Grounding System Design for Isolated Locations and Plant Systems

Marcus O. Durham, *Fellow, IEEE,* and Robert A. Durham, *Member, IEEE*

***Abstract*— Effective grounding is critical for protection of electrical equipment from transients. Grounding for personnel safety requires very distinct considerations. The application of the grounds may be similar in some instances. However, the installation will be radically different in isolated areas. Furthermore, the grounding of controls and computers present even more unusual requirements than the grounding of power devices. Additional concerns are circulating currents and injection of spurious noise. This paper addresses grounding for transients, power, and personnel. Designs include installations in plants and for isolated and remote equipment. The methods have been effectively used for pipelines, production facilities, gas plants, and power plants. Ten case studies of diverse applications illustrate the pertinence of the techniques and procedures.**

***Index Terms*— Case studies, grounding, grounding electrodes, instrumentation, lightning protection, safety, transient impedance.**

I. INTRODUCTION

GROUNDING is a common feature of virtually every electrical installation. However, effective grounding is not always available. Grounding technology is well defined. Nevertheless, the application continues to be an art that depends on both the engineer and the craftsman.

The primary reference is the National Electrical Code.[1] It contains over 35 pages specifically dedicated to grounding. This is not a design document. It simply provides the requirements for protection of personnel and equipment.

The IEEE Green Book [1] is an excellent reference of recommended practices for grounding of industrial power systems. It does not address the problems associated with electronics and instrumentation that are remote from the plant. The IEEE Emerald Book [2] provides recommendations for grounding sensitive equipment. Its primary thrust is power quality rather than lightning-induced transients. The NFPA Lightning Protection Code[2] primarily addresses shielding and shunting of lightning discharges. End device classification is limited.

A previous paper [3] addressed the requirements for effective grounds and provided design procedures for industrial systems. This paper uses ten case studies that identify problems encountered with connection to grounding systems. The format includes environment, analysis, and summary for each of the situations. The environment influences the effectiveness of the grounding protection system. An analysis of each case investigates alternatives and unique problems. The summary is a brief response to the situation.

The overriding observation for grounding implementation is "little things mean a lot." The key for successful grounding is not recognition of the big concepts, but application of the details.

II. CASE 1: REMOTE PUMP SENSORS ERRATIC READINGS

Situation: Operators observed very low readings from pipeline transmitters when clouds passed over the area immediately before a lightning discharge.

Environment: The petrochemical plant is located on the Alabama gulf coast. A pipeline station is located one-half mile from the control center. The soil resistivity typically exceeds 50 000 Ω·cm. The area is subject to numerous intense thunderstorms. The isoceraunic reporting is 80 thunderstorm-days per year. The combination of conditions is among the most difficult in the continental United States.

Analysis: The change in potential between the signal common (negative) at the control center and the remote ground causes signal current fluctuation. A major problem at most facilities is the difference in surge potential between the various grounds. The variation between the main plant and the remote end devices engenders many failures.

When clouds cross an area, a potential builds between the cloud and the earth. The potential will vary under different parts of the storm. 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 earth.

The equipment within the elevated potential is configured to compensate for the rise in potential. If all the electrical equipment is tied together to the same effective ground plane, there will not be a difference in potential between points in the system. The main plant has an extensive ground grid under its electrical equipment. This creates a uniform reference for voltage within the plant.

However, devices connected to wires that egress outside the equal potential grid are subject to damage. An elevated potential can trigger protectors for a short period of time and

Paper PID 96–23, approved by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society for presentation at the 1995 IEEE Petroleum and Chemical Industry Technical Conference, Denver, CO, September 11–13. Manuscript released for publication August 1, 1996.

M. O. Durham is with THEWAY Corp. and the University of Tulsa, Tulsa, OK 74153 USA.

R. A. Durham is with Central and Southwest Services/West Texas Utilities, Abilene, TX 79604 USA.

Publisher Item Identifier S 0093-9994(97)00332-0.

---

[1] *National Electrical Code*, ANSI/NFPA 70, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269 USA.

[2] *Lightning Protection Code*, ANSI/NFPA 780, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269 USA.

dump excessive transient energy on the lines. A time delay on the control response will mitigate the effect of these short-term changes. A first-order filter on the control input or software compensation are the preferred methods.

Regardless, the more desirable technique is complete isolation for the remote transmitter/instrumentation grounds from the plant grid. Because of common metallic bonding, this is not feasible at the pipeline.

In an attempt to resolve the difficulties caused by grounding differentials, a 2/0-AWG ground wire had been used to connect the plant ground to the pipeline pump grounds. Nevertheless, problems persisted. Remote locations cannot be brought to the same potential as the main plant by a common ground wire. A large-size wire can reduce the resistance between the two points. Nevertheless, the impedance will be too large because of the wire inductance and the lightning transient signal frequency.

The inductance of copper wires used for grounding is nonlinear, but it is approximately 0.5 μH/ft. The rapid rise time of a lightning pulse creates a frequency greater than 1 MHz. At these nominal values, the impedance of the wire exceeds 3 Ω/ft

$$\begin{aligned} Z &= R + jX_L \\ X_L &= 2\pi f L \\ X_L &= 2\pi * 1 \text{ MHz} * 0.5 \ \mu\text{H/ft} = 3 \ \Omega/\text{ft}. \end{aligned}$$

The nominal resistance of ground wires is 0.3 Ω per 1000 ft or less. The inductance is four orders of magnitude (10 000 times) greater. Resistance of any size wire is insignificant in the calculations.

Using very conservative estimates, a surge contains in excess of 3 kA [4], [5]. Thus, the voltage drop along each foot of wire is 9000 V

$$\begin{aligned} V_{\text{drop}} &= I_{\text{surge}} Z_{\text{wire}} \\ V_{\text{drop}} &= 3{,}000 * 3 \ \Omega/\text{ft} = 9{,}000 \text{ V/ft}. \end{aligned}$$

Just a few feet of interconnecting wiring will create a very large potential difference between the ends during transient conditions.

The above calculations demonstrate there is no such thing as a common earth potential point. Nevertheless, plant grounding systems are connected to the earth as a point of reference. The effectiveness of the earth connection depends on the soil resistance, the amount of energy to dissipate, and the available structures.

Where multiple devices permit use of remote terminal units, fiber-optic communication is preferred. This eliminates any connection or relationship between plant grounds and remote devices.

Summary: Because of the separation, common transient grounds are not obtainable. It is often better to isolate the protection ground at the remote site from the control center ground system. Notice the equipment grounds must still be bonded together.

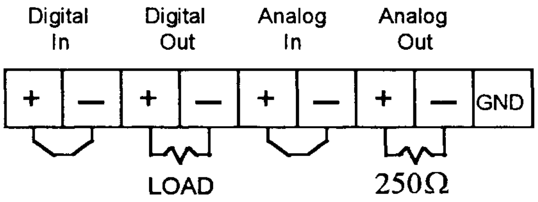

Fig. 1. Unused data terminations.

III. Case 2: Unused Data Points Induce Errors

Situation: Unused analog input points to a distributed control system were damaged when lightning discharged in the area.

Environment: The pipeline pump station is located on the caprock hills of south Texas. The average soil resistivity exceeds 15 000 Ω·cm. Because of the rock outcrops, local resistivity can exceed 100 000 Ω-cm. The isoceraunic reporting is 38 thunderstorm-days per year.

Analysis: Control system input cards generally have more input points than are required for the original operation. Multiconductor cables are commonly used from the control center to the field termination points.

Surges are induced on every wire in a cable. Even unused conductors will pick up and carry the transients. The sensitivity of the analog input circuit makes it particularly susceptible to these spurious signals. Each manufacturer has unique specifications and design goals. Some of these designs are more sensitive, while others use a filter circuit so they are not as vulnerable. However, one installation practice will apply to any system: ground the terminals for unused analog inputs.

Unused analog input circuits are shorted at the control center end of the cable. Intermediate junction box wires are terminated together, but the field-end wires are maintained open. Be careful to isolate the shield terminations from any other grounded surface. Fig. 1 illustrates an appropriate connection.

Typically, digital input and output points are less prone to damage from transients. However, large surges can be coupled onto the input boards. An excellent practice is to never leave digital signals floating. For these reasons, unused digital inputs are shorted. Use the same procedures as delineated for analog inputs. Never short digital outputs, since excessive current will flow if the point is activated. These must be terminated according to manufacturer instructions.

Generally, there are comparatively few analog outputs. A termination is desirable for the 4–20-mA outputs. Apply a 250-Ω shorting resistor across each unused pair of output terminals. This reduces the likelihood of interaction from spurious noise.

Summary: Connect an appropriate load to all terminals. Circuit board inputs are shorted to ground. Outputs are terminated through a load resistor. Unused conductors of cables are grounded at the control center.

IV. Case 3: Remote Sensor and Input Card Failure During Thunderstorm

Situation: When clouds discharged from lightning, sensors commonly failed, even though they did not sustain a direct hit.

Environment: The power generation station is located in southwest Oklahoma. A gas yard is located approximately 200 yd from the plant structures. The plant is in a river bottom with very moist soil having a high mineral content. The average soil resistivity is among the best in the country at 3000 Ω-cm. The isoceraunic reporting is 55 thunderstorm-days per year.

Analysis: The gas yard contains several analog transmitters for monitoring gas pressure and flow. Existing unshielded cables were used to connect the transmitters to the plant control center. This provided an entry point for lightning energy.

Both the plant area and the remote gas yard have an effective ground system providing a low-impedance dissipation path for lightning energy. Although direct strikes to the gas yard are infrequent, strikes to tanks and towers in the direct vicinity of the gas yard are common. This elevates the ground plane of the gas yard and associated equipment.

Two types of lightning associated failures are prevalent in the transmitter loops. The first involves an electric storm in the area, but no evidence of strikes in the direct vicinity of the plant. Under these circumstances, the customary failure is a loss of the distributed control system (DCS) input cards located at the control center. The transmitters usually do not fail in this situation.

The cause of the failure is a high-differential voltage induced in the connection cables. The potential overstresses the input cards. The impedance path to the transmitter is greater than the impedance to the DCS. Therefore, the majority of the energy is dissipated at the DCS.

The second type of failure occurs when there are lightning strikes in the direct vicinity of the plant. Tanks, towers, and elevated structures are susceptible to lightning strikes. This failure is usually catastrophic, resulting in charring inside the case of the transmitter and a loss of the DCS input card. A severe differential mode voltage is induced into the cables, due to the proximity of the lightning strike. In addition, the ground potential of the gas yard is elevated above the plant control center.

Within the main facility, the grounding grid holds a more or less equal potential. Regardless of the effectiveness of the ground and lightning array, install protectors on process transmitters. Protectors shunt the stray transient potential that will invariably exist between two points in a network.

The primary requirement is to isolate the unshielded cable from both the transmitter and the DCS input card. Place in-line protectors on both the transmitter and DCS ends of the cables. Apply common mode protection to the DCS and differential mode to the transmitters.

Transmitters that use a 24-V dc supply can be protected by metallic oxide varistors (MOV's) rated at 36 V and 160 J. Other voltage levels demand alternate peak ratings. Systems with less effective ground grids may require higher energy ratings.

The MOV's are initially installed at the transmitter. The minimum connection is common mode, between each signal wire and the ground grid. A differential connection is also used between the signal wires. The basic connection is shown in Fig. 2.

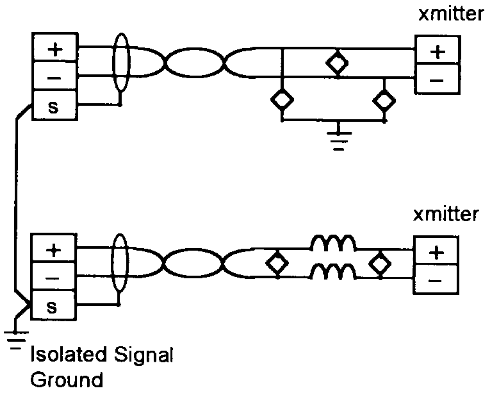

Fig. 2. Protector connections.

Transmitters and electronics remote from the plant grid require a very different protection scheme. The network must provide high-energy differential protection. The voltage change is shunted by a pair of MOV's connected between the signal lines. The current change is restricted by inductors connected between the MOV's.

For isolated transmitters, neither line has common mode protection to ground. Since the local ground probably is not at an equal potential with the power supply signal ground, a huge potential can be coupled through the protection devices to the signal wires.

Many commercial protection modules have the differential protection and the inductor to limit current changes. Unfortunately, most of these have a common mode connection to the earth. While this is acceptable in the plant ground grid area, it often contributes to failures on transmitters remote from the signal power source.

Avoid silicon avalanche suppressers alone. These special purpose zener diodes are very fast, but they can handle very little energy. They must be applied in conjunction with other high-energy protective devices.

Summary: Connect MOV's in common mode when the transmitter ground is an equal potential with the signal common (power supply negative). Connect pairs of MOV's in differential mode when the transmitter ground is remote from the signal power supply. Current changes are limited by in-line protectors.

V. CASE 4: DATA COMMUNICATION FAILURE BETWEEN BUILDINGS

Situation: Numerous problems exist on the communications lines around the perimeter of the plant. Security card readers at the plant gates are subject to copious data errors and to failure. Similarly, the interface to the data terminals in the office have failed five times in one year.

Environment: The location of the petrochemical plant is described in Section II.

Analysis: The difference in ground potential between locations in a plant produces diverse failures. The preferred way to isolate grounds is by the use of optical fiber cable. Optical communications are practical in some areas, such as the line to data terminals. A fiber link can usually be coupled directly to the communication circuit.

There is a mix of other type communications lines. Most are twisted-pair cables. Often these are shielded. Those with shields must have only one end of the shield connected. All these circuits need two common-mode and one differential-mode MOV at each tap.

In addition, in-line protectors may be required. Selection of the inductor is critical. It depends on the communication type (RS 485, RS 232, etc.), the frequency (baud rate), voltage/current rating of each circuit, and the length of the communication cable. In-line protectors on these type circuits are tedious and require very specific design for each circuit.

The remote devices connected to the communications line must have ac power supplied through an in-line protector circuit. As a minimum, the circuit contains a gas tube, a semiconductor protector (MOV or avalanche diode), and an inductor.

Summary: Data terminal power supply circuits require in-line and shunt protection. The signal and protection grounds between buildings are isolated. However, the safety grounds are interconnected.

VI. CASE 5: PROTECTION DEVICES CAUSE BLOWN FUSES AND DATA ERRORS

Situation: Transient protectors operated to safeguard transmitters, but the fuses were blown on the analog input circuits.

Environment: The location of the petrochemical plant is described in Section II.

Analysis: Follow-through current is a side effect of protection schemes. When a protector fires, it will continue conducting for an extended time. Gas tubes are particularly susceptible to this problem. In some conditions, the tube may never shut off. Specific arc extinguishing circuits are required. By comparison, zener diodes clear very quickly, while MOV's may take up to 15 s to clear.

The follow-through disturbs the monitoring system. The protector shorts the transmitter during the triggered time. As a result, the control system experiences false alarms and shutdowns. If possible, a time delay is programmed to bypass the susceptible transmitters. If the circuit timing is critical, an alternative protection scheme is needed to avoid the time-delayed response.

The excessive current that flows during the protector firing causes board failures. One storm caused over 90 fuses to blow on analog input cards. The fuses protect the precision components on the analog input boards. The most appropriate fix is a current-limiting resistor in series with the positive lead of the loop. The resistor makes the circuit nonincendive.

The resistor must be small enough to cause minimal impact on loop compliance. Conversely, it must be large enough to limit the current. Its power rating must be adequate for continuous operation.

Each analog circuit is designed to have a maximum loop resistance. This varies with the applied voltage and the manufacturer. A 4–20-mA loop operating at 24 Vdc typically operates with a maximum loop resistance of 600 Ω. The loop resistance shown in Fig. 3 consists of the indicator load, the wire resistance, and any current-limiting resistors in the circuit.

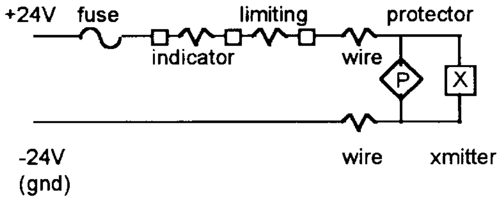

Fig. 3. Current limiting circuit.

The typical indicator load is 250 Ω. An 18-AWG wire has a resistance of 8.5 Ω per 1000-ft length or 17 Ω per 1000-ft run. The remaining resistance can be used for current limiting. However, any added resistance will reduce the responsiveness of the circuit. When the protector fires, the load is shunted and the series resistor provides current limiting for the input.

One manufacturer requires a 50-mA fuse to protect the analog input board. A 24-V supply would need at least 480-Ω loop resistance

$$R_{\text{limit}} = V_{\text{source}}/I_{\text{fault}}$$
$$R_{\text{limit}} = 24/0.050 = 480\ \Omega.$$

After subtracting the indicator resistance of 250 Ω, at least 230 Ω is required to limit the current. This is a nonstandard rating, so a different value is needed. A value of 220 Ω would permit excessive current, which will blow the fuse. A standard size of 330 Ω creates a loop resistance of 580 Ω. This does not include the total wire resistance

$$R_{\text{total}} = R_{\text{series}} + R_{\text{indicator}} + R_{\text{wire}}$$
$$R_{\text{total}} = 330 + 250 + 17/\text{kft} = 580 + \ \Omega/\text{kft}.$$

This creates a real problem. If a smaller current-limiting resistor is selected, the fuse will blow each time the protector fires. If a larger current-limiting resistor is selected, the maximum signal will be less than the 20-mA range.

$$I_{\text{loop}} = (R_{\text{loop}}/R_{\text{total}}) * I_{\max}$$
$$I_{\text{loop}} = (600/R_{\text{total}}) * 20\ \text{mA} = \ \text{less than } 20\ \text{mA}.$$

The power rating of the current-limiting resistor is based on the continuous current of the analog loop

$$P_{\text{rating}} = I_{\text{loop}}^2 R_{\text{series}}$$
$$P_{\text{rating}} = (0.020)^2\ 330 = 0.13\ \text{W}$$

Another manufacturer allows 250-mA fuses on a similar analog board. If nuisance fuse blowing occurs, a standard 180-Ω resistor rated greater than 0.07 W is acceptable. The resistor restricts the maximum follow-through current to 56 mA. Obviously, the 250-mA system is more flexible.

Silicon semiconductors, metallic oxide varistors, and gas tubes will fail in a shorted mode when at the end of their life or when overpowered. Conversely, at very excessive power levels, the device may melt and become an open circuit. The short becomes very obvious if it occurs on the positive lead. The short will cause a large current to flow, which should blow the fuse. However, a short in the negative lead causes serious problems. A short of the negative lead to ground will provide a ground loop resulting in stray currents. This ground loop is not easily detected. For these reasons, the devices must be checked or replaced periodically.

There are various inexpensive instruments that detect the trigger level for protection networks. However, determination of the current capacity and wave response requires a very sophisticated laboratory instrument. If these tests are performed, they are done off site.

Summary: Install current limiting resistors in the positive lead of the analog input circuit. The size is selected to restrict the current to the fuse rating, while not exceeding the loop resistance. The power rating is based on the maximum continuous loop current.

VII. CASE 6: CONTINUOUS CURRENT FLOW INTO THE GROUNDING ELECTRODES

Situation: A large continuous current was measured flowing into the grounding electrodes. Although the current varied at different times, the total current was approximately 14 A at both ground beds.

Environment: The location of the petrochemical plant is described in Section II.

Analysis: The marshaling panel for the digital inputs has positive, negative, and ground terminals. The chassis ground terminal was connected to the plant shield wiring. When these connections were measured, a small circulating current was found at each terminal. Although the current was small at each point, the plant contained 1400 digital inputs. The product of a low quantity with a large number of points resulted in a significant portion of the 14-A current.

The shield wires on the multiple pair cables were another source of leakage current. Numerous shields were shorted together and to ground. In a properly installed system, the shields are not cropped back to the jacket. This would allow the shields to short together. Each shield is individually insulated at the cable terminations. In the field, the ends may never touch any metal. In the plant, the ends are terminated on a shield grounding strip which is connected to the single-point ground.

Fig. 4 illustrates the appropriate ground connections. Separate grounded systems are maintained for the power (neutral), signal common (negative), and shield. Each of these are connected to the grounding network (grid or electrodes) at only one point. The equipment (chassis) are bonded together. Multiple connections are made to the grounding network. Protection component grounds are bonded directly to the chassis. Always maintain a single-point ground system where the different type grounds are bonded together at one location.

Summary: A single-point grounding system eliminates circulating currents or ground loops. Isolate the cable shields from all other grounded elements. Do not allow shields from different pairs to come in contact. Only one end of the shield is connected to a grounded terminal.

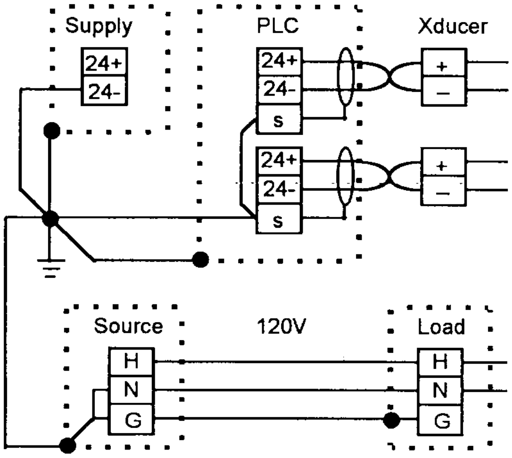

Fig. 4. Different grounded systems.

VIII. CASE 7: FAILURE OF FAN MOTOR LOCATED ON TOP OF STRUCTURE

Situation: A fan motor located on top of a boiler structure was damaged on several occasions over the past 30 years. The casualty occurs when lightning discharges in the area, even without direct hits.

Environment: The power generating facility is located in west Texas. The station sits on a peninsula into a cooling lake. The soil conditions are very rocky, with a shallow 5-ft layer of topsoil. Although the water layer is fairly shallow at the site, the top layer of soil is very dry and sandy. These conditions do not provide a low-resistance ground. The isoceraunic reporting is 43 thunderstorm-days per year.

Analysis: The 4160-V motor is mounted 70 ft above the earth on a steel structure. Unshielded 5000-V triplex rises in a cable tray. A transition is made to conduit just below the top of the structure. An exposed, suspended conduit is run for 30 ft along the structure.

There was no evidence of a direct lightning strike on the motor or casing. The end turns of the winding arced to the case. The damage was caused by excessive induced voltage on the windings.

Various conditions provide a point of entry for surge energy on the wiring. On occasion, lightning strikes the structural steel. This upsets the grounding of the motor and causes excessive voltages. Lightning often strikes in the vicinity of the plant. This creates a difference in potential between earth points in the plant.

In either case, the power cables act as an antenna to pick up the electrical disturbance. Once the induced voltage has entered the electrical system, the transient travels through the cables and motor windings to the point of least impedance, causing a failure. The end turns of the windings are a high-impedance point in the conductor, due to the inductive coupling. Similarly, at this point, the path through the insulation to the motor case is a lower impedance path to ground.

The first step to resolution is improvement to the grounding of the motor casing itself. This involves running individual grounding leads from the motor casing, down the structure to the existing plant earth system. The quicker dissipation of the lightning energy reduces the possibilities of surge energy entering cables and winding. The suspended conduit and termination box are also bonded to the ground leads.

At least two grounding conductors are run from the motor casing to ground. Lightning is a high-frequency signal, due to the rapid rise time. The impedance of the ground path is more affected by induction than resistance. A long copper cable, even without bends, has a large amount of inductance. Bends and turns substantially increase the inductance. If two cables are run, the total impedance of the ground path is halved.

The inductance of a single grounding conductor with no bends is shown below [6]. The equation is modified for feet and inches. The terms are L for inductance in microhenrys, b for length in feet, and a for radius in inches.

Using a 4-AWG wire with a diameter of 0.232 in and a length of 1 ft, the inductance is 0.279 μH. For 100 ft, the inductance is 56.006 μH

$$L = 0.060\,96\ b[\ln(24b/a) - 0.75]$$
$$L = 0.060\,96 * 1[\ln(24 * 1/0.232/2) - 0.75] = 0.279\ \mu\text{H}.$$

The inductance is very nonlinear, but for quick grounding calculations an average of 0.5 μH/ft is acceptable. This is appropriate, since the frequency of the transient and the current in the pulse are highly variable.

For the ground lead from the motor, the total impedance is the resistance and reactance. Resistance in the copper cable is negligible, but the reactance is substantial at lightning frequencies

$$Z = R + jX_L$$
$$X_L = 2\pi f L$$
$$X_L = 2\pi * 1\ \text{MHz} * 0.5\ \mu\text{H/ft} * 70\ \text{ft} = 220\ \Omega.$$

With two cables running to earth, the impedance is cut to 110 Ω. This is still quite high. However, compared to the impedance of the winding path to ground, it is low.

The next response to the situation is to replace the motor leads with shielded cables. This would prevent excessive energy from being coupled into the power cables.

In addition, lightning arrestors added at the motor terminals will shunt the high-frequency energy. As illustrated in Section II, a large transient potential will be developed across a short lead length. Arrestors located several feet away may not provide adequate protection, due to the line inductance. Metal oxide varistors provide appropriate surge protection, while being small enough that they can be mounted in most termination boxes.

It is critical that all metal equipment in the plant be bonded to the same equipotential grounding network. Configuration of the network is detailed in the next case.

Summary: Provide low-impedance grounding paths from all equipment to the earth. Bond conduit and termination boxes to the grounding conductors. Shield susceptible high-voltage power cable to prevent coupling of high energy into the system. Equipotential grounding networks are essential to prevent transient migration from one structure to another.

IX. CASE 8: STRUCTURAL TOWER ATTRACTS LIGHTNING

Situation: An elevated structure in the plant area is frequently observed to be struck by lightning. When this occurs, transmitters and circuit boards are damaged.

Environment: The research facility is located in northeast Oklahoma. The average soil resistivity is 6500 Ω·cm. The isoceraunic reporting is 55 thunderstorm-days per year.

Analysis: This situation is different. In the previous case, the electrical equipment was located on the structure and is exposed to the atmosphere. In this case, the electrical equipment is located away from the structure, but is exposed because of radiated signals.

Although it is not the tallest building in the area, the structure acts as a lightning rod. The steel structure is more conductive than the surrounding buildings. However, it was not adequately grounded to dissipate the energy.

To provide a direct route to earth, create a continuous electrical path down the tower. Place bonding jumpers across the support pins at the base. Also, place bonding jumpers to any supporting framework. These jumpers are straps or wire that has an equivalent cross section of at least 1/0-AWG wire. Noncorrosive terminals avoid cathodic cells between the copper wire and the steel structure. Supporting guy wires for the structure are grounded with noncorrosive terminations.

Protection systems are ineffective without an adequate grounding network to dissipate lightning energy into the earth. Therefore, a rework of the plant grounding system, with additions designed specifically to combat lightning, is often necessary.

To dissipate surge energy, the first component of an effective grounding network is a rat-race ring. The ring encompasses the entire area to be protected. The ring would also be bonded to any existing grid systems. For rings with a diameter of greater than 50 ft, install a criss-cross grid within the ring.

If a low enough impedance cannot be obtained to diffuse the energy, connect radials extending outward from the rat-race ring. Short ground rods bonded to the conductors lower the impedance even further. The preferred network is 1/0-AWG wire connected to ground rods spaced at least 20 ft apart.

Any large surges on the tower will induce voltages on electrical cables. All cables must be relocated to prevent direct contact with the tower. Transient protectors are required on cables transitioning from the tower to the control center.

Summary: Effectively ground all elevated structures. This includes jumpers around connections, as well as a good earth ground. Separate electrical cables from direct contact with the structure.

X. CASE 9: HIGH RESISTIVITY SOIL CAUSES POOR GROUND

Situation: A single large motor is supplied power directly from an overhead power distribution system. High-grounding resistance could not be lowered with multiple grounding electrodes.

Environment: The petroleum production facility is located in eastern New Mexico. The average soil resistivity is 6500 Ω-cm. Because of a shallow layer of rock encountered at 4 ft below the surface, the local resistivity is as much as 50 000 Ω-cm. The isoceraunic reporting is 47 thunderstorm-days per year.

Analysis: The contact resistance of various grounding configurations was proposed by Dwight [7] in 1936. These procedures continue to be recognized as recommended practices [1]. The equation is modified for units of feet and inches. The terms are R for resistance in ohms, ρ for resistivity in ohms/centimeters, b for length in feet, and a for radius in inches.

Using this procedure, an 8-ft ground rod with 5/8-in diameter, when placed in this earth, has a contact resistance of 177 Ω

$$R = [\rho/191.5\ b][\ln(48b/a) - 1]$$
$$R = [50{,}000/191.5 * 8][\ln(48 * 8/0.625) - 1] = 177\ \Omega.$$

Multiple ground rods can be used to reduce the circuit resistance. The *IEEE Recommended Practice for Grounding* [1] provides factors for derating the effectiveness of multiple grounds.

We proposed an alternate calculation in a previous paper [3]. The terms are R for resistance of one electrode, n for number of electrodes, and R_n for resistance of number of electrodes. The net resistance is calculated by this relationship. For three electrodes, the contact resistance would be reduced to 76 Ω

$$R_{\text{net}} = [R_{\text{one}}/n] * [2 - e^{-0.17(n-1)}]$$
$$R_{\text{net}} = [177/3] * [2 - e^{-0.17(3-1)}] = 76.11\ \Omega.$$

The technique of multiple ground rods will not reduce the circuit resistance to the 25 Ω referenced in the National Electric Code. The best way to reduce the circuit resistance is by lowering the soil resistivity.

The National Electrical Code identifies the preferred ground electrodes for power systems. Article 250-81 lists the ground techniques. The first choice is existing piping. The second choice is existing structural steel in concrete. Next is an artificial ground using concrete.

If none of these is feasible, made electrodes must be the alternative. These include other existing underground metal surfaces. The last choice is the common ground rod. The driven rod is a very poor connection to the earth.

In an attempt to improve the soil resistivity, various chemicals have been added by designers. Chemical electrodes are often proposed to accomplish this reduced resistance. However, the maintenance requirements and expense make this a less-than-preferred option.

Concrete is an effective medium for fill around ground conductors for several reasons [8], [9]. Concrete is quite conductive because of the retained moisture and the alkalinity which provides free ions. Furthermore, buried concrete has a resistivity of about 3000 Ω-cm, which is considerably less than the average earth resistivity. The same 5/8-in × 8-ft ground rod in concrete will lower the circuit resistance to 10.6 Ω

$$R = [\rho/191.5L][\ln(48L/a) - 1]$$
$$R = [50{,}000/191.5 * 8][\ln(48 * 8/0.625) - 1] = 10.6\ \Omega.$$

Three electrodes yield a resistance of 4.6 Ω. Although this is not an unusually low value, it is considerably better than the resistance in the native soil.

There are extensive calculations for determining the most effective distance between ground rods [1]. For most conditions, the electrodes should be separated by a distance of 2.2 times the length of the electrode. Closer installation reduces the effectiveness.

Summary: To reduce ground resistance, add multiple electrodes in parallel. The resistance can be reduced further by using chemical electrodes. The preferred chemical electrode consists of the rod placed in concrete.

XI. CASE 10: ELECTRICAL SHOCK WHEN TOUCHING A GROUNDED METAL ENCLOSURE

Situation: A workman was shocked when he came in contact with a metal enclosure. An equipment ground was properly installed to the electrical enclosure.

Environment: The facility is located in northeast Oklahoma. The average soil resistivity is 6500 Ω-cm. The isoceraunic reporting is 55 thunderstorm-days per year.

Analysis: The electrical power panel was located out-of-doors and was mounted on a wooden pole. The power was supplied from an overhead four-wire secondary power distribution system. The system was energized from a 277/480-V grounded wye transformer. Secondary power in the panel was delivered from a 1-kVA 277/120-V potential transformer. The secondary of the transformer was grounded to the metal enclosure. The enclosure was grounded by a 5/8-in × 8-ft ground rod.

One operator reported being shocked on several occasions when he operated the electrical equipment. Other relief operators did not report any shocks. The panel was inspected by the electrician and found to be properly installed and grounded. The panel was returned to service.

After several reported occurrences and inspections, a small control wire was eventually found pinched by an inner door. The pinch was not a direct short, so the secondary transformer did not overload and the fuse did not blow. From the calculated estimates, the pinch made a 50-Ω connection to the metal enclosure. The circuit is shown in Fig. 5.

Since the 277-V primary was grounded, and the 120-V secondary was grounded, it appears there was no potential. However, consider the unbalance current as a current source. With the pinch, there is an alternate path of unbalance for circulating current. One is through the ground rod resistance. The other is through the person and his circuit resistance.

In effect, touching the enclosure provides an alternate ground path. The contact would be in parallel with the metallic ground. The resistance of the alternate contact would depend on physical condition, earth contact resistance, perspiration or other moisture, and skin resistance. Typically, body resistance

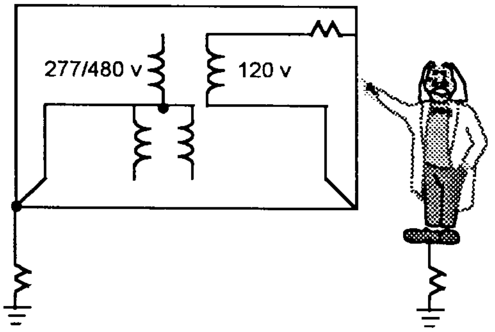

Fig. 5. Conductive ground.

may be as high as 40 000 Ω. Because of changes in fluids near the surface of the skin, this may drop to 1000 Ω during an electrical shock [10].

An example illustrates the range of current that could flow through someone touching the panel. Assume a ground resistance of 25 Ω and an unbalance current flow of only 1 A. Use the typical body resistance in parallel with the ground circuit. Then, the current through the body is calculated. Compare this with a lowered body resistance.

Higher body condition:

$$I_{\text{body}} = I_{\text{circuit}} * (R_{\text{ground}}/R_{\text{body}} + R_{\text{ground}})$$
$$I_{\text{body}} = 1 * (25/40{,}000 + 25) = 0.6 \text{ mA}.$$

Lowered resistance:

$$I_{\text{body}} = I_{\text{circuit}} * (R_{\text{ground}}/R_{\text{body}} + R_{\text{ground}})$$
$$I_{\text{body}} = 1 * (25/1{,}000 + 25) = 24.4 \text{ mA}.$$

Others did not feel the shock for two crucial reasons. Their body resistance may have been higher or the soil conditions may have been different. Regardless, it is apparent from this problem that the ground resistance is critical to the safety of personnel. If the ground contact resistance were substantially less than the 25 Ω, the current would have been considerably lower.

Similarly, under another set of conditions, the current flow could have been fatal. Consider the dramatic impact if the unbalance current were at the level in case 6, and the person had a good contact with the earth, such as standing in a wet spot. With the lower body resistance, the shunt current through the body would be tremendous.

Lowered resistance:

$$I_{\text{body}} = I_{\text{circuit}} * (R_{\text{ground}}/R_{\text{body}} + R_{\text{ground}})$$
$$I_{\text{body}} = 14A * (25/1{,}000 + 25) = 341 \text{ mA}.$$

Numerous references have been made to studies that identify the effect of small quantities of current on the human body [10]. Commonly accepted values are shown in Fig. 6. Ground-fault circuit interrupters (GFCI's) are designed to recognize these levels. Personnel-protection GFCI's must respond to a 6-mA trip level. Equipment protection devices are typically 30 mA or higher. Although it it not required by codes and is not a standard practice, a GFCI on the low-voltage control circuit could have sensed the problem.

Current (Amps)	*Physiology Effect*
0.001	Sensation to mild shock
0.008	Painful shock to most people
0.015	Paralysis of muscles—cannot let go; breathing restarts if circuit broken
0.020	Possible damage to nerve tissue and blood vessels
0.050	Onset of ventricular fibrillation
0.10	Death probable

Fig. 6. Effects of current on the body.

Summary: Install low-resistance earth grounds. The grounded conductor must be connected to the same equipotential ground network.

XII. CONCLUSION

There have been a large number of problems encountered with grounding systems in various environments. The different cases not only represent the diversity of the problem, but also the commonality of the solutions. The overriding design consideration is "little things mean a lot." The key installation concept is "details matter."

1. Consider the environment. There are very few direct lightning hits, nevertheless, there are many side effects. The number and severity of thunderstorms have a direct bearing on the necessity of a good or exceptional earth ground.
2. Analyze the earth resistivity. The soil conditions dramatically influence the ground resistance. Multiple ground rods installed in concrete lower the local resistance.
3. Maintain an equal potential ground network. The fundamental component is a ring constructed around the protected facility. Criss-cross grids and radials reduce the impedance for surges. The network is bonded to the ground rods.
4. Use a single-point network for interconnections. Maintain separate, isolated grounded systems for the power (neutral), signal common (negative), and shield. Connect each of these to the grounding network at only one point.
5. Bond the equipment (chassis) together. Multiple connections are made to the grounding network to maintain equipotential for personnel safety.
6. Use protection devices to mitigate the effect of surges on electrical components. The choice of grounding techniques dramatically influences the effectiveness of these devices.
7. Bond protection component grounds directly to the chassis when located within an effectively grounded plant. Isolate protection devices from the equipment ground at remote sites. The potential difference between the plant and the remote site will invalidate any protective system. Fiber optics provide the ultimate isolation.
8. Terminate all unused connections to electronics and instrumentaion. Otherwise, potential differences will develop during transient conditions. Short inputs to ground, connect load resistors to outputs, and bond unused cable conductors to ground.

ACKNOWLEDGMENT

Appreciation is extended to C. Sandberg at Raychem for his review and insights into several of the problems.

REFERENCES

[1] *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (Green Book)*, ANSI/IEEE Standard 142, 1982.

[2] *IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (Emerald Book)*, ANSI/IEEE Standard 1100-1992, 1992.

[3] M. O. Durham and R. Durham, “Lightning, grounding, and protection for control systems,” *IEEE Trans. Ind. Applicat.*, vol. 31, pp. 45–54, Jan./Feb. 1995.

[4] R. T. Hasbrouck, “Lightning—Understanding it and protecting systems from its effects,” Lawrence Livermore National Laboratory, Livermore, CA, Rep. UCRL-53925, Apr. 1989.

[5] R. B. Carpenter, “Designing for a low resistance earth interface,” Lightning Eliminators & Consultants, Boulder, CO, unpublished.

[6] *The ARRL Handbook*, American Radio Relay League, Newington, CT, 1995.

[7] H. B. Dwight, “Calculation of resistances to ground,” *AIEE Trans.*, pp. 1319–1328, Dec. 1936.

[8] E. J. Fagan and R. H. Lee, “The use of concrete enclosed reinforcing rods as grounding electrodes,” *IEEE Trans. Ind. General Applicat.*, vol. IGA-6, pp. 337–348, July/Aug. 1970.

[9] R. R. Block, “How to build a ufer ground,” *Mobile Radio Technol.*, pp. 42–44.

[10] W. Mapes, “Electrical safety doesn’t cost—It pays,” *Electrified Ind.*, Jan. 1977.

Marcus O. Durham (S’64–M’76–SM’82–F’93) received the B.S. degree in electrical engineering from Louisiana Tech University, Ruston, the M.E. degree in engineering systems from the University of Tulsa, Tulsa, OK, and the Ph.D. degree in electrical engineering from Oklahoma State University, Stillwater.

He is an Associate Professor at the University of Tulsa and is Director of the Power Applications Research Center. He specializes in microcomputer applications and electrical/mechanical energy systems. He is also the Principal Engineer of THEWAY Corp, Tulsa, OK, an engineering, management and operations group that conducts training, develops computer systems, and provides design and failure analysis of facilities and electrical installations. He is President of ADBT Enterprises, an entrepreneurial business development firm using catalog and interactive technology.

Dr. Durham is a member of the Society of Petroleum Engineers (SPE) and a task group member of the American Petroleum Institute (API). He is a Registered Professional Engineer and Licensed Electrical Contractor in Oklahoma and an FCC-licensed radiotelephone engineer. He has served on and been Chairman of many committees and standards groups within the IEEE, SPE, and API and is a member of the IEEE USAB Committee on Man and Radiation. He has been awarded the IEEE Richard Harold Kaufmann Medal “for development of theory and practice in the application of power systems in hostile environments.” He is listed in *Who’s Who of the Petroleum and Chemical Industry of the IEEE* and *Who’s Who in Business Leaders.* He is also a member of Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu.

Robert A. Durham (S’90–M’92) received the B.S. degree in electrical engineering from the University of Tulsa, Tulsa, OK, where he is currently pursuing the Masters of Engineering Management degree.

He has worked for utilities in Oklahoma and Texas and is currently an Electrical Engineer with Central and Southwest Services/West Texas Utilities, Abilene, TX. He is involved in power generation engineering and environmental studies. His projects have included control systems installations, large variable-frequency drives, and other generation projects. His prior experience has included production project management, as well as electric automobiles and computer-aided design.

Mr. Durham is a Registered Engineer Intern in the State of Oklahoma. He is a member of the Society of Automotive Engineers, Tau Beta Pi, and Eta Kappa Nu.