely used to attenuate residual surges left after gap-type arrestors or varistor-type arrestors have shunted the bulk of a surge to ground. In an electronic environment where surges offer hazard to semiconductor components, it is axiomatic that "you have to use a semiconductor to protect a semiconductor." Semiconductor devices offer great speed, sensitivity, and packing density in electronic or electrical circuits. These attributes are made possible by microscopic size of the actual silicon chips that perform the electronic functions, but these same attributes result in extreme sensitivity to total surge energy and to surge voltage transients.

For providing high-speed voltage limitation at levels of a fraction of a volt to a few volts in semiconductor circuits, parallel back-to-back pairs of single silicon diodes or strings of diodes are generally used (Figure 10i). I-V characteristics are depicted in Figure 13. Silicon power rectifier diodes are available that can handle thousands of amperes of instantaneous surge current for very short periods of time. Such diode arrays are more expensive than varistor-type devices, but they do provide very reliable protection, due to practically unlimited speed of operation and extremely rapidly rising current vs. applied voltage. As semiconductor device costs have fallen over the years, the use of silicon diodes as surge suppressing elements has become more economically viable and attractive.

For voltages from a few volts up to a few hundred volts, silicon zener diodes are frequently employed (Figure 10j). These offer a very steeply rising current vs. voltage characteristic in the reverse breakdown region--more steeply rising than any varistor material. In the past, the reverse-breakdown characteristics of selenium diodes have been used to provide voltage limitation in sensitive electronic circuits. They offer current-voltage characteristics intermediate between those of silicon zener diodes and varistor devices, but until recently provided greater reliability than silicon zener diodes at less cost.

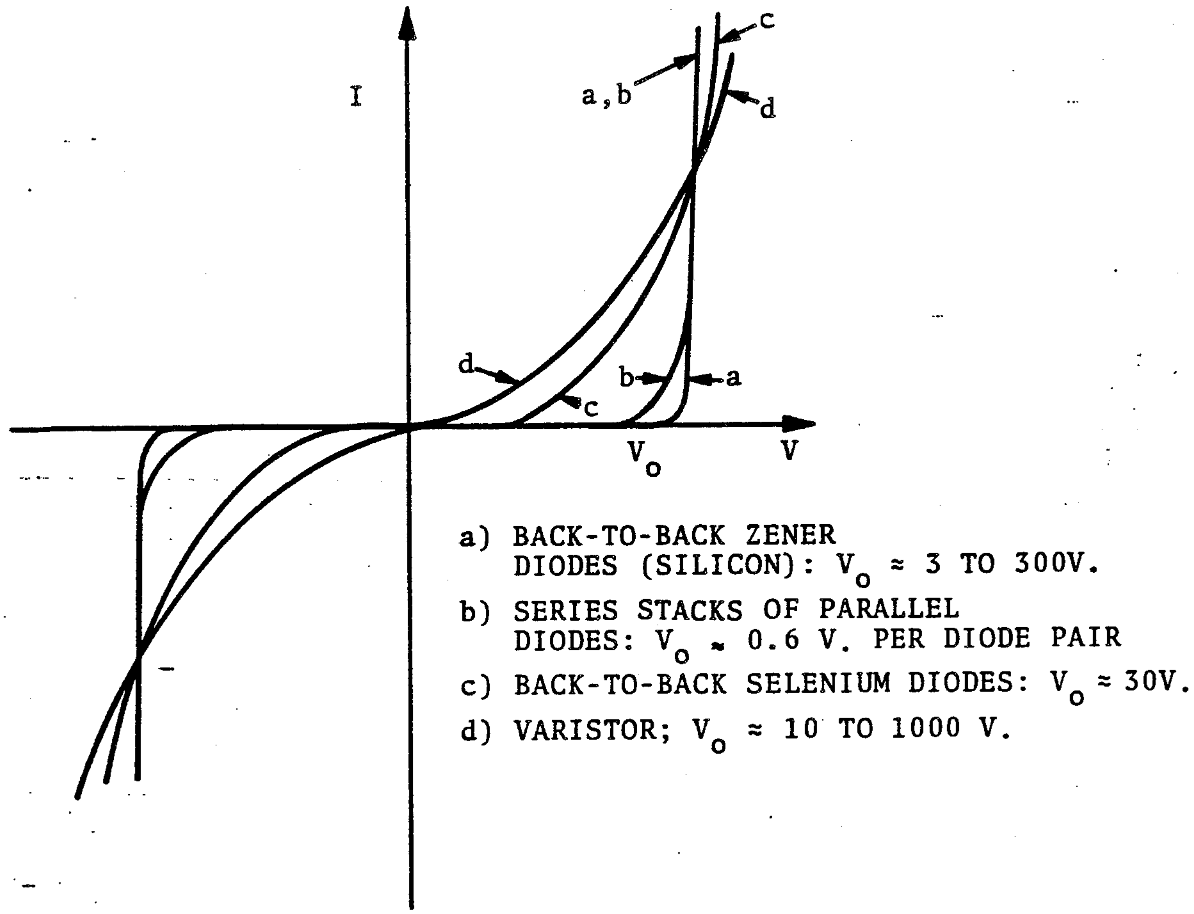


Figure 13. Normalized current-voltage curves for a variety of surge protective devices. In general, the steeper the curve rises for voltages above V_o, the greater the protection against overvoltages.

The power dissipated in any voltage limiter is equal to the instantaneous current times the voltage maintained while current flows. Since the devices mentioned above sustain the voltage instead of switching to a low-voltage "on" state, they will dissipate a great deal of electrical energy during a current surge. This problem can be avoided by using solid-state breakdown devices such as silicon controlled rectifiers or bidirectional breakdown diodes (Figure 10k) to provide voltage limitation. All such devices, including unidirectional breakdown diodes or diacs, and bidirectional SCR's or triacs, are spoken of as "thyristors." Bidirectional breakdown diodes are the solid-state equivalent of a spark gap. Within the silicon wafer of the device, a semiconductor region exists that is insulating until voltage is applied that causes avalanche ionization of the semiconductor material and production of large numbers of holes and electrons. After avalanche ionization occurs, the device becomes a very good conductor and the voltage across the device falls to a fraction of a volt while very high-current surges are passed. Since a very small current is sufficient to maintain the device in the on-state, bidirectional breakdown diodes are unuseable in dc circuits. However, their turn-off speed is so fast that they will turn themselves off in the first zero-crossing of current in an ac circuit. Because of the breakdown mechanism, the same type of voltage overshoot can result when fast-rising transients are applied to these devices as occurs in spark-gap arresters. For this reason, silicon controlled rectifiers with zener diode trigger circuits are frequently used to provide faster response to surges (Figure 10ℓ). SCR's also will not turn off until current is reduced to the milliampere range or less, and therefore, SCR surge protectors are more suitable for ac systems, also.

In industrial power-handling applications, SCR's are used both to switch on dc power, and by use of special reactive "commutator" circuits, switch it off. In principle, it would probably be possible to incorporate such commutator circuits in conjunction with SCR's for providing high-speed protection for dc circuits. However, signal sources of turn-off signals would have to be provided, as well as protection for the commutator circuit. One device currently in the R & D stage is the "gate-turnoff SCR" which will turn itself off upon proper gate signal application. This device will make possible reactanceless commutator circuits, but for providing surge protection in dc circuits, the turn-off gate signal will still be required. For use of SCR's in protection of low-voltage dc circuits, a reliable and inexpensive approach would probably be the use of series circuit-interrupting relays that would remain closed while a surge passes but would open and quickly re-close under the influence of power-follow current, allowing the SCR's to turn off and return the circuit to its operating state.

Composite systems are currently employed using SCR's in series with diode stacks (Figure 10m), to make a low-voltage equivalent of the autovalve arrester. In this case, the diode stack provides sufficient voltage drop to cause the SCR's to turn off completely, presenting essentially an open circuit at normal dc circuit voltage levels. Surges will turn the SCR's on, resulting in lower overall surge voltage than would be possible using a higher diode stack alone.

As far as overall systems design is concerned, it is evident that the best solid-state surge protection, provided by triggered SCR's, is most easily applicable to ac circuits. Therefore, when it is desired to use solid-state equipment for any signal circuit application, there is an advantage in using only ac signals, and in using only ac power to solid-state equipment wherever possible.

5.5 Application of Reactive Elements for Surge Protection

Reactive elements can be nothing but lengths of signal line. For instance, it is frequently advisable in heavy lightning territory to place heavy-duty gap-type arresters from line-to-line and from line-to-ground a few poles distant from where overhead signal lines enter a station, and then to place additional arresters across the lines at the station. The first arresters will eliminate the majority of surge energy, and the line shunt capacitance and series inductance will smooth out the remainder, resulting in a slower rate of voltage rise and lower firing voltage for the second set of arresters. In a typical solid-state signal circuit application, gap-type arresters might be employed to attenuate most surge energy, with series inductors and shunt capacitors then employed to smooth out the remaining pre-ionization voltage spike getting past the gap-type arrester, reducing it to a safe level for further attenuation by solid-state arresters.

5.6 Overall Lightning Arrester and Surge Protector Design

In any system, all of the equipment used for lightning protection and surge suppression should be thought of as a protective sub-system in which each component relates to every other component. More will be said about this concept later in the report. In a geographically extended system incorporating overhead or buried lines, there is a hierarchy of protection that must be provided. Protection must be provided at places for shunting direct lightning strokes to ground; such devices are the first line of defense for the overall system. It is desirable to place these primary protective devices so that the reactances within the system will assist in smoothing out the residual surges. In addition, it might be desirable to add further lumped reactance. Lower-capacity gap-type arresters and varistor devices then further reduce residual surges and induced surges. These in turn provide protection for solid-state protectors, which in turn protect sensitive solid-state equipment.

Given enough money and design time, it should be possible today to protect practically any electronic circuit of any sensitivity from the effects of lightning. A vast array of protective devices are available spanning orders of magnitude of current, voltage, and power levels. The real problem is to determine what level of protection is economically justified. The remainder of this report will attempt to aid in the resolution of this dilemma.

6. CIRCUIT LAYOUT AND INTERCONNECTION CONSIDERATIONS

A number of excellent reports on the importance of routing and shielding power, signal, and ground conductors in complex electrical installations have recently appeared. The most important points of these will be restated and summarized below.

6.1 Grounding Systems

At a specific enclosed location, the most important function that the grounding system performs is to tie to a common potential level all structural parts of the location, including metal framing, relay racks, equipment chassis, metal fixtures, water pipes, and concrete or dirt floor areas. This feature of a properly installed grounding system leads to the physical protection of persons inside the building or enclosure. The second vital part of a grounding system is the connection of the interior ground bus to "true ground" (a hypothetical region deep within the earth at which the electrical potential is never changing) by means of a ground rod driven into the ground, or by means of connection to buried metal pipe. It is important that the resistance between the grounding system and "true ground" be sufficiently low that the resistive voltage drops and ground electric fields present during conduction of lightning surges do not create a safety hazard for people near or just entering the building or enclosure. Properly installed ground rods throughout a geographically extended system will also insure that lightning surges will not propagate through the system beyond the first ground rod encountered.

Current railroad practices call for primary grounding conductors to be of #6 AWG gage or larger, to be as short as possible and free of bends so as to offer minimum inductance, and to be installed so that surge currents conducted in them do not cause inductive coupling or back flashovers to other circuits. Current practices call for a maximum allowable resistance to true ground of 15 ohms. If this cannot be obtained with a single ground rod, multiple ground rods, buried conducting arrays, or salting of the ground are to be employed to get the resistance within the required range.

6.2 Wiring Practices

A number of specific wiring practices can be used to assist in controlling the effects of lightning-induced surges. Overhead lines can be protected from direct stroke currents by use of an overhead ground wire. Differential-mode induced surges can be minimized by running overhead lines in twisted pairs or bundles. Differential-mode surges can be further reduced, and common-mode surges reduced by running bundles or pairs inside metal shielding, with the shielding grounded at both ends. Buried lines can be shielded in a similar manner. The loop inductance of the shield conductor and the ground return path then serves to limit surge current risetimes, and the ac skin effect limits penetration of electromagnetic fields of the surge wave to the enclosed conductors.

Inside enclosures, leads to specific devices should be run in twisted pairs to avoid inductive pickup of differential-mode induced surges. Shielding that is grounded at both ends can be used to reduce common-mode induced surges here as well. Placement of wire bundles should also be made to minimize inductive pickup. Special care should be taken to physically and electrically isolate incoming lines and primary ground leads from lines attached to more sensitive equipment. This practice will be covered further in the next section.

6.3 Levels of Protection

Since the advent of solid-state equipment in railroad signalling applications, the concept of "levels of protection" against lightning and surge effects has gained increasing importance. Figure 14 shows a typical multi-level protective system. When providing lightning protection at a hierarchy of levels, heavy-duty gap-type arresters often called "primary arresters"

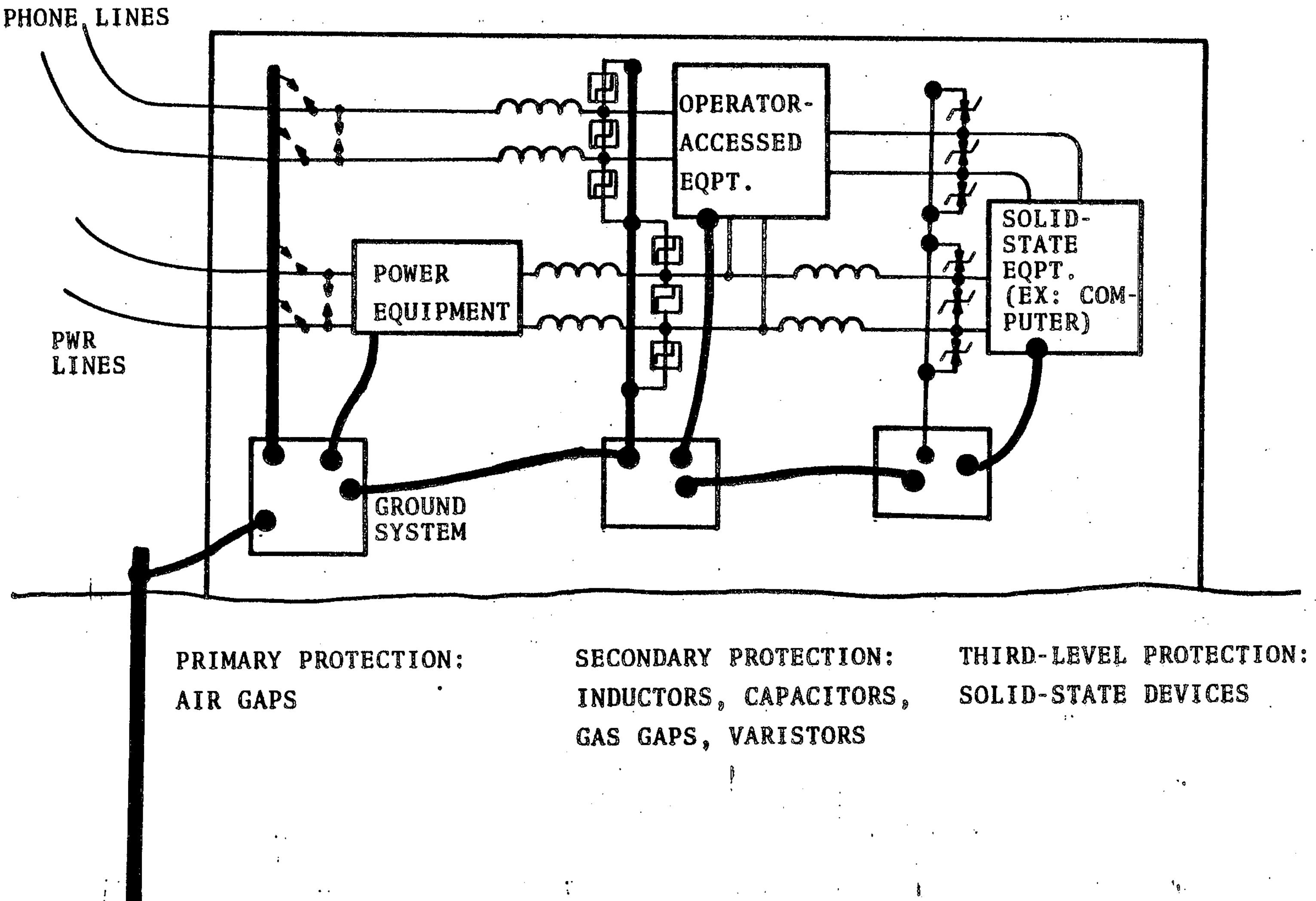


Figure 14. Illustration of electrical system with multi-level lightning protection.

are used to conduct the major surge currents to ground. A primary arrester is connected between every line and ground at the points where lines enter the enclosure or station, and connection is made using heavy ground wire of as short length as possible to a heavy copper bus or plate which serves as the "primary ground point." Power leads, signal leads from overhead or underground lines, and track leads are so protected. All of these leads are potential carriers of direct stroke currents that must not be allowed to enter equipment or cause secondary effects.

Heavy electrical equipment and electromechanical relays will probably be able to survive in the field with only primary protection. More sensitive equipment such as telephones and radios will require additional protection. The additional protection might, for instance, consist of series inductors or resistors and/or shunt capacitors between lines and ground, followed by gas-filled gap arresters or varistors. The ground leads for the second level of protection must run separately to the prime ground terminal, so that they do not carry primary surges.

A third level of protection will be required by semiconductor equipment. It, for instance, will be provided by additional series inductance or resistance, additional shunt capacitance, and finally semiconductor surge suppressors suitable for the system and application, connected from line to line are used to conduct the major surge currents to ground. A primary arrester is connected between every line and ground at the points where lines enter the enclosure or station, and connection is made using heavy ground wire of as short length as possible to a heavy copper bus or plate which serves as the "primary ground point." Power leads, signal leads from overhead or underground lines, and track leads are so protected. All of these leads are potential carriers of direct stroke currents that must not be allowed to enter equipment or cause secondary effects.

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A third level of protection will be required by semiconductor equipment. It, for instance, will be provided by additional series inductance or resistance, additional shunt capacitance, and finally semiconductor surge suppressors suitable for the system and application, connected from line to line and line to ground. The ground leads at this third level should be run separately from those of the primary and secondary levels to avoid coupling. They can be attached to a common third-level ground point that is then attached in turn to the second-level point.

These levels of protection with the inclusion of an unprotected level have been listed by one author as follows:

> The unlimited transient level (unprotected level) contains all outdoor equipment and conductors for signalling, power, and communications, including tracks, that are exposed to the direct and indirect effects of lightning. Maximum lightning current surges of greater than 200,000 amperes can be expected.
>
> The power transient level (first or primary level of protection) is protected by primary arresters, and protection is adequate for ac power and lighting transformers, heavy electromechanical equipment, heavy-duty relays, power switchboards, and most 110 VAC equipment.
>
> The supervisory transient level (second level of protection) is the first level that is safe for personnel on a 24-hour per day basis, and therefore, the level of protection required for telephone equipment, office and lab equipment, control panels, switches, indicators, etc.

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The computational transient level (third level of protection) is required for solid-state equipment such as digital computers and other sensitive semiconductor equipment.

Lightning surges or other surges can be thought of as extremely large pulsed signals that appear on leads. Overhead lines, railroad tracks, and even underground lines serve as antennas or sources of these signals. The signals contain very high frequency components due to their rapid risetimes and short durations. The signal voltages can either appear line-to-line, in which case they are called differential-mode, metallic, or transverse surges; or they can appear line-to-ground, in which case they are called common-mode, or longitudinal surges. The problem of dealing with these surges can be regarded as one of providing limiting or clipping, filtering, and attenuation--functions that are routinely performed in a variety of electronic circuits at much lower power levels. These functions are performed on a step-by-step basis in a multi-level protective system.

It is possible, knowing the statistics of surge currents, voltages, and rise and fall times, and the statistics governing the firing and operation of gap-type arresters, as well as the electronic characteristics of other protective devices, to accurately model the behavior of electrical systems under surge conditions. It is even possible to test systems to some degree in the laboratory by subjecting them to artificially generated surges of considerable power. The size of equipment required for this makes field testing impossible, but artificially generated surges are routinely used by a number of companies in the design, analysis, and manufacture of surge protection equipment. What is more difficult to predict is the exact behavior of a system whose configuration departs in some degree from a system whose behavior is known. Small departures in design can lead to unanticipated consequences.

Over the years, lightning protection practices in the railroad industry have evolved which have been regarded as being generally acceptable to protect the equipment that has been used. The recent introduction of sophisticated semiconductor equipment, and the necessity of multi-level protection have changed the picture dramatically. In order to properly provide the multi-level protection required for semiconductor equipment, further work is called for in the analysis of entire grounding systems. Such efforts may be justified as well for providing updated protection for older equipment, given recent advances in technology and a continually changing economic picture.

7. ECONOMIC CONSIDERATIONS IN LIGHTNING PROTECTION

As mentioned previously, any electrical system can be made arbitrarily immune from the effects of lightning, if one is willing to pay the price. Exposed conductors can be made arbitrarily heavy so that arbitrarily large surge currents will not cause them to melt. As many stages of surge protection as required may be provided. System layout can be analyzed in as detailed a manner as required to accurately predict response to lightning surges. Overall system design concepts can be altered to make for greater ease of lightning protection. All of these steps cost money, and the costs involved must be weighed against potential return.

On the one hand, electrical equipment, such as railroad signalling equipment, costs money to replace when damaged by lightning, but signalling equipment has a lifetime of finite length even when lightning damage does not occur. Therefore, lightning damage is unlikely to rob one of 100 percent of a device's potential lifetime.

On the other hand, in what is known as "heavy lightning territory," replacement of signal system components at intervals shorter than yearly is often required, even when current standard protection practices are followed; and the equipment costs involved, including installation labor, might be many times the cost of updated lightning protection.

One question is, How much does a certain degree of lightning protection cost, including engineering, design, equipment purchase, installation, maintenance, and replacement of damaged lightning protection devices? The other question is, How much money is saved on replacement costs for equipment and labor, reduced maintenance requirements, and greater operating reliability affecting operating continuity of the railroad system?

The true costs of lightning damage are not known. One large midwestern and western railroad estimates yearly equipment replacement costs of several million dollars per year, alone.

Determination of lightning damage costs of all types as a function of geographical location, local considerations, and electrical system configuration must be made in order to accurately answer the question of what degree of lightning protection is most economically justified under what circumstances. What would probably be shown by such a study is that in those areas of the nation where lightning activity is more rare, less protection is called for, and protective equipment of lighter construction is acceptable, since beyond a certain point, equipment lifetimes are limited by factors other than lightning. On the other hand, in those areas where lightning activity is more prevalent, it is probably economically justified to spend more than is currently being done on the design, procurement, installation, and maintenance of improved heavy-duty lightning protection systems, using multi-stage protection even at the primary level, and paying the price for more thoroughly designed layouts.

8. OTHER SYSTEMS CONSIDERATIONS IN LIGHTNING PROTECTION

One prime systems consideration in lightning protection is, of course, the economic one, which has been discussed. The economic aspects of all other considerations must be taken into account. Other considerations, some of which have been previously mentioned in this report, are increased performance capability vs. increased sensitivity to lightning damage on the part of equipment, ease of field maintenance, standardization of circuit design and installation of equipment, specification of surge withstandability on the part of equipment, and specification of surge protection device characteristics including electrical characteristics and lifetime.

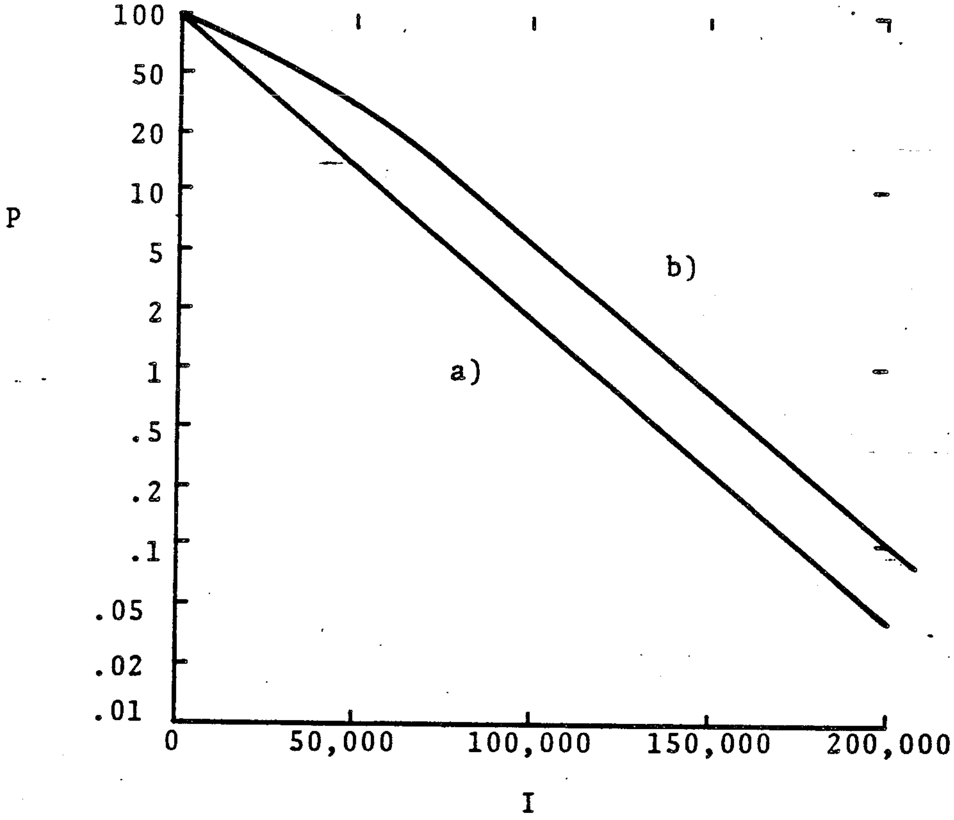
8.1 Present Specifications for Overvoltage Withstandability

Presently, the systems approach to lightning protection in general use for railroad signalling equipment calls for all electromechanical relays, bells, and motors that are used in vital circuits to pass a 3,000 vac withstand test for one minute, or a one-minute withstand test of 800 vac in the case of signal lamp receptacles with lamp removed. Since primary arresters of the gap type with dc arc-over voltages in the range of 700 to 1000 volts will not pass fast-rising surges of greater than 3,000 volts an appreciable portion of the time, the primary protection provided is generally considered adequate. Likewise, AAR standards call for varistor-type devices to be used across lamp filaments and across other signal lead pairs to further limit surges to voltage levels considered tolerable. The standards that exist for ground system installation, wiring layout practices, arrester characteristics, and withstand test standards, can be regarded as forming an overall systematic approach to lightning protection adequate for electromechanical components, but it is not apparent that the existing standards provide the level of overall operating reliability required of electromechanical components at optimum overall cost. In addition, no standards exist within the railroad industry for specifying the surge protection requirements of solid-state equipment, or for specifying the surge withstandability of such equipment.

For instance, one systems approach for guaranteeing the viability of gate arm motors is to insist on passage of the one-minute 3,000 vac withstand test, and then insist on standard primary arrester protection; but a potentially less expensive approach might be to specify the surge withstandability of a motor under true surge conditions at some maximum voltage level and some risetime and falltime, and then to specify the secondary surge protection required to be used with the motor to enable it to survive the residual surges present after primary protection. Such an approach might result in even greater reliability than now enjoyed, and lower cost as well. What is important obviously in railroad signalling applications and other applications is not that all equipment be able to meet a single criterion for surge withstandability, but that the surge withstandability of every piece of equipment be known and accurately stated, so that proper protection can be provided.

8.2 Statistics of Surges and Surge Severity

The isokeraunic map of the United States shown in Figure 4 is one important item of information useful in judging the overall threat presented by lightning in a given geographical area. Another useful item of information is the probability distribution of the magnitudes of surges that occur in various types of systems. For instance, Figure 15 shows the probability distributions of peak surge current magnitudes of surges due to strokes to transmission line ground structures and strokes to underground structures. A significant amount of work has been done over the years in collecting data such as this for application to development of surge protection techniques for power transmission systems. More data of a similar kind directly related to railroad signalling systems needs to be done. This type of information is needed if one is to predict what type of lightning protection is economically justified and



PERCENTAGE OF STROKES EXCEEDING CURRENT I, FOR a) TRANSMISSION LINE GROUND STRUCTURES, AND b) STROKES TO BURIED STRUCTURES. (REF.: E.D. SUNDE, BELL SYSTEM TECH. JOURNAL, VOL. 24, APRIL 1945)

Figure 15. Example of lightning stroke current magnitude statistics.

what the energy-handling capabilities of lightning arresters must be to serve reliably, in a given situation for the desired lifetime.

8.3 Specification of Test Surges and Surge Withstandability

The statistics of surges, including peak current and voltage probabilities and waveform behavior, is one type of information required for specifying standard test surge amplitudes and waveforms to be used in testing equipment. Another type of information is knowledge of the vulnerability of various types of equipment that will be used. Based on these two types of information, test surges to be used in equipment design and in manufacturing quality control can be specified. It is uneconomical to specify and use test surges which in some way are more severe than anything found in the real world, since that will lead to spending money for protection against threats that do not exist in the real world.

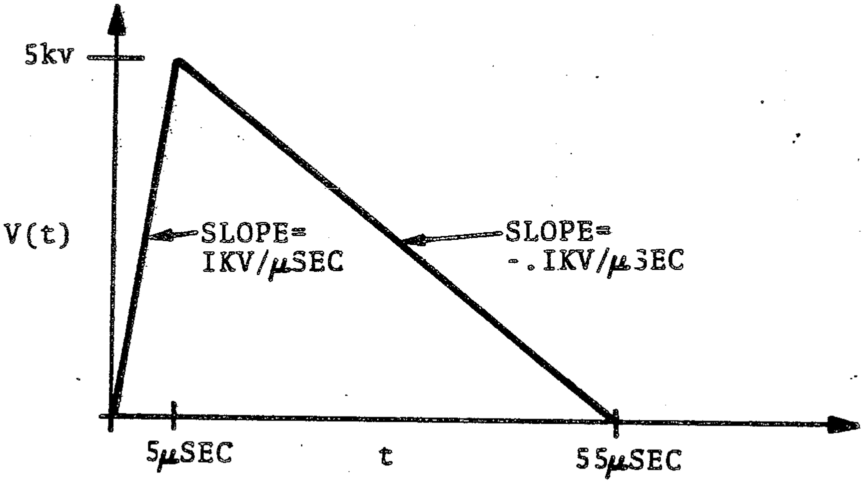
The optimum test surge for use in design and quality control work is perhaps one that represents the worst-case surge likely with some probability to be encountered by a piece of equipment during its service life. For instance, a relay might be specified as having a service life of 10 years. In a typical installation, surge statistics predict that once every 8 years on the average, a surge will occur with peak voltage greater or equal to 5,000 volts and duration 100 microseconds or greater. This voltage level and duration might then form the basis of specifying that relays be designed to withstand and be tested with 5,000-volt, 100-microsecond surges.

For use in "heavy lightning territory," where surges of 5,000 volts and duration of 100 microseconds might occur on the average of once every 2 years, and surges of 10,000 volts and duration of 150 microseconds might occur every 8 years, it might be desirable to insist on relays that can take a 10,000-volt, 150-microsecond surge test. On the other hand, it might be more economical to compromise on a 7,500-volt, 125-microsecond surge withstandability and lower cost, knowing that expected failures from lightning will increase.

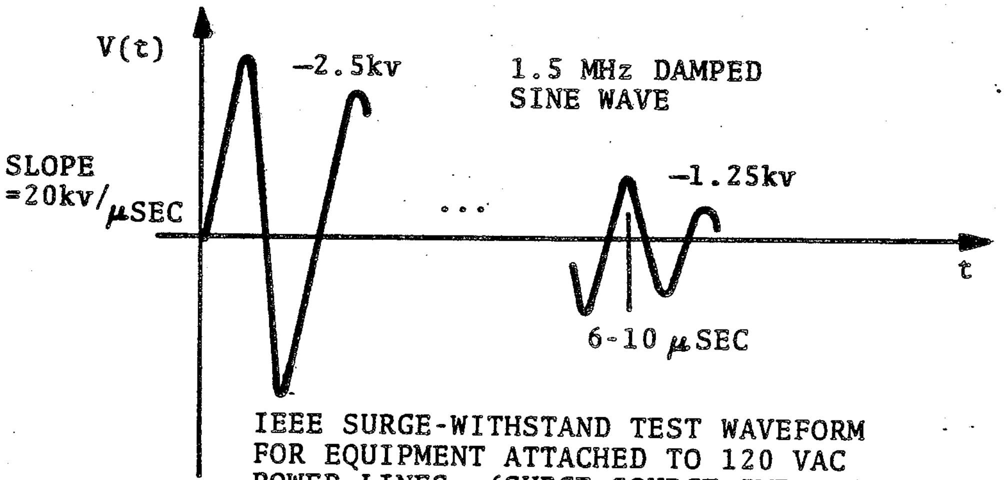
The IEEE Relaying Committee has proposed two types of surges to be used as test surges for use in testing equipment to be used in typical situations. These are probably near-optimum for certain types of equipment in certain environments, and are shown here in Figure 16 as examples of standard surges being considered for specific situations.

8.4 Specification of Levels of Protection

As indicated previously in this report, modern surge protection calls for employment of a multi-level scheme of providing lightning and surge protection. Solid-state equipment needs a number of levels of protection, whereas heavy electromechanical equipment might need one or at most two. In order



A TRIANGULAR TEST WAVEFORM FOR
EQUIPMENT ATTACHED TO 120 V-60 Hz
POWER LINES. (SURGE SOURCE IMP.=100Ω)



IEEE SURGE-WITHSTAND TEST WAVEFORM
FOR EQUIPMENT ATTACHED TO 120 VAC
POWER LINES. (SURGE SOURCE IMP.=150Ω)

Figure 16. Examples of standardized test surge voltage waveforms.

to insure the most economical systems designs for the greatest number of users, there should be standardization of the surge withstandability specifications to be used at each level. That will allow purchasers of electronic and electrical equipment to know what levels of surge protection are built into equipment the way it comes from the manufacturer, and it will allow purchasers to know specifically what protective devices must be added to increase the level of protection so that the equipment can be used alone at some more severe level. If such a scheme were adopted, variation in amount of protection in a system as a function of severity of the environment would probably be made at the primary level. Then, after the primary protective level, where heavy electromechanical equipment is found, the local electronic environment would be no more severe than average, and standardized protective techniques for higher levels could be used reliably by all users throughout the nation.

9. SUMMARY AND CONCLUSIONS

In gathering and analyzing information for this report--from the technical literature, from experts in the field of lightning protection, and from railroad signalling personnel--the following general conclusions were reached:

Lightning itself as a natural phenomenon is incompletely understood. The specific nature of the charge separation process within clouds, and between clouds and ground is complex and varying from one situation to the next. However, once the current waveforms of lightning strokes are specified (and they can be measured), the consequences of lightning to electrical circuits and systems can be quite accurately predicted on the basis of electromagnetic theory and electrical circuit theory, and this is the important point--that known scientific and analytical techniques are available to calculate the surge behavior of electrical systems. Of course, given the nature of lightning, and given the nature of electrical breakdown and arcing in air and in insulating media, the analysis of surge behavior depends upon statistics and probability theory, as well as circuit and wave theory.

Lightning-caused surges are not limited to direct-stroke currents. Induced surges are of great overall importance in determining the total severity of the surge environment for electrical equipment and are caused by a variety of electrical, magnetic, and electromagnetic effects.

A great variety of surge-protective devices are available within the electrical and communications industries. These can be grouped generally into spark-gap devices, varistor devices (silicon carbide or metal oxide), solid-state breakdown devices (the SCR and triac), solid-state voltage-limiting devices (forward-biased diodes, Si zener diodes, reverse-breakdown selenium diodes), impedance elements (shunt capacitors, series inductors, series resistors), and more complex multidevice surge suppression circuits using a series of devices.

Within the railroad industry, surge protective devices are generally not described in a manner that indicates their specific electrical characteristics in a standard and unambiguous manner. One symbol often is used to indicate a variety of specific devices in circuit and wiring diagrams, and specifics of lead dress and circuit layout, very important in determining the electrical behavior of arresters and circuits under surge conditions, are generally not recorded. In addition, technical data concerning the performance of specific lightning arresters and surge suppressors is often not made routinely available in manufacturers' catalogs.

The problem of lightning and surge protection of railroad signalling systems is a multifaceted problem having interrelated technical and economic aspects. The problem has been addressed in the past primarily by a trial-and-error process slowly evolving over many years. With a few exceptions, it appears that recent advances in semiconductor technology and recent introduction of new semiconductor circuits in railroad signalling applications have raced ahead of the ability to provide protection using traditional techniques.

Rapid advances have been made in recent years in development of new surge protection devices and techniques, and in analysis of electrical systems under surge conditions using computer modelling. These advances have been utilized to a lesser extent in the field of railroad signalling than they have in other fields, and there certainly appears to be handsome payoff from undertaking more analytical work in a way that relates directly to railroad signalling electrical systems.

Standards exist within the railroad industry for specifying performance of older types of vital electrical equipment under overvoltage conditions. However, these standards are not directly related to the electrical characteristics of surges that actually occur. Standards applicable to newer solid-state equipment have not been developed. Overvoltage requirements that do exist are written in such a way that they apply to separate pieces of equipment only. They are not performance-oriented--that is, they do not specify the type of realistic surge that a piece of equipment with its surge protection in place is supposed to withstand, and it is completely unclear that the required level of reliability in the field is most economically guaranteed by use of the current standards.

10. RECOMMENDATIONS

Based on the analysis of the information gathered from which this report was prepared, and based on the conclusions drawn, the following recommendations are made:

1) Information on surge statistics should be gathered in a variety of situations and in a number of geographical regions throughout the United States, by making measurements of surge currents and voltages in actual railroad signalling systems. This information would be useful in calculating the exact dimensions of the threat faced by various types of electrical equipment to damage from lightning-induced surges. It will lay the groundwork for modelling and analysis of the behavior and consequences of surges in railroad signalling circuits.

2) More experimental work should be undertaken, using currently available information about the nature of surges, to devise and test advanced lightning protection concepts based on existing devices and techniques, such as multi-level protection, improved circuit layout, and use of heavier-duty arresters at the primary level. This should be done by field testing new concepts and gathering statistical data on their effectiveness. This work can be updated in nature as further information on the nature of the surge environment is developed.

3) Information on the statistics of lightning damage to railroad signalling equipment should be collected from around

the country in an accurate and uniform manner, covering standard systems now in use and newer developmental systems as well.

4) Modelling and analysis of the behavior of surges in railroad signalling systems should be pushed forward, based on the best information available; and new surge protection concepts should be evaluated for predicted usefulness.

5) The economic factors related to lightning damage to railroad signalling systems should be investigated, including not only equipment and labor costs, but also costs of interrupted service. This information will be necessary for determining what level of lightning protection expenditure is economically justified, after safety considerations have been met.

6) Standardized specifications for surge testing and surge withstandability should be developed, based on a multi-level protection system. Specification of standardized test surges and surge withstandability should be based on known statistics of the surge environment, required equipment lifetimes in that environment, and the known failure modes under surge of various types of electronic equipment. Special attention should be given immediately to preparing interim standards for solid-state equipment.

7) Standardized symbols for protective devices should be adopted that denote clearly their function, internal operating mechanisms, and electrical behavior. These could be directly

based on IEEE standards for such devices as spark gaps, varistors, zener diodes, SCR's, etc.

8) Standardized specifications for surge protective devices such as spark gaps, varistors, etc., should be developed, such as currently exist in the electronics industry for transistor and diode parameters. Wide availability of this information should stimulate and aid design work and analysis of new surge protection techniques. (It should be pointed out that some manufacturers currently do make such information available.)

9) In general, more interest in the problem of lightning and surge protection specifically as it relates to railroad signalling should be stimulated within the electrical engineering community. In recent years, surge protection of electronic systems, computers, and communications equipment has been worked on hard. (Unfortunately, the work on protecting such equipment from the surges induced by the electromagnetic pulse (EMP) of nuclear blasts has been classified.) The power industry over the years has had a large and continuing research and development effort for surge protection which has paid handsome dividends. In closing this report, the final observation the author has to make is that more work directly related to the railroads' problems by existing trained specialists in the surge protection field should pay handsome dividends in terms of return on labor invested.

11. BIBLIOGRAPHY

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Books

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Allan Greenwood, Electrical Transients in Power Systems, Wiley-Interscience, New York, 1971. A technical survey and review of causes and effects of transients in power systems, including switching and lightning transients; one chapter is specifically devoted to lightning and the protection of power systems from lightning damage.

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