

Lightning, Grounding and Protection for Control Systems

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Abstract— Protection for installations that have been modernized or retrofitted presents a unique mix of problems that require a different perspective from a new installation. The paper addresses lightning, transients, and radiation that cause problems on programmable logic controllers, distributed control systems, and remote electronic transducers. While complex grounding grids and networks were not required for analog systems, newer digital equipment requires a very effective means of maintaining equal potential throughout the facility. Methods of protecting circuits include a variety of sophisticated and not-so-elegant techniques.

Special consideration must be given to the impact that towers have on a protection system. The investigation ranges from no air terminals to lightning arrays. The protection problem is compounded when different soils such as clay and rock are encountered. Methods of calculating the grounding circuit resistance are identified.

Although the paper is based on a retrofit, the techniques are appropriate for any industrial installation using distributed control.

I. INTRODUCTION

DEVELOPMENT of design procedures for grounding and transient protection of electrical equipment is based on traditional electrical concepts, but the application can be very complex. While the concepts may be a science, the application is an art.

Every installation is unique. The location, access, soil conditions, atmospheric interaction, and equipment to be protected all impact the design of a protection system. There are numerous gadgets, gismos, and unverifiable procedures for protecting equipment. Nevertheless, reasonable decisions can be made when adequate information is available.

A tutorial on the components of an effective protection system will be provided first. This gives the basis for the design and installation procedures that follow.

As much money can be thrown at the problem as one desires. This is seldom necessary. A conservative, effective, fundamental design should be the first choice. This will resolve the problems at most sites. If problems continue to exist at certain locations, enhancements can be made at only those places requiring additional help.

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The data and descriptions that are provided are based on years of experience from industry-recognized practices. Before any high technology protective devices can be installed and expected to operate consistently, a viable grounding system is necessary to provide for the dissipation of transients and surges.

II. GROUNDING DIFFERENTIATION

Not all grounding is the same, although all these methods are usually connected to a common earth point. Because all of these grounding considerations occur in a typical plant location, care must be exercised to prevent interaction between the different grounding needs.

Power grounding is intended to carry low frequency or direct current fault currents back to fuses or other protective devices. This is primarily a current consideration. This occurs via the system grounding electrode [1]-[3].

Bonding is to provide an equipment ground to prevent potential differences which may shock an individual or flash over and cause a fire. This is primarily a voltage consideration. This is accomplished by connecting all metal equipment together to a single point of reference.

Shielding is used to prevent higher frequency electromagnetic noise from interfering with the desired signal. This is primarily a frequency-related consideration. It is accomplished by isolation of the signal wires from sources of noise. This is accomplished by use of a Faraday shield.

Lightning protection is intended to provide a path to dissipate high energy into the soil. This is primarily an energy consideration. This is accomplished by having an equal potential grid under the area to be protected.

Electrical system grounding electrodes are not to be used in lieu of lightning protection ground rods. Nevertheless, the electrodes of different systems must be bonded together. Because of the location of lightning arrestors on power lines in relation to electrical system grounding electrodes, the two systems often appear to be the same. A clarification will assist in understanding grounding in general.

The system grounding electrode is installed at the point of service as defined in the NEC [3]. There are a variety of devices that can be used, but the generally recognized electrode is the 8-ft ground rod driven at the meter or entrance. The ground resistance of these systems are required to be only 25 Ω .

All other grounding electrodes, ground wells, and connections to piping have another purpose. These may be for lightning protection, personnel protection, or other equipment

protection. Nevertheless, these must be bonded to the system grounding electrode.

III. TRANSIENTS AND SURGES

There are a variety of sources of transients and surges that can interfere with the operation of electrical equipment.

Transients can be caused by the way electrical equipment is operated. Electromagnetic interference is generated by switched mode power supplies in computers, SCR controllers, and variable frequency drives [4]. The interference caused by switched mode power supplies must be corrected by increasing wire sizes, changing transformer design and configuration, and using active filters. Single frequency passive filters composed of capacitors and inductors are not generally effective. The cutoff frequency of the filter is physically too close to the fundamental to allow a good filter design [5].

The switching of large motor loads and the switching of transmission lines and power factor correction capacitors can create substantial noise. The breaking of large currents can cause surges on the line that damage electronics and even some machines. The surges may be in the form of voltage spikes, voltage dips, or current transients. Although the energy levels for these disturbances are not as great as those from lightning, they can create problems for equipment connected to the same power lines. Some lightning arrestors (protectors) may compensate for problems caused by the switching surges on the power line.

Radio frequency interference (RFI) can be caused by communications transmissions. However, interference is more often a problem from the spurious emissions from electronics that are operating at high frequency. Both digital and analog circuits can cause these emissions. Furthermore, the RFI may be fairly broad band since it will often result from multiple subcircuits operating at the same time. Shielding is the preferred way to handle RFI. The best approach is to shield the noise from escaping the source device.

Electromagnetic induction (EMI) is noise that is picked up from a stray source and converted to a voltage on the electrical system. The sources are often the same as those generating RFI. However, appropriate isolated grounding is an additional tool used to handle this noise.

Electromagnetic pulse (EMP) interference is derived from nuclear detonation. This is a radiated broad band electromagnetic pulse with a very high energy. The energy form is very similar to lightning but is approximately 10 times faster. The radiation is induced on all conductors and is converted into a voltage. Protectors designed for EMP will work for lightning. However, they are expensive and do not work substantially better than devices specifically designed for lightning [6].

Lightning is a source of tremendous electric, magnetic, and thermal energy from nature. It is generally the predominant motivator for designing a protection system.

IV. LIGHTNING

Lightning is the discharging of an electric field that has built up between a cloud and the ground or other clouds. This occurs with a breakdown of the atmosphere in a local area.

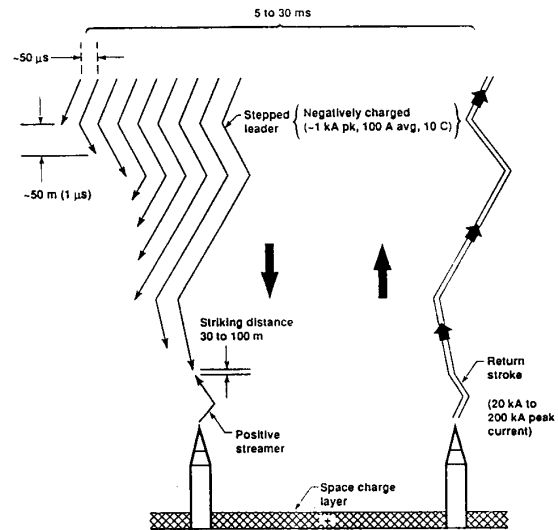


Fig. 1. Lightning discharge.

The atmospheric breakdown is called the step leader. The leader progresses approximately 150 ft in 1-μs increments. Then there is a 50-μs dormant phase followed by another discharge. The downward vector has a velocity of 0.1 to 0.2 m/μs while the upward velocity is 35 to 100 m/μs. Fig. 1 shows negative cloud to ground lightning as described by Hasbrouk [7]. Less frequent positive stroke lightning begins in the positive charged cloud region.

The location for the plasma column of the next strike (return stroke) will be to the lowest potential point within a 150-ft radius hemisphere. Any object that is within this 150 ft can be the point for the next strike. As long as the point is more than 150 ft above the average terrain, it may be the location for the attachment of the return stroke, even if the point is below the height of a tower.

Lightning strokes can cause large potential differences on electrical systems that are distributed outside a single protected structure or buildings. Large current magnitudes may flow in the ground and metal material in an attempt to equalize the potential. Often large surge currents flow in a wire between two isolated points. Furthermore, a strike creates a large electromagnetic field that can cause interference in electronic and communications signals.

Even without a direct strike, a moving, charged cloud can create potential differences between locations on the earth that the cloud is moving over. The electric field under a cloud is generally considered to be about 10,000–30,000 V/m. This static energy is dispersed when a cloud is discharged by lightning. Fig. 2 illustrates the charge.

Lightning is a high-frequency, high-potential, high-current signal. Lightning is equivalent to a high frequency because of the rapid rate of rise of the signal, approximately 1 μs. Designing a path to handle high-frequency signals requires a significantly different technique than for power frequency conductors.

As with all electrical signals, the current will flow in the path of least impedance. This consists of resistance as well as

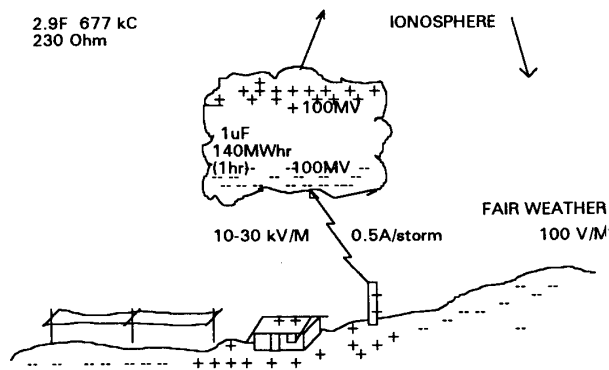


Fig. 2. Cloud charge.

reactance. Higher frequency increases the inductive reactance of a circuit. The inductance of copper wires used for grounds is approximately $0.5 \mu\text{H}/\text{ft}$. At the equivalent frequency of lightning, the impedance due to inductance is many times greater than the impedance due to the conductor resistance.

Conductor lengths of more than 30 ft have essentially infinite impedance which will prevent their carrying the lightning current [8]. However, when multiple paths are provided to the earth, the potential is distributed over a comparatively large area of ground. This in effect equalizes the potential and reduces the voltage difference between two points inside the paths.

These high-frequency signals will not follow a sharp turn. A bend increases the inductive reactance. By comparison, a coil is an excellent inductor and is simply made of turns in a wire. Therefore, all lightning grounds must have bends made with a sweeping radius, not squared corners. No bend should be made with less than 90° in the included angle. Bends should have a radius of at least 8 in [9].

V. LIGHTNING PROTECTION

A lightning protection system consists of three basic components. The initial item is an air terminal or protector that intercepts the surge. Next, a conductor system transfers the energy through a low impedance path. Finally, the energy is dissipated through a system of ground terminals (electrodes).

A key to the ground terminals is the area of contact with the earth. The resistance will not necessarily be as low as alternate systems, but the total impedance is low. The large surface area permits the dissipation of the stroke energy.

A fundamental design criteria for a lightning protection system is to minimize the earth potential differences between all electrical components within a site.

Lightning occurs at different levels. A system should be designed to handle a typical-to-large strike in the area. Strikes cannot be stopped, but the energy can be diverted in a controlled manner. Attempting to protect from direct strikes may involve excessive cost.

Lightning protection involves providing a controlled, low-impedance path to earth for the energy rather than allowing it to choose a random, higher impedance path through

the structure. When the high energy travels along the high-impedance path, extensive damage occurs because of the heat and mechanical forces created [2].

Building and structure protection is more tolerant than electronic protection. A building may tolerate up to 100,000 V while 24-V electronics typically will be damaged by sustained energy over twice its rating.

At the time of a strike, the ground system will saturate and have an elevated potential relative to the surrounding area. The elevated potential will persist until the transient propagates through the system into the ground.

The equipment within the elevated potential area is configured to compensate for the rise in potential. If all the electrical equipment is tied together to the same effective ground system, there will not be a difference in potential between points on the system. However, devices connected to lines that egress outside the equal potential area are subject to damage. The elevated potential can trigger protectors for a short period of time and dump excessive transient energy on the lines.

Several items impact the chance of a strike. The strike frequency of lightning goes up with the square of the height above the average terrain. This makes isolated structures particularly vulnerable [6].

Sharp points increase the likelihood of a strike. The high electric (E) field below a charged cloud will create ions in the neighborhood of sharp points. These ions increase the air conductivity and probability of a cloud discharge (strike).

When a cloud does discharge, the point of impact of lightning will be the center of a wave that is dissipating into the ground. The wave appears to be circular rings around the point of impact. These waves move outward much like ripples of water.

The velocity of propagation of the wave corresponds to the rate that the energy will dissipate into the ground. The soil resistance and the inductance of the grounding circuit form a time constant. The wave will propagate faster with larger contact surface area and lower resistance soil.

VI. EARTH AND RESISTIVITY

The earth does not have uniform resistivity at all points. Different soils conduct an electrical current differently. Because of the difference in resistivity, a potential will exist between two pieces of metal placed in the earth. Hence multiple grounding electrodes create the likelihood of a potential difference between the desired ground points.

The potential difference problem between electrodes is compounded when a charged cloud with a high electric (E) field moves over the electrodes. First, a nearby lightning strike will cause currents to flow in the ground in an attempt to reestablish charge equilibrium. This current will flow between the grounding electrodes which establishes a higher potential difference between the ground rods. This greater potential difference will result in a ground loop current flowing in any ground wire [4].

Second, a magnetic (H) field is caused by a cloud discharge whether to ground or to another cloud. This field induces a current in any wire or metal in the vicinity of the discharge. If

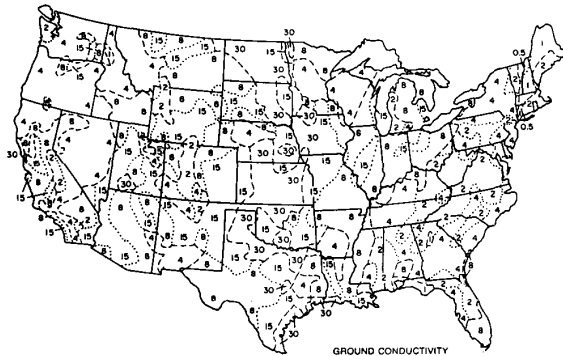


Fig. 3. Soil conductivity for U.S.

there are two different grounding electrodes on either end of the induced current, a ground loop current will flow between the points. A pipeline can be a prime contributor to provide a path for the current to flow. This can transfer the current a large distance from where the lightning discharge took place.

The grounding system for lightning protection depends on soil conditions. The following are accepted designs for ordinary structures based on NFPA 78 [2].

- *Deep, Moist Clay Soil:* A single 10' ground rod is adequate.
- *Sandy or Gravelly Soil:* Two or more ground rods are required at not less than 10' spacing.
- *Shallow Topsoil:* Trenches extending away from the building are used. These are 12' long and 2' deep in clay soil. For less conductive soil, the length is increased. If rock is shallower, the conductor may be placed on the rock.
- *Rocks:* In very shallow soil, a loop conductor installed in a trench or crevices can be placed around the structure. Ground plates with at least 2 ft² may be added to enhance ground contact.

Normal clay soil will have a resistivity of 4,000–50,000 Ω -cm. A 10-ft ground rod extended into the ground will produce a circuit ground of 15–200 Ω respectively. The resistivity of rock is 500,000 Ω -cm and higher. Trying to develop a low resistance ground in this earth is virtually impossible.

The typical soil resistivity varies with the region of the country. Fig. 3 illustrates the effect [10]. The conductivity of mS per m is equal to a resistivity of 100,000 Ω -cm.

Another consideration in earth resistivity is moisture content variations at different times. During certain seasons, the soil may dry out to the point that it is not effective as a conductor for a grounding system. The system is designed to provide effective grounding at the worst times.

Soil obviously is not uniform. Within the depth of a typical 10' ground rod, at least two different layers or strata are typically encountered [1], [11]. The upper strata is the more conductive if there is sufficient moisture throughout the year.

Many of these soil and weather conditions indicate a low resistance ground system may not be reasonably possible. However, an effective ground system can be built by using an extensive wire network laid on the rock and surrounding the structure to be protected. The resistance at the end of

one of the wires may be high, but the potential distribution about the structure would be essentially the same. In essence the structure appears to be resting on conducting soil which provides effectively the same protection.

VII. TOWERS

If a lightning strike hits a tower, the tower will conduct the majority of the current to ground. The remaining current will be conducted by ground wires, beacon wiring, and coax.

A tower will radiate the radio frequency of a direct strike. Adding distance between the tower and the equipment building and using a Faraday shield can reduce the impact on the equipment in the building.

Considerable variations exist about how to protect a tower. One approach is to place a lightning rod at the top of the tower. Then a copper ground wire is run down the tower. However, dissimilar metals between the copper and steel cause a corrosion problem. In addition, the inductance of the long wire creates a high-impedance path which may not be effective as a ground circuit.

On new installations, place as much distance as possible between the tower and the building entrance. This distance provides time for the ground to absorb the energy from the tower.

Cable entrance from the tower into the building is made through a grounding bulkhead. The connection from the bulkhead to the external perimeter ground is at least as large as the cross sectional area of the coaxes. A 3-in to 6-in strap is generally adequate for the grounding strap.

Coax grounding kits are placed on tower cables at the 150-ft level and at each 100 ft above that point. Another kit is placed at the tower base and another at the building bulkhead entrance. The 150-ft level is critical because of the diameter of the lightning ball discharge hemisphere.

Tower beacon lights require protectors on the power lines. The protectors are also placed on the tower wires and grounded at the bulkhead.

VIII. TANKS

Certain tanks are effectively self protected against lightning. A tank that is electrically continuous and at least 3/16-in-thick prevents puncture by lightning strokes. In addition, the tank must be sealed to prevent the escape of vapors which may be ignited [2].

Tanks are grounded to conduct away the surge from direct strokes and to prevent static buildup. This may be accomplished in three ways. The simplest is connection to a grounded metallic piping system without insulated joints. The second method requires resting on earth or concrete for tanks 20 ft in diameter or resting on blacktop for tanks 50 ft in diameter. A manufactured method consists of bonding through a minimum of two ground terminals spaced no more than 100 ft apart around the perimeter of the tank.

Fiberglass and plastic tanks and piping present a unique problem since the material is not conductive. However, these systems are very prone to static potentials [1]. All metal valves, flanges, and fittings are bonded to earth to drain off any build-

up. Additionally, an electrode suspended inside the tank and connected to a perimeter ground will bleed off internal charges.

Fluid dumped into the top of the tank and allowed to fall will develop a strong static charge. If possible, fluid is released through a spreader in the lower area of the tank below the liquid to gas interface.

IX. AIR TERMINALS AND DISSIPATERS

Air terminals are electrodes that are placed above structures to be protected from lightning. These terminals are a minimum of 10 in above the structure [2]. When this minimum height is used, the terminals are placed 20 ft apart or closer. At least two paths to ground for each air terminal provides reasonable assurance of a ground connection.

The downcomers are electrical conductors between the air terminals and a grounding electrode. Downcomers are placed no more than 100 ft apart. Bonding the downcomers to any metal within 6 ft provides equal potential, prevents side flashes, and eliminates arcing.

For structures more than 60 ft in height, the lightning protection system ground and all other grounded equipment is more effective when connected by a ground loop conductor.

A halo ground system consists of conductors arranged above the structure to be protected. These can provide some protection as a limited Faraday shield. To make the shield effective, multiple down comers are connected to the perimeter grounding system.

Lightning array systems have proved to be effective [2]. The principal of the array is to provide a number of spikes for point discharges. This is essentially placing air terminals in the configuration of a Faraday shield. To be effective, the points of the spikes are at least as far apart as the spikes extend above the grid. If long spikes are used, the separation angle may be reduced. The direction of all spikes are pointed in the direction that lightning may originate. In general, this is away from the structure to be protected. However, in some conditions where the array is above a device, the lightning leader may attach from below the array.

By having a number of points, the total charge that is to be dissipated will be distributed. This eliminates the single point arc of an air terminal and creates a diffused discharge as St. Elmo's fire. The configuration of the array is such that a continuation of its surface to the earth would create a shade over the area to be protected.

In essence, the installation of the array physically elevates the ground to a point above the structures to be protected. However, when the complete installation is analyzed, the major benefit is derived from building an effective ground grid and properly grounding the equipment.

One caution should be considered for arrays on radio towers. Because the ground plane has changed, the effective radiated pattern of transmissions may be changed. The array may also somewhat shield certain low-level reception.

X. RADIALS, RINGS AND RODS

To dissipate the energy from lightning and other electromagnetic surges, ground radials are run away from the structure

to be protected [9]. It is more effective to make all the radials originate from a single point than to have multiple ground rings around the location.

Radials can be less than 100 ft in length if the soil is adequate and the ground rods are effective. The radials will disperse the lightning energy outward from the hub of the radial. Since radials share current approximately in equal proportion, the more radials that are installed, the more the current is divided. The lower current is easier to dissipate and will have less impact on elevating the ground potential of the system.

Ground rods along the radials will disperse the energy to lower resistivity soil. If lower resistivity soil is not available, a large electric (E) field will develop over the length of the ground rod. This field will dissipate out the end of the ground rod. However, any arcing in high-resistivity soil can cause formation of insulating glass around the ground rod. This glass will begin at the bottom of the ground rod and build up to the top as more strikes and energy are dissipated.

Ground rod diameter is not as important as radial diameter since length contributes more to the rods effectiveness than does area.

The contact resistance of one ground rod is given by Dwight's formula where the dimensions are in cm [13].

$$R = [p/2\pi L] * [\ln(4L/a) - 1]$$

where p is the soil resistivity in Ω -cm, L is the rod length, and a is the rod diameter.

If the length is feet and the diameter is inches, the relationship changes.

$$R = [p/192L] * [\ln(48L/a) - 1].$$

The resistivity is based on the effective resistivity of the soil around the rod [14]. Approximately 90% of the resistance depends on the local resistivity and 10% occurs because of the average value of the Earth.

A single deep well casing or one long deep rod is not as effective as an array of radials for dissipating surge energy. The deep well may have a lower resistance, but its circuit inductance is greater resulting in a greater total impedance.

Ground rods cannot be placed too closely together [13]. Each ground rod impacts the circuit impedance. When placed adjacently, the effectiveness is reduced by interference which causes the net shunt impedance to be greater.

In good soil, the ground rods are separated by a distance dependent on their lengths. Approximately ninety-one percent of the resistance of the ground rod occurs within a protective hemisphere with a radius about 1.1 times the length, L . Hence, rods are separated by the diameter of the protective hemisphere which is a distance, D , defined by the approximate relationship [1], [10].

$$D = 2.2 * L.$$

In poorer soil, the distance between rods may need to be reduced so the ground rods can more effectively shunt the inductance of the radial.

When multiple rods are used, each additional rod does not contribute a proportional reduction in circuit resistance. Two

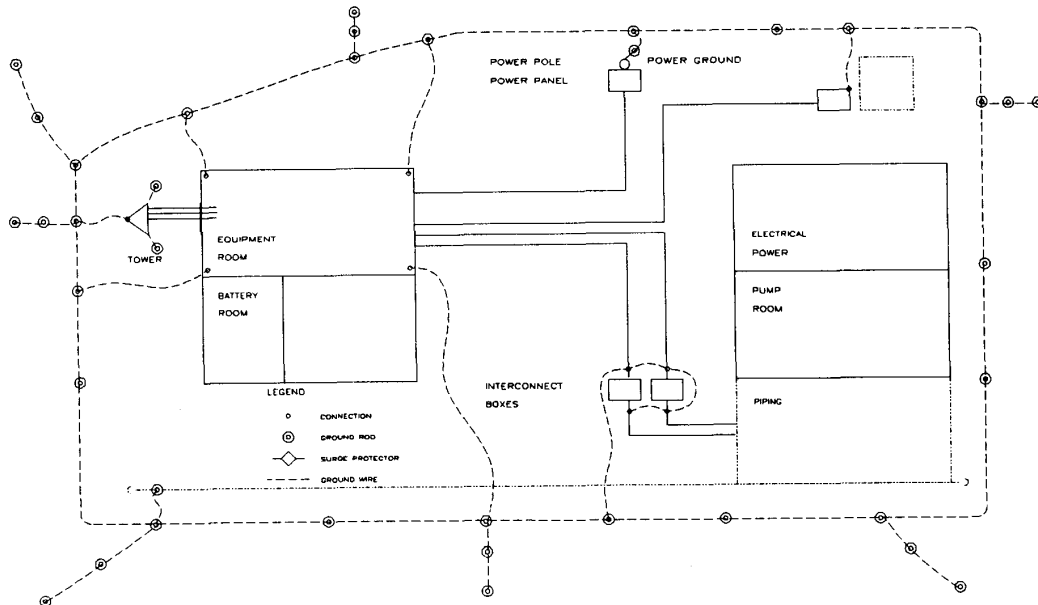


Fig. 4. System grounding.

rods reduce the resistance to 58% of one, while 20 rods reduce the resistance to 10% of the resistance of one rod.

The net resistance for n rods, R_n , is determined from the resistance of one rod R . This is an approximate value we developed and assumes the rods are spaced apart by the protective hemisphere distance.

$$R_n = [R/n] * [2 - e^{-.17(x-1)}].$$

This represents the decay in the capacitance associated with propagation in the earth.

In addition, multiple short rods tend to be more effective than a few longer rods. This can be verified by combining the individual and net resistance equations. Consider 100,000 Ω -cm soil. One 10-in rod provides a grounding resistance of 300 Ω . Two 5-in rods provide a circuit resistance of 210 Ω . This is 2/3 the resistance.

One major assumption is the soil in the 5-ft strata is reasonably conductive. For drier regions, even longer rods may be desired to reach a permanent moisture layer.

Perimeter ground rings are used around a facility to be protected to provide an equal potential plane around the building and equipment. This keeps the potential the same for all equipment within the ring.

Fig. 4 shows an installation containing an equipment building and a tower. The preferred arrangement separates the tower from the building. In that design, a perimeter ground ring is constructed around the building and radials emanate from the tower. A single connection is made from the tower to the ground ring. The connection is below the coax cable path. In effect the ground ring performs like one radial.

In many existing installations, the tower is adjacent to the building. These preclude running an effective ground ring around the building separate from the tower. For these

installations, the tower is included inside the building ground ring. The majority of radials still emanate from the tower; however, radials are distributed around the ring to equalize the potential field.

For new construction, the rebar in the concrete can be used to enhance the ground. If the rebar is mechanically and electrically interconnected, the current is distributed throughout the system [15].

Concrete is an effective medium for fill around ground conductors for several reasons. Concrete is quite conductive because of the retained moisture and the alkalinity which provides free ions. Furthermore, concrete buried in the ground has a resistivity of about 3000 Ω -cm, which is considerably less than the average earth resistivity.

In the situation where the soil has a high resistivity, there is no permanent moisture level accessible, and rocks are encountered near the surface, it may be impossible to drive ground rods. For lightning protection of isolated motors and other equipment, it may be necessary to create an effective ground bed. Environmental considerations often prohibit adding conductivity enhancement materials to the soil where the material may leech.

Under these conditions, made electrodes of at least 20 ft of copper encased in at least 2 in of concrete may be used. If holes can be drilled for ground rods and backfilled with the concrete, the made electrode system may be better than a single horizontal wire. Steel rods in concrete placed in irregular excavations in rocks are much better than other types of electrodes.

XI. CABLES, SHIELDS, AND CONDUIT

Buried cables and electrical conductors are not immune to interference from lightning, EMI, and EMP effects. The high

voltage stresses and high currents from lightning may prefer to travel on the metallic conductor rather than through the earth. This can destroy insulation. It will also cause a potential difference between a shield and the internal conductors [4].

Cables and interface circuits must withstand the voltage stresses caused by differences in potential between two points in the grounding system. Fiber optic cables eliminate the problem. However copper conductors provide a low impedance path for the current flow between the earth points resulting from lightning.

The high current flow from transients can cause a very high voltage between the outer shield and the inner conductors. Insulation may be punctured by the stress and electronics may be damaged.

Cable shields are usually a solid conductor or metallic coated plastic with a drain wire. For shielding to work it is maintained over the terminations of the cable. A continuous metallic cover is placed over the center conductors. A short wire to ground instead of maintaining the shield is not effective. An inadequate ground path can also eliminate the effectiveness of the shield.

Braided shields are not as effective as solid covers. The individual braids do not provide good electrical connections between themselves at high frequencies. In addition the spaces between braids may be adequately large to permit leakage through the voids.

Shielded cables present two contradictory problems. For improved performance in blocking high frequency interference, both ends of the shield would be well grounded. However, unless these two ends are at the exact same potential, a ground loop current will flow in the ground path between the two grounded ends. The circuit path will be complete through the shield. Hence, shields are connected on one end for most noise frequencies.

Similarly, a conduit that is used to carry logic level signals is isolated. The conduit should not provide a continuous metallic path. A PVC conduit stub or a cable run can be provided to isolate one end of the conduit. Nevertheless, one end of the conduit is still bonded to the grounding network.

Communication cables run more than 5 ft from high-voltage and high-power cables eliminate the majority of the induced noise. If it is necessary to cross power cables, cables run at right angles avoid induction.

XII. COMMUNICATIONS PROTECTION

High-tension stresses induced on wiring will exceed the voltage rating of the input to most electronics. Hence this equipment can be damaged when surges occur near the electronics. It is not necessary for a surge to directly hit the electronics. The wiring will transfer the effects of the surge over a very large area.

Most signals with field transducers and communications systems are similar. The voltages and current levels are much less than for a power system. As a result, noise is a substantial consideration at the lower levels.

In order to cancel induced noise on lines, twisted pair cables are used. The same noise will be induced on both wires, but the

twisting will cancel the effect at the end. For higher frequency signals, coax is preferred.

Since a transient is noise, this signal also will be induced on the wires. Twisted pair cable bundles will mutually couple the total available surge energy to all the pairs in a cable bundle. The same amount of energy is available whether the cable has one pair or multiple pairs. Therefore more energy is dissipated in each pair if there are fewer pairs.

For more than six pairs in a bundle, shunt type protectors are usually adequate to dissipate the energy. For less than six pairs, more energy is present on each pair, so in-line protectors are required. The inline protectors include filters as well as shunt protectors. The line impedance, permissible loop resistance, and data frequency impact the insertion impedance of protectors. For PLC applications, standard protectors are usually adequate.

Regardless of the number of pairs, all unused pairs are grounded. Any surge energy induced on these lines will then be directed to the earth.

All wiring into the equipment building needs protection. These lines include power lines, communications systems, and telephone circuits. Lightning protectors installed on electric and telephone service entrances and on radio and television antenna lead-ins provide protection for the structure. If possible these are mounted and grounded at the common bulkhead entrance. Alternate entries can be grounded to the common bus ground at the point of entry. These lines should also be protected again before distribution in the cable trays.

Additional protectors may be needed to protect electrical equipment. These protectors would be installed on the input/output modules of equipment such as programmable logic controllers and other electronic supervisory control and data acquisition systems.

To provide a more complete shielding of the terminations and to protect the equipment in dirty environments, the complete programmable logic controller could be placed in a NEMA 12 enclosure. If this is done, sufficient air circulation must be provided for cooling [16].

XIII. GROUNDING ISOLATION AND SINGLE POINTS

If the communications wiring leaves the area protected by the local ground, isolation protectors are used on the wiring at both ends. The protectors provide separate physical grounds at each end. In addition, they electrically isolate the communication signal wiring from those grounds.

Because of the requirements for power system grounding and equipment ground bonding and because of the metallic piping used within a plant, it is virtually impossible to galvanically isolate all the different metallic ground paths. This creates paths for ground loops which may be disastrous to the electrical equipment.

With the nonisolated arrangement of electrical and mechanical equipment, a modified single point *protection* grounding bus technique is used. This requires recognizing and isolating different types of grounds, but bonding them all together. The bonding is done in a pattern to prevent ground loop currents flowing through the bond.

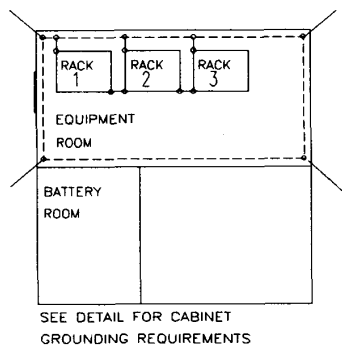


Fig. 5. Building grounding.

One method of creating a common bus location in a building is to use a large surface area connection to the ground system. A typical arrangement is a grounding plate such as a bulkhead panel with a large grounding strap to the perimeter ground. From this common point, use a star configuration to make connections to equipment.

Another method of creating a common bus location is to use an internal ground grid system. A typical arrangement is a rat race or ground ring run around the inside of the building or instrument room. Then multiple connections are made from this ground ring to the external perimeter ground. These connections should be approximately the same length and arranged in a symmetric pattern. Bonding connections to equipment are made directly to this rat race. Fig. 5 illustrates the grounding method.

Whether a plate or ground ring method is used depends on the distances between the equipment to be bonded. The bonding path must be short enough that a voltage differential does not exist between the end of the bonding conductor and other components in the building.

Regardless of the method used to create a common location, the path is crucial. Do not bond from one device through a connection to another device. Always connect each device bond to the common bus location.

A separate connection is required between each equipment rack and the common ground bus. Connection of equipment chassis to the common ground bus is often assumed to be completed through the mounting rack. Because of paint and mounting problems, this does not always work. A separate, insulated ground wire is preferred to connect the chassis together. This insulated ground is then bonded to the common ground bus. By using insulated conductors, the chassis ground does not short to the mounting rack ground. Fig. 6 demonstrates internal grounding.

The shield grounding and signal wire grounding are an integral part of the protection and grounding design. Shields are used to reduce noise from electromagnetic interference (EMI) and radio frequency interference (RFI).

Isolate the logic power grounding from shields and from all other grounds in the system. Logic power grounding is used to provide a common reference for the low-level information signals. Logic power grounds are usually the negative terminal on the power supply. The low-level equipment is very sensitive

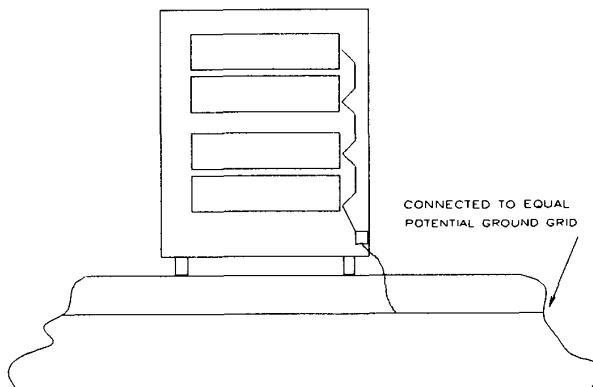


Fig. 6. Cabinet grounding.

to any circulating currents or surge voltages that may feed back from the ground. A separate conductor run from the signal ground to the internal protection ground isolates the systems.

Where galvanic isolation of cables is possible, usually a single point *signal* ground is preferred. The single point is a dedicated ground connected to earth. The cable shield is bonded by a separate conductor to the common bus location on the *protection* grounding system rather than to the *signal* single point ground. This shield connection satisfies the requirements of the National Electrical Code that all equipment grounding conductors be bonded to the power grounding electrode.

Where several components exist in an assembly or cabinet, a ground plate or strip may be used within the assembly. The plate is located as close to the shielded cable entrance as possible. The bonding wires are then run to the other components in the assembly in a star connection. A separate bonding conductor is run from the grounding plate to the common bus location and a separate bonding conductor is run from the rack to the location.

In addition to providing a ground system without ground loops, all other lightning protection devices should also be connected to the common ground bus as shown in Fig. 4.

XIV. PROTECTION DEVICES

Protection devices are often added to the electrical system to aid in managing surges. The devices may shunt current, block energy from traveling down the wire, filter certain frequencies, clamp voltage levels, or perform a combination of these tasks. Regardless of the function, only a few basic components are available to economically build the protectors.

The simplest arrangement is physical separation. Gaps may be used to provide arc paths above a certain level. These may be air gaps, or spaces between conductors in a dielectric material. Classical lightning arrestors fit in this category. Often the devices are built so that the path will become a low impedance once breakdown occurs. Gas tubes and other breakover materials fit in this category. This is the slowest class of protection equipment, but the energy handling capability is very large for the cost.

The next common arrangement uses passive electrical elements. Capacitors and inductors are applied to the circuit.

Bypass or bandpass filters can be constructed. In-line filtering uses inductors. Air core is preferred to ferrite core inductors. The air core has less attenuation, a higher cutoff frequency, and is larger. However, it is preferred because the ferrite core characteristics change with magnitude and frequency of the current to be dissipated.

Semiconductor devices are the most advanced arrangement. These devices are faster, but they generally handle less energy than comparably priced alternatives. Because of the limited range of operation, these devices must be more precisely specified. Silicon devices fit into two groups: voltage or current protective elements.

Metal oxide devices are primarily voltage triggered and are manufactured to handle very precise quantities of energy (joules or watt-seconds). The device is selected for a turn on voltage that is greater than the peak expected voltage from the power supply. The energy dissipation is based on a standard waveform such as ANSI C62.1 8/20 waveform. Each metal oxide varistor (MOV) will have a resulting surge current rating. The device has an inherent capacitance. Higher energy units tend to have a higher capacitance. However, this creates a problem with high-frequency signals. The high capacitance at high frequency will increase the impedance and attenuate the signal. An MOV degrades with time as it ages. Each surge that it takes will cause small holes to be punched in the silicon. When enough of these holes are punched, the device will no longer work. The preferred device for a 24-V circuit is a 36 V, 160 J MOV.

Zener, avalanche, or silicon junction diodes are much faster devices than varistors but can not sustain as much energy. Since the unit has essentially no energy dissipation rating, it is coupled with a primary arrestor such as a gas tube. The diode will trigger first, then the high energy will be dissipated through the gas tube. The circuit of a zener consists of a resistor or inductor placed in-line and the zener shunting the output. As long as the zener range is not exceeded, the device does not significantly age. However, because of the very limited current capability, a zener without a primary arrestor will fail often.

More surge protection is provided from devices with the lowest throughput energy at a particular frequency. The throughput energy is the amount of energy that gets past the protector onto the equipment being protected. Most lightning energy can be restricted with devices designed for less than 1 MHz. Above that frequency, there is less throughput energy.

Silicon semiconductors, metallic oxide varistors (MOV's), and gas tubes will die in a shorted mode when at the end of their life or when over powered. Nevertheless, at very excessive power levels, the device may become open circuits. For semiconductors including MOV's, the open will occur at power above the fusing level of the wires. In other words, the wire melts. For gas tubes, the open occurs at power levels which explode the tube and vent the gas. Properly designed gas tubes can work to the limits of lightning levels [6].

Lightning protection for power lines depends on the load. The voltage, number of phases and configuration describe the type protection. Nonelectronics can be protected adequately with shunt type protectors.

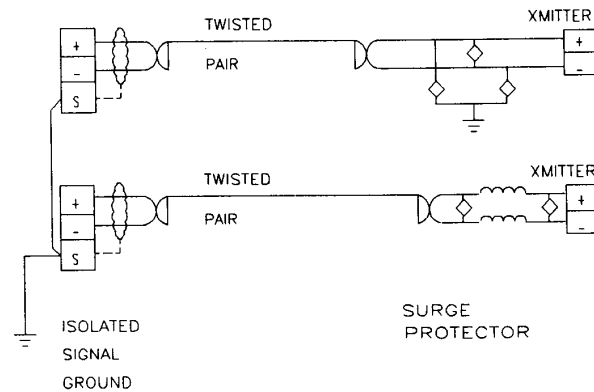


Fig. 7. Transducer protection.

Electronics generally are protected with in-line devices connected and grounded close to the equipment. An exception is electronic circuits that are fed from multiple cable pairs. These pairs share the energy and permit less to be imposed on one piece of electronics.

The mode of protection depends on the connection of the protection circuit. Differential mode units are connected between the two signal wires of a circuit. A common mode unit is connected between a signal wire and ground. As a minimum, a common mode device should be placed on both ends of each conductor. This is shown in the top part of Fig. 7.

A system that has been used for transducers that are remote from the controllers is shown in the lower circuit Fig. 7. This design assumes that there is not a good common ground between the transducer and controller.

XV. MAINTENANCE

Routine and preventative maintenance is conducted at least on a yearly basis. Staggered inspections evaluate the system during different seasons so moisture changes are considered.

Reasonable tests include testing protectors, measuring the ground system, checking soil conditions, pulling on ground rods, cleaning connections, and inspecting connections for corrosion and tightness.

The overall system design should be reconsidered every time new equipment is installed, moved, or modified. This particularly applies to cable, conduit and wires. What appears to be insignificant changes can dramatically affect the protection system. The change may create ground loops, interfere with the energy dissipation path, or provide a path for entry of surges from outside the protection network.

Records and test data are maintained for inspection authorities [2]. It is not desirable to keep records merely for the sake of keeping files.

XVI. SUMMARY

The priority of successful grounding practices is dependent on the seriousness of potential problems. The first priority is given to the absolute minimum requirements. The subsequent recommendations are in order of cost increase.

Construct separate grounding electrodes for the power entrance, telephone entrance, and radio frequency entrance. Bond the systems together. Bond the conduit to this system. These are mandated by various regulations.

For the control and communications equipment, create a common termination (rat race) ring or single point ground. Avoid intermediate connections between the device and the ground.

As a minimum for the initial installation, install a perimeter ground ring only around the outside of the building. Connect the common internal bus rat race and the required grounding electrodes to this ring.

Use MOV common mode protection devices on each cable with more than six pairs. A 36-V, 160-J device is a good compromise. Use in line protectors with MOV's, gas tube, and avalanche diodes for more sensitive lines, and cables with fewer than six pairs.

If an enhanced earth ground is required, the only change for this second level of protection would be to build an extensive perimeter ground grid with radials.

The third level of protection requires more sophisticated protection devices. These are generally active devices with multiple filters and solid state components for dissipating the energy. This will generally be inappropriate without a very effective ground grid.

Under the most severe conditions, consider lightning protection arrays. Although these are effective, the cost is substantial.

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