PDHonline Course E300 (4 PDH)

Electrical Distribution Overvoltage Protection

Instructor: Lee Layton, P.E

2025

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
Email: PDHonline@Gmail.com
www.PDHonline.com
www.PDHcenter.org

An Approved Continuing Education Provider

Electrical Distribution Overvoltage Protection

Lee Layton, P.E

Table of Contents

Introduction

Overvoltage situations occur every day on electric distribution power systems. The overvoltages may be the result of external conditions such as lightning or from internal conditions such as from switching surges and ferroresonance. These overvoltages may break down equipment insulation causing equipment damage and failure and often result in disruption in service to customers.

The most common cause of distribution overvoltages is lightning strikes from electrical storms in the atmosphere each year. In the United States alone there are over 30 million cloud to ground lightning strikes, so the potential for damage to an electric distribution system is significant. Lightning may cause an insulation breakdown in a single transformer, which results in only few homes losing power, or the lightning strike may flash over an insulator on a three-phase line interrupting power to thousands of homes. Usually, the damage from a single lightning strike to an electric distribution system is not a sufficient economic loss, but considering the total number of strikes, the annual economic impact is in the millions of dollars, not to mention the interruption in electrical service that occurs.

In comparison to lightning, switching surges and ferroresonance have only a minor economic or service impact on an electric distribution system. Transient switching surges are not much of an issue with distribution systems and will not be discussed here, but we will briefly look at how ferroresonance may cause an overvoltage condition.

To analyze overvoltages, we must first understand something about how lightning occurs and how it impacts the electric system. The first section of this course describes how lightning occurs, the characteristics of lightning, and how to calculate ground flash densities. Next, we will look at the design and operation of surge arresters. Subsequent sections include information about electrical line design methodologies to minimize the impacts of lightning, equipment protection strategies, and the impacts of grounding on lightning protection.

But first, we will look at how lighting is created and how it impacts an electric system.

Chapter 1
Lightning

According to mythology, the Greek god Zeus used lightning as a weapon, throwing it at his enemies. According to Viking beliefs, lightning occurred when Thor rode his chariot through the clouds and created sparks by striking his hammer against an anvil. Today we know much more about how lightning originates, but we are still in awe at its power. And we should be, because each year lightning is responsible for numerous deaths in the U.S. and millions of dollars in property damage to utility equipment and consumer electronics.

Since 1989 a lightning detection network has been in place over the continental 48 states. During this time, an average of 20,000,000 cloud-to-ground flashes have been detected every year. In addition, about half of all flashes have more than one ground strike point, so at least 30 million points strike the ground on average each year in the US. There are 5 to 10 times as many cloud to cloud flashes as there is cloud to ground flashes.

Damage from lightning occurs because of both direct and indirect strikes. Lightning may directly contact a power line causing damage or it may contact a nearby tree or other object where the current flows through the ground and into the power line circuit. Quite often underground power equipment is damaged when lightning strikes an overhead line and the lightning strike current travels along the power line damaging insulation in the underground cable or underground equipment.

Lightning Flash Mechanism

Lightning originates in cumulonimbus clouds, which are the cloud formations that generate thunderstorms. These thunderstorm clouds are formed wherever there are enough upward motion, vertical instability, and sufficient moisture to produce a cloud that reaches up to levels colder than freezing. Thunderstorms are divided into two types: convective and frontal system storms. Convective thunderstorms are usually short-lived, lasting for 30 minutes to a few hours. Frontal storms can cover hundreds of miles as they travel across the country.

The formation of a thunderstorm requires three basic ingredients, moisture, cooling, and lifting action. The basic fuel is moisture, or water vapor, in the atmosphere. The air above the water vapor must cool off rapidly with height. There must be something in the atmosphere to push the moist air from near the ground up to where the air around it is cold. This may be a cold front or the boundary between where the cold air from one thunderstorm meets the air outside of the storm (called an outflow boundary) and anything else that forces the air at the ground together. When this happens, the moist air is pushed up. As the moist air rises it cools off and some of the water vapor condenses into liquid water cloud drops. This warms up the rest of the air mass so that it does not cool off as fast as it would if the air were dry. When the air mass gets into the colder atmosphere, it will be warmer and less dense than the air around it. Since it is less dense, it will start to rise faster without being pushed. Then more water vapor turns into liquid in the air mass, and the air mass warms up more and rises even faster until all of water vapor is gone and the air mass eventually reaches a point in the atmosphere where it is not warmer than the environment.

Strong updrafts and down drafts occur with regularity, even within small thunderstorms. The updrafts transport water droplets up into the cloud, while ice particles descend from the frozen upper regions of the cloud. As they do, they bump and collide with each other. Through this process, electrons shear off the ascending water droplets and collect on the descending ice particles. This generates an electric field within the cloud, with the top having a positive charge, and the bottom having a negative charge. An electric field is also generated between the bottom of the cloud and the surface of the earth, though not as strong as the field within the cloud. As a result, most lightning occurs within the cloud itself. Lightning is a transient discharge of static electricity that serves to re-establish electrostatic equilibrium within a storm environment.

In a developing storm cloud, there is an electric attraction (i.e., electric field) between its top and bottom. As the charges begin to separate, the field strength grows. The greater the magnitude of separation, the stronger the field, and the stronger the attraction between the positively charged top and the negatively charged bottom. However, the atmosphere is an exceptionally good insulator, so a tremendous amount of charge must build up before lightning can occur. When that threshold is reached, the strength of the electric field overpowers the atmosphere's insulating properties, and lightning results.

There are two types of lightning discharges: Cloud to ground (CG) discharges, which have at least one channel connecting the cloud to the ground and cloud discharges that have no channel to ground. Cloud discharges fall into three categories: in-cloud (IC), cloud-to-air (CA), or cloud-to-cloud (CC).

Cloud-to-ground (CG) lightning is the most damaging and dangerous form of lightning. Although not the most common type, it is the one that is best understood. Most flashes originate near the lower-negative charge center and deliver negative charge to Earth. However, an appreciable minority of flashes carry positive charge to Earth. These positive flashes often occur during the dissipating stage of a thunderstorm's life. For some unknown reason, positive flashes are also more common as a percentage of total ground strikes during the winter months.

Intra-cloud (IC) lightning is the most common type of discharge. This occurs between oppositely charged centers within the same cloud. Usually, the process takes place within the cloud and looks from the outside of the cloud like a diffuse brightening which flickers. However, the flash may exit the boundary of the cloud and a bright channel, like a cloud-to-ground flash, can be visible for many miles.

The ratio of cloud-to-ground and intra-cloud lightning can vary significantly from storm to storm. Storms with the greatest vertical development may produce intra-cloud lightning exclusively. Some suggest that the variations are latitude-dependent, with a greater percentage of cloud-to-ground strikes occurring at higher latitudes. Others suggest that cloud-top height is a more important variable than latitude.

Depending upon cloud height above ground and changes in electric field strength between cloud and Earth, the discharge stays within the cloud or makes direct contact with the Earth. If the field strength is highest in the lower regions of the cloud a downward flash may occur from cloud to Earth.

Cloud-to-cloud (CC) lightning, as the name implies, occurs between charge centers in two different clouds with the discharge bridging a gap of clear air between them.

Cloud-to-Air (CA) lightning occurs between charge center in a cloud and the surrounding air.

Figure 1 is a graphic showing the different types of lightning strikes.

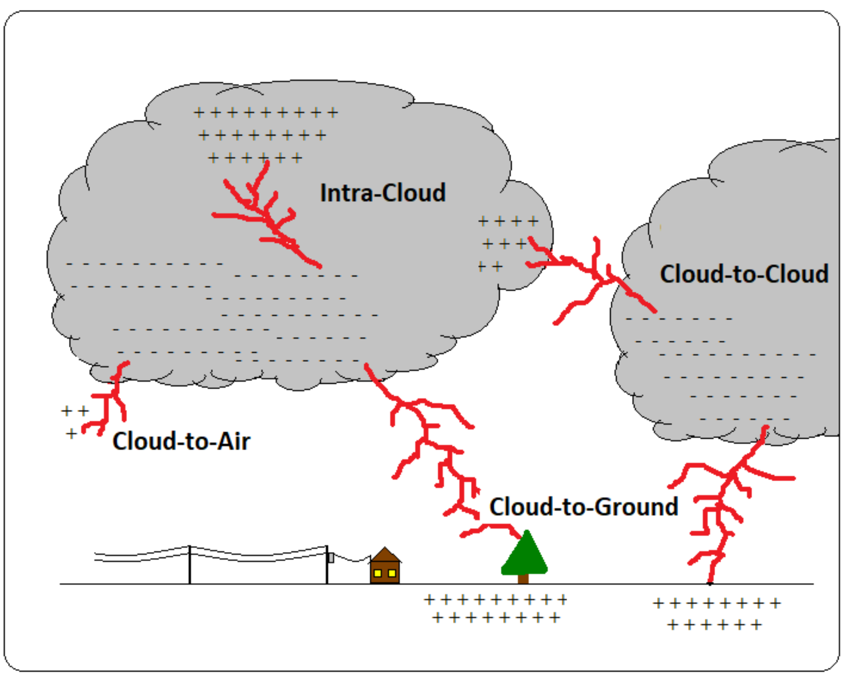

Figure 1

For a detailed explanation of a lightning strike, consider the following scenario of a typical cloud-to-ground lightning strike (intra-cloud, cloud-to-cloud, and cloud-to-air lightning strikes are similar.) While lightning occurs instantaneously, it takes place over several steps:

Step 1. Stepped Leaders

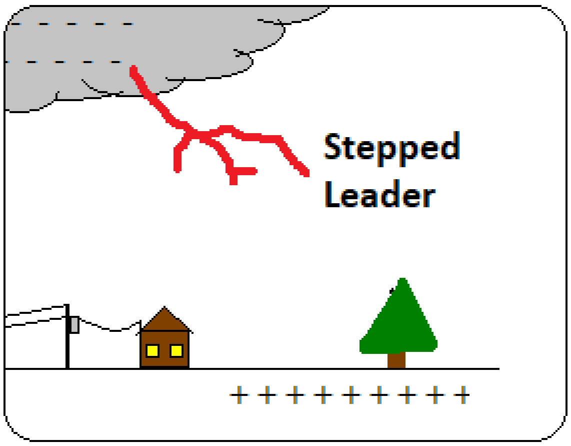

Figure 2

A cloud-to-ground lightning discharge typically initiates inside the thunderstorm. When enough electrons collect in the bottom of the cloud, a very faint, negatively charged channel, called the stepped leader, emerges from the base of the cloud. Under the influences of the electric field established between the cloud and the ground, the leader propagates towards the ground in a series of luminous steps about 50 meters in length and one microsecond in duration, which is s an "avalanche of electrons". Between steps there is a pause of about 50 microseconds, during which time the stepped leader "looks" around for an object to strike. If objects are not found, it takes another step and repeats the process until it finds a target. It takes the stepped leader about 50 milliseconds to reach its full length. As the stepped leader's channel approaches the ground, it carries about five Coulombs of negative charge and has an extraordinarily strong electric potential of about 100 million volts with respect to the ground. Note: A coulomb is the amount of charge transferred in one second by a current of one ampere (1 ampere second). It is equal in magnitude to the charge of 6.28×10^{18} electrons.

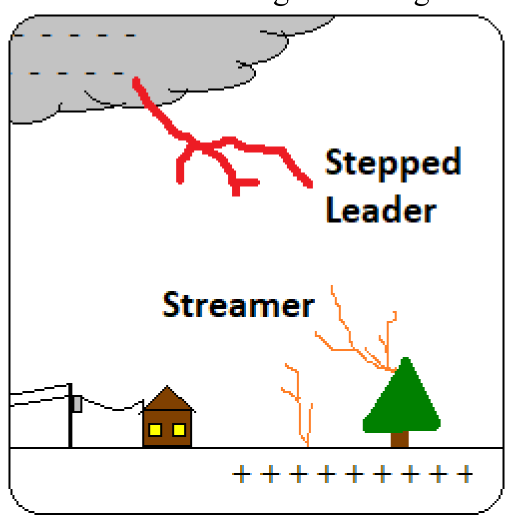

Figure 3

Step 2. Streamers

When the stepped leader approaches the ground its strong negative electric field repels all negative charge in the surrounding ground, while attracting all positive charge. This induces an upward moving positive charge from the ground and/or objects on the ground. When this positive charge collects into a high enough concentration, it forms bolts of ground-to-air paths known as streamers.

Step 3. Ground Connection

When one of these positively charged streamers contacts the tip of a negatively charged leader, the following occurs:

- The leader channel's electric potential connects to the ground.
- All other branches of the leader channel cease further propagation toward the ground, and all negative charge within these branches start flowing to the ground through the newly established ground/cloud connection.

Step 4. The Return Stroke

An electric current wave then propagates up the channel as a bright pulse. This discharge process takes less than 100 microseconds and is known as the return stroke. It produces all the luminosity and charge transfer in most cloud-to-ground strokes. The lightning is traveling from the ground into the cloud, but because the process takes place so quickly, to the unaided eye appears that the opposite is true. Electric charge flows up the channel behind the wave front and produces a ground level current. This current has an average peak value of about 30,000 amperes, though it can be as high as 300,000 amperes.

Step 5. Dart Leaders

After the current has ceased flowing up the leader channel, there is a pause of about 20 to 50 milliseconds. After that, if additional charge is available at the top of the leader channel, another leader can propagate down the established channel. This leader is known as a dart leader because it is continuous instead of stepped. Dart leaders are what give lightning its flickering appearance. Not every lightning flash will produce a dart leader, as sufficient charge to produce one must be available within about 100 milliseconds of the initial stepped leader.

The dart leader deposits about one coulomb of charge along the channel and carries additional electric potential to the ground. The negatively charged dart leader then will induce a new, positively charged return stroke from the ground. The peak amplitude of the current usually decreases as additional dart leaders occur. Therefore, the induced field changes are also smaller in amplitude and have a shorter duration than those of the first return stroke. Dart leaders and their subsequent return strokes do not normally branch like the initial stepped leader and return stroke.

The combination of each leader (stepped and dart) and the subsequent return stroke is known collectively as a stroke. All strokes that use the same cloud-to-ground channel constitute a single cloud-to-ground flash. A flash can a single stroke, or as many as tens of strokes.

The bright light of the lightning flash caused by the return stroke mentioned above represents a great deal of energy and this energy generates a sound wave (thunder). The energy of a lightning strike heats the air in the channel to above 50,000 degrees F in only a few millionths of a second.

The air is heated to such a high temperature has no time to expand, so it is at a high pressure. The high-pressure air then expands outward into the surrounding air compressing it and causing a disturbance that propagates in all directions away from the stroke as a shock wave, which then decays to an acoustic wave (thunder) as it propagates away from the lightning channel.

Positively charged stepped leaders initiate cloud-to-ground lightning. The resulting return stroke carries a negative charge and transfers positive charge from the cloud to the ground. The combination of the leader and the return stroke is known as a positive flash. Usually there are no subsequent dart leaders down the existing channel, so only one stroke makes up a positive flash.

Positive flashes constitute less than 10 percent of all cloud-to-ground flashes and occur on the periphery of a thunderstorm away from the central rain shaft. Positive flashes occur in winter storms and during the dissipating stage of thunderstorms. However, the peak current of their return strokes is often much larger than the peak current of the negative return strokes. Thus, they are more lethal and can cause greater damage than negative flashes. Positive flashes cause a large percentage of forest fires and power line damage.

Electrical characteristics of lightning

The return stroke and subsequent stroke are important in the design of protection systems for electric power systems. Of particular interest are the currents involved in the strokes. A lightning strike acts like a current generator and the associated voltages are the result of current generated and the impedance of the electrical circuit.

The current and duration of the waveform defines the electrical characteristics of a lightning strike. The properties of interest include peak current, rise time, and time to half-value. Figure 4 shows the relative properties for both a current waveform and a voltage waveform. This figure is based on a *negative* waveform.

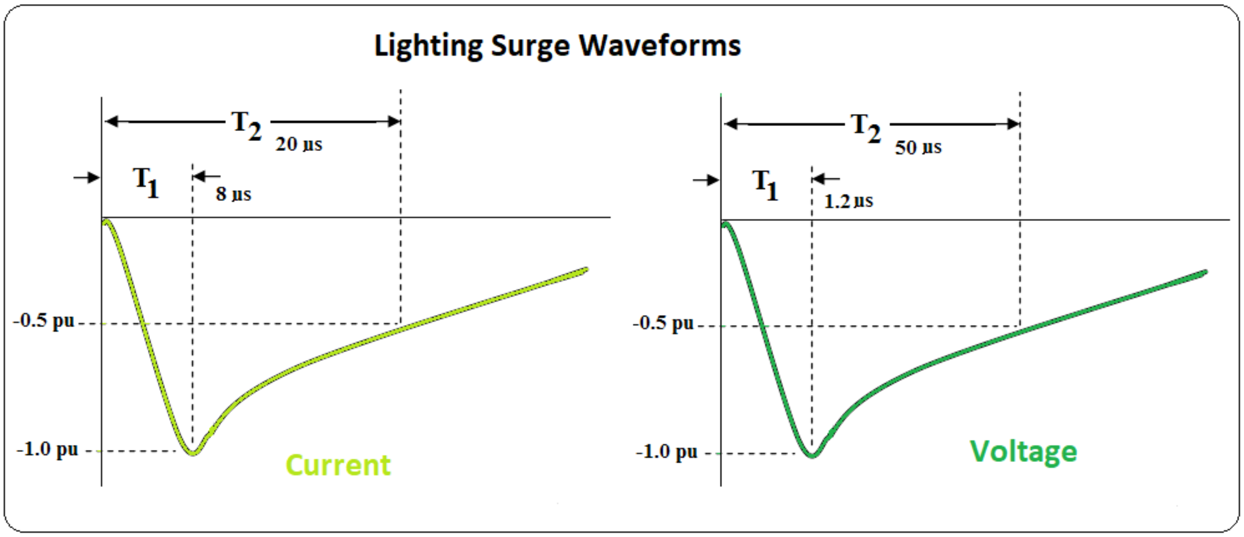

Figure 4

Looking at the current waveform in Figure 4, we see that the negative current waveform rises from zero current to a peak negative current (defined as -1.0 per-unit) in time T_1. The waveform then decays and at time T_2 it has reached one-half its original value (-0.5 per-unit.)

Manufacturers have defined a standard waveform for test purposes to be a current wave with an 8 microsecond rise time and a 20-microsecond time to decay to 50% of the peak magnitude. This value is known as an "8x20 current wave". However, many strikes have faster rise times and much longer decay periods. Some researchers claim that a "1x1,000" waveform may be more representative of a typical lightning strike. A 1x1,000 waveform would have significantly more energy than an 8x20 waveform. Tests have shown that median peak current magnitude is about 30,000 amps, with some strikes of over 300,000 amps.

Figure 4 also shows a typical voltage waveform. The characteristics are similar, except the standard rise time is 1.2 υs and the time to 50% of the peak voltage is 50 υs, or a 1.2 x 50 voltage waveform. As previously mentioned, the magnitude of the peak voltage is dependent on the current waveform and the impedance of the circuit.

Ground flash density

When discussing the impact of lightning strikes on electric power systems an obvious question is "How often is the line struck by lightning?" It is impossible to predict how often a line will be struck by lightning, but there is a great deal of data on how many lightning strikes occur in a given area each year. The traditional method to determine the likely impact of lightning strikes is to correlate the number of thunderstorms in each area to the number of lightning strikes that may occur.

The National Weather Service publishes details on the number of thunderstorms that occur in the United States each year. The data is in a map form that shows the isokeraunic levels.

Isokeraunic maps show areas where a similar number of thunderstorms occur each year. Figure 5 is an isokeraunic map. The levels range from 100 (see Tampa, Florida) to 10 (see California), which means that Tampa, Florida can expect approximately 100 days of thunder each year while California only experiences about 10 days of thunder each year.

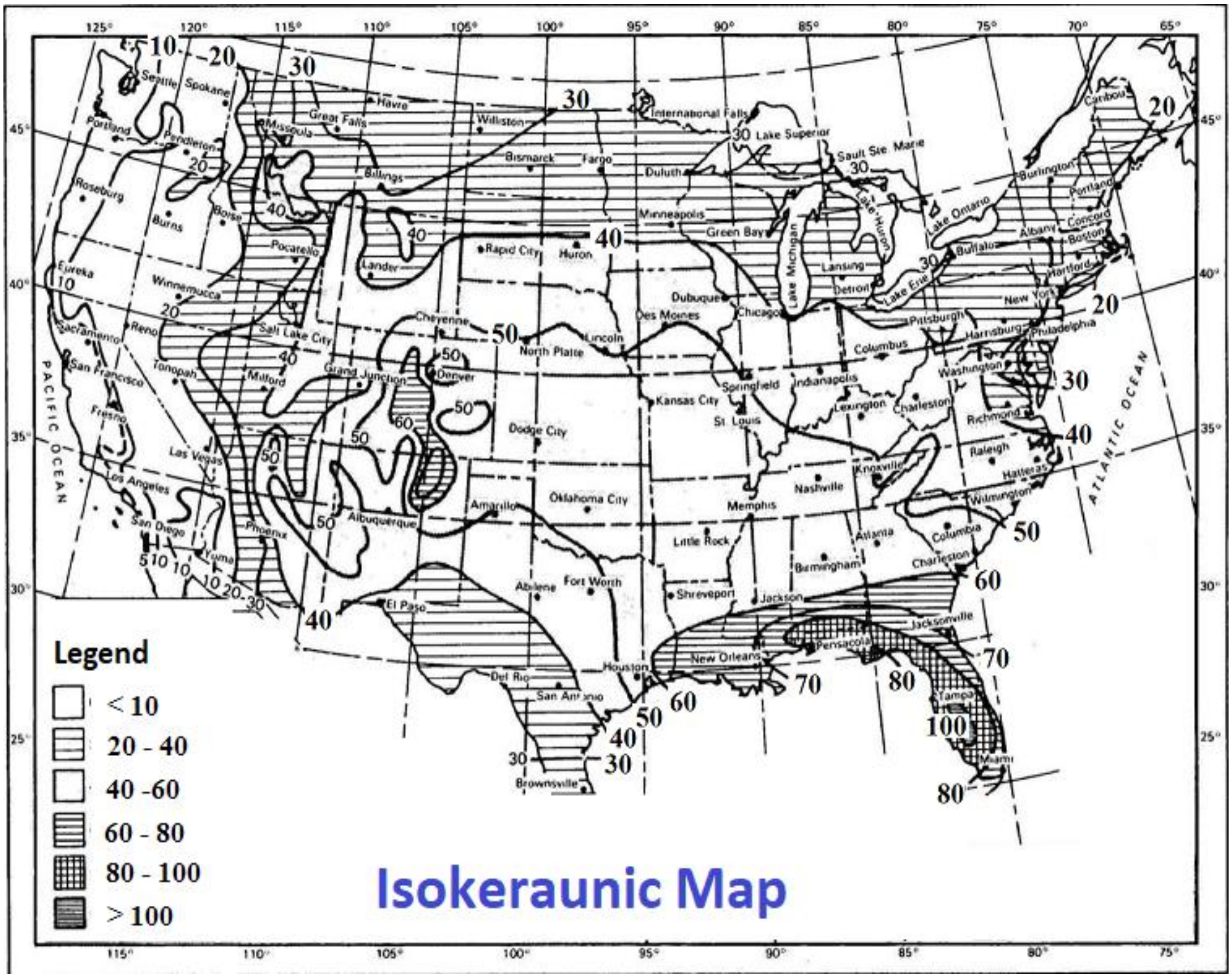

Figure 5

But what we need to know is how many lightning strikes occur, and we can estimate this using an empirical formula. The formula calculates the estimated number of lightning strikes per square mile that strike the ground and is based on the isokeraunic level for the area under study. If you recall, we know that most strikes are cloud-to-cloud and do not strike the ground, so the formula compensates for how many strikes make ground contact. The following formula is used to calculate this ground flash density,

$$\mathbf{Ng = 0.30 * IKL}$$

Where,
Ng = Ground Flash Density, Strikes/mi^2/yr.
IKL = Isokeraunic level, from Figure 5.

Example. What is the expected ground flash density in Missouri?

Using Figure 5, we can estimate that the isokeraunic level is between 50 and 60 and an average of about 52 for the state. Therefore, the ground flash density is,

$$Ng = 0.30 * 52$$

$$Ng = 15.6 \text{ strikes/mi}^2\text{/yr.}$$

Having a prediction of the ground flash density is important to understanding the potential exposure to lightning damage for electric power systems. There are lightning detection networks that monitor the number of lightning strikes occurring in the U.S. The Vaisala Group is a company that manages the U.S. National Lightning Detection Network (http://www.vaisala.com/). The data that their system is collecting has the potential for giving us much better ground flash density data than isokeraunic maps.

Chapter 2
Surge Arresters

A surge arrester is a protective device that limits voltages on equipment by discharging or bypassing surge current and prevents the continued flow of current to ground. A surge arrester functions as a variable resistor that limits overvoltages on an electric distribution system. Surge arresters are also known as *lightning arresters* since their primary purpose is to limit damaging voltages that result from lightning, but there are other sources of over-voltages such as switching surges and ferroresonance conditions.

Lightning surges and switching surges have different electrical characteristics and the arresters are designed to handle either event. A lightning surge acts as a current generator and the traveling wave impressed on the system has an extremely fast rate of rise. In contrast, switching surges have slow rise times because the energy is stored in the magnetic fields in the system. However, as previously mentioned, switching surges are not a significant event in distribution systems, so most of the effort focuses on applying surge arresters to protect circuits from lightning events.

Arrester Design

A valve arrester is the most common form of arrester in operation today. A valve arrester usually has a nonlinear resistor in series with some type of air gapped structure. Figure 6 shows a schematic of a valve arrester that has several gaps in parallel, which are in series with the variable resistance valve blocks. The arrester connects between the high-voltage line and electrical ground.

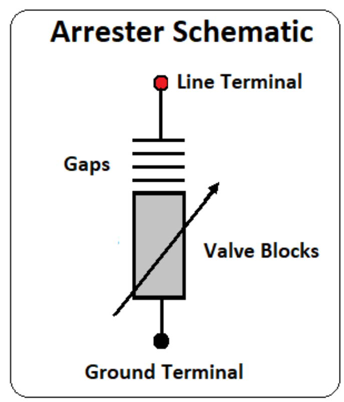

Figure 6

When a surge current reaches an arrester, a voltage is applied across the arrester and if it is more than the breakdown level of the gaps, the gaps sparkover and surge current flows to ground through the valve block. A voltage develops across the valve block that is dependent upon the magnitude of the surge current and the resistance of the valve block. As the surge current begins to dissipate, the voltage across the valve block diminishes and the resistance of the valve block increases further limiting the current flowing through the arrester until the voltage drops to a level that the gaps can again withstand.

The design of the gaps withstand normal system voltages, including temporary overvoltages that occur during faults, sparkover at an appropriate level to allow the surge current flow through the valve block, and then restore the gap to withstand system voltage once the surge current has dissipated. Individual gap components are rated 1.5 kV each and the gap units are paralleled to achieve the design breakdown level.

Silicon carbide (SiC) and zinc oxide (ZnO) are the predominate materials used for valve blocks in surge arresters. Arresters employing zinc oxide blocks are known as metal oxide varistors (MOV's). Silicon carbide blocks are nonlinear resistors, and the resistance varies inversely with the applied voltage. The individual blocks are rated at either 3 kV or 6 kV, and the diameter varies with the energy discharge requirements of the arrester. Zinc oxide arresters have an even more non-linear characteristic than silicon carbide and can operate without the series gaps. However, "gapless" MOV's do not suffer temporary overvoltages very well, and as a result, many MOV designs today employ some type of series gap.

Figure 7 shows the design of a typical gapped MOV arrester. Notice that there are two MOV blocks in series with three resistance gaps.

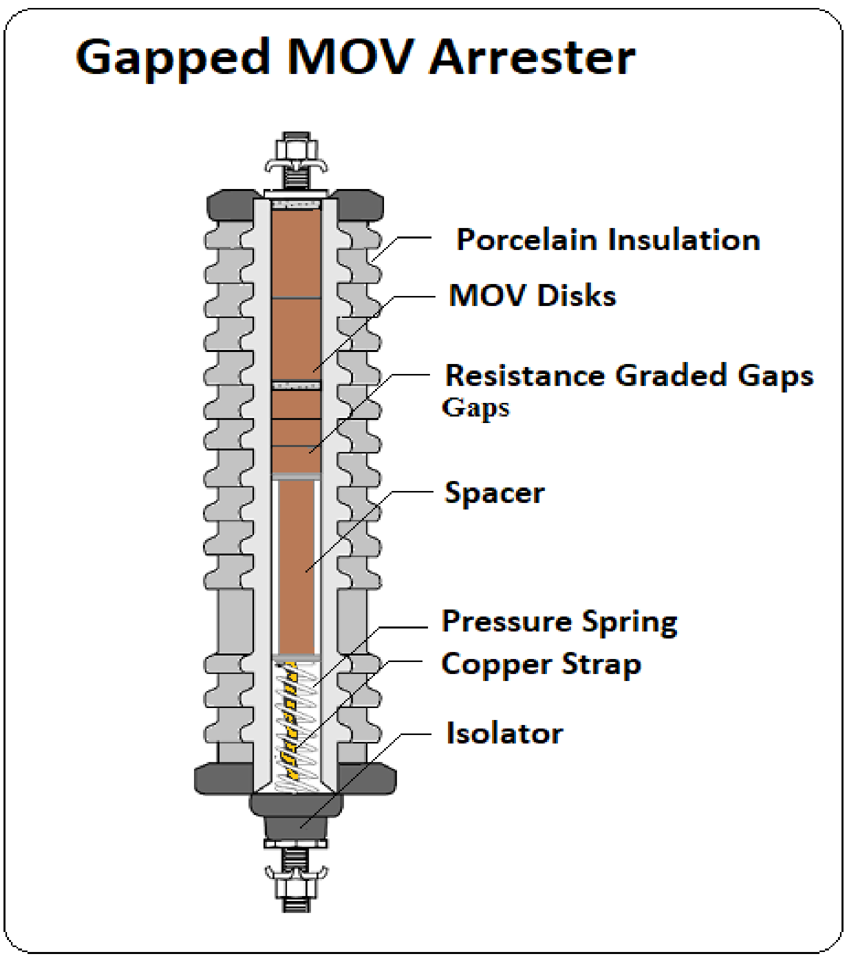

Figure 7

The resistance gaps and MOV disks are held tightly together with a spring and a spacer. In this design a copper strap carries the discharge current to the ground lead. The "isolator" shown on the bottom of the arrester is used to automatically disconnect the arrester from the line if an internal fault occurs in the arrester. The entire arrester is encapsulated in a porcelain case.

Arrester Operation

There are several significant operating characteristics to consider when specifying an arrester for a given application. These include the arresters maximum continuous operating voltage, minimum 60 Hz sparkover voltage, front-of-wave withstand voltage, insulation withstand, and discharge voltage.

To discuss these characteristics, we will use the following table, which has representative characteristics of an MOV distribution class arrester. The first column in Table 1 is the *arrester rating* and is a standards definition for arresters with similar characteristics. It does not imply that the arrester is suitable for a given system voltage.

Table 1

Distribution Class Arrester Protective Characteristics

1	2	3	4	5	6	7	8	9	10	11
Arrester Rating (kV)	**MCOV (kV)**	**Minimum 60 Hz Sparkover (kV)**	**Front-of-Wave (kV)**	**Maximum Discharge Voltage (kV)**						**Insulation Withstand Voltage (kV)**
				1.5	**3.0**	**5.0**	**10.0**	**20.0**	**40.0**	
3	2.55	7.0	12.0	9.6	10.5	11.4	13.5	15.4	19.1	45
6	5.10	14.0	23.0	17.8	19.2	21.1	24.7	28.3	35.0	60
9	7.65	16.5	25.0	19.3	20.9	23.0	26.9	30.7	38.1	75
10	8.40	16.5	28.0	21.7	23.6	25.9	30.3	34.7	43.0	75
12	10.20	21.0	37.0	28.9	31.3	34.4	40.4	46.2	57.2	95
15	12.70	25.0	41.0	31.8	34.4	37.9	44.3	50.7	62.9	95
18	15.30	31.0	49.0	38.6	41.8	46.0	53.7	61.6	76.2	125
21	17.00	34.0	53.0	41.2	44.6	49.1	57.4	65.8	81.5	125
24	19.50	39.0	65.0	51.1	55.4	60.8	71.2	81.6	101.0	150

27	22.00	45.0	74.0	57.9	62.7	68.9	80.6	92.3	114.4		150
30	24.40	50.0	81.0	63.6	69.0	75.8	88.7	101.6	125.8		200

Notes:

1. Discharge Voltage is based on an 8x20 current wave.
2. Insulation Withstand Voltage is based on a 1.2x50 impulse.
3. Front-of-Wave sparkover is based on a 100 kV per 12 kV per microsecond rise time.

As the name implies, the *maximum continuous operating voltage* (MCOV) is maximum system voltage (phase-to-ground) that the arrester should be able to withstand on a continuous basis. This does not include temporary overvoltages due to transients. For instance, the system voltage for an electric distribution system may be 7,200/12,470Y, which says that the phase-to-ground voltage is 7,200 volts and the phase-to-phase voltage is 12,470 volts. In this example, you would expect that the arrester would need to be capable of operating at a continuous voltage of 7.2 kV. However, many electric systems operate at up to 5% above the nominal voltage, which in this case is 7.56 kV. Therefore, an arrester should be selected that can withstand an MCOV of at least 7.56 kV. From column 2 of Table 1 we can see that a 9 kV arrester has a MCOV of 7.65 kV, so it should be sufficient for the expected voltages on this electric system.

The next column in Table 1 shows the *minimum 60 Hz sparkover voltage*. The minimum sparkover voltage is highest transient overvoltage that the arrester can withstand before beginning conduction. This characteristic prevents the arrester from conducting normal switching surges and fault conditions that cause temporary overvoltages. For instance, closing individual fuses on an overhead bank of distribution transformers where the wye configured primary is not grounded, may cause a temporary overvoltage as the last fuse is closed. The standards require that a distribution arrester be capable of withstanding at least 1.5 times rated voltage, but most manufacturers build in a greater margin of protection. If you will notice in Table 1 for a 9 kV arrester, the minimum 60 Hz sparkover voltage is 16.5 kV, which is over two times the MCOV of 7.65 kV.

The f*ront-of-wave sparkover* (FWSO) is the point at which the arrester goes into conduction and begins shunting current to ground. The FWSO should be low enough to prevent the surge from approaching the *chopped wave withstand* of the equipment the arrester is protecting. The front of wave sparkover is determined based on applying a 1.2 x 50 υsec voltage wave rising at 100 kV per 12 kV of arrester rating per microsecond. In Table 1, the FWSO for a 9 kV arrester is 25 kV.

The *discharge voltage* is the voltage that appears across the arrester while current is being shunted to ground. The discharge voltage is the voltage that the equipment will be subjected to while the arrester is conducting. The discharge voltage is based on an 8x20 υsec current wave. As you would expect, the higher the current surge, the higher the discharge voltage that is experienced for a given arrester. Columns 5-10 in Table 1 show the discharge voltage for various levels of surge current. For a 9 kV arrester, the discharge voltage is 26.9 kV for a 10-kA surge (column 8) and 38.1 kV for a 40-kA surge (column 10). When selecting an arrester, the discharge voltage must be below the equipment's basic impulse level by a suitable margin. Studies have shown that the average lightning strike generates about 30,000 amps of current, but currents of 100,000-amps or more are possible.

The final characteristic to consider is the insulation withstand voltage of the arrester. The *insulation withstand voltage* is highest voltage that can be seen by the arrester without the insulation flashing over. Any surge that produces a voltage above this level will cause current to flow over the outside of the arrester effectively bypassing the arrester and destroying the arrester. From a practical standpoint, the insulation withstand voltage of an arrester should equal or exceed the basic impulse level of the equipment it is protecting.

Arrester Types

Most arresters sold today use MOV blocks. There are still many silicon carbide arresters in use though. The earliest arresters where known as expulsion arresters which had a gapped device is series with a hollow tube that would blow the gases formed by the surge out the bottom of the arrester to extinguish the arc. Earlier arresters, including many silicon carbide arresters had an external gap. The external gap completely isolates the arrester from the system during normal operation and protects the system from a faulted arrester. The problem with externally gapped arresters is that the gap is easily damaged during installation and during surge conditions. An appropriately spaced gap that remains at the correct gap setting is critical for the proper operation of an arrester. Externally gapped arresters frequently miss-operate when bugs or small birds make contact across the external gap. Figure 8, shown on the right is a drawing of an arrester with an external gap.

There are three classes of arresters defined by ANSI standard C62. They are distribution, intermediate, and station. The differences among the three classes are primarily related to the voltage ratings, protective characteristics, durability, and venting characteristics of the units.

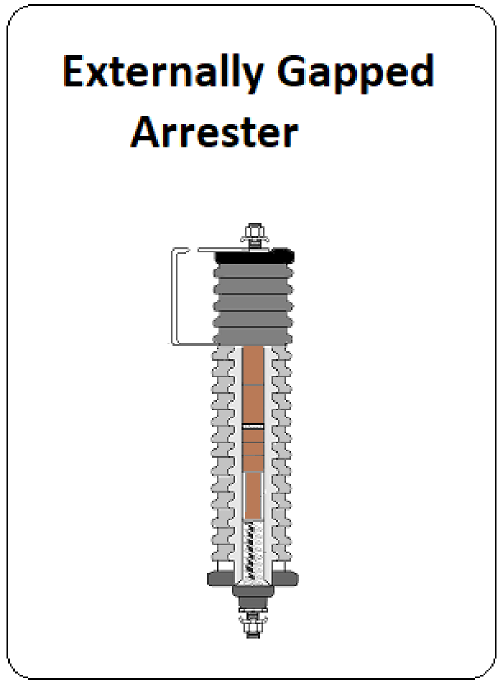

Figure 8

Distribution arresters have voltage ratings between 3-36 kV and are not required to have pressure relief capability. Their use is intended to protect distribution of class equipment such as transformers, insulators, and voltage regulators. Intermediate arresters have voltage ratings between 3-120 kV. Their protective characteristics are better than distribution class arresters (discharge voltage is lower for a given surge current), but they cost significantly more than a distribution class arrester. Pressure relief is required for an intermediate arrester. Station class arresters are rated from 3-684 kV and have much better discharge characteristics than either a distribution or intermediate class arrester. Pressure relief capability is required for station class arresters. A station class or intermediate class arrester can be used in a distribution application, but the economics does not support the added benefits of the higher-class arresters.

Manufacturers sometimes promote a fourth class of arrester called a riser pole arrester. A riser pole arrester is not defined by the standards, but it is a distribution class arrester with discharge characteristics like an immediate arrester.

Chapter 3
Equipment Protection

The proper application of a surge arrester involves selecting an arrester that will protect the insulation of equipment from dangerous overvoltages. Insulation is classified into two categories: self-restoring and non-self-restoring. The term *self-restoring* insulation refers to items that do not normally suffer permanent damage or loss of dielectric strength after a flashover. Porcelain insulators, wood crossarms, and even air are considered self-restoring insulations. Paper insulation, such as is found in transformers, oil, and other insulating liquids are considered *non-self-restoring* insulations because they do suffer loss of dielectric strength when a flashover occurs.

The strength of insulation is defined by its ability to withstand a flashover during voltage surges. A withstand curve can be developed for an insulation based on tests of the maximum crest voltage versus the time of the voltage to crest. The first test is a full wave withstand test where a 1.2 x 50 υsec wave is applied to the insulation. The crest value of the full wave withstand is referred to as the Basic Impulse Level (BIL) of the insulation. Another test is known as the chopped wave withstand test. This test begins as a standard 1.2 x 50 υsec test, but an air gap "chop", or allows the surge to sparkover very quickly. The chopped wave withstand (CWW) is approximately 115% of the BIL. Another test that is normally only performed on higher voltage transmission equipment is known as the Basic Surge Level (BSL) of the insulation and is 83% of the BIL. The results of these tests are a *volt-time equipment withstand curve,* and an example is shown in Figure 9 below.

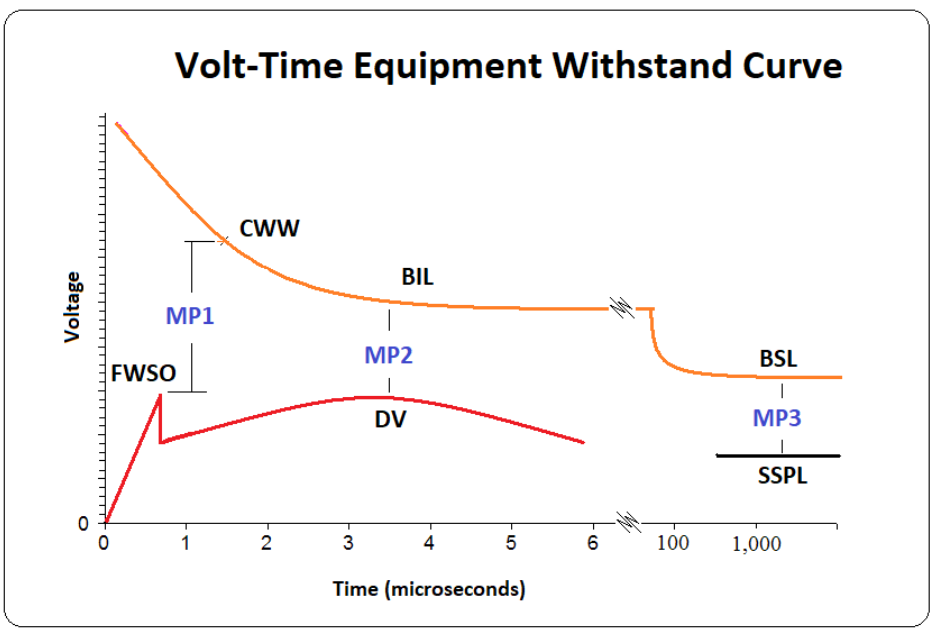

Figure 9

In Figure 9 a volt-time equipment withstand curve is shown along with the operating characteristics of a surge arrester. If you will notice, the front-of-wave surge rises until about ½ microsecond when the arrester sparks over and shunts current to ground. Once this happens the valve blocks conduct and the voltage rises slightly as the surge current discharges to ground. This continues until the arrester restores normal system insulation.

Finding the proper arrester to protect a device, such as a transformer, involves selecting the appropriate arrester voltage rating and then comparing the protective characteristics of the arrester with the withstand characteristics of the equipment.

As previously mentioned, most manufacturers have made the voltage rating selection easy by listing a maximum continuous operating voltage (MCOV) of the arrester. However, we must also consider the temporary overvoltages that occur during switching and fault conditions. Determining the overvoltage impact of a fault involves complex calculations, but from empirical data we can assume that a fault on a four-wire wye, multi-grounded system may be 25% greater than the normal operating voltage. For four-wire, wye, multi-grounded spacer cable systems, the fault voltage may be up to 50% greater than nominal, and for three-wire, delta systems, the overvoltage may be equal to up to the line-to-line voltage. For example, what arrester is appropriate for an open-wire, 24,940 Grd Y/14,400-volt system?

Since the phase-to-ground voltage is 14,400, we need an arrester that has an MCOV that is at least 5% greater or 15.1 kV. Also, the arrester must be capable of withstanding temporary overvoltages of 25% greater than nominal or 18 kV. Looking at Table 1, we see that an 18 kV arrester is capable of operating at an MCOV of 15.3 kV, which is greater than the nominal overvoltage of 15.1 kV. The minimum 60 Hz sparkover voltage is 31 kV, which is above the 18 kV that is likely to occur.

The next items to consider are how the protective characteristics compare to the equipment withstand characteristics. Two points are considered (a third is for higher voltage systems only.) At each point a margin of protection is analyzed. The first point compares the chopped wave withstand of the insulation to the front-of-wave sparkover of the arrester. The chopped wave withstand is assumed to be 115% of the BIL. The formula is,

$$\mathbf{MP1} = \left(\frac{\mathbf{CWW}}{\mathbf{FWSO}} - \mathbf{1}\right) * \mathbf{100}$$

Where,
MP1 = Margin of Protection level one.
CWW = Chopped wave withstand, kV.
FWSO = Front-of-wave withstand, kV.

The second compares the Basic Impulse Level (BIL) of the insulation to the discharge voltage of the arrester at a given discharge current. The margin of protection two is,

$$\mathbf{MP2} = \left(\frac{\mathbf{BIL}}{\mathbf{DV}} - \mathbf{1}\right) * \mathbf{100}$$

Where,
MP2 = Margin of Protection, Level two.
BIL = Basic Impulse Level of protected equipment, kV.
DV = Discharge voltage at a specified surge current, kV.

The third point compares the Basic Surge Level (BSL) of the insulation with the switching surge protective level of the arrester. The Basic Surge Level is normally considered to be 83% of the BIL.

$$\mathbf{MP3} = \left(\frac{\mathbf{BSL}}{\mathbf{SSPL}} - \mathbf{1}\right) * \mathbf{100}$$

Where,
MP3 = Margin of Protection, Level three.
BSL = Basic Surge Withstand Level, kV.
SSPL = Switching Surge protective level, kV.

Example. What are the protective levels for a 125 kV BIL transformer that is protected by an 18 kV arrester at a surge current of 20,000 amps? Use the characteristics for the 18 kV arrester shown in Table 1. Assume the SSPL is 45.0 kV.

From Table 1, we see that the front-of-wave sparkover of an 18 kV arrester is 49.0 kV (column 4) and the discharge voltage at 20,000 amps is 61.6 kV (column 9). If the chopped wave withstand is 115% of the BIL and the BSL is 83% of the BIL, the margins of protection are,

For MP1,

$$\mathrm{MP1} = \left(\frac{\mathrm{CWW}}{\mathrm{FWSO}} - 1\right) * 100$$

$$\mathrm{MP1} = \left(\frac{1.15 * 125}{49} - 1\right) * 100$$

MP1 = 193%.

For MP2

$$MP2 = \left(\frac{BIL}{DV} - 1\right) * 100$$

$$MP2 = \left(\frac{125}{61.6} - 1\right) * 100$$

MP2 = 103%.

For MP3

$$MP3 = \left(\frac{BSL}{SSPL} - 1\right) * 100$$

$$MP3 = \left(\frac{0.83 * 125}{45} - 1\right) * 100$$

MP3 = 131%.

The acceptable level of protection is left to the engineer to determine, but the ANSI C62.2 standard says the minimum level of protection is 20% for MP1, 20% for MP2, and 15% for MP3.

The chopped-wave withstand value of transformers is only valid for oil-filled units. Transformers with a dry-type insulation do not exhibit this additional short-time withstand characteristic, so for dry-type transformers the MP1 calculation should consider the BIL of the transformer instead of 115% of the BIL.

Based on the previous example, these levels will be easy to achieve. However, in this example we have only looked at the arrester's involvement in protecting the transformer.

Another item that we must consider is the arrester lead length. The arrester lead length is the parallel path from the top of the piece of protected equipment to the bottom, or grounded end of the equipment that is parallel to the arrester. See Figure 10.

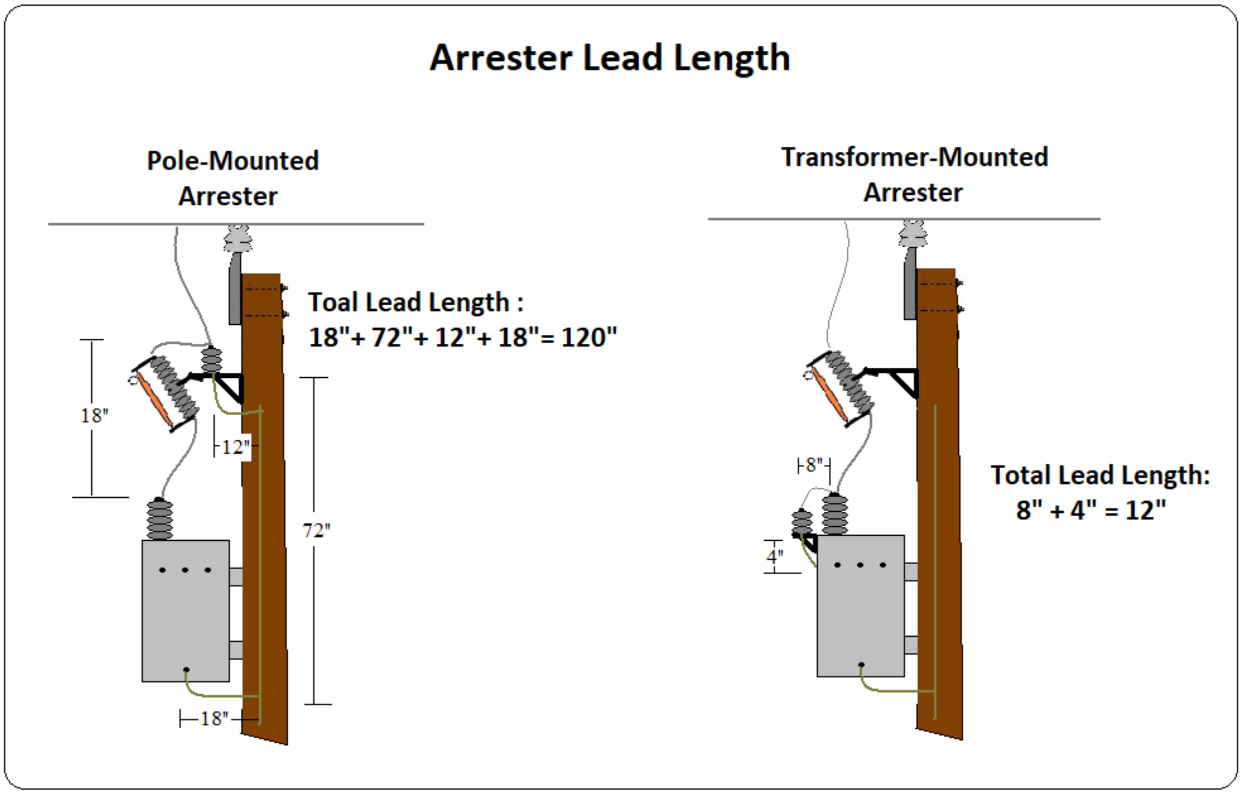

Figure 10

In this diagram, the total lead length for the transformer on the left is from the top of the transformer bushing, through the fused cutout to the arrester and then from the bottom of the arrester to the transformer winding grounding lug on the bottom of the transformer tank. In this case the total lead length is 120". For the transformer on the right the arrester is mounted directly on the transformer, and the total lead length is only 12".

The arrester lead length adds to the arrester discharge voltage when calculating the margin of protection two (MP2). On average, a grounding conductor will have an inductance of about 0.4 micro-Henries per foot. The voltage developed across an inductance is based on the change in current over a specific period or,

$$\mathbf{V = L\frac{\Delta i}{\Delta t}}$$

Assuming a typical rise time of a lightning surge it can be shown that the voltage developed across the grounding conductor is about 1.6 kV/ft. This number may vary based on the value of the lightning surge and values of up to 5 kV/ft are possible with 65 kA surges.

Remember from our previous example where the discharge voltage at 20,000 amps was 61.6 kV for an 18 kV arrester protecting a 125 kV BIL transformer. In this example, the MP2 was 103%. Next is a look at the protection level after including the transformer lead length. We will assume that the transformer lead length is 10 feet, and the leads will develop a voltage of 1.6 kV/ft. The formula now becomes,

$$\mathbf{MP2} = \left(\frac{\mathbf{BIL}}{\mathbf{DV + L}} - \mathbf{1}\right) * \mathbf{100}$$

Where,
MP2 = Margin of Protection, Level two.
BIL = Basic Impulse Level of protected equipment, kV.
DV = Discharge voltage at a specified surge current, kV.
L = Arrester lead length voltage, kV.

Example. MP2 considering the arrester lead length is,

$$\mathrm{MP2} = \left(\frac{\mathrm{BIL}}{\mathrm{DV + L}} - 1\right) * 100$$

$$\mathrm{MP2} = \left(\frac{125}{61.6 + 16} - 1\right) * 100$$

MP2 = 61%.

What if, because of a 65-kA surge, the arrester lead length voltage is 5 kV/ft? What is the MP2 in this case?

$$\mathrm{MP2} = \left(\frac{125}{61.6 + 50} - 1\right) * 100$$

MP2 = 12%.

With a 65-kA surge, the arrester MP2 is not adequate with a 10-foot lead length. What if the lead length is reduced to 12 inches by mounting the arrester directly onto the transformer?

In this case, the lead length is only one foot, so the MP2 is,

$$\mathrm{MP2} = \left(\frac{125}{61.6 + 5} - 1\right) * 100$$

MP2 = 88%.

Mounting the arrester directly on the transformer will result in a significant safety margin even for very severe lightning surges.

Lightning surge protection for voltage regulators is calculated in the same manner as a distribution transformer. The series winding of the regulator is a special case and protection is usually supplied by the manufacturer. For autotransformers, arresters should be placed across both windings of the unit.

Power capacitors present a special case to consider for lighting surge protection. The same principles apply to capacitors as with transformers, except capacitors introduce another component, which is the discharge energy that can be generated by the capacitor.

The problem with capacitors is that the overvoltage created by a lightning surge initially tries to charge the capacitor, which prevents the arrester from drawing any current. Once the arrester sparks over, the capacitor will discharge a tremendous amount of energy into the arrester. The arrester must be sized to handle the anticipated energy discharge of the capacitor. Modern arresters have the capability to handle between 2.0 kilojoules per kV and 10 kilojoules per kV (kJ/kV) of energy. Many manufacturers do not publish the energy discharge value in their literature since there is not an ANSI standard test for energy discharge capability.

The amount of energy that can be generated by a capacitor can be found from the following formula,

$$\mathbf{E = 0.5 * \frac{C}{377 * V^2} * FWSO^2}$$

Where,
E = Energy discharge of the capacitor, kilojoules (kJ).
C = Capacitor size, kVAR.
V = System voltage, phase-to-ground, kV.
FWSO = Sparkover voltage of the arrester, kV.

Example. Is a 10 kV arrester (see Table 1) with an energy discharge rating of 3.6 kJ/kV suitable for a 1,200 kVAR capacitor on a 12,470 GrdY/7,200 system?

$$E = 0.5 * \frac{C}{377 * V^2} * FWSO^2$$

$$E = 0.5 * \frac{1200}{377 * 7.2^2} * 28^2$$

E = 24.1 kJ.

Since the 10 kV arrester has a rating of 3.6 kJ/kV, or 36 kJ, the energy discharge capability of the arrester is adequate for this installation.

Chapter 4
Overhead Line Protection

Direct lightning strikes to power lines are a major cause of power line outages. The protection scheme for a power line may be designed to either: Prevent flashovers due to lightning strikes or allow flashovers to occur and use circuit breakers to momentarily interrupt the power follow current.

For many years, the conventional wisdom was that it was best to protect line equipment such as transformers with arresters, but to allow the power line structures to flashover for direct strikes (It was thought that power lines could be protected from indirect strikes with sufficient structure BIL.) However, with the increased emphasis on reliability and the prevalence of digital devices in homes today, momentary interruptions are considered a major annoyance to most consumers. Therefore, utilities are looking more closely at methods to prevent flashovers. In addressing overhead line protection, we will look at three items: shielding, arrester application to power line protection, and the impact of the power line structure design in preventing flashovers.

Shielding

One method of protecting power lines from lightning strike flashovers is to shield the lines from the lightning strike. By placing a shield wire above the power line conductors, the lightning strike can be intercepted by the shield wire, which diverts the surge current to ground before sufficient voltage builds up on the structure to flashover the structure's insulation.

Shielding is commonly used on transmission lines and in substations but is infrequently used on distribution circuits. On a distribution line, placing the neutral conductor above the phases makes it difficult to connect equipment to the neutral and it presents a hazard to lineman, who must climb above the phase conductors to reach the neutral conductor. Also, running a ground connection up past the phase conductors to the neutral may lower the BIL of the structure. Finally, this design requires taller poles since the phase conductors cannot be lowered a corresponding height as the relocated neutral conductor. There are cases though where overhead shielding is a logical choice for structure protection.

Shielding provides a "zone of protection" around the structure. From empirical data we know that a shield wire will provide protection around a structure for a certain distance based on the intensity of the lightning strike. The formula for strike distance is,

$$\mathbf{r_s = 26.25 * k * I^{0.65}}$$

Where,
r_s = Strike distance, ft.
k = constant, 1.0 for wires and other structures, 1.2 for lightning masts.
I = Strike current, kiloamps (kA).

Example. For, a 40,000-amp lightning strike, the strike distance is,

$$r_s = 26.25 * 1 * 40^{0.65}$$

$$r_s = 288.7 \text{ ft.}$$

Every component has a strike distance, including adjacent structures, buildings, and trees. The nearest strike distance zone to the lightning strike will normally receive the lightning surge. See the drawing below for an example.

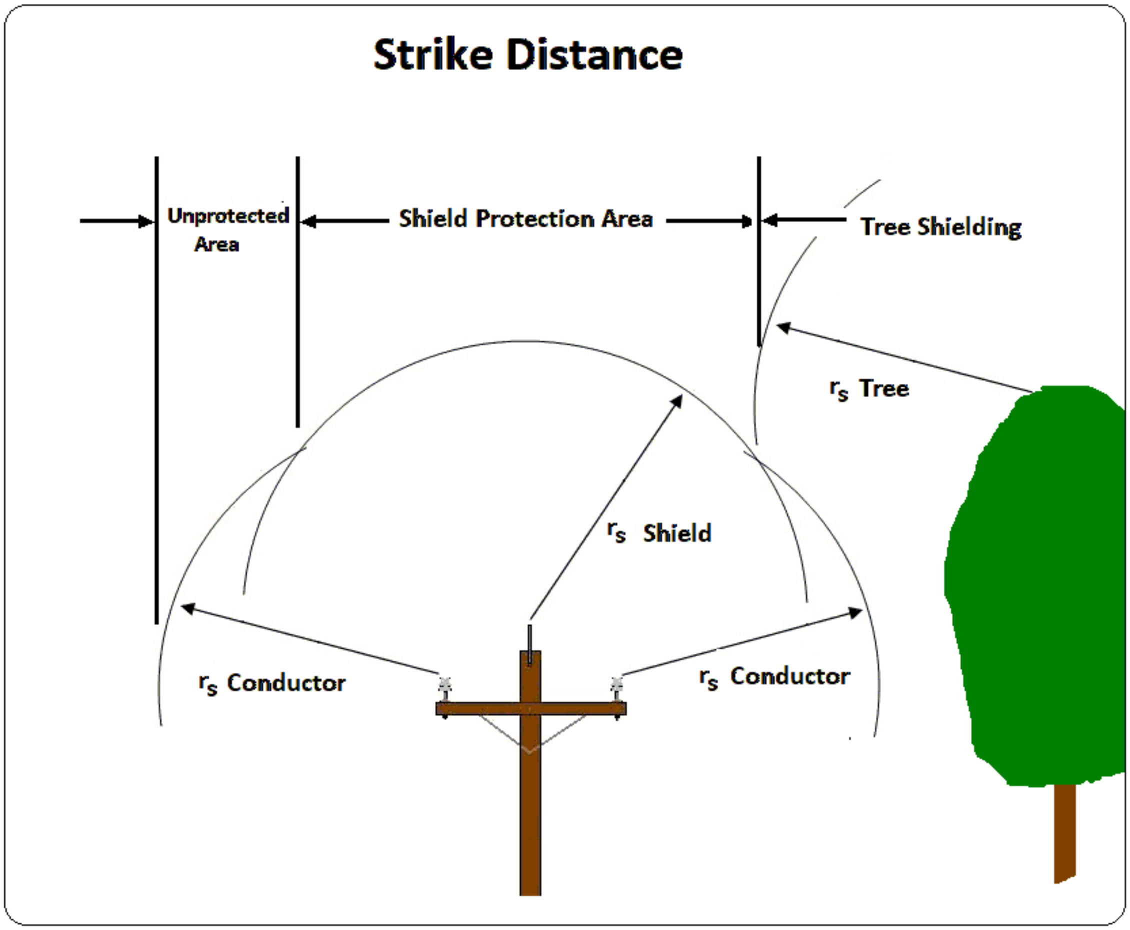

Figure 11

In Figure 11 the top shield wire protects a large area directly above the structure. The left conductor has an area that is not protected by the shield wire. The right conductor also has an area that is not protected by the shield wire, but the conductor is protected by the adjacent tree. When a phase wire is within a 45-degree cone under the shielding wire, it will be protected from a lightning surge. Even within the 45-degree cone, shielding is not always effective.

Between 80-100% of direct strikes to a power line conductor will result in a momentary outage. Any direct strike can be assumed to be a shielding failure. The number of shielding failures, or the shielding failure rate (SFR) can be determined by using the following formulas. The first formula is a modified form of strike distance considering the height of the neutral or shield wire and the phase conductors. The anticipated shielding angle must be known (or assumed) for this calculation. The second formula relates the maximum strike distance to the isokeraunic level to determine the anticipated shielding failure rate per 100 miles per year.

$$\mathbf{r_{s\,max} = \frac{H_n + H_c}{2 * (1 - \sin(\emptyset))}}$$

Where,
$r_{s\,Max}$= Maximum strike distance of the structure, feet.
H_n = Height of the shield wire, feet.
H_c = Height of the highest conductor, feet.
ϕ = Design shield angle, degrees.

For the shielding failure rate,

$$\mathbf{SFR = Ng * [(0.000005 * r_{s\,Max}^2 - 0.0027) * (r_{s\,Max} + 0.05)]}$$

Where,
SFR = Shielding failure rate, failures/100 miles/year.
IKL = Isokeraunic level.
Ng = Ground flash density, 0.30 * IKL, strikes/mi^2/yr.
$r_{s\,Max}$= Maximum strike distance of the structure, feet.

Example. Consider a structure where the shielding wire is at a height of 34 feet and the nearest phase conductor is at a height of 31 feet. The isokeraunic level is 60 and assume the shield design angle is 45 degrees. What is the expected shielding failure rate for this structure?

$$r_{s\,max} = \frac{H_n + H_c}{2 * (1 - \sin(\emptyset))}$$

$$r_{s\,max} = \frac{34 + 31}{2 * (1 - \sin(45))}$$

$r_{s\,Max}$= 111.0 ft.

For shield failure rate,

SFR = Ng * [(0.000005 * $r_{s\,Max}^2$ – 0.0027) * ($r_{s\,Max}$ * 0.05)]

SFR = (0.30 * 60) * [(0.000005 * 111^2 – 0.0027) * (111 * 0.05)]

SFR = 5.88 failures/100mi/yr.

This electric power line could expect to have 5.88 failures per 100 miles of line per year for the given shielding design.

Arrester application to overhead lines

There are several different methodologies to use to apply arresters to overhead line protection. A couple of the different approaches will be discussed here. The issue really is a matter of what the spacing should be between arresters on the line. The arresters should be placed close enough together so they will clamp the voltage buildup from a lightning strike to some value less than the BIL of the line.

There are other considerations such as whether arresters should be placed on all three phases or on just the top phase. The first approach is simplistic but can be used to determine the approximate arrester spacing for unshielded overhead power lines.

For this first approach we assume that the voltage from a lightning surge will build at a specified rate, and the resulting wave will travel down the line at a specified propagation rate. We have previously discussed that the standard rate of rise for a voltage wave is 100 kV/υsec per 12 kV of arrester rating. This value is a good rule of thumb for the rate of rise of a voltage surge. The propagation speed of the wave can be assumed to be 1000 ft/υsec.

For a safety factor, the arrester spacing should be such that the voltage does not exceed 80% of the BIL of the line. For a worse case situation, we assume that the surge occurs midway between the arresters. With these considerations, a formula for the arrester spacing can be developed such as,

$$\textbf{Arrester Spacing} = \frac{(\mathbf{0.8} * \textbf{BIL}) - \textbf{FWSO}}{\frac{\textbf{Rating}}{\textbf{120}}}$$

Where,
Arrester Spacing = Acceptable distance between arresters, feet.
BIL = Design BIL of line, kV.
FWSO = Front of wave sparkover of the arrester, kV.
Rating = Arrester Rating, kV.

Example. For an application of this approach to lightning arrester spacing, consider a situation that has a 300 kV BIL line is protected by a 9 kV arrester, which has a 28 kV front of wave sparkover. What is the maximum acceptable spacing of the arresters for the given line design?

$$\text{Arrester Spacing} = \frac{(0.8 * \text{BIL}) - \text{FWSO}}{\frac{\text{Rating}}{120}}$$

$$\text{Arrester Spacing} = \frac{(0.8 * 300) - 28}{\frac{9}{120}}$$

Arrester Spacing = 2,827 ft.

In this example, the arresters could be spaced up to 2,800 feet apart and still provide protection for the line insulation. This is a very imprecise method and only provides a very rough rule of thumb calculation.

The next model takes a little different approach to the arrester spacing problem. This approach is based on several major studies of the operation of electrical power lines during lightning surge conditions. The object of this approach is to determine the number of flashovers that will occur per 100 miles of line per year with a given arrester spacing. This approach considers both shielded and unshielded lines as well as three-phase arrester applications and single-phase arrester applications.

To use this approach, the utility must first decide on an acceptable outage rate due to lightning induced flashovers. Common value is four outages per 100 miles per year.

Next, the anticipated number of strikes to the line must be found. The number of strikes to the line is based on the isokeraunic level, the height of the line, conductor spacing, and the sag in the line. In addition, a factor must be applied to convert the isokeraunic level to strike frequency. The anticipated number of strikes has been modeled as,

$$\mathbf{NL = \frac{N_g * 100 * 4 * [h - (0.67 * Sag) + D]}{5,280}}$$

Where,
NL = Number of strikes per 100 miles of line per year.
Ng = Ground flash density, 0.30 * IKL.
h = Pole height, ft.
Sag = Conductor sag at mid-span, ft.
D = Horizontal distance to outer conductor, ft.

Once we know the number of strikes per 100 miles of line per year, the number of outage induced flashovers can be determined from the following formula. This calculation considers any natural shielding that occurs from nearby trees, buildings, etc. It also includes a probability value for the number of flashovers that will develop into an arc.

$$\mathbf{Z = \frac{100 * N_O}{NL * (1 - X) * Y}}$$

Where,
Z = Y-axis of chart in Figure 12.
N_O = Acceptable number of flashover outages per year.
NL = Number of strikes per 100 miles of line per year.
X = Percent natural shielding, decimal value.
Y = Probability of flashover developing into an arc, decimal value.

The next step is to look up the “Z” value on the Y-axis of the chart in Figure 12 and determine the arrester spacing for the type of installation (shielded, three-phase arresters, top-phase only arresters).

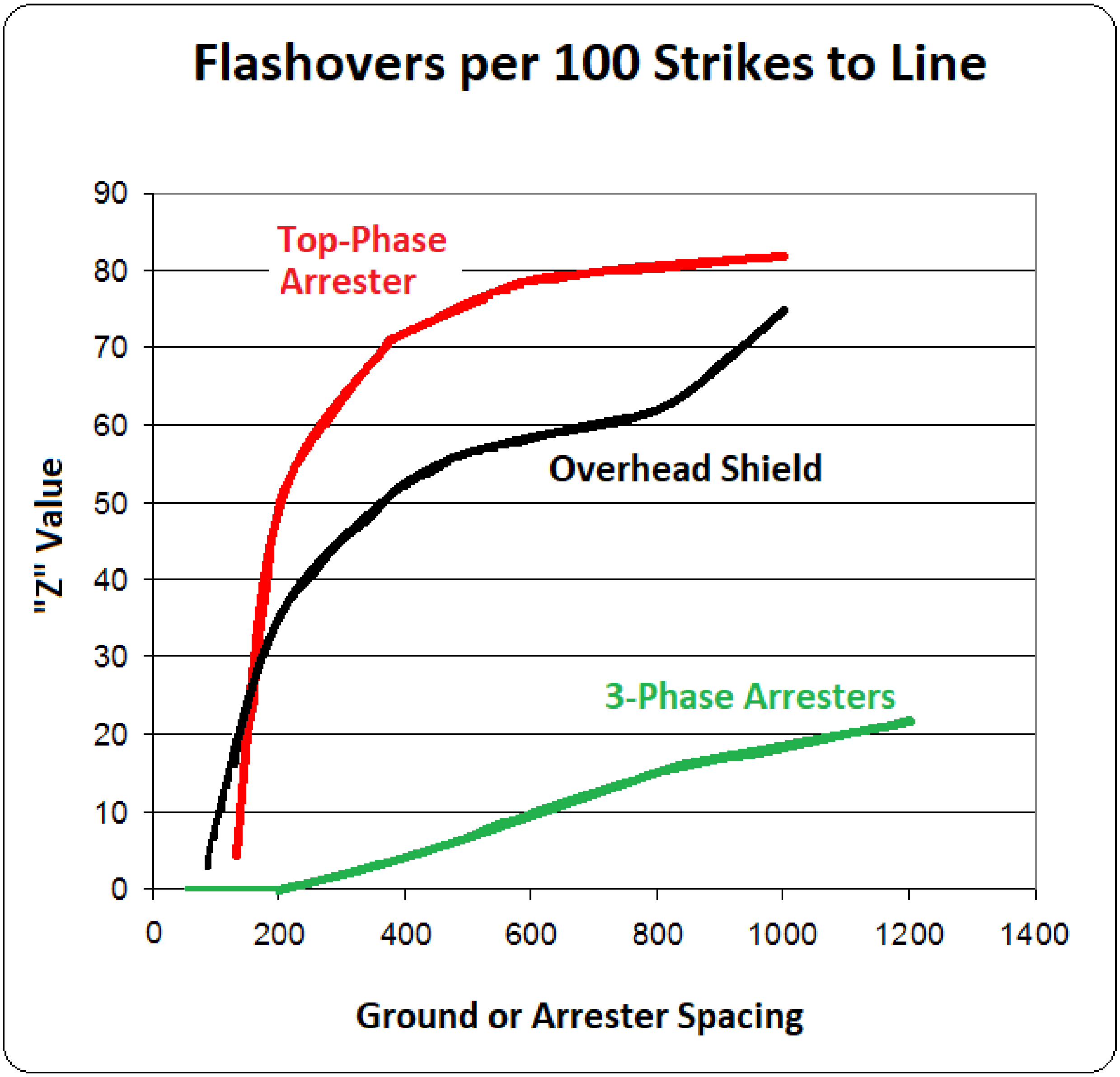

Figure 12

Example. The following example will show how to apply this approach to lightning arrester spacing.

What should the arrester spacing be for an electric power line in a 40 isokeraunic level area with typical pole heights of 34 feet, sag of 2.5-feet, and center phase to outer phase distance of 3.75 feet? Assume there is no natural shielding, and all flashovers develop into an arc. The acceptable flashover outage rate is 4 per year, and the utility plans to install arresters on all three phases.

For number of strikes,

$$NL = \frac{N_g * 100 * 4 * [h - (0.67 * Sag) + D]}{5,280}$$

$$NL = \frac{0.30 * 40 * 100 * 4 * [34 - (0.67 * 2.5) + 3.75]}{5,280}$$

NL = 32.8.

For the “Z-value,”

$$Z = \frac{100 * N_O}{NL * (1 - X) * Y}$$

$$Z = \frac{100 * 4}{32.8 * (1 - 0) * 1}$$

Z = 12.2.

By looking up the Z-value of 12.2 on the chart in Figure 12, for a three-phase arrester application, the spacing should be about 700 feet. Note that if only top-phase arresters were being used, the arresters would need to be spaced about every 180 feet.

If only a shield wire is being considered, the chart in Figure 12 is used to show the spacing of grounds for the shield wire.

Structure Design

The proper application of shielding or surge arresters is based on the basic impulse level (BIL) of the line under consideration. Therefore, to adequately design a protection scheme for a power line, we must understand the BIL of the line. The BIL of a line is based on the various components that make up a structure such as the wood pole, wood, or fiberglass crossarms, insulators, ground wires, and spacing between components. Each of the components has its own withstand characteristics and with knowledge of these characteristics and how the various components interact, we can estimate the BIL of any power line structure.

It is important to point out that the insulation withstand characteristics of the different components are not necessarily additive. While this is not technically correct, from a practical standpoint the withstand characteristic of a wood crossarm does not add to the withstand characteristic of an insulator. Or at least, the most conservative response is to make this assumption.

When studying the BIL of a structure, we must look at the withstand characteristics of the line for both phase-to-ground and phase-to-phase scenarios. The lower of the two is taken as the BIL of the structure. Furthermore, for each case, phase-to-ground, and phase-to-phase, we must look at the surge paths through the wood and fiberglass, through the insulators, and through the air. Of these, the BIL is based on the greater of the wood/fiberglass paths or the insulators, unless the air-path is less, in which case, the air-path governs.

<u>Impulse insulation characteristics of insulators</u>

The insulation characteristic of an insulator is defined by its *Critical Flashover Voltage* (CFO). The critical flashover voltage is a 1.2 x 50 υsec impulse voltage at which a discharge occurs over the surface of the insulator. The CFO is based on an average of several tests and is defined as the level at which flashover occurs 50% of the time. The critical flashover voltage is found for both positive and negative impulses. Table 2 has typical CFO values for several common types of insulators.

Table 2

Insulator Characteristics

Pin Type	CFO		Post Type	CFO		Suspension	CFO	
	Negative (kV)	Positive (kV)		Negative (kV)	Positive (kV)		Negative (kV)	Positive (kV)
55-1	70	50	57-1	155	130	52-3	130	125
55-2	95	75	57-2	205	180	52-5	130	125
55-3	130	100						
55-4	140	110						
55-5	170	140						
55-6	170	150						

Note: Manufacturers sometimes refer to the CFO as the "Average flashover voltage."

From Table 2, we can see that a 55-3 Pin Type insulator's negative CFO value is 130 kV, and its' positive CFO value is 100 kV. Since the CFO value is derived as an average of many tests, it is common to assume the BIL of the insulator is 90% of the CFO. And even though most lightning surges have negative polarity, the most conservative response is to use the positive CFO value to determine the BIL. An insulator is modeled as a capacitance.

Impulse insulation characteristics of wood

The insulation characteristics of wood are highly dependent on the condition of the wood. The type of wood, cracks, moisture content, and type of preservative used will all have an impact on the BIL of wood. A good general BIL value for wood is 100 kV per foot, but it may range from 50 kV to over 200 kV depending on the condition of the wood. Wood is modeled as a capacitance in parallel with a resistance and it is not additive with the insulation values of an insulator, but it is additive with fiberglass.

Impulse insulation characteristics of fiberglass

The impulse insulation values of new fiberglass may be in the range of 200 kV per foot, and moisture does not seriously degrade the value since the moisture tends to bead-up on the fiberglass. As the fiberglass ages though, moisture has an impact on the insulation value and a conservative value of 100 kV per foot is assumed for fiberglass. Like wood, fiberglass is modeled as a capacitance in parallel with a resistance and it is not additive with the insulation values of an insulator.

Impulse insulation characteristics of air

A conservative value for the insulation characteristics of air is 200 kV per foot. The air gap is modeled as a capacitance and is not additive with other forms of insulation. If the insulation value of the air gap is lower than either the wood/fiberglass or the insulators then the air gap defines the BIL of the structure.

Examples. Following are several examples of BIL calculations of various structures. The first structure is a simple single-phase structure using a horizontal post insulator with 48 inches of separation between the insulator and the neutral (grounded conductor).

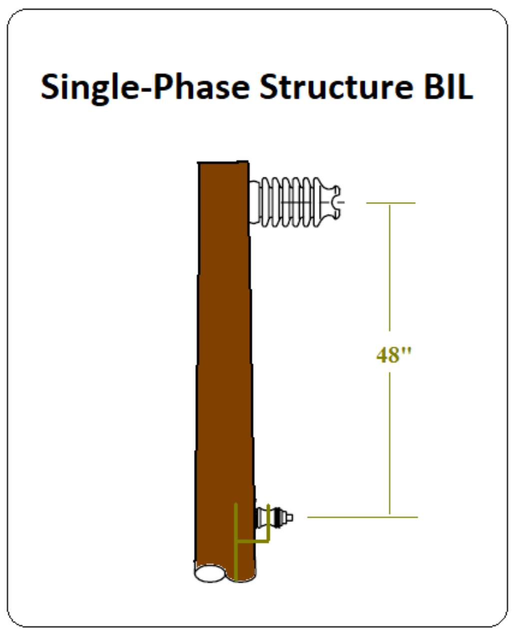

Figure 13

In Figure 13, assume the post insulator is a type 57-1 with a positive CFO of 130 kV. What is the BIL of the structure?

First, we need to determine the BIL based on the insulator.

$$BIL_{Insulator} = 0.9 * 130 = 117 \text{ kV}$$

Next, we determine the BIL based on the wood pole,

BIL_{Wood} = 4 * 100 = 400 kV.

Finally, we determine the BIL based on the air gap between the conductor and the ground wire,

$BIL_{Air\ Gap}$ = 4 * 200 = 800 kV.

Since the BIL of the air gap is greater than either the insulator or the wood, the air gap does not define the BIL. In this example the wood pole defines the BIL and is 400 kV. A good rule of thumb is that a distribution structure (up to 25 kV, phase-to-phase) should have a BIL value of at least 350 kV.

Next, look at the three-phase structure shown is Figure 14. This structure has 55-3 Pin Type insulators on 18" fiberglass arms mounted vertically on a wood pole with 48 inches of spacing between the arms and the neutral. From Table 2 we see that a 55-3 Pin Type insulator has a positive CFO of 100 kV.

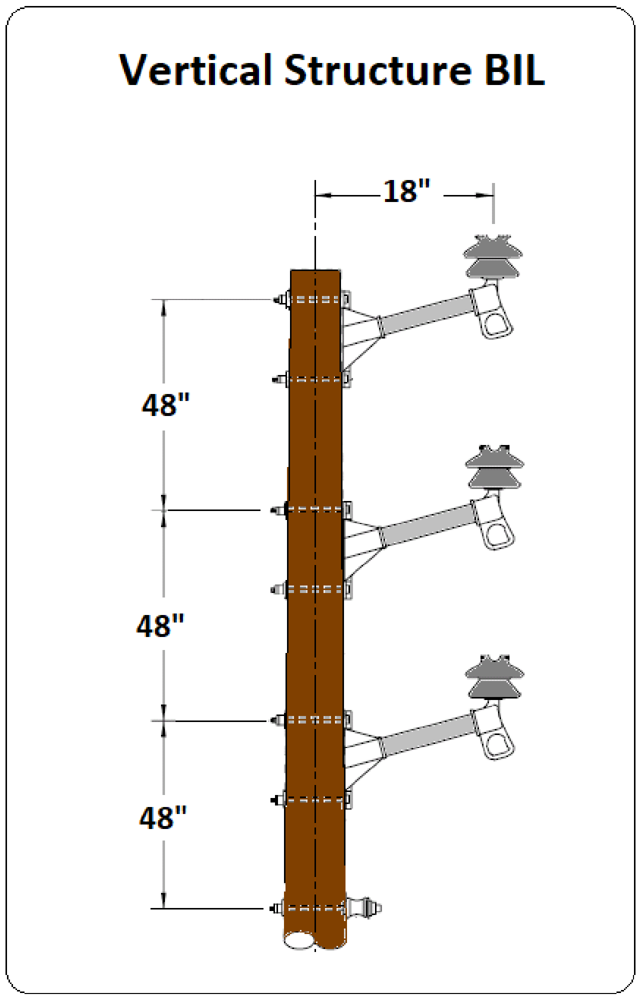

Figure 14

For the phase-to-phase path:

$BIL_{Wood/Fiberglass}$ = 4 * 100 + 1.5 * 100 + 1.5 * 100

$BIL_{Wood/Fiberglass}$ = 700 kV.

$BIL_{Insulators}$ = 0.9 * 100 + 0.9 * 100

$BIL_{Insulators}$ = 180 kV.

$BIL_{Air\ Gap}$ = 4 * 200

$BIL_{Air\ Gap}$ = 800 kV.

For the phase-to-neutral path:

$BIL_{Wood/Fiberglass}$ = 4 * 100 + 1.5 * 100

$BIL_{Wood/Fiberglass}$ = 550 kV.

$BIL_{Insulator} = 0.9 * 100$

$BIL_{Insulator} = 90$ kV.

$BIL_{Air\ Gap} = 4 * 200$

$BIL_{Air\ Gap} = 800$ kV.

The table below summarizes the results of these calculations.

Component	Phase-to-Phase	Phase-to-Neutral
Wood/Fiberglass	700 kV	550 kV
Insulators	180 kV	90 kV
Air Gap	800 kV	800 kV

Again, in this example, the wood/fiberglass component controls the BIL of the structure. In this case, it is the phase-to-neutral value, which is 550 kV. Since the air gap value is higher, it is not the controlling value.

Example. This example is the same as the single-phase structure in Figure 13, but in this example the ground conductor extends from the neutral position up to the top of the pole as a "lightning rod". This was a common practice in the 1950's and 1960's and many of these structures are still in service. See Figure 15.

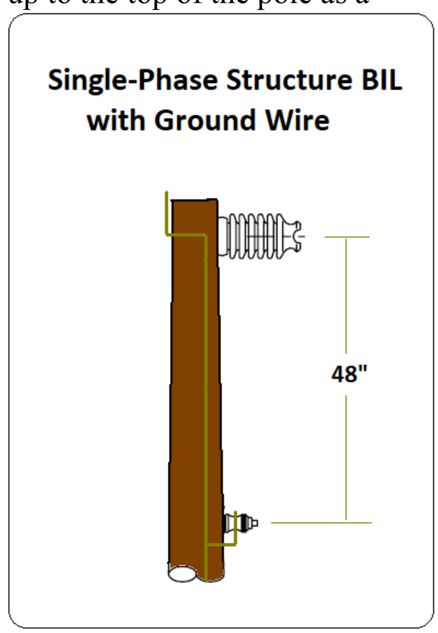

Figure 15

In Figure 15, assume the post insulator is a type 57-1 with a positive CFO of 130 kV. The distance from the ground wire to the insulator base is 3 inches. What is the BIL of the structure?

First, we need to determine the BIL based on the insulator.

$BIL_{Insulator} = 0.9 * 130 = 117$ kV.

Because the ground wire is only 3 inches from the base of the insulator, the BIL of the wood path is only,

$BIL_{Wood} = 3/12 * 100 = 25$ kV.

Likewise, the air path is across the insulator to the ground wire, which is only 11 inches,

$BIL_{Air\ Gap} = 11/12 * 200 = 183$ kV.

The ground wire destroyed the BIL that is provided by the spacing from the neutral to the phase. The BIL of the structure is now based on just the insulator, which is 117 kV. This is far below the 350 kV BIL standard.

A lightning surge will often travel thousands of feet until it finds a structure with a low BIL to flashover. To prevent flashovers, it is imperative that these weak links in a power line be upgraded. Special attention should be paid to down guys, steel crossarm braces, steel crossarms, and ground wires that extend too close to the phase conductors. The use of fiberglass links and stand-off brackets to provide separation between the phase conductors and the ground can help improve a structure's BIL.

Chapter 5
Underground Line Protection

The normal practice for many utilities is to place a surge arrester on the underground termination pole, or "riser" structure. The theory is that the arrester will prevent damaging overvoltages from entering the underground cable. However, because a significant voltage will still be present across the cable insulation a wave will travel down the cable and be reflected at the first change in impedance. The reflected wave may be up to twice the voltage that was clamped by the riser pole arrester. To mitigate the traveling wave some utilities place "elbow" arresters on the last transformer in an underground circuit and occasionally at other transformers in the circuit.

Protecting underground lines is a special case of the equipment protection that was discussed in section III. The margin of protection formulas that we previously discussed in section III are also useful for underground line protection, except the voltage doubling that occurs in underground cables must be considered. With the voltage doubling considered the margin of protection calculations become,

$$\mathbf{MP1_U} = \left(\frac{\mathbf{CWW}}{\mathbf{2 * FWSO}} - \mathbf{1}\right) * \mathbf{100}$$

Where,
$MP1^U$ = Margin of Protection level one.
CWW = Chopped wave withstand, kV.
FWSO = Front-of-wave withstand, kV.

The next formula compares the Basic Impulse Level (BIL) of the cable insulation to the discharge voltage of the arrester at a given discharge current. The margin of protection two is,

$$\mathbf{MP2_U} = \left(\frac{\mathbf{BIL}}{\mathbf{2 * (DV + L)}} - \mathbf{1}\right) * \mathbf{100}$$

Where,
$MP2_U$ = Margin of Protection, Level two.
BIL = Basic Impulse Level of the cable, kV.

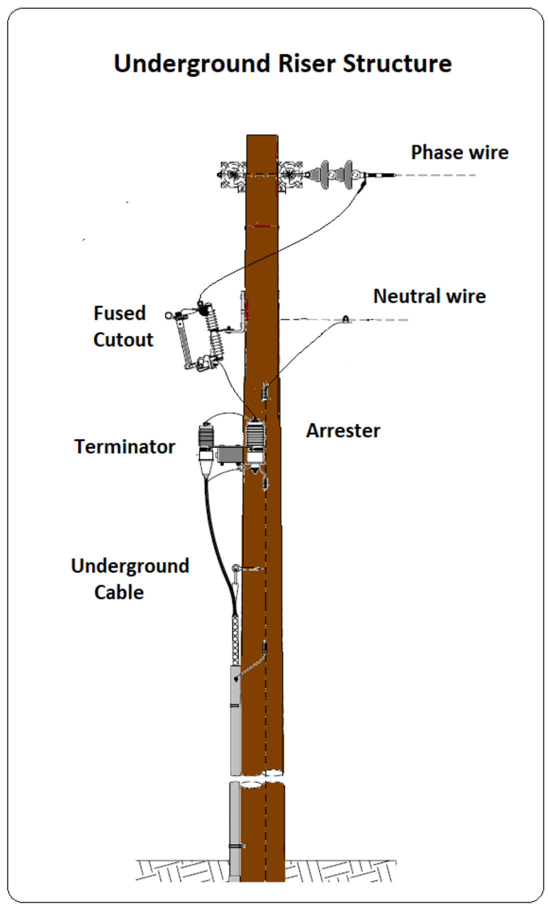

Figure 16

DV = Discharge voltage at a specified surge current, kV.
L = Arrester lead length voltage, kV.

The lead length to consider in $MP2_U$ is the distance from the top of the underground cable terminator to the concentric ground on the underground cable. In the case shown in Figure 16, where the arrester is mounted next to the cable termination, the total lead length is about two feet. The margins of protection, both $MP1_U$ and $MP2_U$ should be 20% or greater.

Examples. Consider a case where a 9 kV distribution class arrester is protecting a 15 kV, 95 kV BIL, concentric neutral underground cable. What are the margins of protection for the cable for a 40-kA surge? (Assume the lead length voltage is 1.6 kV per foot.)

From Table 1 for a 9 kV arrester the FWSO is 25 kV, and the 40-kA discharge voltage is 38.1 kV. With 3 feet of lead length, the lead length voltage is 4.8 kV. If the CWW is 115% of the BIL the margins of protection are,

For $MP1_U$,

$$MP1_U = \left(\frac{CWW}{2 * FWSO} - 1\right) * 100$$

$$MP1_U = \left(\frac{1.15 * 95}{2 * 25} - 1\right) * 100$$

$MP1_U = 118.5\%$.

For $MP2_U$,

$$MP2_U = \left(\frac{BIL}{2 * (DV + L)} - 1\right) * 100$$

$$MP2_U = \left(\frac{95}{2 * (38.1 + 4.8)} - 1\right) * 100$$

$MP2_U = 10.7\%$.

The margin of protection 1 is okay, but the margin of protection 2 is not adequate with this arrester and lead length. To improve the margin of protection 2 calculation a shorter lead length, different arrester rating, or downline arresters may be needed.

The preceding $MP2_U$ equation is only used for cases where an arrester is protecting a riser pole without any downline protection on the underground. If the electric system has additional arresters on the underground transformers then the margin of protection 2 calculation become more complicated. One method is addressing this case that is sometimes used is to assume the maximum voltage on the cable is equal to the discharge voltage of the riser pole arrester plus one-half the front-of-wave sparkover voltage of the downline arrester plus the lead length voltage. The margin of protection 2 formula is then,

$$\mathbf{MP2_U = \left(\frac{BIL}{DV_{RP} + (0.5 * FWSO_{TX}) + L} - 1\right) * 100}$$

Example. Continuing with the previous example, assume that an elbow arrester is installed at the end transformer with the same characteristics as the riser pole arrester. The $MP2_U$ calculation is then,

$$MP2_U = \left(\frac{BIL}{DV_{RP} + (0.5 * FWSO_{TX}) + L} - 1\right) * 100$$

$$MP2_U = \frac{95}{38.1 + (0.5 * 25) + 4.8} * 100$$

$MP2_U$ = 71.5%.

With the downline arrester the margin of protection 2 is now at an acceptable level of 71.5%.

0

Chapter 6
Grounding

Grounding is important for proper operation of overvoltage protective equipment. Arresters will operate properly with a wide range of ground resistances, but the performance of shielding systems is related to the condition of the system ground. Of course, grounding is also important to minimize shock hazards and to provide a path to ground during all types of fault conditions.

To be an effective ground, the system must:

- Provide a low impedance path to ground.
- Withstand and dissipate fault and surge currents.
- Provide corrosion resistance to various soil chemistries.
- Be mechanically strong enough to withstand physical damage.

Twenty-five (25) ohms is the accepted ground resistance standard for most applications. However, many applications require much lower ground resistance levels such as transmission lines, substations and generating stations. Even for distribution lines resistance values of 10-ohms or less are desirable.

A ground rod driven into the earth of uniform resistivity conducts current in all directions. As the distance from the electrode increases, the impact of the earth's resistance decreases. At a distance equal to the depth of the electrode, the earth does not create additional resistance to the electrode. Therefore, a distance equal to the depth of the electrode is known as the "Effective Resistance Area".

Most ground rods installed consists of a single electrode, driven vertically into the earth. The ground resistance with a single rod is dependent on the soil resistivity, rod length, and the rod diameter.

When multiple rods are installed they should be separated by a distance equal to the twice the length of the rods to prevent the additional rods from encroaching on the effective resistance area of the other rod. Figure 17 shows the ground field surrounding a ground rod.

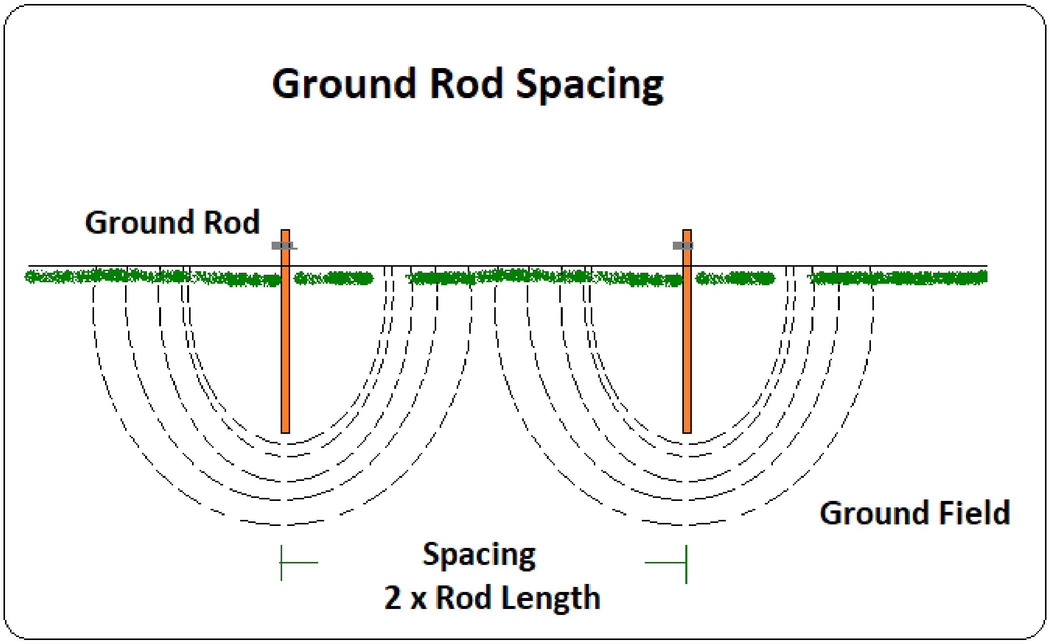

Figure 17

The resistance to current through an earth electrode system has three components:

- Resistance of the ground electrode itself and the connections to it.
- Contact resistance between the ground electrode and the earth adjacent to it.
- Resistance of the surrounding earth.

Soil resistivity has the greatest impact on the performance of a grounding system. In fact, soil resistivity is the key factor that determines what the resistance of a grounding electrode will be, and to what depth it must be driven to obtain low ground resistance.

The electrical resistivity of the earth is a major issue when designing a grounding system. Soil moisture, soil mineral content, and temperature all affect earth resistivity.

The type of soil affects earth resistivity. Table 3 has estimates for soil resistivity for several different types of soil conditions. Because of moisture in the soil the resistivity can vary even for the same type of soil.

Table 3 **Soil Resistivity**	
Soil Type	**Resistivity (meter-ohms)**
Loam	5 - 50
Clay	5 - 100
Sand	50 - 1,000
Limestone	5 - 10,000
Sandstone	20 - 2,000
Granite	1,000
Slate	500 - 5,000

The most common grounding system consists of just one ground electrode connected to the electric system. Other common designs include a multiple electrode installation with the electrodes installed in a linear arrangement, and multiple electrodes installed in a rectangular grid. We will look at the calculations for the design of a grounding system using a single rod and a multiple rod linear system.

Single Ground Rod

Ground resistance with a single rod is calculated by using the formula,

$$\mathbf{R = \frac{\rho}{1.915 * L} * \ln\left(\frac{35.316 * L}{D}\right)}$$

Where,
R = Electrode resistance to ground, ohms.
ρ = Earth resistivity, meter-ohms.
L = Electrode length, feet.
D = Electrode diameter, inches.

Example. An 8-foot rod, 3/4 inch in diameter is driven completely into homogeneous clay with an earth resistivity of 75 meter-ohms. What is the anticipated ground resistance of the electrode?

$$R = \frac{\rho}{1.915 * L} * \ln\left(\frac{35.316 * L}{D}\right)$$

$$R = \frac{75}{1.915*8} * \ln\left(\frac{35.316*8}{0.75}\right)$$

R = 29.0 ohms.

Multiple Electrodes - Straight Line Design

When one rod will not yield the desired ground resistance, multiple rods must be installed. Installing two or more electrodes in parallel is an effective method of reducing ground resistance.

Rods can be installed in a straight line or in some form of circle, triangle, or rectangle and connected by a bare copper wire. The specific geometric pattern is unimportant if the proper spacing is maintained between the rods.

The resistance calculation for multiple ground rods includes the mutual interaction of the resistance between the wires and the rods, but a conservative approach is to just consider the effect of the rods alone. The resistance calculation for multiple rods is,

$$\mathbf{R_r = \frac{1}{n} * [R + \{\frac{\rho}{0.9576 * S} * \left(\frac{1}{2} + \frac{1}{3} + \frac{1}{4} \ldots + \frac{1}{n}\right)\}]}$$

Where,
R_R = Parallel resistance of the electrodes in ohms.
R = Resistance of one electrode (From the previous equation), ohms.
n= Number of electrodes in parallel.
ρ = Soil resistivity, meter-ohms.
S = Spacing between electrodes.

Example. Consider a straight-line grounding system using four, 8-foot, ¾-inch diameter rods, which are spaced 20 feet apart. What is the ground resistance if the soil resistivity is 75 meter-ohms?

The previous example yielded a resistance, R, at 29 ohms. The resistance of the multiple rods is:

$$R_r = \frac{1}{n} * [R + \{\frac{\rho}{0.9576 * S} * \left(\frac{1}{2} + \frac{1}{3} + \frac{1}{4} \ldots + \frac{1}{n}\right)\}]$$

$$R_r = \frac{1}{4} * [29 + \{\frac{75}{0.9576 * 20} * \left(\frac{1}{2} + \frac{1}{3} + \frac{1}{4}\right)\}]$$

R_R= 8.31 ohms.

As you can see from these two examples, using the same conditions a single rod yielded a ground resistance of 29.0 ohms where four rods in parallel reduced the ground resistance to 8.31 ohms.

Chapter 7
Ferroresonant overvoltages

Ferroresonance is a condition where extremely high, and sustained, overvoltages occur very quickly in concert with severe harmonic distortion. It is the result of a capacitance in series or in parallel with a saturable inductor. Once a ferroresonant condition occurs the rapid change in voltage and current can damage transformers, cables, surge arresters, and other electrical equipment.

Ordinarily it should be easy to calculate the resonant point in a circuit if we know the basic circuit parameters, but by having a saturable inductor in the circuit the exact point of resonance becomes harder to quantify. As the inductor goes into saturation, its inductance changes rapidly and this changes the point at which resonance occurs. And because of the hysteresis of the inductor, there may be several points or conditions that will cause the Ferroresonant condition to occur.

Originally it was thought that ferroresonance only occurred in high voltage systems, but with the advent of concentric neutral underground cables in the 1960's, even 15 kV systems experienced ferroresonance. For ferroresonance to occur there must be a ferromagnetic inductor, such as a distribution transformer, a capacitance, such as the capacitance between the phase conductor and neutral of a concentric neutral underground cable, and a low resistance, which may be the result of a lightly loaded feeder. The most common cause of ferroresonance on a distribution system is when a wye-delta connected transformer bank is left ungrounded on the high side, is supplied by an underground cable, and has one or two phases open-circuited. The open-circuited phase may be the result of single-phase switching or a faulted phase causing a fuse to open. See Figure 18 for a schematic of this scenario.

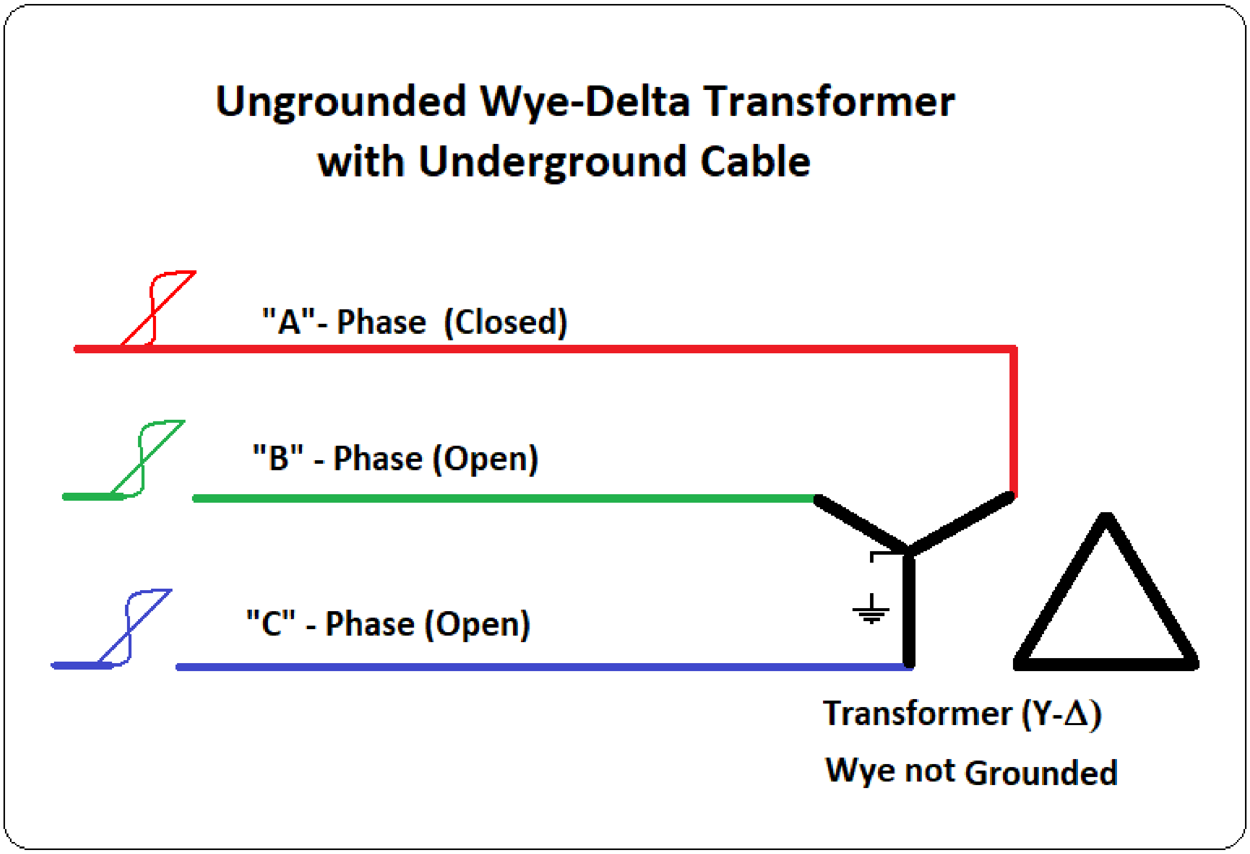

Figure 18

There are many other scenarios though where ferroresonance may occur, but since this is the most common we will look at it in more detail. A conservative approach is to design the electric system so that at no point is the ratio of the zero-sequence cable capacitance X_{C0} to the transformer magnetizing impedance, X_M, less than 40. Table 4 has estimates of expected overvoltages based on the ratio of X_{C0} to X_M for two phases open and one energized phase.

Table 4 X_{C0} / X_M Two Open Phases and One Energized Phase	
X_{C0} / X_M Ratio	Expected Overvoltage
<0.02	4 per unit or greater
0.01 - 10	2.8 per unit
10 - 30	2.0 per unit
30 - 40	1.5 per unit

40 >	1.25 per unit or less

The transformer magnetizing impedance is a function of the transformer exciting current, primary system voltage, and the transformer capacity.

$$\mathbf{X_M = \frac{1000 * KV^2}{I_{EX} * KVA}}$$

Where,
X_M = Transformer magnetizing impedance, ohms
kV = Primary voltage, kV.
I_{EX} = Percent transformer exciting current, decimal value.
kVA = Transformer capacity, kVA.

Example. What is the transformer magnetizing impedance of a three-phase 12.47 kV, 500 kVA, transformer, which has a 1.2% exciting current?

$$X_M = \frac{1000 * KV^2}{I_{EX} * KVA}$$

$$X_M = \frac{1000 * 12.47^2}{0.012 * 50}$$

X_M = 25,917 ohms.

The zero sequence capacitive reactance of a concentric neutral underground cable is found from the log of the ratio of the diameter of the insulation to the diameter of conductor times the frequency and the insulation dielectric constant. The formula for the capacitive reactance is,

$$\mathbf{X_{C0} = \frac{\log(\frac{D}{d})}{0.0046 * f * \varepsilon * L} * 100,000}$$

Where,
X_{C0} = Capacitive Reactance, Ohms.
D = Diameter of insulation, inches.
d = Diameter of conductor, inches.
f = frequency, Hertz.
ε = Dielectric Constant of the insulation.

L = Length of cable, 1000's feet.

"D" is the diameter of the conductor with the insulation and excludes the insulation shield and jacket. The diameter, "d," is the conductor diameter and includes the conductor shield. The term, "ε," or epsilon, is the insulation dielectric constant and is 2.4 for XLPE cable and 2.9 for EPR cable.

Example. What is the capacitive reactance of a 5,000-foot XLPE cable if it is operating at 60Hz, "D" is 1.1 inches, and "d" is 0.58 inches?

$$X_{C0} = \frac{\log(\frac{D}{d})}{0.0046 * f * \varepsilon * L} * 100{,}000$$

$$X_{C0} = \frac{\log(\frac{1.1}{0.58})}{0.0046 * 60 * 2.4 * 5} * 100{,}000$$

X_{C0} = 8,393 ohms.

The ratio then of X_{C0} to X_M from the previous calculations is,

X_{C0} / X_M = 8,393 / 25,917 = 0.32.

Therefore, ferroresonance may occur in this circuit and the overvoltage may be in the range of 2.8 per unit.

Ferroresonance can be reduced by avoiding single-phase switching, using transformer banks with grounded wye connections, and keeping underground circuits short and well loaded.

Summary

Whether the cause is a lightning surge or ferroresonance, overvoltages on electric utility distribution systems are disruptive events that frequently damage equipment and interrupt the flow of power.

Properly applying surge arresters, shielding, and structure design minimizes the impact of lightning surges. Careful attention to BIL coordination ensures all components work together to minimize the impacts of lightning surges. Minimizing overvoltages from ferroresonance requires attention to underground cable lengths and switching procedures.

+++