GUIDE FOR TRANSMISSION LINE GROUNDING

Signposts for Designing Effective Grounding Systems

Transmission Subcommittee

Transmission and Distribution Engineering Committee

August 2025

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ABBREVIATIONS

°F	Degrees Fahrenheit
°C	Degrees Celsius
A	Amperes
ac	Alternating Current (also AC)
ADSS	All-Dielectric Self-Supporting
ASTM	American Society for Testing and Materials
BIL	Basic Insulation Level
coulomb	The SI unit of electric charge equal to the quantity of electricity conveyed in one second by a current of one ampere
Cu	Copper
CWC	Copperweld Conductor
FOW	Front of Wave
GFN	Ground-Fault Neutralizer
Hz	Hertz (cycles per second)
IEEE	Institute of Electrical and Electronics Engineers
kA	Kiloampere, one is equal to 1,000 amperes, which are the electrical current equal to the flow of one coulomb per second
kcmil	Kilocircular mils (1000 circular mils)

km	Kilometers (1000 meters or 1608 feet)
kV	Kilovolt (1000 volts)
m/s	Meters per second, a unit of velocity or speed
MCOV	Maximum Continuous Operating Voltage
mi	Mile
mil	One Thousandth of an Inch
MJ	Megajoule, a unit of energy equivalent to one million joules
MOV	Metal-Oxide Varistor
mph	Miles Per Hour
NEC	National Electrical Code
NESC	National Electrical Safety Code
OHGW	Overhead Ground Wire
OPGW	Optical Ground Wire
rms	Root Mean Square
SI	Système International, the international metric system of units used for scientific measurements
TOV	Temporary Overvoltage

DEFINITIONS

Ampacity—the current-carrying capacity of a conductor, measured in amperes

Back Flashover—characterized when lightning strikes a structure or a switching surge occurs which does not have a sufficiently low resistive path to ground, causing the surge to "flash over" the insulation, depending on the impedance path, resulting in a line-to-ground fault

Basic Impulse Level (BIL)—measured in voltage, the maximum crest value of electrical impulse (*i.e.*, lightning) utility equipment can withstand

Basic Switching Impulse Level (BSL)—measured in voltage, the maximum crest value of a switching impulse that utility equipment can withstand

Cathodic Corrosion—an electrochemical process in which one metal corrodes preferentially to another when both metals are in electrical contact and immersed in an electrolyte

Cathodic Protection—a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell

Chemical Well—a type of grounding electrode consisting of a hollow metal tube with breather holes and leach holes; the tube is filled with special electrolytic salts which gradually leach out of the bottom of the rod, thereby lowering the soil resistivity.

Counterpoise—a set of underground grounding conductors radiating from the pole footing to provide adequate grounding protection where ground resistance is high.

Corona—a physical phenomenon at high voltage levels which is caused by an excessive electrostatic flux density on or near conductors and/or attachment hardware in close proximity to conductors, appearing as a luminous discharge; it can also cause wear or degradation to conductors and insulators

Crow's Foot—a type of counterpoise extending in a pattern of multiple radial lines

Dielectric—a material that either does not conduct electrical current at all or else does so poorly

Electrolyte—a mineral that, when dissolved in water, becomes electrically conductive; soil with a higher presence of electrolyte minerals has much better grounding potential

Electromagnetic Induction—formation of electrical current on a conductor moving through a magnetic field

Effectively Grounded—a connection that has sufficiently low resistance to ground, providing safe operation of equipment and minimizing hazards to personnel

Exothermic Weld—a welding process for joining two electrical conductors that employs superheated copper alloy to permanently join the conductors

Fault Current—any abnormal flow of electric current as a result of a short circuit; it may involve one or more phases and ground, or may occur only between phases (in a ground fault or earth fault, current flows into the earth)

Flashover—an unfavorable electrical discharge over an insulated material which usually occurs after a voltage surge beyond the rated value of the equipment's electrical capacity

Footing Resistance—the measured ground resistance at an individual structure location

Ground Resistance—the electrical resistance between the grounding system and the earth, ideally at near-zero ohms

Ground Rod—a metal shaft driven into the earth to create a low-resistance path for electrical current to flow into the ground (*i.e.*, function as a grounding electrode)

Grounding Conductor—a conductor that connects electrical equipment or another conductor to a grounding electrode

Grounding Electrode—a conductor that is embedded in the earth to facilitate the dissipation of electrical currents (*i.e.*, establish a ground)

Grounding Plate—a type of grounding electrode made with flat metal plate

Grounding System—all interconnected grounding connections in a specific area

Isokeraunic Level—typically represented on a map, numerically indicating the frequency of thunderstorm activity for a given area in a year; areas with higher isokeraunic levels are more prone to lightning strikes

Lightning Arrester—see Surge Arrester

Metal Oxide Varistor (MOV)—a type of surge arrester that contains a ceramic mass of zinc and other metal oxides sandwiched between two metal plates

Multigrounded—grounding of a neutral conductor at multiple locations along the circuit

Neutral Conductor—a system conductor that provides a return path for current to the source

Overhead Ground Wire (OHGW)—a shield wire typically made from galvanized or aluminum-clad steel

Optical Ground Wire (OPGW)—a shield wire that may also be used for communications made of an optical fiber core surrounded by layers of steel and aluminum

Reactance—opposition to the flow of electric current by capacitance or inductance

Resistivity—measurement of how strongly a material withstands electrical current

Shielding Angle—an angle measured from the vertical between the shield wire and the phase conductors that provides recommended shielding protection for conductors based on structure height

Shielding Failure—when lightning strikes a phase conductor instead of the shield wire

Shield Wire—in a power line system, one or two grounded wires assembled above phase conductors to protect the power line system from lightning

Soil Resistivity—a measure of how much the soil resists the flow of electricity

Soil Ionization—a current leaking into the earth that is high enough to produce an electrical field sufficient to lower the ground impedance

Step Potential—the possibility of voltage flowing from one foot to the other if one foot is near an energized grounded object; a person may be at risk of electric shock by standing near the grounding point

Surge Arrestor—a device that limits voltage surges (caused by lightning strikes or switching transients) by discharging or bypassing the resulting surge current to the ground system

Static Discharge—the spark or arcing associated with an excess charge that is neutralized by a flow of charges across hardware components that are loosely connected

Switching Surge—a voltage surge resulting from switching operations that may lead to arcing or flashover

Touch Potential—the voltage difference between an energized object and a person's feet when in contact with the object, potentially leading to an electric shock

Transfer Potential—similar to touch potential, but where a voltage difference exists between two grounded points and a conductive path allows current to flow between them; the transfer potential increases as the distance from the grounded structure or equipment increases

CONTRIBUTORS

The Transmission Subcommittee of the Transmission and Distribution Engineering Committee (TDEC) provided invaluable assistance in preparing this document.

DISCLAIMER

LEGAL NOTICE

1. INTRODUCTION

The purpose of this grounding guide is to provide useful, practical information applicable to designing effective grounding systems for electric transmission lines to: (1) manage steady state and fault currents, and (2) enhance safety and reliability by reducing lightning outages due to insulator flashover. This guide is not intended to instruct the engineer in how to use specific proprietary analytical modeling tools, nor is it intended to discourage the engineer from using those tools, because they can be extremely helpful. Contained herein are recommendations and signposts to help guide the engineer in designing effective grounding systems.

OVERVIEW

Effective grounding is comprised primarily of overhead ground wires, ground conductors, and ground electrodes. The primary focus of this guide is on ground conductors and ground electrodes whose physical characteristics vary with climate and geographical location. Since underlying soil or rock conditions and earth resistivity may vary from structure to structure, the design of ground electrodes may also vary by location. Differences in designs at each location may include electrode size, depth, and/or width, in order to provide low values of structure ground resistance.

Lightning

In general, lightning causes insulation flashover through three mechanisms:

1. Electromagnetic induction;
2. Direct stroke (*i.e.*, shielding failure); and
3. Back flashover (*i.e.*, grounding failure).

In a direct lightning strike to an electric transmission line structure, the lightning current is discharged to the earth via the structure and its grounding system. The voltage rise of the structure may be several times the electric transmission line voltage. If the voltage rise exceeds the dielectric strength of the insulators, then a back flashover may occur, setting up a fault along the path created by the lightning, across the insulators. When lightning strikes, it may travel at speeds between 0.2 and 0.9 times the speed of light and current waves move along overhead ground wires to other structures, flow to ground, and reflect back to the point of impact, which can interfere with the ongoing discharge of the originating current.

Performance Predictions

In the timeframe leading up to the 1950s, lightning performance predictions based on approximate methods appeared satisfactory (*i.e.*, predictions were in line with actual experience) and more rigorous approaches were not deemed necessary. However, circumstances changed in the 1950s with the expansion of the electric transmission system. Due to the more dispersed (and in some cases, more lightning-prone) locations of some transmission lines, a new focus was placed on outage analysis and proactively implementing ways to reduce outages on lines with higher-than-expected outage rates from lightning strikes.

Insulator manufacturers also sensed an opportunity to provide technical assistance and offer new products to help reduce outages. In 1955, an open letter to the industry from one insulator manufacturer described a study of the phenomena that might produce flashover of the top string of a vertical conductor arrangement on a steel tower line, stating that, "shielded transmission line outages can result from either fractional microsecond high-voltage pulses or from the conventionally considered voltages generated by the product of the crest current magnitude and footing resistance."[1] Further study revealed that the fractional, microsecond-duration high-voltage pulses could be present on conducting members such as steel tower sections, which were often the structure of choice for many new transmission lines around this time period.

Eventually, analytical models and computer-aided simulations were developed to assist the engineer in designing effective grounding systems. These models required careful consideration before simplifying the assumptions used. Some of the more important modeling assumptions involved representing lightning as an ideal current generator, lumping ground resistance at each structure, accounting for soil ionization near ground-conductor elements, using zero ohms for the earth's resistance, using structure equivalents, and simplifying conducting elements.

2. TRANSMISSION LINE GROUNDING

LIGHTNING

Lightning, one of nature's most spectacular and powerful forces, can cause severe damage to electrical systems and is the number one reason for providing proper shielding and a ground resistance as low as possible for transmission grounding systems. A bolt of lightning can produce currents of 30 kA and transfer a charge of 5 coulombs and 500 MJ of energy, producing enough energy to develop 54,000°F (30,000°C) of heat and can travel at speeds of 130,000 mph (60,000 m/s).[2] The power of lightning can set poles on fire and burst poles apart. Direct strikes of lightning damage grounding conductors (*i.e.*, shield wires and, especially, optical ground wires) and/or conductors, causing faults on the electrical system. Lightning striking transmission lines in areas with poor grounding or poor soil resistivity can result in insulator flashover, which can cause insulator failure and system outages.

The best defense against lightning damage is a coordinated shielding and well-designed grounding system. On overhead lines, lightning can cause line outages in two ways: (1) as a result of induction when it strikes in the vicinity of the line, and (2) by direct contact when it terminates either on a grounded structure or shield wire or onto phase conductors.

Induction is not considered important for transmission lines because the level of induced voltage (generally lower than 300 kV on unshielded lines) is lower than the line insulation level and is unlikely to cause a flashover. On lines with overhead ground wires, lightning-induced over-voltages are even lower; therefore, induction is not considered further in this guide.

[1] Ohio Brass Company, open letter dated June 17, 1955.

[2] Munoz, Rene, "Lightning," Fact Sheet, April 10, 2000, University Corporation for Atmospheric Research, Boulder, Colo. www.ucar.edu/communications/factsheets/lightning.html, viewed June 21, 2011.

Direct strikes to the line can cause flashover in two ways. One way is by terminating on the phase conductor, which is called a shielding failure. Flashovers as a result of shielding failure are prevented by the correct placement of the overhead ground wires or shield wires to intercept the lightning stroke and direct it to ground. Another way is by terminating on the tower or shielding arrangement, which causes a so-called back flashover (see Figure 1) as a result of the voltage buildup over the grounding system. The most common remedy for back flashover is to lower the tower footing impedance.

From a shielded transmission line grounding perspective, back flashover is the most important lightning condition that must be considered.

Insulator Back Flash

When lightning strikes an electric transmission line structure or shield wire, the lightning current is discharged to the earth via the structure and its grounding system. The voltage rise of the structure may be several times the electric transmission line voltage. If the voltage rise exceeds the dielectric strength of the insulators, then a back flashover may occur, setting up a fault along the path created by the lightning across the insulators, resulting in track marks and potentially even broken or cut insulation. When lightning strikes, it may travel at speeds between 0.2 and 0.9 times the speed of light and current waves move along overhead ground wires to other structures, flow to ground, and then reflect back to the point of impact, which can interfere with the ongoing discharge of the originating current.

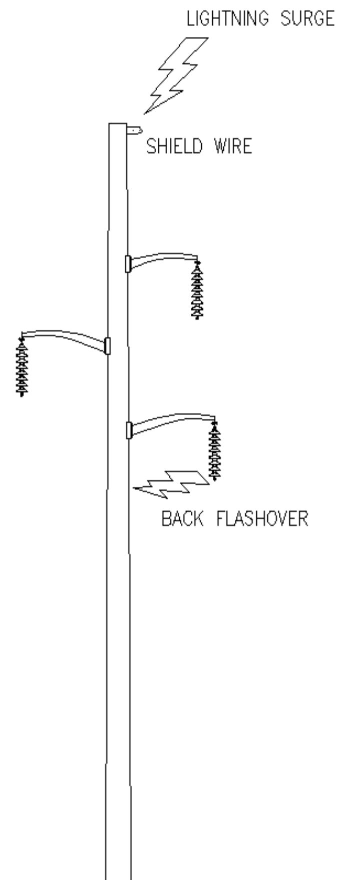

Figure 1: Back Flashover

About 20% to 25% of lightning strokes are cloud to ground. The magnitude of the strokes are anywhere from 5 kA to 140 kA, depending on the storm system. The cloud typically is charged negatively and the Earth has a positive charge with respect to the cloud. The lightning will start with a downward stream of electrons from the cloud and will be met with an upward stream of positive charges from the ground and produce the first flash. The return stroke is through the ionized path from the first stroke.

The cause of the transmission line flashover will be a result of exceeding the design BIL (insulation levels). For example, if a 69-kV transmission line is experiencing a 25-kA stroke, the ground resistance is approximately 25 Ohms, and the combination BIL of the wood and the insulators is about 420 kV, the result will likely be a flashover (25 kA × 25 Ohm = 625 kV > 420 kV). The structure voltage (625 kV) flashes to the phase conductor and creates an ionized path in the air; the power frequency voltage flashes back to the tower through the ionized path, creating an outage. This back flash occurs approximately 85% of the time and is dependent on the point of time on the voltage sine wave at 60 Hz during the time of the event. If the ground resistance is 10 Ohms, the voltage is not high enough; therefore, no flashover would occur (25 kA × 10 Ohm = 250 kV < 420 kV). Higher voltage transmission lines will be more reliable due to the higher structure BIL levels. For example, 115-kV transmission lines have BIL in the neighborhood of 700 kV to 850 kV depending on steel or wood poles.

RUS Requirements

RUS Bulletin 1724E-200, paragraph 8.7.4, requires that, "A lightning outage rate of 1 to 4 per 100 miles (160 km) per year is acceptable with the lower number more appropriate for lines in the 161- to 230-kV range. Generally, experience has shown the footing resistance of individual structures of the line, especially within 0.5 miles (0.8 kilometers) of the substation, should be less than 25 Ohms in high isokeraunic areas." Paragraph 8.7.3 requires that, "An overhead wire should be used in all locations where the isokeraunic level is above 20" [thunderstorms in a year]; see map in Figure 2. The overhead ground wire should be grounded at every structure by way of a structure ground wire. "In areas where the isokeraunic level is 20 or less, an overhead ground wire should still be used for a distance of 0.5 miles (0.8 kilometers) from a substation."

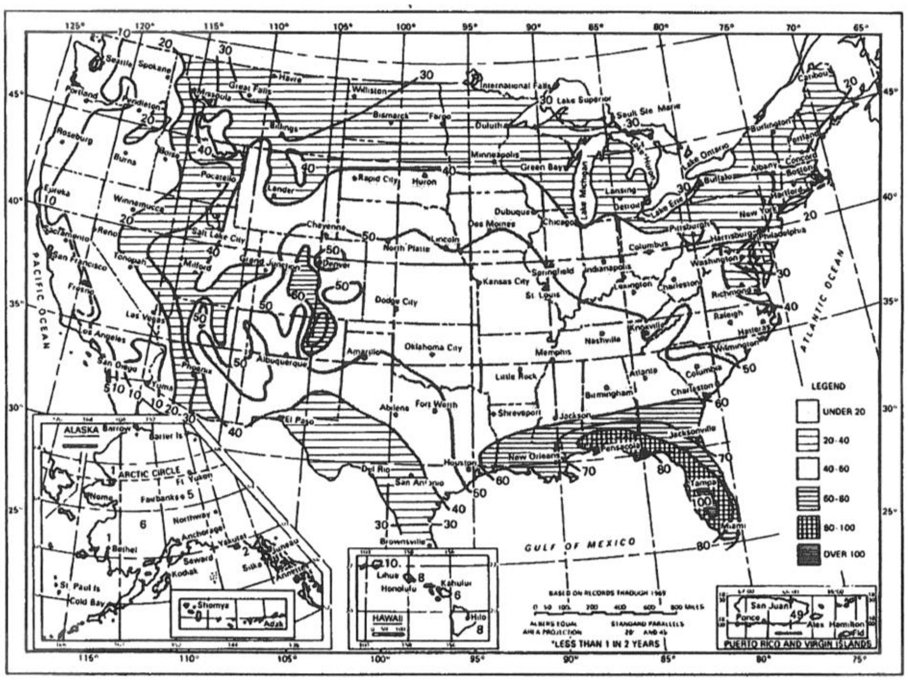

Figure 2: Map of Isokeraunic Levels for the United States

Shielding

Overhead ground wires intercept lightning strokes and prevent them from terminating on the phase conductors or other equipment that needs to be protected. The rest of the grounding system provides a low-impedance path for the lightning current to discharge into the general mass of the earth. It must do so without developing high voltages on the tower that could lead to flashover of the line insulation.

The placement of the shield wire can affect the performance of the transmission line. When lightning strikes the conductor and not the shielding, it is called a shielding failure. RUS Bulletin 1724E-200, paragraph 8.7.2, recommends that the conductor be placed with a shielding angle of 21° to 30° depending on structure height. (See Table 1.) (Shielding angle is defined as the angle measured from the vertical line of overhead shield wire and the conductor.)

Table 1: Reduce Shielding Angle Values.

Structure Height (feet)	Shield Angle
Up to 92	30
93 – 99	26
>99	21

There are two basic types of shielding: positive and negative. Positive shielding is when the conductor is placed outside the shielding. Negative shielding is when the conductor is placed inside the shielding (see Figure 3).[3]

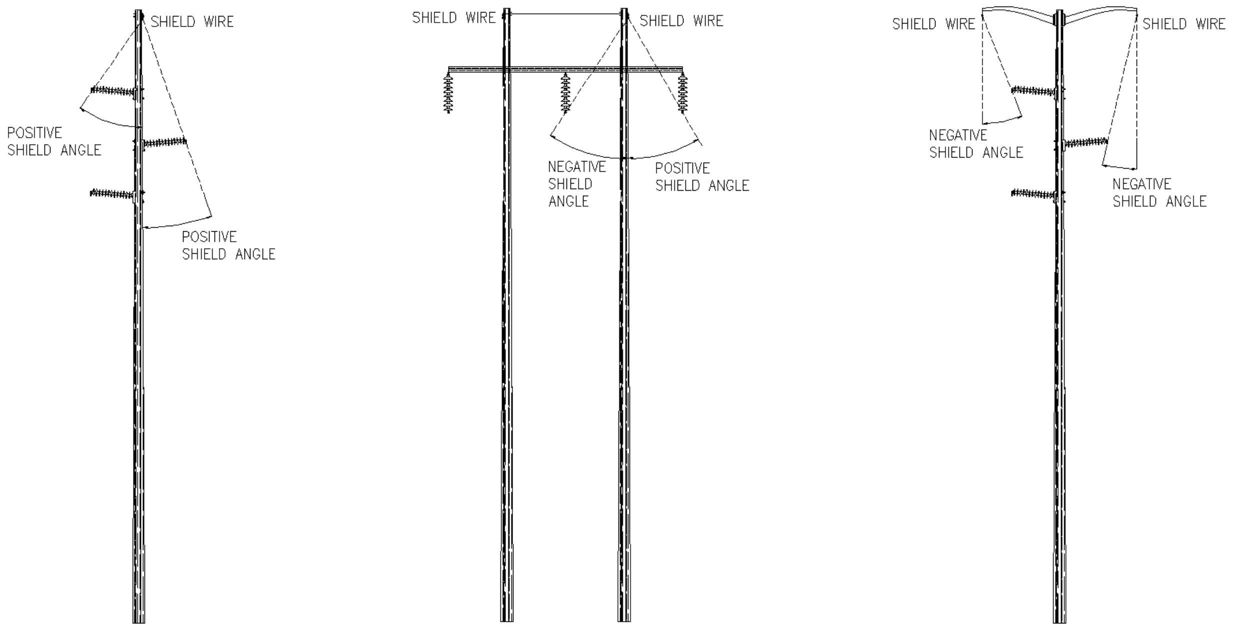

Figure 3: Negative Versus Positive Shield Angles

The Effect of Footing Resistance on the Outage Rate of a Transmission Line

Electricity flows to the point of least resistance and this is true with lightning. It makes sense that, when lightning strikes the shielding, it will flow to the structure with the lowest footing resistance and cause an insulator flashover on this structure if the voltage exceeds the insulator withstand voltage. If the lightning has a 20% chance of equaling or exceeding 50 kA and the footing resistance is 40 Ohms, then the possible voltage rise seen by the structure is 50 kA × 40

[3] IEEE Standard 1243-1997, Lightning Performance of Transmission Lines, Page 7.

Ohms = 2,000 kV. Assuming the insulator only sees 25% of the available voltage, 500 kV still will exceed the insulation strength of a 138-kV insulator. One can see that there is a direct relationship to the grounding resistance and the outage rate. Figure 4 shows the effect of the outage rate for a 50-kA lightning strike at various footing resistances for different transmission line voltages.[4]

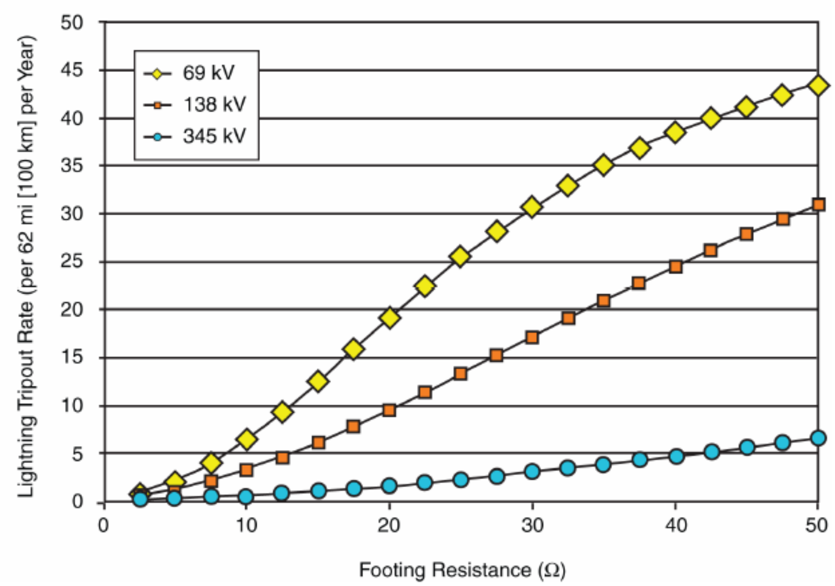

Figure 4: Lightning Back Flash Reliability of Single-Circuit Lines Vs. Footing Resistance

Lightning Reliability Levels for Various Lines

The reliability of a line can be calculated by knowing the total number of lightning strikes and the number of flashovers. It's safe to assume that the shield wire is adequate and 100% of the flashovers are caused by actual flashovers rather than other phenomena. The reliability rate for direct lightning strikes to the conductor will be nearly zero (virtually all strikes will cause a trip-out). The number of flashovers is related to the grounding resistance, but it does not seem to be linear. Lightning reliability decreases as footing resistance increases. These estimates neglect shielding failures where lightning flashes contact the phase directly. For these rare failures, footing resistance was not a major influence.

For lines with an unacceptable reliability rate, possible solutions include reducing the grounding resistance, verifying that all structure grounds are installed correctly, improving the shielding, adding lightning arrestors, or increasing the BIL (basic insulation level) of the insulators used.

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[4] *Guide for Transmission Line Grounding: A Roadmap for Design, Testing, and Remediation: Part I—Theory Book.* EPRI, Palo Alto, Calif. 2007. 1013900. p.5-33.

SURGES AND FAULTS

A transmission overhead ground wire (OHGW) and ground system will be exposed to phase-to-ground faults, including lightning. The OHGW and related grounds must be capable of withstanding the current levels placed on them by a lightning strike and/or station fault. With a good grounding system, not all lightning strikes should result in insulator flashover and phase-to-ground and/or phase-to-phase faults, even in areas with high isokeraunic levels.

A phase-to-ground fault can be caused by the following:

- Insulator flashover (see earlier discussion for more on flash backs),
- The OHGW making contact with the phase conductor,
- The ground wire breaking and coming in contact with the phase conductor, or
- Foreign objects coming in contact with the energized phase.

Design and maintenance of the OHGW and ground wire are critical to preventing these faults.

Phase-to-phase faults can occur during a flashover if the lightning energy is great enough to bridge (flash over) the air gap from phase to phase. Conductor contact during galloping and foreign objects in the air gap can also cause phase-to-phase faults. These types of faults are not normally associated with OHGW or pole ground failures.

The magnitude of fault current out of some substations (especially within the first mile or so) can be high enough to melt the OHGW if not designed properly or for lines with fiber optical ground wire (OPGW) and must be considered in the design. Most manufacturers of OPGW recommend that OPGW be well-connected to the ground at each structure to minimize the potential of damage to fibers from lightning or other surges.

Lightning arresters can be used on lines to reduce high flashover rates. For older lines without OHGW (typically in areas with low isokeraunic levels), lightning arresters have been installed in place of installing a shield wire. In areas with higher isokeraunic levels, lightning arresters used in addition to shield wire has improved performance; however, using lightning arresters alone (*i.e.*, without shield wire) may lead to increased maintenance issues such as lead failure and difficulty with hot line replacement.

GROUNDING OVERVIEW

Grounding Systems for Substations, Generation, and Switching Stations

Station grounding differs from transmission line grounding. A typical substation is a fenced enclosure with restricted access to qualified personnel where electrical equipment, circuit breakers, disconnects, buswork, transformers, control buildings, and other equipment are located. A substation without transformers is generally referred to as a switching station. A generation substation would be located adjacent to a generation fossil fuel power plant or other electrical producing facility (solar, chemical, nuclear, wind, or hydro).

IEEE Standard 80-2013, *Guide for Safety in AC Substation Grounding*, states that, in principle, a safe substation grounding design has the following two objectives:

1. To provide the means to carry electrical currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service; and
2. To ensure that a person in the vicinity of grounding facilities is not exposed to the danger of critical electrical shock.

Grounding systems for substations are designed to handle fault currents to protect personnel in addition to protecting the system and electrical equipment. While stations can experience faults generated by lightning strikes, they must also be provided protection from all faults, including phase-to-phase as well as phase-to-ground. Typically, station grounding is planned using a grid system designed to provide safe touch and step potentials while dissipating fault current into the ground. The two controlling factors for substation design are fault circuit and soil resistivity.

Grounding Systems for Distribution

Distribution grounding also differs from transmission grounding. For the purposes of this guide, distribution is defined as being 34.5 kV and below. Distribution systems typically supply electricity to the end user—business, residential, or commercial. Distribution systems use a neutral conductor as the system ground. NESC defines a neutral conductor as a "system conductor other than a phase conductor that provides a return path for current to the source" and states that "not all systems have a neutral conductor." An example is an ungrounded delta system containing only three energized phase conductors. Ground conductor is defined as a "conductor that is used to connect the equipment or the wiring system with a grounding electrode or electrodes."

A distribution line has a neutral conductor independent of the number of phases. For example, a single phase is one phase and a neutral, a two-phase (also known as "V-phase") is two phases and a neutral, and three-phase is three phases and a neutral. The neutral can be located either above the phases (typical in single-phase distribution), in-between the phases, or below the phases. Depending on the distribution configuration, the neutral conductor may be connected to the pole ground or not.

A neutral conductor is used to establish a ground for electrical equipment (transformers, capacitors, regulators, and lightning arrestors) to earth. Sizing of the distribution neutral conductor is dictated by the requirements of the electrical equipment. When distribution electrical equipment shares the same transmission structure, the grounding conductor can be common or kept separate for the transmission and distribution. When common grounding conductors are used, guarding covers are required if not classified as multigrounded per NESC Rule 93D.

Chapter 16 of RUS Bulletin 1724E-200, *Design Manual for High-Voltage Transmission Lines,* provides the requirements for designing distribution underbuild. NESC Chapter 9 provides the requirements for sizing the grounding conductor and Part 2 provides the clearance needed. The designer must ensure that both sets of standards are met or exceeded.

Grounding Systems for Home and Commercial Grounding

The National Electrical Code (NEC) defines Ground as a "conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth, or to somebody [who] serves in place of the earth." NEC defines Grounding Conductor as a "conductor used to connect the grounding circuit of a wiring system to a grounding electrode or electrodes."

Therefore, the grounding conductor for a house or commercial application is used to complete the circuit and to establish a ground. The ground conductor must be connected to a well-established common ground using a ground rod and/or a metallic water pipe (refer to NEC for restrictions). Grounding for housing and commercial buildings must be designed and installed per the NEC.

For structures or other facilities with radio equipment (communications and/or microwave sites), the design and installation grounding system is critical to ensuring that static noise is not introduced to the system. All grounding connections are designed to prevent stray electrical currents that could cause noise on the radio.

Ground Resistance

RUS Bulletin 1724E-200, Chapter 8, Page 7, does not set a level for the ground resistance; rather, it provides two references for designing a grounding system. For further discussion on grounding resistance, see Section 5 on Grounding Electrodes.

RUS does recommend that, "when a line is being built, ... the footing resistance of the ground connection be measured and recorded, as a minimum, on a spot-check basis. If footing resistance problems are expected, more frequent measurements should be made and recorded. If experience indicates that the lightning outage rate is not acceptable, these measurement readings can be useful when taking remedial measures."

Grounding of Towers Near Substations

Within the first 0.5 miles (0.8 kilometers) away from any substation, it is particularly important that tower ground resistances be as low as practicable. Line faults near a station can generate short-circuit duty great enough to damage circuit breakers, transformers, and other electrical equipment because of the low line reactance to the fault. Lightning strikes near the substation are particularly hazardous if the voltage wave created by the lightning is of high enough magnitude to reach and possibly damage the transformer winding or an open breaker terminal. The designer may wish to investigate the possibility of installing a continuous counterpoise to reduce the fault current capability of the overhead ground wires and reducing the possibility of back flashover and local touch potentials on the first few towers outside the station.

Figure 5: Pole Fire With Close-Up

Grounding of Wood Poles

Lightning can sometimes split a pole without a ground wire. A direct lightning hit to one or more of the phases can create voltages as high as 1,000 kV or more at the top of the pole. If the heartwood is sufficiently dry and dielectrically strong, an arc will tend to develop on the surface, possibly blowing off splinters of sapwood but usually causing no significant damage. Heartwood used in crossarms tends to be dry at both ends and also remains dielectrically strong. However, the heartwood in the interior of some poles tends to wick moisture from the ground, making it dielectrically weak compared with sapwood. This effect increases as the pole decays. In these cases, a breakdown path can avalanche down the pole interior to ground. The consequent arc and stream pressure can then blow the pole apart.

OVERVIEW OF SAFETY ISSUES

National Electric Safety Code (NESC)

Designers of transmission lines are responsible for meeting all applicable codes, including the NESC. A designer is responsible for becoming knowledgeable with the NESC and providing a design that meets all codes. Unlike the *RUS Design Manual*, the NESC has plenty of requirements and some different definitions; it defines the pole ground as the “ground conductor” and the ground is “earth.” The following are some of the key requirements found in the Code.

NESC Section 2—Definitions of Special Terms

The engineer/designer must be aware of the definitions used in NESC as they may differ from what is used in RUS Bulletins. A good example is the definition used for conductor, as it can include fiber-optic wire (OPGW) and ground wires. “Ground” is not defined but is referred to as “earth.”

The following are defined as applied to a transmission system:

- **Grounded.** "Connected to or in contact with earth or to a conductive body that extends the earth connection."
- **Grounded System.** "A system of conductors in which at least one conductor or point is intentionally grounded, either solidly or through a current-limiting device. For a transmission line, this would be the ground electrode and the pole ground."
- **Grounding Electrode.** Section 094 defines electrode as driven ground rods, buried wire, strips, or plates (counterpoise), and pole-butt plates or wire wraps (pole-butt wraps).
- **Electrical Supply Lines.** "Those wires, conductors, and cables used to transmit electric or light energy and their necessary supporting or containing structures, equipment, and apparatus that are used to provide public or private electric supply or lighting service."
- **Shield Wire** (also referred to as overhead ground wire, static wire, or surge-protection wire). "A wire or wires, which may or may not be grounded, strung parallel to and above phase conductors to protect the power system from lightning strikes."

NESC Section 9—Grounding Methods for Electrical Supply and Communications Facilities

This chapter states it is "to provide practical methods of grounding, as one of the means of safeguarding employees and the public from injury that may be caused by electrical potential."

- Paragraph 93.C.2; Distribution Underbuild: "A system conductor (*i.e.*, a neutral conductor) for an AC transmission line must be rated to carry 1/5th the current of the (phase) conductor."
- Paragraph 93.C.8; Ampacity Limit: "No grounding conductor (*i.e.*, pole ground) need have greater ampacity than either (a) the phase conductors that would supply the ground fault current, or (b) the maximum current that can flow through it to the ground electrode or electrodes to which it is attached." (Note: For multiple grounded systems that are in good condition, the fault current is shared with multiple grounds.)
- Paragraph 94; Ground Electrodes (for distribution): "The grounding electrode shall be permanent and adequate for the electrical system involved" and allows for the use local systems such as metallic water piping, metallic piping connecting to wells having sufficiently low resistance to earth, and reinforcing steel in concrete.
- Paragraph 94.C; Made Electrodes: The *IEEE NESC Handbook* defines "made electrodes" as "an electrode of any form buried in the ground for the special purpose of attaching a grounding conductor (*i.e.*, pole ground) to it." Paragraph 94.C.1 adds, "where made electrodes are used, they should penetrate permanent moisture level and below the frost line" and "made electrodes shall be of metal or combinations of metals that do not corrode excessively under the existing conditions for the expected service life."
- Paragraph 94.C.2,a; Driven Rods: Allows for iron, zinc-coated steel, or steel rods [0.625" (1.58 cm) minimum diameter] or copper-clad, stainless steel, or stainless steel-clad rods [0.5" (1.27 cm) minimum diameter] and also covers wire, strips, butt plates, concentric neutral cable, concrete-encased electrodes, and directly embedded metal poles

or metal posts. RUS requires that all ground rods have copper cladding (coating) of 13 mils or greater. Extra-thick coatings or copper-clad rods can be used in areas where a utility is having corrosion problems.

- Paragraph 94.C.2: Defines the requirements for buried wire or straps (*i.e.*, counterpoise).

- Paragraph 94.B.3: Defines the requirements for pole-butt plates and wire wrap.

- Paragraph 94.B.6: Directly embedded steel poles shall constitute an acceptable electrode, if the following requirements are met: (a) backfill around the pole is native earth, concrete, or other conductive material such as conductive grout (not gravel); and (b) not less than 5.0 ft (1.5 m) of the embedded length is exposed directly to the earth, without non-conductive covering. Directly embedded steel poles having a nonconductive covering below ground that limits the length of direct exposure to earth to less than 5.0 ft (1.5 m) are not considered as an acceptable electrode. Aluminum installed below ground is not considered as an acceptable electrode. Weathering steel may not be an acceptable material for this application. There are structural and corrosion concerns that should be investigated prior to using metal poles as grounding electrodes. Other lengths, configurations, or type metal may be used if their suitability is supported by a qualified engineering study.

- Paragraph 95; Method of Connection to Electrode: "The grounding connection shall be as accessible as practical and shall be made to the electrode by methods that provide the required permanence, appropriate mechanical characteristics, corrosion resistance, and required ampacity."

- Paragraph 96; Ground Resistance Requirements: "Grounding systems shall be designed to minimize hazard to personnel and shall have resistances to ground low enough to permit prompt operation of circuit protective devices. Grounding systems may consist of buried conductors and grounding electrodes."

- Paragraph 96.C; Note 2: "Multigrounded systems extending over a substantial distance are more dependent on the multiplicity of grounding electrodes than on the resistance to ground of any individual electrode. Therefore, no specific values are imposed for the resistance of individual electrodes."

- Paragraph 96.C: The intent is to ensure that grounding electrodes are distributed at approximately ¼ mi (400 m) or smaller intervals, although some intervals may exceed ¼ mi (400 m).

- Paragraph 215.C; Grounding of Non-Current-Carrying-Parts: "Metal or metal-reinforced supporting structures—including lamp posts; metal ducts, conduits, and raceways; cable sheaths; messengers; metal frames, cases, and hangers of equipment; and metal switch handles and operating rods—shall be effectively grounded." This rule does *not* apply to frames, cases, and hangers of equipment and switch handles and operating rods that are 8 ft (2.45 m) or more above readily accessible surfaces or are otherwise isolated or guarded and where the practice of not grounding such items has been a uniform practice over a well-defined operating area.

Special Protective Measures

Normally, transmission grounding is not a danger to utility workers or the public (the NESC doesn't require protecting the transmission grounds). The potential of being electrocuted from lightning strikes, faults on the line, and misoperation of the electrical system are all possible but extremely rare, considering the probability rate for a given event and the probability that someone is in contact with ground at the same instant the event happens.

Special protective measures are needed when:

- The distribution neutrals are connected to the ground,
- Maintenance crews are operating line disconnects, or
- Transmission grounds are used by a line maintenance crew to establish a working ground.

Neutrals on distribution lines provide a return path for neutral current to flow from the source to earth (ground). Transmission lines with underbuilt distribution usually have a neutral connected to the transmission ground.

When utility operating personnel disconnect a transmission line, anyone in the area can be exposed to faults resulting from switching surges, equipment failures (arcing), and phase-to-phase flashovers. A switching surge is a voltage surge resulting from switching operations and can cause arcing or flashovers. Switching platforms—along with protective personnel equipment (hardhat, fire resistant clothing, insulated gloves, and shoes)—must be provided.

When transmission maintenance crews are working on the line, they are exposed to lightning, faults, and misoperation of equipment. Depending on the operational practice of the utility, the crews will establish working grounds by connecting to the structure ground or the shield wire in a preferred location (usually either closer to a substation source or within visual sight of the work being done). The crew must also be aware of—and provide protection for—three potential safety risks: step potential, touch potential, and transfer potential.

"Step Potential" is defined by IEEE as "the potential [voltage] difference between two points on the earth's surface, separated by a distance of one [human] pace, which will be assumed to be one meter, in distance of maximum potential gradient."

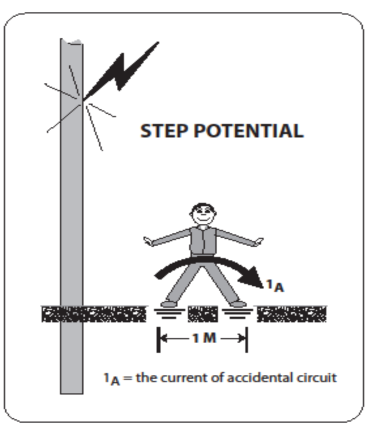

Figure 6: Step Potential

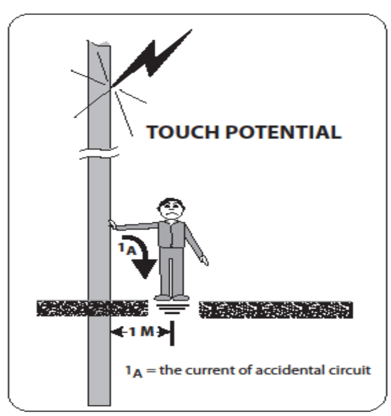

Figure 7: Touch Potential

“Touch Potential” is defined by IEEE as “the potential [voltage] difference between a grounded metallic structure and a point on the earth’s surface equal to the normal maximum horizontal reach [of a human], approximately one meter.”

“Transfer Potential” is defined as the electrical voltage potential between remote earth and a power system, such as a transmission tower. For example, if an aerial lift used by the maintenance crew is grounded to the earth but not to the working ground, a potential difference of voltage and formation of circulating currents could be measured around the lift.

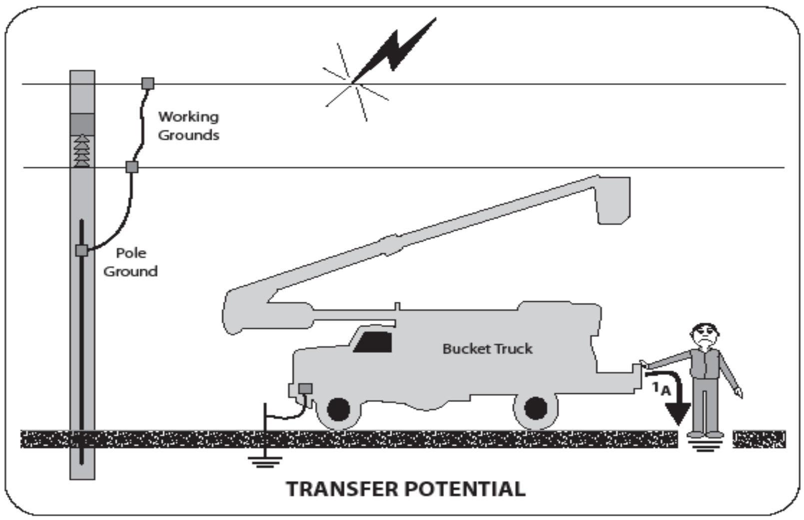

Figure 8: Transfer Potential

How do you design protection against both Touch and Step Potential? Possible solutions are:

- Touch potential can be solved by preventing the person from contacting the surface that is carrying electric current.
  - Wood or plastic guards are placed over the ground.
  - Grounds can be installed with PVC insulation.
  - Install insulated ground wires.
- Installing a ground mat. See IEEE Standard 80.
- Placing barriers to prevent access to the area.
- At line disconnects, install switching platforms or mat.

4. GROUNDING DESIGN THEORY

This section provides a general overview of grounding design theory as it relates to high-voltage transmission lines. While grounding fundamentals are generally the same whether the location is a transmission line or a substation site, the approach to transmission line grounding is typically a good deal different.

For a substation or other localized site, the grounding design process would begin with an investigation of the site-specific soil characteristics to a reasonable depth that might be expected for grounding. This is most commonly done by making soil-resistivity measurements at several locations across the site and entering the data into a computer program that facilitates grounding analysis and design. Unlike a transmission line corridor, the substation site is a relatively small area and detailed soil information can be acquired and utilized very economically.

For a transmission line corridor, the structures may be located hundreds of feet apart and continue for many miles. While an investigation of soil characteristics can be made at every structure location, this can become rather time-consuming and uneconomical. The typical approach to transmission line grounding is to forego or limit the soil-resistivity measurements and to begin the installation of grounding electrodes at each structure location based upon assumed or historical criteria. Adjustments to the grounding system are made as ground resistance readings are taken at each step along the way.

Rather than taking a completely reactive approach to the grounding installation, however, the engineer should first try to understand the fundamentals about the electrical circuit that includes the soils and the most common variables that have the greatest effect on the grounding system. Most of those variables are hidden well below the surface and are a function of the soil characteristics.

ELECTRICAL CIRCUIT

The potential rise of a grounding system during ground fault conditions is directly proportional to the resistance of the grounding system. Resistance of the grounding system is important for the satisfactory operation of over-current devices. Ohm's Law applies to all electrical circuits, including the electrical conduction in soils.

The resistance of a conductor between two points is directly proportional to the potential difference or voltage across the two points, and inversely proportional to the current through the conductor.[5] The mathematical equation that describes this relationship is shown in Equation 1.

Equation 1: Ohm's Law

$$R = V / I$$

where,

R = resistance (Ohms)
V = potential difference (volts)
I = current (amperes)

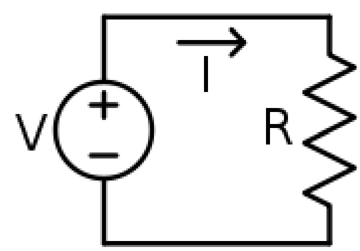

Figure 9: Electrical Circuit

To quantify the electrical conduction through soil, the expression "soil resistivity" has been developed to relate the length and cross-sectional area of the soil, as shown in Equation 2.

[5] Ohm's Law states that the current through a conductor between two points is directly proportional to the potential difference across the two points. Source: *Wikipedia*. Retrieved July 25, 2009.

Equation 2: Soil Resistivity

$$\rho = R \times A / L$$

where,

ρ = average soil resistivity (ohm-meters)
A = cross-sectional area of the soil (meters squared)
L = length, or distance, across the soil (meters)

Before proceeding in greater detail with the measurement of soil resistivity, the various soil characteristics that commonly affect the soil resistivity are described in the following section.

SOIL CHARACTERISTICS

While there are many variables that could affect the resistance of the grounding system, there are several soil characteristics that typically have the greatest influence. Because of this, the resistivity of soil is highly dependent on the factors that influence the electrolyte, or dissolved mineral content, in the soil. The engineer should have a general understanding of these influences in order to facilitate the planning and design of the grounding system.

Effect of Soil Type

Soils consist of a large number of grain particles that differ in size, shape, and chemistry. Depending on these attributes, plus the general compaction of the soil, the volume of spaces between these particles in the soil will vary. These minute spaces are the key to the soil's ability to carry or retain moisture, thus affecting the soil's resistivity.

For soils that consist of many different grain sizes, the smaller grains fill up the tiny gaps between the larger grains, thus limiting the moisture content in the soil. Denser soils have fewer of these minuscule spaces than a loose soil.

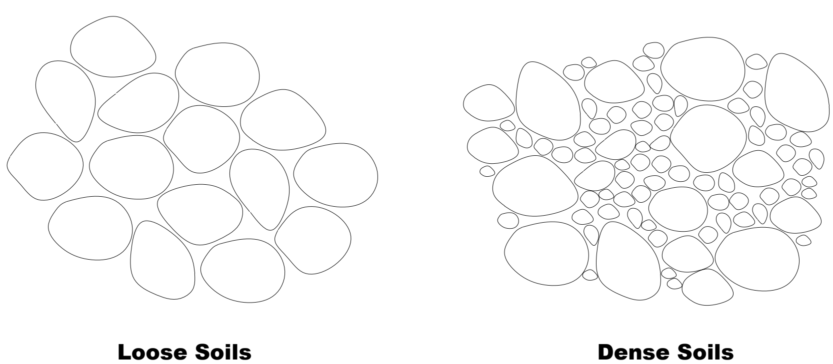

Figure 10: Loose Versus Dense Soils

While types of soil can be broken down into a large number of categories (according to variations in texture, grain size, density, and so forth), Table 2 reduces all soils to four general types, each with its approximate range of resistivity values.

The average values shown in Table 2 should not be utilized in grounding calculations without further assessment of the specific conditions at each structure location. The intention of the table is to show an increase in resistivity as soil characteristics move from wet clayey soils to dry sandy soils to hard rock.

For any given soil type, the range of values to be expected at the structure location can be immense. For example, while soils described as "moist" may have an average resistivity of about 100 ohm-meters, the range could be from 20 to 200 ohm-meters or more, depending on other influencing factors.

Table 2: Average Resistivity of Various Soils

Type of Soil	Resistivity (Ohm-meters)
Wet organic soil	10
Moist soil	100
Dry soil	1,000
Bedrock	10,000

Effect of Moisture

Resistivity of the soil rises sharply when the moisture content falls below about 15% by weight. As explained above, some soils have higher moisture content than other soils. Typically, moisture content ranges between 5% (dry, sandy soils) and about 30% (wet, clayey soils). In general, the soil resistivity can increase by a factor of ten as moisture content drops from 30% to below 5%.

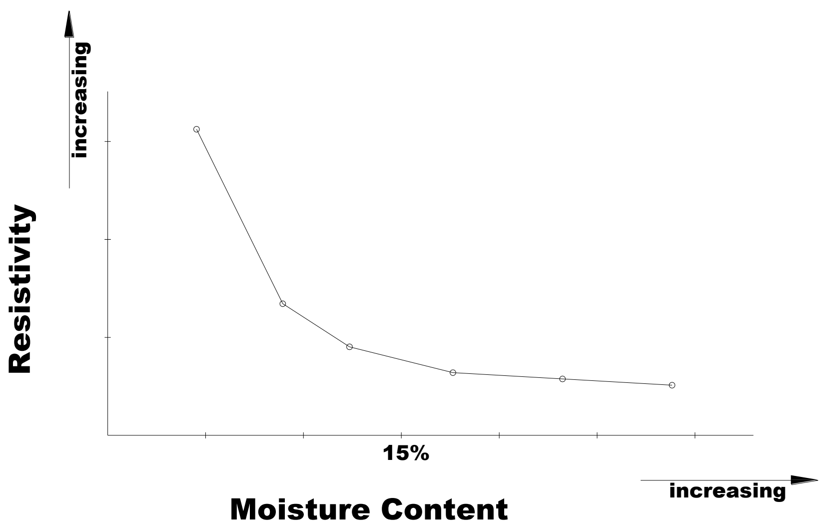

Figure 11: Changes in Resistivity Based on Moisture Content in Soil

The overall resistance of the grounding system varies with seasonal fluctuations in rainfall, humidity, and changes in the groundwater table attributable to other influences. Essentially, any change in the moisture content of the soil will affect soil resistivity. The deeper the system is below the surface, the less the effects of seasonal fluctuations.

The engineer cannot necessarily control the amount of moisture in native soils or control exactly what season the installation will take place, but the engineer should have an understanding of those influences on soil resistivity and act accordingly. As such, it is most important to note that the grounding electrodes should be buried deeply enough to ensure contact with permanently moist soils.

If this cannot be readily accomplished, the engineer should plan for an increase in soil resistivity as the moisture content fluctuates during the dry season. In this case, greater dependence will usually be placed on a well-distributed system of vertical rods bonded to the ground grid and reaching deep layers. Crushed rock coverings, usually about 6" in depth, are helpful in retarding evaporation of moisture and, thus, limiting the drying out of the top layer.

Effect of Chemical Composition

Chemical composition refers to the mineral or dissolved salt content of soils, most often defined as an "electrolyte" solution. An electrolyte is basically a material that, when dissolved in water, results in a solution that conducts an electric current. Sodium chloride may be the most familiar type of salt in soils, but there may be other types present as well. Some electrolytes are more conductive than others.

Typically, the engineer will not be concerned with the electrolyte content in soils, but he or she should have an understanding of those influences on soil resistivity. When there is a need to improve the grounding at any location by using alternative methods, one of the methods discussed later in this guide is to increase the electrolytes in the vicinity of the grounding electrode.

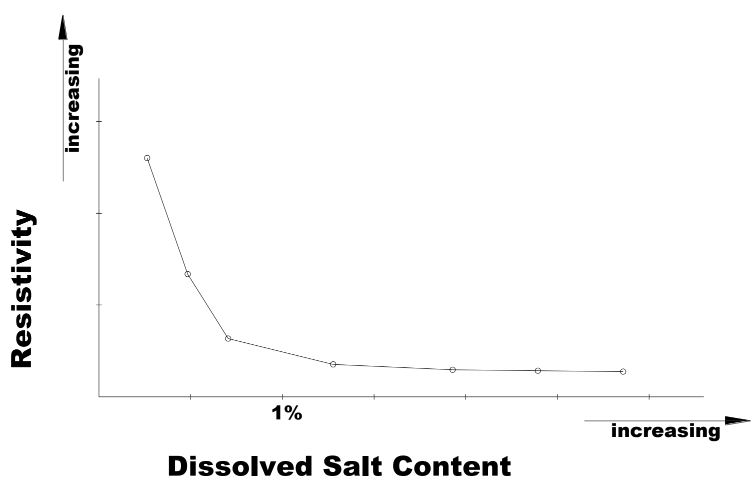

Figure 12: Changes in Resistivity Based on Dissolved Salt Content in Soil

Effect of Temperature

Resistivity of soil rises abruptly when the soil temperature falls below 32°F (0°C) and the moisture in the soil freezes. Because of this, the grounding electrode should extend below the frost line wherever feasible to minimize seasonal variation of the grounding system resistance. Once below the frost line depth, the actual soil temperature has little influence on the soil resistivity.

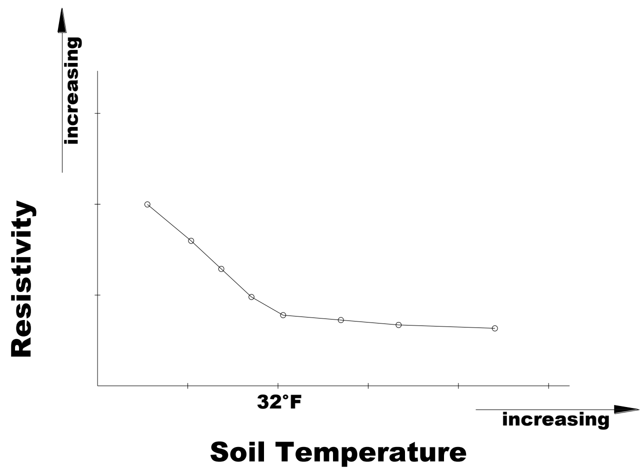

Figure 13: Changes in Resistivity Based on Soil Temperature

Effect of Soil Layering

While it is often assumed in grounding system design that there is uniformity in the soil characteristics down to the depth that influences the grounding system, the reality is there can be many separate soil layers, each affecting the overall resistivity at the site. Most often, the soils will consist of a few distinct horizontal layers within the limits of the grounding system at each structure location.

As an example, a transmission line structure location may consist of an upper layer of moist soils and a lower layer of rock. In this situation, the grounding electrodes should be installed above the rock in the soils that have an expected lower resistivity. While the actual depth to the rock may not be known until during the installation, the engineer should have alternate plans in place to achieve the desirable ground resistance at that location.

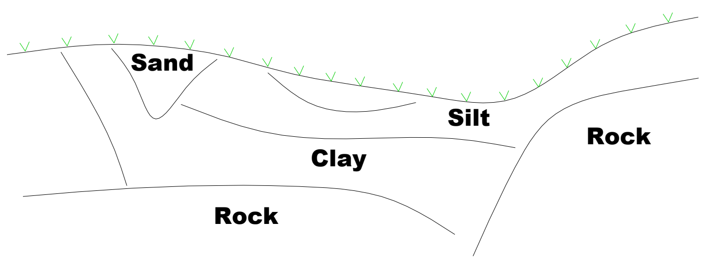

Figure 14: Soil Layering

SOIL RESISTIVITY

Soil resistivity measurements are required for the design of a grounding grid and safety analysis. Soil resistivity is the key factor that determines the resistance of a grounding electrode driven to a specific depth. The soil resistivity is different at various locations and changes seasonally. The potential rise of a grounding system during ground fault conditions is directly proportional to the resistance of the grounding system. Touch and step voltages, too, are related to the soil resistivity.

As described in the previous sections, there are many unseen subsurface variables that will influence the ground resistance at each structure location. In some instances, it may be desirable to better define those subsurface variables so that the extent and layout of the grounding electrodes can be reasonably predicted or even completely designed ahead of the actual installation. The most common proactive approach is to make soil resistivity measurements at structure locations of interest (*i.e.*, structures with special foundations, occasional structures along the corridor, places with noticeable changes in soils, and so forth) and then use those soil resistivity parameters in the design of the grounding system.

Testing for soil resistivity is a fairly simple process and can be handled by the utility's trained personnel or by consultants with such expertise. Regardless of who does the measurements, the engineer should lay out clear instructions for how the testing is to be done and be specific describing the locations, number of tests at each location, layout, etc. Examples of outside personnel that could be used by utilities to obtain soil resistivity are land surveyors who are contracted to survey the transmission line and geotechnical engineering consultants who are performing soil borings along the transmission line.

Wenner Four-Electrode Method

A number of standard procedures exist for the soil resistivity measurements, but by far the method of choice is the Wenner four-electrode method.[6] Four probes are arranged at equal distances in a straight line, and driven into the soil no more than 1/20th of their horizontal separation, as shown in Figure 15.

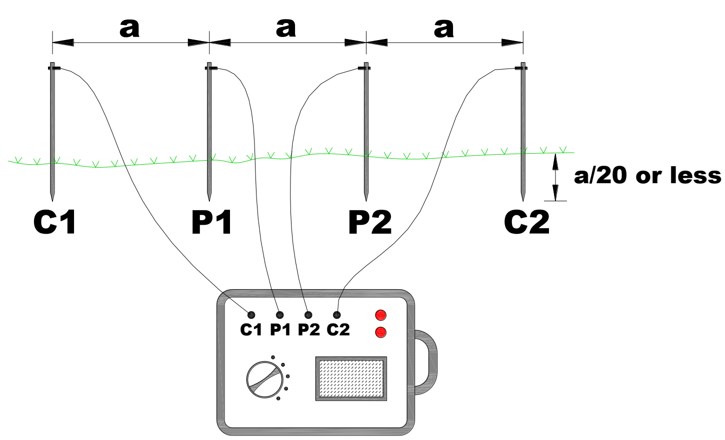

Figure 15: Soil Resistivity Measurement by Wenner Method

[6] Wenner, F. *A Method of Measuring Earth Resistivity*, Bulletin of the National Bureau of Standards, Vol. 12, Washington, D.C. 1916.

Soil resistivity is derived from the voltage drop between the center probes (P1 and P2), with current flowing between the two outside probes (C1 and C2). The soil resistivity tester is energized and a resistance reading is taken. The soil resistivity is calculated using the simplified Equation 3.

Equation 3: Soil Resistivity Calculation

$$\rho = 2\pi a (0.3048) R$$

where,

ρ = Average soil resistivity, Ohm-meters
a = Distance between the electrodes, feet
R = Resistance, Ohms

[The 0.3048 conversion factor is to account for distance measurements in feet, rather than meters.]

From this measurement, the average soil resistivity is determined for a hemisphere of soil whose depth is equivalent to the probe spacing. It indicates how the soil will respond to the flow of electric current and is invaluable to any effort to establish maximum grounding protection. In Figure 16, the lines shown between the outside probes (C1 and C2) would represent the current flow path in the soil based on the probe spacing at the time of measurement.

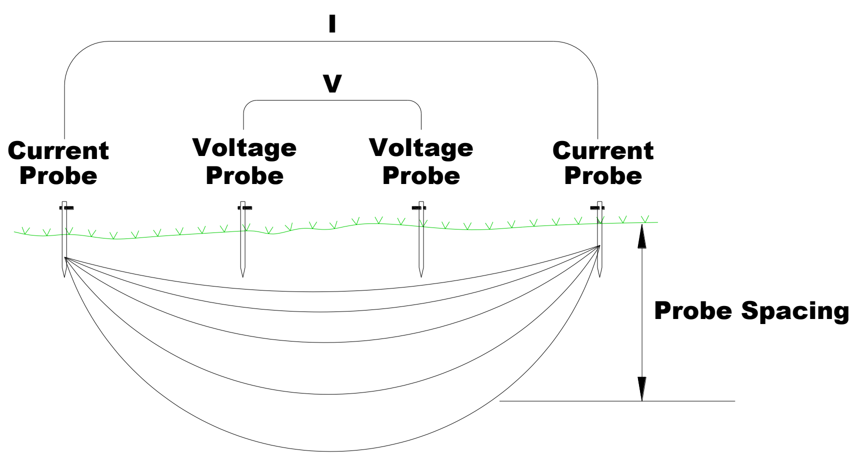

Figure 16: Effect of Probe Spacing on Depth of Reading

Additional test readings are made after changing the distance between test probes, essentially spacing the probes further and further apart along a straight line. At the beginning, the test probes may be spaced a few feet apart. Depending on the soil resistivity readings taken as the testing continues, the probe spacing is increased until sufficient data is obtained. The spacing relates to grounding electrode depth. If the test data suggests that only a shallow grounding electrode system is needed at a structure location, then there's little reason to increase the probe spacing far beyond the length of the expected grounding electrode depth.

Multiple Sets of Readings

Once a set of readings is obtained, another set of tests may be made along a different straight line alignment, usually skewed or perpendicular to the first set of test data. Figure 17 illustrates a possible orientation of multiple sets of readings. The purpose of the multiple alignments is to ensure that sufficient soils are included and to minimize external influences such as large buried objects and any parallel metallic object such as rails, pipelines, and utilities.[7]

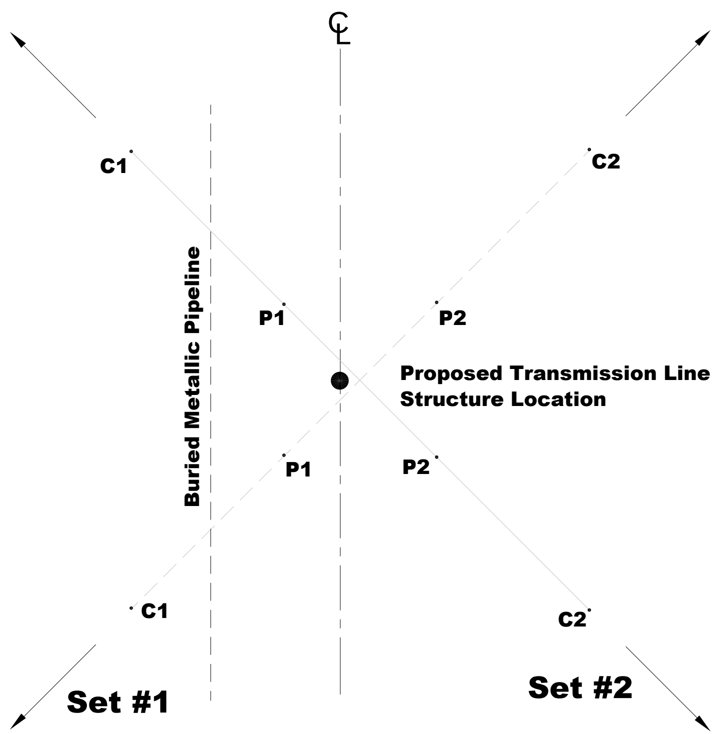

Figure 17: Possible Alignments for Multiple Readings

[7] IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System. IEEE Std. 81-2012, IEEE, New York, N.Y. 28 December 2012. pp.12-13.

Using Soil Resistivity Data

Once soil resistivity measurements are made, the data can be used to design a grounding system suitable for the structure location or may be used to predict the grounding needs for multiple structure locations.

For each set of soil resistivity readings taken at various probe spacings along a line, a plot of the apparent soil resistivity versus probe spacing can be made. If the resistivity readings are about the same for all the probe spacings, then that would indicate somewhat uniform soil characteristics down to a depth equivalent to the largest probe spacing.

Most likely, the soil structure will not be completely consistent and a plot of the data may indicate some sort of geological variation. For example, based on the shape of the graph, evidence of multiple soil layers might be apparent. Figure 18 might be representative of a specific three-layer structure.

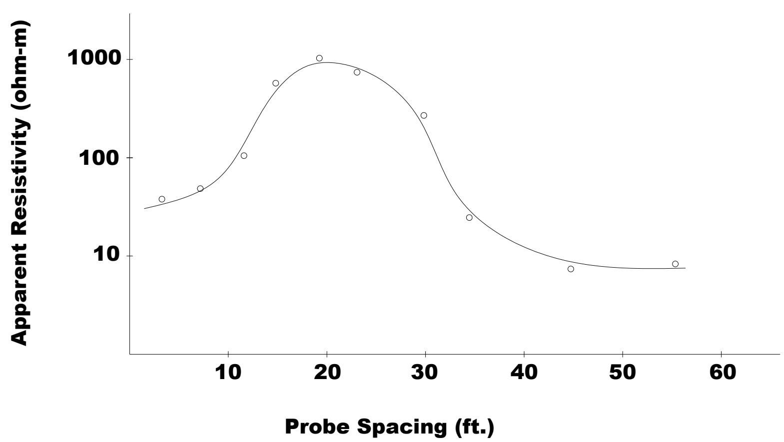

Figure 18: Example of a Three-Layer Resistivity Curve

For a somewhat uniform soil layer, the next step might be to use a simple grounding nomograph, or alignment chart, that correlates the apparent soil resistivity to the number of driven ground rods required for the desired ground resistance. For more complicated situations, such as multiple soil layers, various computer programs can also be used to design the grounding system, especially when the site may require a more complex solution than simply driving ground rods to a certain depth.

Example 1: Soil Resistivity in Single-Layer Soils

For this example, assume soil resistivity measurements are made as directed by the engineer and in accordance with the instructions for the testing instrument. For a specific location, the results are submitted to the engineer for one set of test data as shown in Table 3.

Table 3: Example Soil Resistivity Field Report

Set Number	Distance Between Electrodes (Feet)	Meter Reading Resistance (Ohms)	Average Soil Resistivity (Ohm-meter)
1	5	1.5	14
	10	5.2	100
	15	3.6	103
	20	3.1	119
	30	1.7	98
	40	1.6	123
	60	1.3	149
	80	2.5	383
	100	2.4	459

In Table 3, each value in the right column is the soil resistivity for each probe spacing and is calculated as described earlier in Equation 3. From that equation, the constants are combined to make a simplified equation as follows.

Equation 4: Constants Combined from Equation 3

$$\rho = 1.915\, a\, R$$

where,

ρ = Average soil resistivity, Ohm-meters
a = Distance between the electrodes, feet
R = Resistance, Ohms

From the calculated results in the table, it appears that the soils are nearly uniform in resistivity down to a depth of about 60', then a significant rise in resistivity occurs. This rise could be due to a second layer of soil that differs significantly from the upper layer.

Referring back to the typical soil-resistivity soil types shown earlier in Table 2, with the resistivity readings in the range of 100-150 ohm-meters, the engineer can reasonably assume the upper layer of soils is somewhat "typical" with little likelihood of rock.

The engineer can input these soil-resistivity values into one of many computer programs available to determine the number of ground rods necessary for a desired grounding resistance (*e.g.*, 25 ohms) at a specific location or the engineer may use a simple nomograph to obtain similar results.

Example 2: Soil Resistivity in Varying Soil Layers

As in the previous example, assume soil resistivity measurements are made as directed by the engineer and in accordance with the instructions for the testing instrument. For this specific location, the results are submitted to the engineer for one set of test data as shown in Table 4.

Table 4: Example Soil Resistivity Field Report

Set Number	Distance Between Electrodes (Feet)	Meter Reading Resistance (Ohms)	Average Soil Resistivity (Ohm-meter)
1	5	1.5	14
	10	5.2	100
	15	11.1	320
	20	13.3	510
	30	9.6	550
	40	5.6	430
	60	1.0	120
	80	0.8	130
	100	0.5	90

As in the previous example, the average soil resistivity is calculated by Equation 3 and the results listed in the right column of the table. From a review of the data, one can see that there are probably two or three layers of soils within the depth tested. Note that there is significant improvement in resistivity at depths below 40', perhaps due to significant increase in moisture content or just an improvement in soil type.

Since there are multiple layers, the use of the simple nomograph mentioned in the previous example would not be the best choice. The engineer could assume a uniform layer and use a nomograph with the higher resistivity values listed, but that might lead to a significant increase in cost of a grounding system that may not be warranted. It may be possible to design a grounding system that stays above that middle layer, taking advantage of the lower resistivity readings in the range of 5' to 10' deep. T better choice may be to extend the ground rods through the middle layer and into the better soils in the range of 60' to 100' deep.

As stated in this example, there are several approaches to the design of the grounding system at this one test location. There are computer programs that can be used to derive a grounding system based on an input of the multilayered soil data. It may be necessary to reduce the data to some type of equivalent two-layer model to stay within the limitations of most computer programs. For transmission line engineering, the two-layer equivalent model is accurate enough without being too involved mathematically.[8]

Design, Installation, and Testing

The purpose of this section is to describe the basic principles that will influence the grounding system at each structure location and to describe the testing procedure for situations where soil-resistivity testing is desired.

In the upcoming sections of this grounding guide, the actual design, installation, testing, and improving of the grounding system will be covered in detail.

5. GROUNDING ELECTRODES

In the previous section, a brief discussion of grounding design theory was presented. A familiarization of those concepts will be beneficial as the engineer moves into the grounding system design process.

Whether or not soil-resistivity testing was performed prior to construction, the engineer must develop drawings and specifications for the grounding system to be used in the construction of the transmission line.

Based on prior experiences, the engineer may simply begin by specifying the installation of ground rods, one after the next, in some defined pattern. Then, the ground resistance will be tested after each rod is installed until the targeted resistance is reached. While this approach is successful most of the time, the engineer still must have alternatives ready for situations at structure locations where this technique does not work.

In this section, a brief discussion of grounding electrode basics will be presented so that the engineer will be better prepared to design and specify an appropriate grounding system.

GENERAL CHARACTERISTICS

A primary purpose of the grounding electrode is to protect people and equipment. For a transmission line structure, the grounding electrode discharges lightning current into the soil so that the insulators on the structure do not experience a back-flashover to the phase conductors.

The grounding electrode is essentially a metal conductor buried in the earth. It is typically attached to the transmission line structure by a grounding conductor. In some cases, the structure itself may also be a grounding electrode. An example of this might be a direct-embedded steel pole where sufficient metal is in contact with the earth.

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[8] IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System, IEEE Std. 81-2012, IEEE, New York, N.Y. 28 December 2012. pp.15.

Most transmission line structure grounding is accomplished using pole-wrapped ground wire, butt plates, counterpoise, and/or one or more sets of vertically driven ground rods, which is the most common installation. The following will be a brief discussion of the response of the ground rods to lightning surge conditions.

SPHERES OF INFLUENCE

When a high current from a lightning strike reaches the grounding electrode, the current flows into the surrounding soil. This is typically described as flowing through a series of concentric shells of earth as illustrated in Figure 19 with each of the concentric shells having the same thickness. The current flows radially outward from the grounding electrode through each of the shells. Each adjacent shell has a greater area for the current flow and, with the greater area, the resistance is lower. As the current dissipates through the earth, the resistance becomes negligible.

The earth ground resistance for a single vertical electrode can be calculated as shown in Equation 5.

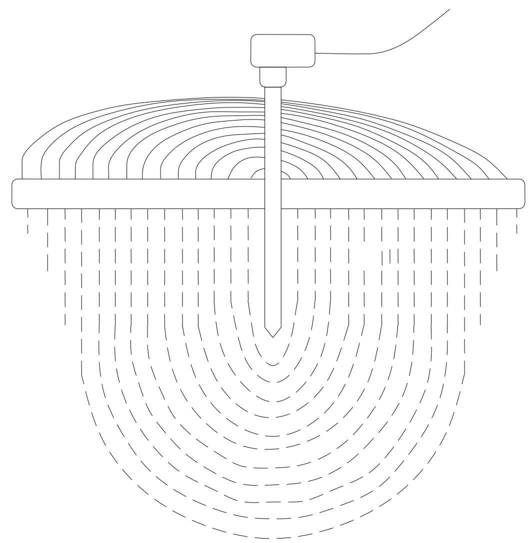


Figure 19: Single Electrode Sphere of Influence

Equation 5: Ground Resistance for a Single Vertical Electrode

$$R = \frac{\rho}{2\pi L}\left[\ln\left(\frac{4L}{a}\right) - 1\right]$$

where,

R = Resistance (Ohms)
ρ = Average soil resistivity (Ohm-cm)
L = Length of rod (cm)
a = Radius of rod (cm)
ln = natural logarithm

MULTIPLE ELECTRODES

If multiple ground rods are placed very close to each other, the spheres of influence will overlap, as shown in Figure 20. This reduces the electrodes' ability to dissipate the current into the soil. To take full advantage of each electrode's sphere of influence, the ground rods are to be placed at a minimum distance of two times the rod length.

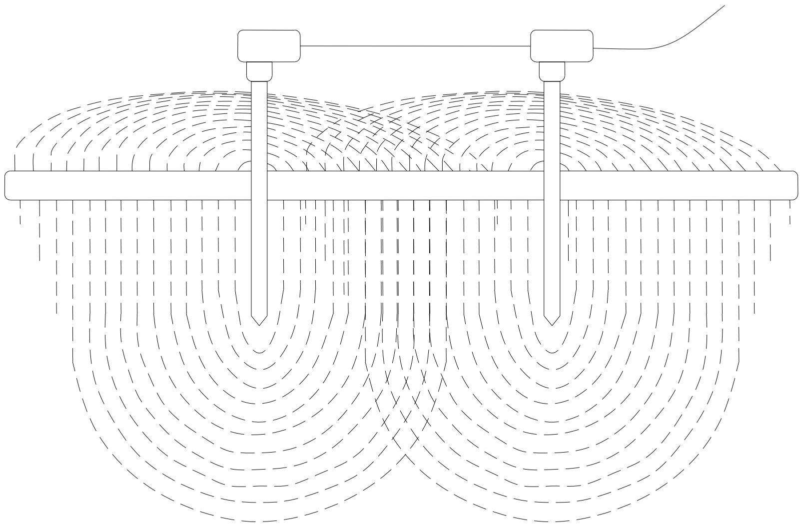


Figure 20: Multiple Electrodes Spheres of Influence

LENGTH OF ELECTRODES IN A DEFINED SPACE

As previously discussed, spacing ground rods too closely will be less effective in dissipating the current into the soil. Likewise, there is a diminishing return in value when vertical ground rods are driven too deeply. Figure 21 depicts a typical change in resistance when the electrode length is increased. The primary assumption is that the soils are nearly uniform throughout the depth of the soil profile. Initially, the increase in grounding electrode depth results in a significant reduction in ground resistance. At some point, the addition of a ground rod provides very little decrease in ground resistance.

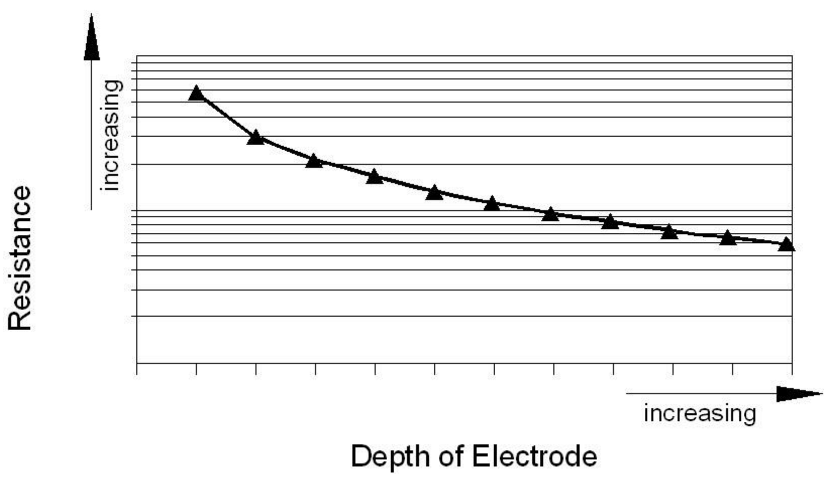


Figure 21: Resistance vs. Electrode Length in a Defined Space

NUMBER OF ELECTRODES IN A DEFINED SPACE

When two or more ground rods are well-spaced, they tend to reduce the ground resistance. Figure 22 shows a typical reduction in resistance due to multiple rods located in a given space. At some point, the addition of electrodes in a defined space will not have a significant effect in lowering the ground resistance. Once this point is reached, it will be necessary to increase the grounding system area in order to lower the ground resistance further.

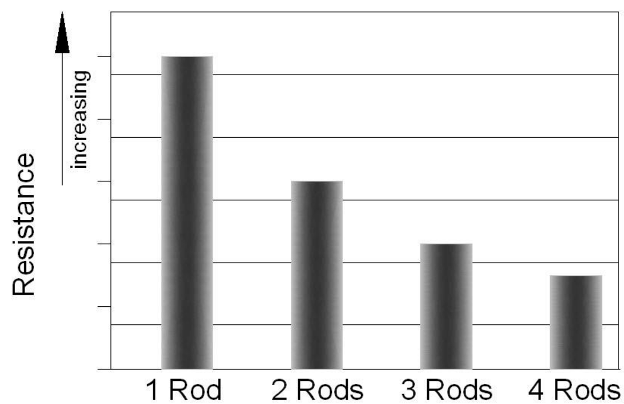


Figure 22: Resistance vs. Number of Electrodes in Defined Space

SHAPES OF ELECTRODES

For most transmission line grounding applications, the vertically driven ground rod, or some form of that, is the most common installation. Other types of grounding electrodes may be necessary, depending on site conditions. Many of these other shapes have also been studied and the configuration reduced to some type of solid spheroid shape, from long thin spheroids to short wide spheroids. Much like the equation for the vertically driven ground rod, other equations have been developed for variations from that configuration. Typical configurations that have been equated are as follows:

- Single vertical rod (Equation 5)
- Two vertical rods
- Horizontal wires
- Ring of wire
- Horizontal round plate
- Vertical round plate

For each of these configurations, equations have been developed to determine the average resistance. The equations are quite lengthy algorithms and include the relevant variables, such as length, radius, depth, separation, and so forth. Most have been incorporated into computer programs and some have required simplified assumptions.

Most of the same principles associated with vertically driven electrodes apply to the other shapes, also. Some form of concentric shells and spheres of influence are applicable as well as the concepts associated with the number of electrodes in a defined space.

In the following section, the physical properties of the electrodes commonly used in transmission line grounding applications will be described.

TYPES OF GROUNDING ELECTRODES

Transmission line grounding electrodes provide the connection to the earth for lightning strikes and phase-to-ground faults to dissipate, thus protecting the facility. Grounding electrodes are typically metal objects buried or driven into the ground which have a conductor (ground wire) connected mechanically and electrically to a transmission line structure. An electrode should be easy to install, resistant to corrosion, and should not cause galvanic corrosion to nearby metals.

Grounding electrodes consist of ground rods, ground wire (butt wraps/coils), counterpoise, grounding plates, and chemical wells. The resistance of ground electrodes is dependent upon shape, size, and soil resistivity. Lower resistances are achieved with rod, pipe, and wire electrodes, as compared to electrode plates with equivalent metal surface areas. All other factors being equal, larger electrode surface areas provide lower resistances and spreading out fault currents over larger volumes of soils provide lower resistances. The use of each of these types of electrodes follows.

Ground Rods

Vertically driven ground rods are the most common electrode. They can be driven into very hard clays or rocky soils. The grounding resistance of a vertical ground rod is inversely proportional to both the length of the rod and the ground conductivity. It is relatively independent of the rod diameter. Rather than being installed near the surface, ground rods should be extended downward as far as possible, into an area of high soil conductivity, actually reaching the water table, if achievable. Multiple ground rods, which have mutual coupling effects, may be used to establish effective grounding at individual structure locations. Some of the types of ground rods used are:

1. Copper-clad steel ground rods (steel rod coated with copper, see Figure 24);
2. Solid copper ground rods (used when better conductivity and corrosion resistance is required);
3. Stainless steel ground rods (used in corrosive soil conditions); and
4. Galvanized steel ground rods (used when cathodic protection of the structure is the primary concern, see Figure 23).

Figure 23: Typical Galvanized Steel Rod

Figure 24: Typical Copper-Clad Steel Rod

In the case of bedrock, the electrode should be driven at an angle not to exceed 45° from the vertical or shall be buried in a trench that is at least 30" deep. Typical specifications of ground rods are listed in Table 5 for a few example cases.

Table 5: Typical Specifications of Ground Rods

Material	Diameter × Rod length	Weight, lb	Application
Solid copper	5/8" × 8'	10	General
	3/4" × 10'	18	
Stainless steel	5/8” × 8'	9	For corrosive soils
	3/4" × 10'	15	
Galvanized steel	5/8" × 8'	8	Cathodic protection
	3/4" × 10'	15	

Depending on the soil conditions and application requirements, the necessary grounding rod can be selected. The available rod diameters are ⅜", ½", ⅝", ¾", and 1". The available rod lengths are 6', 8', 10', 12', and 15'.

Ground Wire

Ground wire consists of wood pole butt wraps and coils. Ground wires should only be used in areas of low soil resistivity. They usually are made from soft drawn copper or soft annealed steel which are easy to bend and form in a wrap or coil (see RUS Bulletin 1728F-810, Drawing TM-9 on Grounding Assemblies). On wood pole lines at 138 kV and above, additional ground electrodes may be necessary to achieve adequate ground resistance, since ground wires may not provide enough surface area, especially where soil resistivity is higher.

Counterpoise

In areas of soil with high resistivity, counterpoise is used when a high level of lightning protection is needed. Counterpoise electrodes can be a ground wire or a flat conductor buried horizontally below ground level and connected to the grounding system. Such horizontal conductors reduce the ground resistance of the structure footing. Grounding resistance of buried horizontal conductors is inversely proportional to the length of the wire.

They are often easier to install than a vertical rod of the same length and they are preferable from a practical point of view. The counterpoises can be arranged in different formats as dictated by local regulations. The position of the counterpoise conductor with respect to the shield conductor is shown in Figure 25. Some of the typical counterpoises used in transmission system between two towers are shown in Figure 26. These include single parallel continuous, double parallel continuous, radial, and continuous and parallel. These conductors are buried at 18" to 24" below the ground level on the transmission line right-of-way. Example counterpoise conductors are #6 buried bare copper wire or galvanized 5/16" soft annealed steel.

Radial, ring, and mesh counterpoise electrodes are susceptible to changes in soil moisture content at their typical depth. Radial and ring counterpoise grounding resistance can be improved in drier conditions by driving vertical rods to deeper depths. Mesh counterpoise can be improved in drier conditions by deeper burying of the outer ring or by driving vertical rods.

Multiple radial counterpoise electrodes have mutual coupling effects. Also, radial counterpoise electrodes longer than 200' to 300' in length have been found ineffective due to small current magnitudes beyond these lengths.

Examples of radial, ring, and mesh configurations are depicted in Figures 25 and 26.

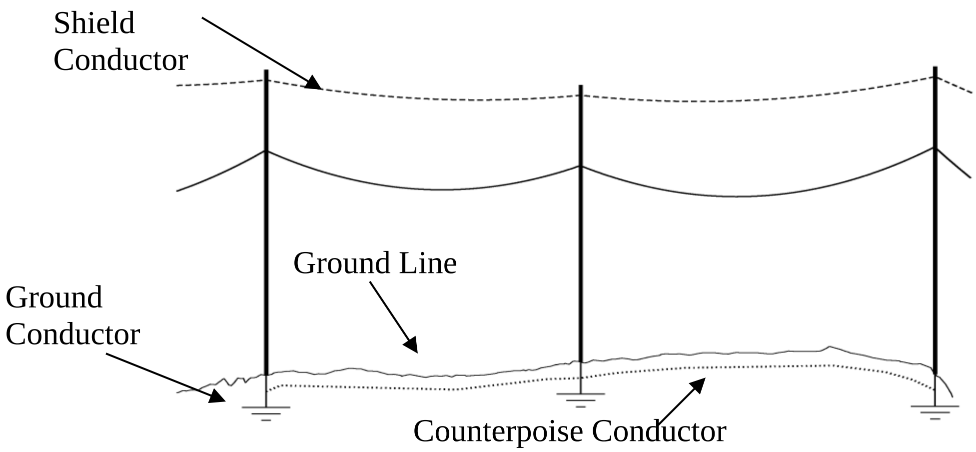


Figure 25: Position of the Counterpoise Conductor

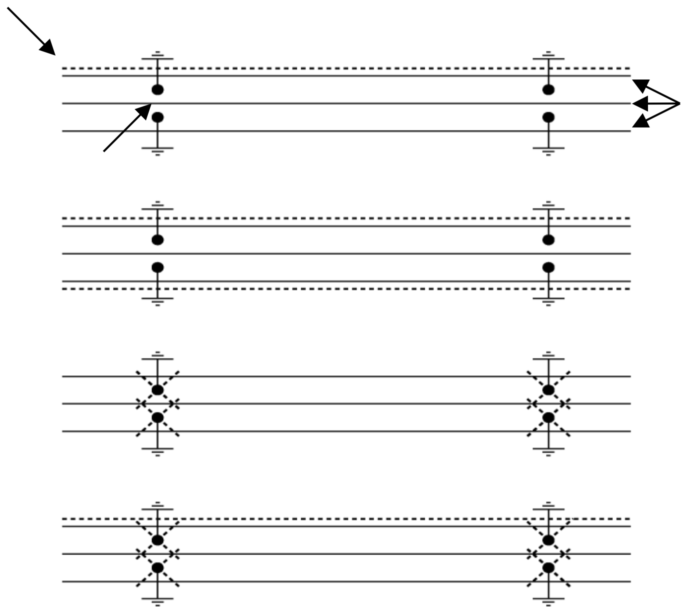


Figure 26: Example Counterpoise Conductor Configurations

Counterpoise electrodes are usually installed in radial, ring, or mesh configurations. Counterpoise electrodes can also be installed in combinations of these configurations. Radial counterpoise electrodes are generally recommended and are buried and extended in straight lines from each structure. Radial configurations include a buried horizontal wire, a right-angle-turn of wire, a three-point star, a four-point star, a six-point star, and an eight-point star. Ring counterpoise electrodes are buried in a circle around each structure. Mesh counterpoise electrodes are buried in grids to form concentric rectangular or circular rings. See Figures 27 and 28 for typical installation diagrams.

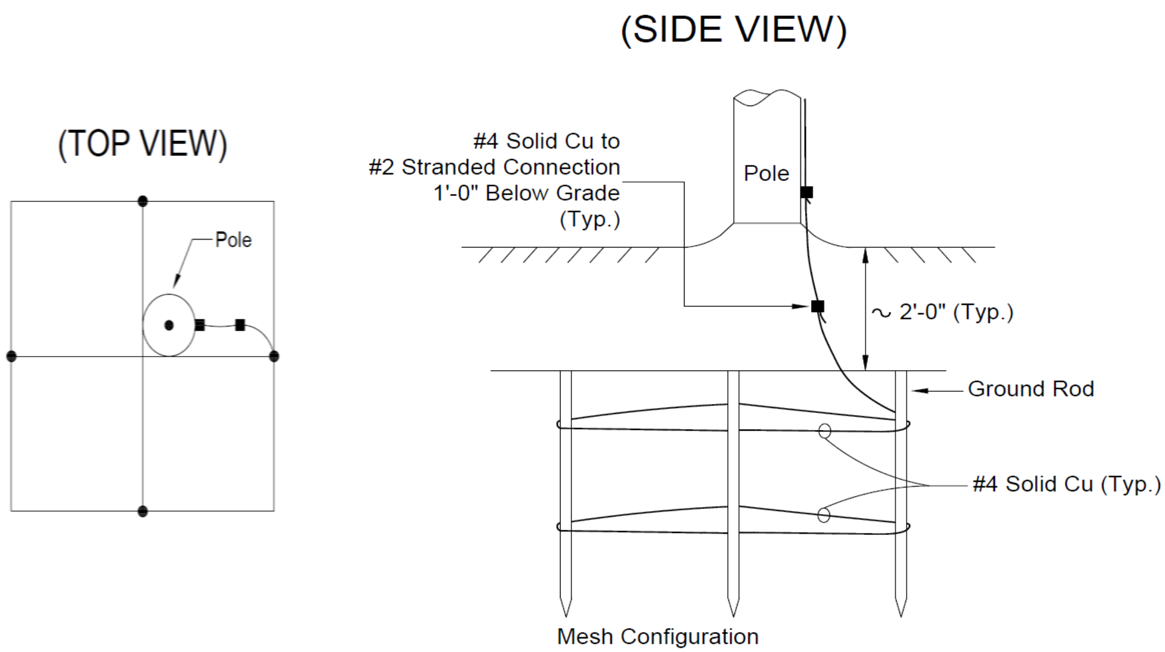


Figure 27: Mesh Ring Counterpoise Configuration

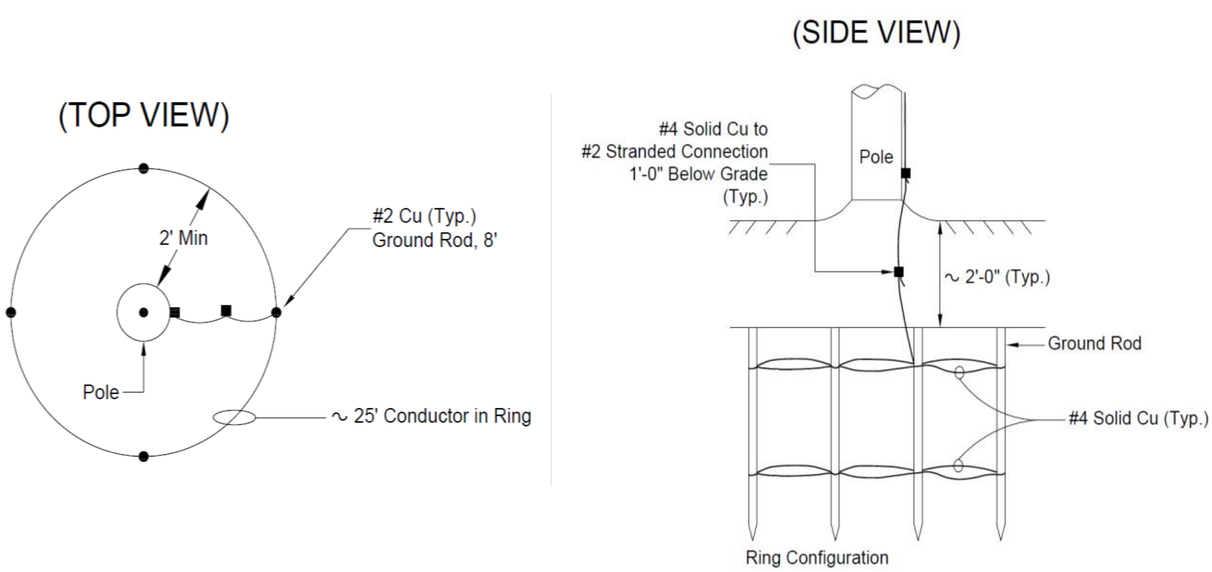


Figure 28: Ground Ring Counterpoise Configuration

Grounding Plates

Grounding plates are generally made of galvanized steel or a copper alloy. The grounding plates are usually installed in a horizontal position and are used in areas having little or no topsoil. The grounding plate can also provide a dual purpose by being used as a structure-bearing plate. Grounding plates should be metal plates or sheets not less than two feet square and not less than ¼" thick (except that nonferrous metal electrodes should not be less than 0.06" thick) and placed at a depth of not less than 5'. A typical, single-connection, copper ground plate is shown in Figure 29.

Figure 29: Copper Ground Plate

Chemical Wells

Typical chemical grounding electrodes are displayed in Figures 30 and 31. These may be installed vertically or horizontally in an L-shape. The main components are a hollow copper tube with solid connections, breather holes, and leach holes. The tube is filled with special electrolytic salts. This saline solution leaches out of the bottom of the rod, which gradually lowers resistivity of the surrounding soil, forming "electrolytic roots" over time.

The salt mixture is a combination of sodium chloride and calcium chloride or magnesium chloride. These salts must be activated by adding water, which may lower resistivity initially. However, unless water is continually added, the salts dry out over time and resistivity of the electrode goes back up. An exothermically attached conductor (tail) to the ground rod enables connection to the pole ground conductor.

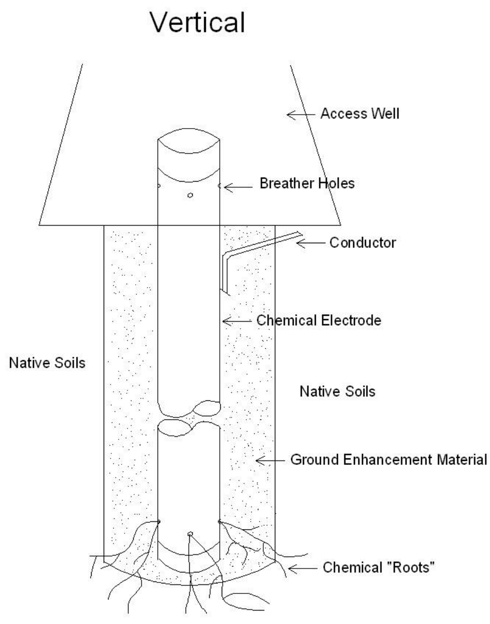


Figure 30: Vertical Chemical Grounding Electrode

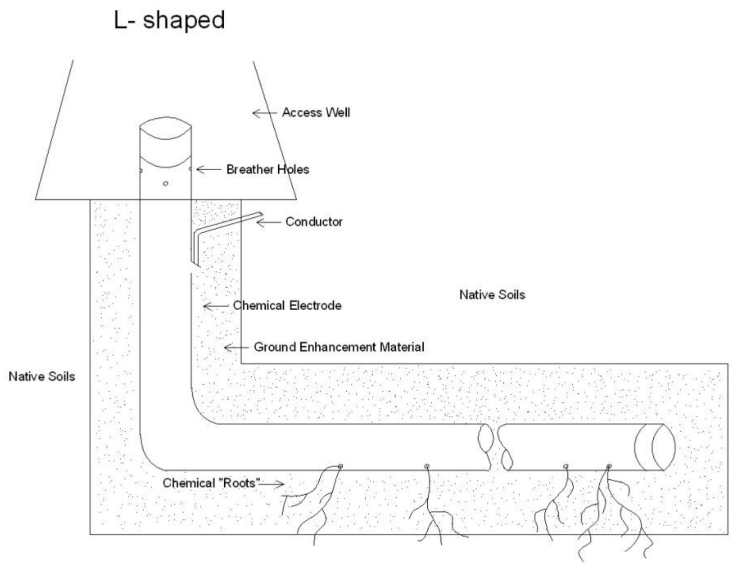


Figure 31: L-Shaped Chemical Grounding Electrode

GROUNDING CONDUCTORS AND OVERHEAD GROUND WIRES

This section covers overhead ground wires (shield wires), pole grounds, and ground leads to grounding electrodes, which provide the path to the earth for dissipating lightning strikes and phase-to-ground faults. Grounding conductors are typically made of copper, aluminum, steel, or a combination of copper and steel or aluminum and steel. Overhead ground wires (OHGW) are used to shield transmission lines from lightning and help improve substation grounding. Protection against lightning strikes requires an OHGW to prevent lightning from striking the electrical conductors. OHGW should be used in areas where the isokeraunic level is above 20. In locations where the isokeraunic level is below 20 and lightning exists, the use of OHGW will help improve the facilities' performance.

The OHGW should be placed where it provides a maximum 30° angle cone of protection for the conductors (see Figure 32). The selection of OHGW is usually based on mechanical rather than electrical considerations. OHGW are typically made of steel with a coating of galvanizing aluminum or zinc/5% aluminum/mischmetal alloy (ASTM A-855). For more physical design considerations, see RUS Bulletin 1724E-200, "Design Manual for High Voltage Transmission Lines," Chapter 9–Conductors and Overhead Ground Wires.

Types of Grounding Conductors

Copper Conductors

Copper is by far the most commonly used grounding conductor in the United States. Three kinds of copper wire are in use: hard-drawn copper, medium-hard-drawn copper, and annealed copper, also called soft-drawn. For grounding purposes, both soft-drawn and copper-clad wires are used.

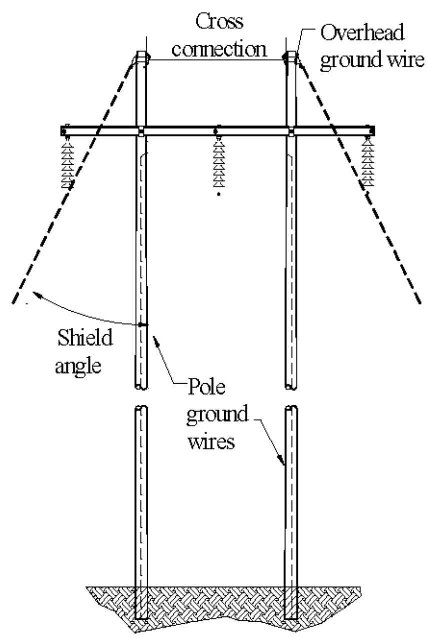


Figure 32: Shield Angle, Conductors, and OHGW

Aluminum Conductors

Aluminum is seldom used in transmission line grounding; it is not wise to bury aluminum in the ground because of possible electrolytic action. However, it is widely used for transmission line conductor applications. Its conductivity is only about two-thirds that of copper. Compared with a copper wire of the same physical size, aluminum wire has 60% of the conductivity, 45% of the tensile strength, and 33% of the weight. The aluminum wire must be 100/60, or 1.66 times as large as the copper wire in cross-section to have the same conductivity. When an aluminum conductor is stranded, the central strand is often made of steel that serves to reinforce the conductor.

Copper-Clad Steel Conductors

In this type of conductor, a protective copper coating is securely welded to the outside of the steel wire. The copper acts as a protective coating to the steel wire, thus giving the conductor approximately the same life as if it were made of solid copper. At the same time, the layer of copper greatly increases the conductivity of the steel conductor, while the steel gives it greater strength. This combination produces a satisfactory yet inexpensive line conductor. Its chief fields of application are for rural lines, guy wires, ground rods, and overhead ground wires.

Galvanized Steel Conductors

In the grounding application, the galvanized steel used is typically soft-drawn. This is because strength is less of a consideration than workability. In RUS Bulletin 1728F-810,[9] in Drawing TM-9, "Grounding Assemblies, Multiple Pole and Anchor Grounding," one of the pole grounds shown utilizes a galvanized 5/16" soft annealed iron.

Other Types of Conductors

Conductors are classified as solid or stranded. A solid conductor has a single solid wire; a stranded conductor is composed of strands of fine wire twisted together in common contact. A stranded conductor is used when the solid conductor is too large and not flexible enough to be handled readily. Large solid conductors are also easily damaged by bending. The need for mechanical flexibility usually determines whether a solid or a stranded conductor is used, and the degree of flexibility is a function of the total number of strands. The strands in the stranded conductor are usually arranged in concentric layers about a central core.

Types of Overhead Ground Wires

Galvanized Steel Wire

To make galvanized wire, the wire goes through a process where it is coated in zinc, thus giving the wire a protective coating from rust. Typically, high-strength and extra-high-strength galvanized steel are used for OHGW. The design requirements will help determine the size and which of the two is the best fit. The extra-high-strength steel is used when a reduction in sag is needed in very heavy ice loading areas or where the spans are very long.

Aluminum-Clad Steel Wire

Aluminum-clad steel wire offers the advantages of both metals. There is a wide range of properties and sizes of steel wire and thicknesses of aluminum cladding. The cross-sectional area ratio of the aluminum is designated by ASTM to be 25%. The steel provides the strength and the aluminum coating makes the steel resistant to corrosion and improves its conductivity.

[9] RUS Bulletin 1728F-810, *Electric Transmission Specifications and Drawings, 34.5 kV Through 69 kV*, 1999 (www.rurdev.usda.gov/SupportDocuments/UEP_Bulletin_1728F-810.pdf).

Zinc/5% Aluminum/Mischmetal Alloy

This is a 95% zinc, 5% mischmetal aluminum alloy that is used to coat steel wire. This OHGW has the same steel wire strength characteristics as galvanized steel and aluminum-clad. The alloy coating exceeds galvanized Class C corrosion requirements.

Optical Ground Wire

Conductor Size Determination

The conductor should be sized to handle the maximum future fault current that the grounding system could experience during an amount of time, *i.e.*, the maximum clearing time. Fault current limits can be determined by the fusing formula from IEEE Std. 80-2013, as shown in Equation 6.

Equation 6: Fusing Formula

$$A_{kcmil} = (I)\,(K_f)\,(\sqrt{t_c})$$

Where:

A = Area of the conductor in kcmil
I = rms current, kA
t_c = Fault clearing time, seconds
K_f = Material constant at the melting temperature, T_m, using ambient temperature of 40^o C (see Table 6)

Table 6: Material Constants

Material	Conductivity (%)	T_m [a] (^{o}C)	K_f
Copper, annealed soft-drawn	100.0	1083	7.00
Copper, commercial hard-drawn	97.0	1084	7.06
Copper, commercial hard-drawn	97.0	250	11.78
Copper-clad steel wire	40.0	1084	10.45
Copper-clad steel wire	30.0	1084	12.06
Copper-clad steel rod	17.0	1084	14.64
Aluminum-clad steel wire	20.3	657	17.26
Steel 1020	10.8	1510	18.39
Stainless-clad steel rod	9.8	1400	14.72
Zinc-coated steel rod	8.6	419	28.96
Stainless steel 304	2.4	1400	30.05

Example 3: Selecting a Suitable Conductor

Problem

Using the fusing formula for a 20-kA fault current and three-second fault clearing time, find a suitable conductor.

Solution

Consider soft drawn copper conductor, with $K_f = 7.0$.

$$A_{kcmil} = (20\ \text{kA})\ (7.0)\ (\sqrt{3}) = 242.5\ \text{kcmil}$$

Select a soft drawn copper conductor greater than 242.5 kcmil. You need to base your actual decision of selecting a conductor on more than just the fusing formula. Consideration should also be given to the following:

- Mechanical needs,
- Environmental concerns (corrosion),
- Factors of safety,
- Life expectancy of the system, and
- Conductor temperature.

The fusing formula can also be used to find the fusing current of a known conductor size. Rearranging Equation 6, we get:

$$I = \frac{A_{kcmil}}{K_f \sqrt{tc}}$$

This formula is based on assuming the cable and connectors are able to withstand temperatures up to cable thermal limits. This is not realistic, however, if using bolted connectors on grounding wire which have thermal annealing limits of approximately 482°F (250°C). See Table 10 for fusing values assuming 482°F (250°C) annealing thermal limit for the calculations of common grounding material based on IEEE Standard 80-2013[10] formula.

Example 4: Finding the Fusing Current Value

Problem

Find the fusing current value of a 4/0 soft drawn copper conductor. The area of the 4/0 copper conductor is 211.6 kcmil. Use a fault clearing time of 1.0 second.

[10] IEEE Standard 80-2013, *Guide for Safety in AC Substation Grounding*, pages 42-51.

Solution

$$I = \frac{211.6}{7.0\sqrt{1.0}} = 30.2 \text{ kA}$$

Thus, based on the preceding formulae and data, typical short circuit current values for copper-weld, copper, and steel conductors are presented in Table 7. The values in Table 7 are for the wire only and do not take into account melting temperatures of connectors, which may be more restrictive and limiting than the wire. The short circuit current values for other materials with different fault clearing time can be calculated using the fusing formula.

Table 7: Short-Circuit Current Values for Grounding Conductor (Amps)

AWG	Diameter inch	Area Cmil	tc = 0.1 sec	tc = 0.256 sec	tc = 0.5 sec	tc = 1 sec	tc = 1.5 sec
Copper-weld conductors							
4/0	0.4600	211600	63971	39982	28609	20229	16517
3/0	0.4096	167800	50729	31706	22687	16042	13098
2/0	0.3648	133100	40239	25149	17995	12725	10390
1/0	0.3249	105600	31925	19953	14277	10096	8243
1	0.2893	83690	25301	15813	11315	8001	6533
2	0.2576	66360	20062	12539	8972	6344	5180
3	0.2294	52620	15908	9943	7114	5031	4107
4	0.2043	41740	12619	7887	5643	3990	3258
5	0.1819	33090	10004	6252	4474	3163	2583
6	0.1620	26240	7933	4958	3548	2509	2048
Soft drawn copper conductors							
4/0	0.4600	211600	95455	59659	42689	30185	24646
3/0	0.4096	167800	75696	47310	33852	23937	19545
2/0	0.3648	133100	60043	37527	26852	18987	15503
1/0	0.3249	105600	47637	29773	21304	15064	12300
1	0.2893	83690	37753	23596	16884	11939	9748
2	0.2576	66360	29936	18710	13388	9466	7729
3	0.2294	52620	23737	14836	10616	7506	6129
4	0.2043	41740	18829	11768	8421	5954	4862
5	0.1819	33090	14927	9330	6676	4720	3854
6	0.1620	26240	11837	7398	5294	3743	3056
Steel conductors							
4/0	0.4600	211600	28694	17934	12832	9074	7409
3/0	0.4096	167800	22754	14221	10176	7196	5875
2/0	0.3648	133100	18049	11281	8072	5708	4660
1/0	0.3249	105600	14320	8950	6404	4528	3697
1	0.2893	83690	11349	7093	5075	3589	2930
2	0.2576	66360	8999	5624	4024	2846	2323
3	0.2294	52620	7135	4460	3191	2256	1842
4	0.2043	41740	5660	3538	2531	1790	1461
5	0.1819	33090	4487	2804	2007	1419	1159
6	0.1620	26240	3558	2224	1591	1125	919

Notes: (1) The data for the typical conductors used for the overhead shield conductors are presented in Tables 5.4 and 5.5. (2) Values do not include bolted connection limitations (482°F/250°C).

Table 8: Electrical Characteristics of High-Strength (HS) Conductors

Size	Rdc Ohm/mile	Rac Ohm/mile	Xi,Ohm /mile	Xc,Mohm -mile	Diameter inch
5/8	2.19	2.27	1.12	0.1083	0.621
1/2	3.44	3.57	1.24	0.115	0.495
7/16	4.45	4.62	1.33	0.1188	0.435
3/8	6.51	6.75	1.5	0.1244	0.36
5/16	9.7	10	1.8	0.139	0.3125

Table 9: Electrical Characteristics of Extra-High-Strength (EHS) Conductors

Size	Rdc Ohm/mile	Rac Ohm/mile	Xi,Ohm /mile	Xc,Mohm -mile	Diameter inch
5/8	2.26	2.32	1.08	0.1083	0.621
1/2	3.56	3.66	1.2	0.115	0.495
7/16	4.61	4.74	1.28	0.1188	0.435
3/8	6.74	6.93	1.44	0.1244	0.36

Notes for Tables 8 and 9:
Xi = Inductive reactance at one foot spacing and at 60Hz, Ohms/mile
Xc = Capacitive reactance at one foot spacing and at 60 Hz, Megohm-mile

Table 10: Maximum Allowable Fusing Currents for Copper/CWC/Steel Ground Wire

Assumption: Bolted connectors limited to 250°C, ambient temperature 40°C

AWG	Diameter Inch	Area Cmil	s= 0.1 sec 6 cycle	s= 0.25 sec 15 cycle	s= 0.50 sec 30 cycle	s= 1 sec 60 cycle
Copper-annealed soft drawn						
4/0	.4600	211,600	57.56	36.4	25.74	18.2
1/0	.3249	105,610	28.73	18.17	12.85	9.08
#4	.2043	41,850	11.38	7.20	5.09	3.60
#6	.1620	26,250	7.14	4.52	3.19	2.26
Copper-clad (CWC) 40%						
1/0	.3249	105,610	19.14	12.11	8.56	6.05
#4	.2043	41,850	7.58	4.8	3.39	2.40
#6	.1620	26,250	4.76	3.01	2.13	1.5
Zinc-coated steel rod						
7/16	.435	189,230	16.58	10.49	7.42	5.24
3/8	.360	129,600	11.36	7.18	5.08	3.59
5/16	.312	97,340	8.53	5.40	3.81	2.70

The above table is based on the following equation from IEEE 80-2013.

Equation 7: Maximum Allowable Fusing Currents[11]

$$I = 5.07 \cdot 10^{-3} A \sqrt{\left(\frac{TCAP}{s\alpha_r \rho_r}\right) \ln \left(\frac{K_0 + T_m}{K_0 + T_a}\right)}$$

Where:

I	=	Maximum fusing current (Amps)
A	=	Conductor cross section area (kcmil)
T_m	=	Maximum allowable temperature in degrees Celsius
T_α	=	Ambient Temperature in degrees Celsius
P_r	=	Resistivity of ground conductor at T_r (μΩ-cm) (Cu=1.72, CWC=4.40, Steel=20.10)
K_o	=	$1/\alpha_o$ (degree Celsius) (Cu=234, CWC=245, Steel=293)
α_r	=	Thermal coefficient of resistivity at T_r (1/°C) (Cu=.004, CWC=.004, Steel=.003)
s	=	Time of current flow in seconds
TCAP	=	Thermal capacity per unit volume (J/cm^3 × °C) (Cu=3.42, CWC=3.85, Steel=3.93)

6. INSTALLATION AND TESTING

INTRODUCTION

This section covers the essential elements involved with the installation, testing, and improvement of Transmission Line Grounding. It is intended to provide the design engineer with a basis for an elemental understanding of the issues, concepts, and methodology entailed in the grounding of transmission structures and transmission structures with underbuilt distribution.

Each application has its unique aspects; individual members have their unique standards of application representative of their regional characteristics. The design engineer must have a working understanding of the NESC and its requirements, as well as a basic understanding of the concepts of allowable step and touch voltage as defined in IEEE Std. 80-2013, *IEEE Guide for Safety in AC Substation Grounding*.

This section deals specifically with the grounding and testing of the transmission facility in its normal application as it relates to the installation of the structure grounds themselves. This guide assumes that the lines will be designed in three possible ways:

- with shield wire,
- without shield wire but with lightning arrestors, or
- with both shield wire and lightning arrestors.

[11] IEEE Standard 80-2013, Section 11.3.1, equation 38.

It addresses the specifics of the design, construction, or the testing of the structure or the construction and integrity of the conductors, shield wire, or arrestors.

Where the transmission facility is adjacent to planned substation, generation, or industrial facilities, it is understood that the design of the adjacent facilities must consider the existence of the transmission line and its underbuilt distribution facilities. Where these adjacent facilities pre-exist, it is the responsibility of the design engineer to coordinate with the facility representatives to ensure that the facilities' impact on step and touch voltages at the transmission structure has been considered.

Consideration must be given to the fact that significant current split for ground faults within substations and switchyards will occur, resulting in a percentage of the station ground fault returning to far ground via the transmission line shield wire and through distribution line neutrals. It is necessary that these structures, as well as all structures on the line, be properly grounded and that the footing resistances achieved be consistent relative to each other.

Additionally, step and touch voltage conditions will exist at the nearest structures to the stations and the structure grounds must be included in the station ground grid analysis.

See Section 4, Grounding Design Theory, for discussions relative to soil characteristics and soil resistivity testing. This section presumes that the designer has sufficient information available on the structure environment to complete adequate grounding designs for the application. Similarly, Section 5, Grounding Electrodes, and Section 7, Grounding Connectors, provide guidance on the selection of appropriate materials and solutions that will yield satisfactory grounding designs.

BASIC DESIGN CONSIDERATIONS AND ASSUMPTIONS

This section is based on the following considerations and assumptions as defined in referenced sections of this document.

1. The objective of structure grounding is to provide adequate, reliable electric service. Experience has indicated that a minimum ground impedance at the grounding location of 25 ohms, after the installation, is a good objective ground impedance, depending upon experience within the area or from the results of soil resistivity measurements in the absence of experience.

2. The lightning performance of transmission lines is strongly related to the tower footing resistance. This footing resistance has a strong bearing on back flashover rates. In cases of transmission lines traversing different soil compositions, high footing resistances for even a few structures can degrade the overall line performance.

3. This guide assumes that grounding is accomplished utilizing copper conductor and copper-weld steel ground rods. In highly corrosive environments, stainless steel rods can be used, but the design must be confirmed with experts in corrosion prevention.

4. Where cathodic corrosion due to dissimilar metals is probable, such as grounding adjacent to guy anchors, anchors must be designed with materials or coatings necessary to prevent this condition.

5. Grounding connections are made with mechanical-type bolted connections or compression connections above ground. The maximum fusing temperature for these connections is 482°F (250°C).

6. Grounding connections to ground rods and to underground cables are made with an exothermic welded connection.

7. Wood poles may be designed with wrap-around ground conductor provided ("butt-wrapped"). While this method initially contributes to adequate ground resistance, this procedure is susceptible to installation damage or, more significantly, deterioration over time when the conductor used is copper-clad steel. Where this has been used, the pole grounding (described subsequently in this guide) should be tested with the pole wrap disconnected from the rest of the ground installation, assuring that the measured ground resistance will remain over time.

8. Some uncoated, directly embedded steel poles can be self-grounded if deeply implanted. In these cases, these poles should be tested and any pole which proves to be insufficiently grounded should be grounded as described within this guide.

9. Given the above constraints, the conductor used in grounding must be large enough to prevent fusing under the maximum fault current (see Section 5).

INSTALLATION OF TEMPORARY GROUNDS

Most utility work practices require temporary grounds to be installed on conductors being worked on near the proximity to the work being completed. Below are some considerations to take into account when installing temporary grounds, although for specifics to your area please contact your local safety representative.

- Temporary ground connections should be made between pole ground and neutral or OHGW to eliminate problems with ground connections.
- Continuity of the pole ground should be checked to rule out damage due to vandalism or theft.
- Use ground attachments designed for the item you are connecting the temporary grounds to (*i.e.*, wires, angle steel, steel poles, etc.).
- Mechanically remove any protective coating/corrosion on both ends of temporary grounds to ensure proper connection.

Note: Since most temporary grounds bite into the material they are connecting to, make sure galvanized surfaces are repaired to prevent corrosion.

For poles with distribution underbuild:

- If separate distribution and transmission grounds are run on the pole, check to make sure bonding between grounds is intact.
- When grounding transmission, connect temporary ground to distribution common neutral.

GROUNDING METHODOLOGIES

Typically, footing grounding for structures without switch mechanisms will be achieved by the following successive methodology:

1. Install a crow's-foot ground rod installation.
2. Extend the crow's-foot installation by adding extensions (*i.e.*, counterpoise) parallel to the ROW.
3. Connect the grounding to adjacent structures via a counterpoise installation.

Figures 33 to 36 are typical design representations of the above sequence. It should be understood that each member has its own definition of standard installations and the above is not intended to represent a firm procedure. Historical understanding of the native terrain is essential to establishing standard grounding practices. The above is intended to be a guide to those seeking to understand the objectives and typical approaches to achieving a satisfactory grounding system for a transmission line.

Where a single structure presents grounding difficulties, a ground well may be considered, as opposed to connection to adjacent structures via counterpoise.

Where the engineer anticipates that grounding will be difficult to achieve through the length of the line, utilizing radial counterpoise at design onset should be considered.

In all cases, it must be noted that, depending on soil composition, voids can occur between the soil and the grounds, caused by variations of the rod couplers used at connection points where multisections are required. This may have an effect on the contact resistance between the rod and soil, causing higher readings that may mitigate themselves over time as soil readjusts and compacts. Similarly, soil conditions resulting from very high or very low amounts of rainfall at the time of the readings may result in very different readings over time.

Where conditions are excessively wet but not normally wet, such as after prolonged rainfall, measurement readings should note the conditions. Under these conditions, readings should be subsequently repeated under normal conditions to ensure that the ground resistance threshold of 25 ohms has been achieved.

If high readings may be attributable to dry or loose soil conditions around the ground rod stations, readings should be subsequently repeated after soil conditions have returned to normal or compacted to ensure that the ground resistance threshold of 25 ohms has been achieved. Significant variances in footing resistances should be avoided to the extent practical, since that condition can affect back flashover performance. It is imperative that both soil and moisture conditions be noted and reported to the engineer at the time of the resistance readings; the engineer should determine whether return readings are necessary before considering the installation of additional grounding.

The following describes normal expectations.

Normal, Full ROW Applications

Normal, full right-of-way (ROW) applications are where:

1. the structures are located in the center of the ROW, and
2. the ROW is of sufficient width, with available room for normal grounding installation.

For these applications, single-pole structures would typically be grounded employing the installation of a “crow’s foot” ground conductor connection from the bottom grounding pad to a ground rod station (*i.e.*, the center of the crow’s foot). This would be located approximately 10' from the pole foundation along the centerline for a single pole or located approximately 10' from the center of the ground conductor connecting multiple poles measured at a 90° angle to this conductor.

The depth of the rods at each ground rod station is a function of local experience and typically consists of one to three rods at a depth of 10' or more (*i.e.*, an 8' rod buried 2' below grade). If it is not possible to drive the first rod to a sufficient depth to achieve the desired resistance (*i.e.*, 25 ohms), then either reattempt the station at another location at least 5' away or install a crow’s foot. The objective is to drive the rod or rods to a depth that provides acceptable resistivity.

The crow’s foot is completed by extending four grounding conductors at 45°, 135°, 225°, and 315° (*i.e.*, in an “X” pattern, see Figure 33) extending from the ground rod station to 5' inside the ROW edge. Each grounding-conductor extension will include a ground rod. In cases where a narrow ROW is being utilized, the extension angles may be narrowed accordingly. Again, if it is not possible to drive rods to a sufficient depth to achieve the desire resistance, take actions as described in the preceding paragraph.

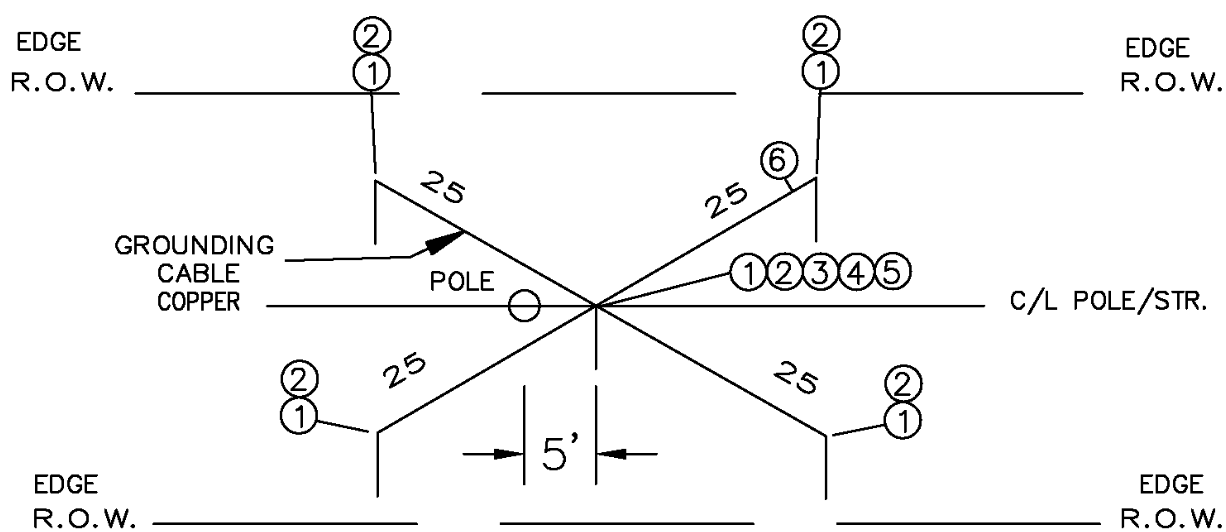


Figure 33: Crow’s Foot Ground Conductor Connection

Should the installation not achieve a 25 ohm or less reading, up to four 75' extensions are then added to each leg of the crow's foot (parallel to the ROW) and a ground rod driven at the end of each extension. Should this subsequent installation fail to achieve the 25 ohm reading, all readings should be recorded and final resolution of additional remedies—which may include the installation of counterpoise—should be determined by the engineer.

Limited ROW or Multistructure Applications

Typically, structures may be grounded by installing a ground conductor along the centerline in one direction (ahead or back) or by installing ground conductors in both directions (ahead and back). Typically, ground conductors are installed in increments (*e.g.*, 75' or less), first in one direction along the centerline and, if the desired resistance is not achieved, installing another along the centerline in the other direction. These ground conductors are then extended if necessary (to a maximum overall length of 225') to achieve the desired resistance measurement. Please refer to Figure 34.

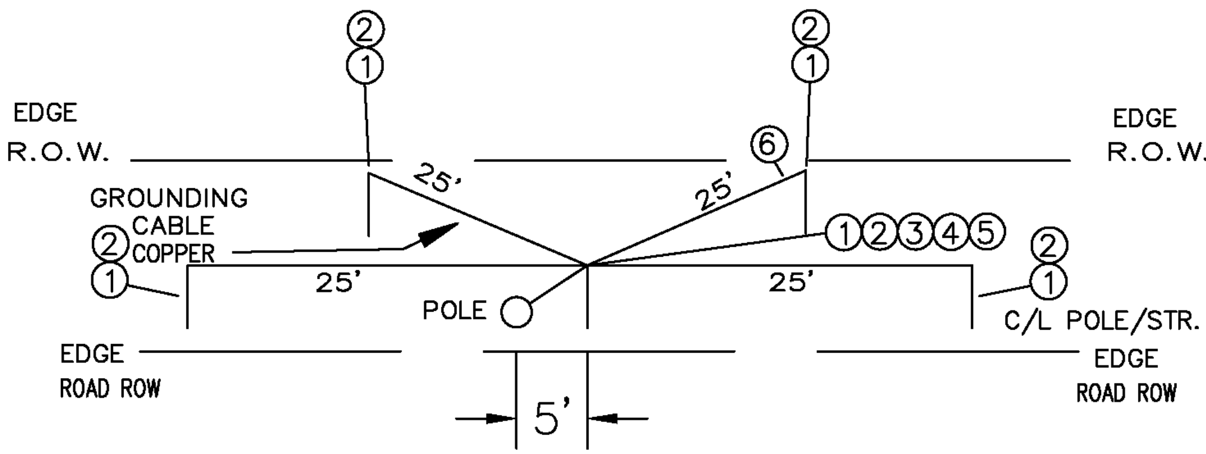


Figure 34: A Limited ROW Ground Conductor Application

Where Achieving 25 Ohm Measurements is Unlikely

For extreme ROW restricted areas (such as angle locations) or areas where resistivity measurements indicate that achieving 25 ohms is unlikely, a single ground well may be installed. This can be accomplished by drilling an approximately 7" diameter core to a sufficient depth or to where ground water is encountered. This core is then back filled with bentonite or a bentonite equivalent. The ground rod is driven in the center of the core. Refer to Figure 35.

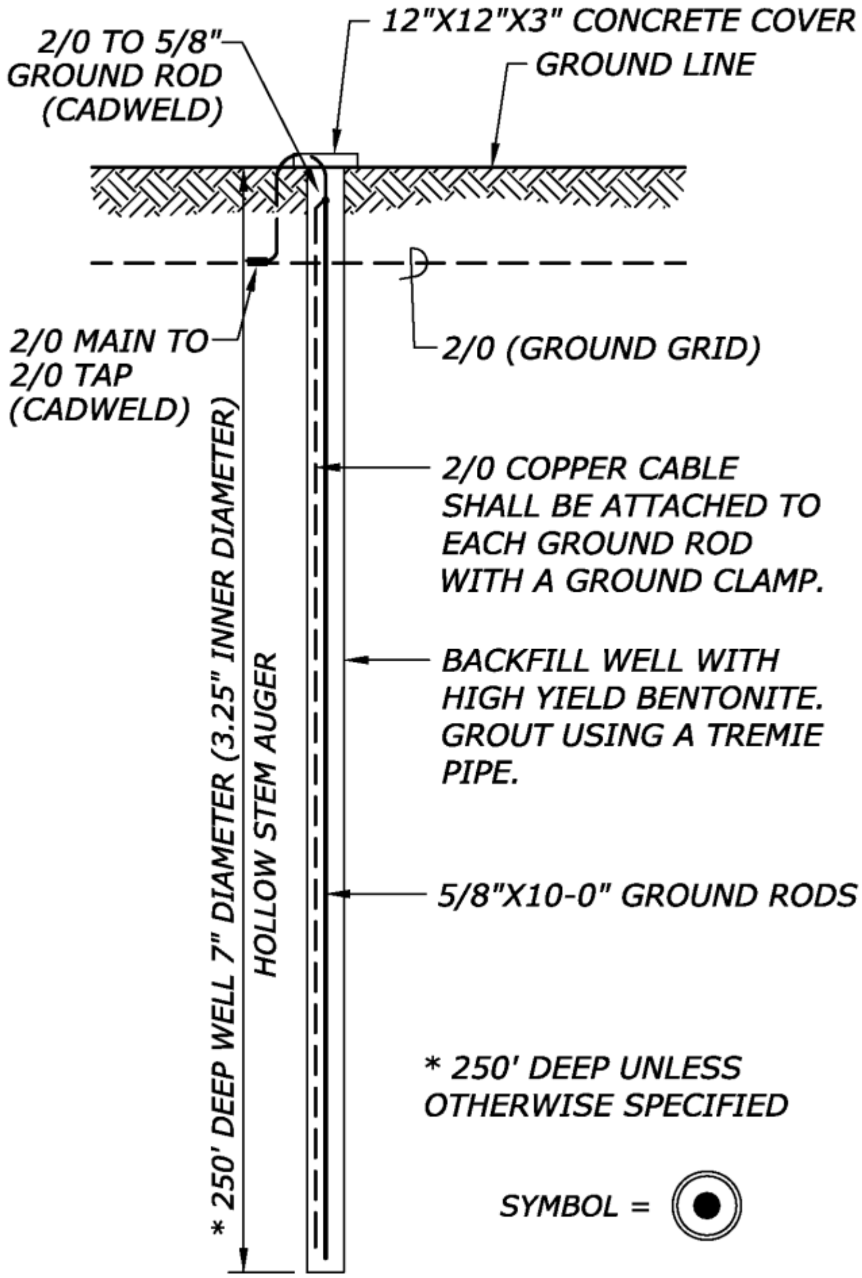


Figure 35: Ground Well

Alternatively, counterpoise can be installed to one or both of adjacent structures. Refer to Figure 36. This consists of installing ground conductors between poles at a minimum depth of 24". Ground rods are generally installed every 75' along the run.

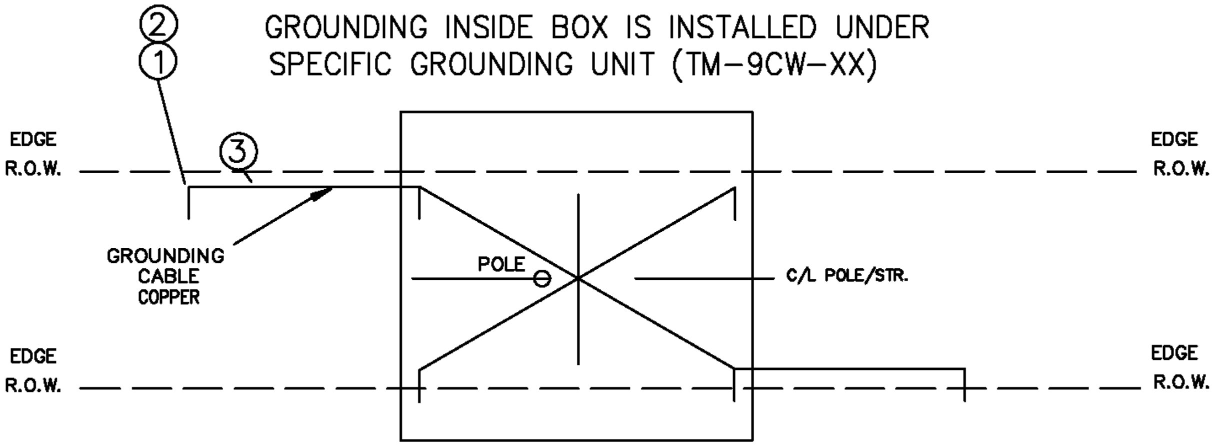


Figure 36: Counterpoise

GROUND RESISTANCE MEASUREMENT

The ground electrode resistance has to be checked periodically in order to ensure adequate grounding. Some of the methods available for the ground resistance measurement are the fall-of-potential method, simplified fall-of-potential method (62% rule), and the digital methods. The clamp-on method and the digital ground resistance tester are commonly used methods.

Clamp-On Method

Ground testers of the clamp-on style have been available since the 1980s. Clamp-on jaws contain both voltage and current windings. They can be clamped over a grounding conductor and will inject a test current into the system. The current travels through the soil, seeks its own return through a parallel ground, and loops back through the system neutral. The voltage transformer senses the voltage drop around the loop and the tester calculates resistance. An oscillator produces a distinctive frequency and filters help suppress interference. The resultant measurement is a series resistance, which should be comprised almost entirely of the contribution from the soil.

The method also simultaneously checks the bonding of grounding conductors, so that an open or corroded bond would show up in a high measurement. A typical clamp-on meter suitable for a ground resistance test is shown in Figure 37. This method is useful on underbuild distribution systems where the ground lead cannot be disconnected from the structure. Any measured resistance above 25 ohms indicates a ground problem such as

Figure 37: Typical Clamp-On Meter for Ground Resistance Measurement

(Courtesy of AEMC; Model 6417)

dried soil, ground rod problem, or open circuit. Measured resistance below 25 ohms indicates acceptable value and has to be compared with previous records.

Digital Ground Resistance Tester

The digital ground resistance tester is designed for measuring very low resistance on large grounding systems, such as ground grids and ground mats. A typical digital ground resistance tester is shown in Figure 38. It rejects high levels of interference voltages at DC or 60 Hz and its harmonics, and can be used under difficult conditions, such as high stray currents or excessive auxiliary electrode resistance. The important features of typical equipment are:

- Fall-of-potential method measures ground resistance and soil resistivity (4-point).
- Step voltage tests and touch potential measurements.
- Selectable: multiple test current and resistance ranges.
- Measures very low resistance on large grounding systems and grids.
- High test current also enables geological surveys.
- Large LCD display for easy reading.
- Display includes indicators for excess stray current, high stray voltage, high auxiliary rod resistance, and fault connection.
- Step or touch voltage levels under true fault conditions can be determined by injecting a simulated low-level fault into the electrical system.

Ground Current Measurements

Steel structures are used in transmission systems for supporting the conductors. These structures are grounded in order to provide personnel safety. If there are multiple voltage sources, or if the structures do not have adequate grounding (smaller ground conductor, pressure type connection to ground rod, inadequate ground grid, or corroded ground rod), then there will be some current flow on a continuous basis. Such a current can be measured using a clamp-on current sensor as shown in Figure 39. This approach can be used when there is enough extra grounding conductor to clamp the jaw just above the bonded location. If the ground rod and the ground conductor are bonded rigidly without any room to mount the claw, a temporary jumper has to be installed to make a measurement.

Figure 38: Digital Ground Resistance Tester

(Courtesy of AEMC; Model 6417)

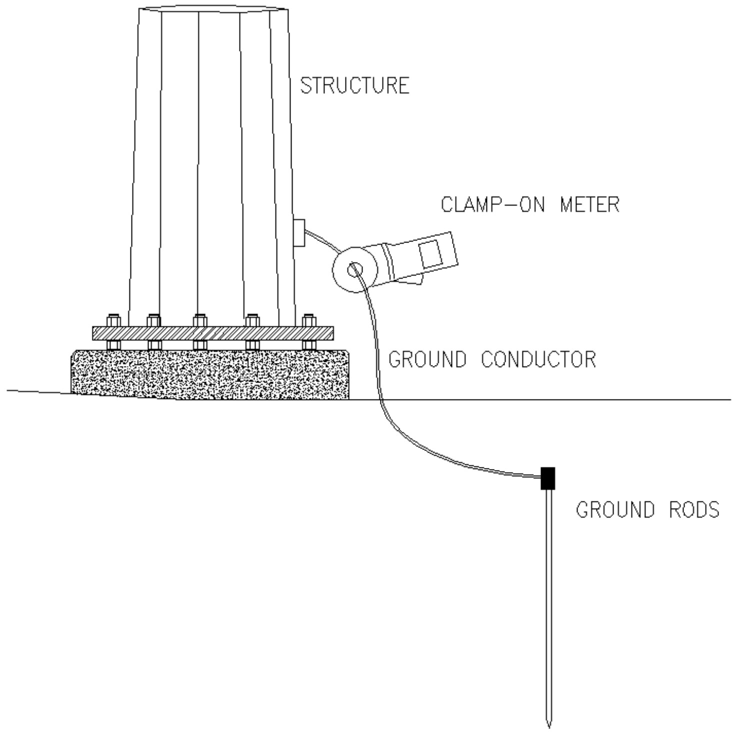


Figure 39: Measuring the Ground Current at a Structure Location

A measured current of a few milliamperes indicates a balanced three-phase system. A measurement on the order of a few amperes indicates a system with some imbalance or harmonics in the system. A measurement on the order of hundreds of amperes indicates significant problems in the three-phase system.

Touch Voltage Measurements

Using a suitable digital multimeter, the touch voltage on equipment can be measured with respect to the ground. For very accurate measurements, the digital ground resistance tester can be used.

CONCLUSIONS

The Wenner method is used for soil resistivity measurement. The best approaches for the measurement of ground resistance are the clamp-on method and the digital ground resistance tester.

The digital ground resistance tester can be used to measure soil resistivity, ground electrode resistance, touch voltage, step voltage, and ground currents. The range of values expected in the soil resistivity, ground resistance, and ground current measurements are indicated by the device. The maintenance-related measurements are to be taken every four to six months based on the industry standards but depend on the specific utility practice.

7. GROUNDING CONNECTORS

The connections between the grounding conductor and the overhead ground wire, the ground rod, counterpoise, or anchor are as important as the grounding conductors themselves in maintaining a permanent, low-resistance path to ground. The grounding conductor can be either an internal ground wire, external ground wire, or the structure itself in the case of conductive materials such as steel poles and lattice towers.

When considering the type of connector, you must consider the type of bond connection, temperature limits, and the location of the connector (*i.e.*, above or below ground).

Mechanical, pressure-type connections (bolted, compression, and wedge) are most frequently used for the overhead ground wire, metal hardware, insulator bases, wood davit arm bases, or connectors to ground rods, counterpoise, or anchor rods. Pressure-type connections produce a mechanical bond between conductors and connectors by holding the conductors in place or squeezing them together. This provides surface-to-surface contact with the exposed strands.

Exothermically welded type connectors, while used in substations, are not typically used in overhead transmission line construction. The exothermic process fuses the conductor ends together to form a molecular bond between all strands of the conductor.

Temperature limits are important considerations for connector selection. How effectively a connection carries current indicates how well it will maintain low resistance. IEEE Standard 80-2013 rates the maximum allowable temperature limits for both pressure-type and welded connections. IEEE Standard 837-2014 gives additional information.

TYPES OF COMMON CONNECTORS USED ON OVERHEAD TRANSMISSION LINES

Clamps to Ground Rods

A universal ground rod clamp can be manufactured of bronze, stainless steel, malleable iron, or galvanized (see Figure 40). These types of connectors are readily available for ⅜", ½", ⅝", and ¾" ground rods. They develop a high-pressure contact between the rod and the grounding wire and have the advantage of being easily disconnected when it is desired to measure resistance of the ground.

Figure 40: Bronze Hex-Head Ground Rod Clamp

Another type of ground rod clamps are parallel groove clamps. This clamp can be made with ⅜" or 7/16" silicon bronze bolt, nuts, and lockwashers and a high copper content alloy body. It can also be made as a hot dipped galvanized 7/16" U-bolt and a galvanized drop-forged clamping piece. The clamping piece is made to accommodate up to three ground wires to connect to ground rods (⅝" and ¾"), or anchor rods (¾" and 1").

The direct burial ground rod clamps are usually all bronze/noncorrosive-copper alloy and are used on copper-clad ground rods. The benefits of this type of connector are that they are low-resistance, easy to install, and make a secure compression connection.

Clamps to Hardware

Metal hardware should be grounded to avoid a difference in potential between the metal hardware and the pole ground wire for wood, concrete, or fiberglass poles. Because the metal hardware is galvanized, the common method of grounding is using a galvanized clamp designed to accommodate a ground wire. It is usually attached to the hardware using the mounting bolts of the hardware. One common way to achieve grounding of hardware is seen in Figure 41. The clamp is held firmly in place with spring lockwashers and/or locknuts.

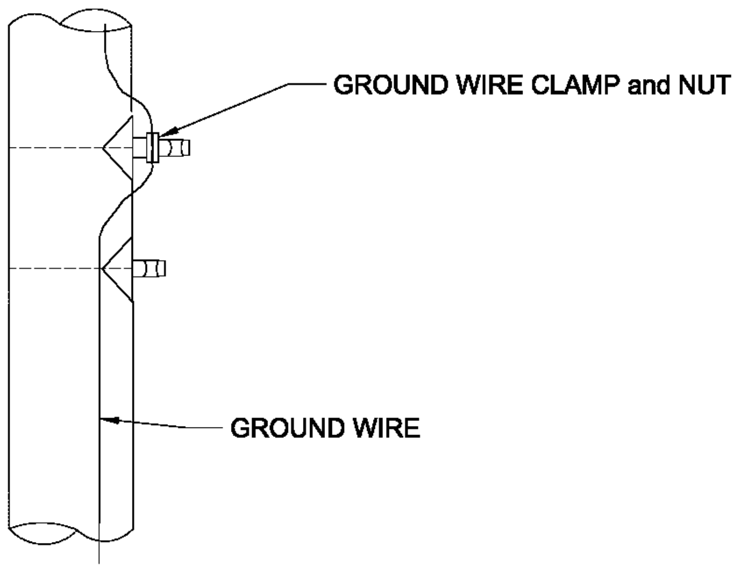


Figure 41: Ground Wire to Hardware

In the case of metal davit arms or the metal bases of horizontal post insulator construction, grounding using the mounting bolts is possible, or else grounding is achieved via a ground connector on the bases connected to the pole ground by a ground lead.

Grounding of the Guy Wire

In the case of guy attachments, the guy wire is sometimes grounded directly by a lead from the guy wire to the pole ground wire. In other instances, the guy wire is grounded at the pole by using the mounting bolt. In these instances, the connector on the bolt should be to the bolt in tension. The lead goes from this connector to the pole ground wire, and is attached to the pole ground wire via connector.

At the other end of the guy wire is the anchor. In the case of transmission lines, the guy wire should remain taut and is considered to maintain a positive electrical contact to the anchor rod, providing for an adequate ground. Many installations, however, will use a connector to make sure the ground rod and guy wire maintain positive contact. This is especially true for any guy in which the wire may become slack. There are several ways to make sure the guy wire maintains a proper connection to the anchor.

One method is to bond a jumper to both the anchor and to the guy wire using either a mechanical clamp or a compression style connector. Another method is to clamp the grip to the anchor eye or use an expansion wedge to maintain contact between the anchor and the guy.

OPGW Grounding

Optical ground wire (OPGW) combines the roles of shielding, grounding, and communications. An OPGW consists of a tubular cylinder central core containing a number of optical fibers for high-speed communications that is surrounded by layers of aluminum clad and aluminum alloy wire. Manufacturers have different ways of enclosing the fibers. The outer layers protect the fibers from lightning strikes and satisfy the strength and fault current requirements. It is very important to calculate the maximum fault current and the duration of the fault when selecting the size of the OPGW. The fault current and lightning resistance performance is also dependent upon the aluminum and cross-sectional area. OPGWs are typically rated using the maximum I^2t value.

The pictures in Figure 42 show the grounding connections of an OPGW which was added to an existing transmission line wood pole and a wood pole with a steel bayonet.

Figure 42: Optical Ground Wire Grounding Connections

GROUNDING OF CONCRETE POLES

Prestressed concrete poles are made with steel reinforcement inside the concrete. All internal reinforcing should be bonded electrically to the external pole ground wire. This will lower the potential voltage differences between the external ground and internal reinforcement during lightning events. There have been cases reported of step lugs and other materials embedded in the concrete—that were near or in contact with the reinforcing—being dislodged by lightning.

A minimum of one longitudinal steel strand should be bonded electrically to a threaded bronze insert at the top and bottom of the pole (see Figure 43). Each bond should be located within the top two feet of the pole and at one foot below groundline.

Spliced poles should have reinforcing on each side of the splice, bonded electrically to the external pole ground wire. This should lower potential voltage differences of the steel reinforcement between each pole section. This is typically accomplished using a bronze insert within 24 inches of the splice on each pole section.

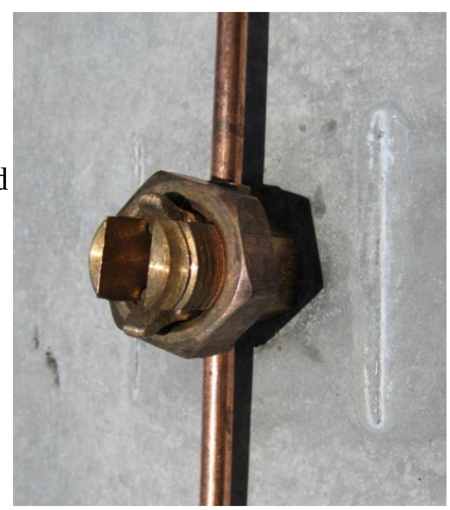


Figure 43: Grounding Lug Bonded to Internal Steel Reinforcement

CONCLUSION

The selection of the type of grounding connector will depend on wire size, rod size, type of ground wire and ground rod or anchor rod, location of the connector, application, and ease of installation. In most instances, a galvanized connector should be used with either a galvanized iron ground wire and galvanized ground rod or anchor rod.

Bronze or copper connectors are used with copper-clad ground wires and ground rods or anchor rods. Using similar metals for the connector as the ground wire and ground rod reduces the possibility of galvanic corrosion. Whenever there may be a question of vandalism, compression connectors are useful.

8. JOINT POLE USE

Joint pole use between the transmission owner and the distribution system has a number of challenges. One of the issues with joint pole use includes lineworkers climbing near the distribution system to maintain the transmission lines. The distribution provider may drop the neutral on the pole, causing a potential fatal path through the lineworker if he or she makes contact with the phase wire while climbing past the neutral wire. The RUS prefers the neutral to be on the cross arm to mitigate this danger, with a clearly marked label "CN" for common neutral so line personnel will know this is not an energized phase conductor.

Another issue the transmission line designer will need to address is the addition of other equipment to the pole, which will also limit climbing as well as increase the structural loads. The additional equipment will also need to be properly grounded, per NESC Rules 93C7 and 96C.

Rural electric distribution systems which use effectively grounded neutrals are considered multigrounded systems. The 2023 edition of the NESC[12] defines "effectively grounded" and "multigrounded system" as follows:

- **Effectively Grounded.** "Bonded to an effectively grounded neutral conductor or to a grounding system designed to limit the likelihood of hazards to persons and having resistances to ground low enough to permit prompt operation of circuit protective devices," *i.e.*, a system grounded with a low enough impedance to prevent dangerous voltages from building up during a ground fault.
- **Multigrounded/Multiple Grounded System**. "A system of conductors in which a neutral conductor is intentionally grounded solidly at specified intervals. A multigrounded system may or may not be effectively grounded."

The ground wire for the transmission provider is designed to protect the transmission circuit from a lightning event. The distribution provider, however, is concerned with using the ground wire to serve as one of the four grounds per mile required by the National Electrical Safety Code to be the return path of 1/5 of the current flow from the phase wire for a multigrounded system

[12] IEEE National Electrical Safety Code, C2-2023, pages 9 and 13

(see NESC Rules 93C2 and 96C). The system grounding conductors must have continuous total ampacities at each ground location of not less than 1/5 that of the conductors to which they are attached (see NESC Rule 93C). The pole ground wire size should be able to withstand this fault current without melting or damaging the conductor or melting the insulation, if provided. (See Table 11.)

Table 11: Neutral and Grounding Conductor Ampacities

Grounding Conductor	Grounding Conductor Ampacity*	5 Times the Ground Wire Ampacity for Neutral Conductor Capacity
#6 Cu	124 amps	620 amps
#4 Cu	155 amps	775 amps
#2 Cu	209 amps	1,045 amps
1/0 Cu	282 amps	1,410 amps
#6 CWC	140 amps**	700 amps
#4 CWC	180 amps**	900 amps
#2 CWC	240 amps**	1,200 amps

**Taken from Table 310.21 of the 2023 NEC for Cu bare wire based on 104°F (40°C) ambient and 2 ft/sec wind*

***Copperweld (copper) Conductor (CWC) ampacity values taken with permission from Southwire[13] catalog based on 77°F (25°C) ambient temperature, 2 ft/sec wind speed, and 167°F (75°C) conductor temperature. Different options available for each conductor size may affect these values slightly.*

Ideally, for a balanced three-phase system, the neutral current should be zero; however, distribution systems typically have unbalanced loading, which will result in neutral current flow. Other sources of current flow in a ground wire will result from lightning arresters attached to distribution equipment, which will have some current leakage. NESC Rule 93C4 requires a minimum grounding conductor of #6 copper or #4 aluminum for this application.

Typical installations with underbuild utilize a single pole ground wire and is effective as long as the ground wire is properly sized for the application. If separate pole ground wires are used, make sure they are both bonded at the neutral location on the pole, to prevent both pole damage due to lightning strikes and voltage potential between the wires, resulting in safety concerns of personnel climbing the pole. The neutral shall be bonded to the pole ground wire at the neutral location with proper connectors. Consider using similar grounding materials to reduce the possibility of galvanic corrosion. The NESC doesn't specify to connect or not connect the transmission line shield wire to a distribution neutral and either method is acceptable as long as both systems are meeting the multigrounding and effective grounding requirements.[14] A communication system ground on a joint use structure, however, is required to be bonded with the electric supply grounding system (see NESC Rule 97G).

[13] Southwire Overhead Conductor Manual Table 1-40 page 1.92

[14] Allen L. Clapp, "A Discussion of the National Electrical Safety Code," *NESC Handbook*, fifth edition. Page 66

In some rural areas, a neutral isolator can be used (at a transformer location) to separate the primary neutral from the secondary neutral due to stray voltage concerns. In this instance, the primary ground wire will need to be separated from the secondary ground wire, with one or both of the ground wires insulated at 600 volts to prevent contact between the neutrals. This is done to prevent neutral-to-earth potentials from impacting farm animals when no other option is available. Separate ground rods will need to be a minimum of 6 feet apart, per NESC Rule 97D2. This minimal distance is required to prevent the influence of current from the primary system to the secondary system.

NESC Rule 94C3a states that butt wrap plates (used typically on transmission structures) are considered one-half of a driven rod. When planning circuit underbuild, the designer will need to consider four full grounds per mile and also a driven rod at a transformer or other equipment locations, per NESC Rules 93 and 94C3a.

The ground rod dimension must not be less than a minimum length of 8' and a diameter not less than 0.5" if copper or copper-clad (Rule 94C2a2). If additional grounding is required, a method of adding rods in parallel will require the additional rods to be installed a minimum of 6' away from the first rod (see NESC Rule 94C2a(2)). Other methods involve adding sectional rods deeper to meet the desired ohm readings.

Lightning on a shielded transmission line can cause a backflash to the lowest conductor due to poor grounding conditions. If the transmission line is in sandy or rocky areas with a ground resistance greater than 10 ohms, the underbuild will likely flashover during a lightning event. Mitigation techniques include adding lightning arresters to both the underbuild circuit as well as the transmission line circuit; however, this is an expensive solution. On an unshielded transmission line, lightning arresters can be applied to all the phases, which will result in a backflash again to the underbuild.

NESC rules applying to grounding for joint use:

- Section 9—Grounding methods for electric supply and communication facilities
    - Rule 092—Point of connection of grounding conductor
    - Rule 093—Grounding conductor and means of connection
    - Rule 094—Grounding electrodes
    - Rule 095—Method of connection to electrode
    - Rule 096—Ground resistance requirements
    - Rule 097—Separation of grounding conductors
    - Rule 099—Additional requirements for grounding and bonding of communication apparatus
- Guys should be typically bonded to pole grounds and neutrals (Rules 92C and 93C5).
- Corrosion near substations and potential lightning damage for rock anchor applications may be situations where the pole grounds and neutrals should be separated or grounded differently.
- Equipment on a pole must be properly bonded to the grounding wire through a suitable lug or terminal (Rules 92B and 93C5).
- Steel poles need to provide a grounding connection (NEMA pad or lug) to the neutral conductor and guy wires (Rule 93).

- Usually a ground wire is attached to the climbing clips down a concrete pole to a driven ground rod. See Section 7 of this Guide on methods of grounding concrete poles.

When communications facilities are underbuilt on transmission systems, the following should be considered:

- Messengers need to be bonded to the pole ground.
- If the messenger is not large enough to be effectively grounded, use ground rods eight per mile instead of four per mile (Rule 354D3).
- Messenger must be bonded to guys and pole ground at crossing structures (Rule 92C3b).

9. MAINTENANCE CONSIDERATIONS

INSPECTION AND MAINTENANCE

A well-established transmission line maintenance and inspection program must include grounding as part of the scope. In addition to preventing damage from fault currents, a properly functioning grounding system is essential to the safety of operations personnel who may be working on or near the transmission lines. A typical inspection program should include the following, with localized variation for geographical conditions, structure types, and previous history of problems.

Foot Patrols

- **Visual inspection of ground conductors and ground connections.** Check the physical continuity of the conductor, paying special attention to broken or kinked conductors, especially at eye or ground level. Although foot patrols limit the ability to identify issues at the upper levels of the structure, they can provide a general indication of the overall condition of connections and conductor integrity. The use of binoculars is highly recommended to help with upper-level inspections.
- **Concrete poles.** Check clamps for sharp edges, cracks, splits, or other defects, and check if clamps and other connections are tight. Also check below-grade grounds, especially if evidence of concrete blow-out is found.
- **Wood poles.** Check for loose staples; repair and replace as needed (see below).
- **Steel poles.** Check ground-level connections on NEMA pads or stainless steel pad on a COR-TEN® steel pole.

Noise and Loose Hardware

- For transmission lines, the main causes of noise and static are loose hardware and corona. Corona is caused by sharp conductor or hardware edges, or the conductor may be undersized for the voltage level of the line. Loose connections found on shield wire or conductors/grounds can cause radio static or TV interference. If a connection is loose, the static discharge (arcing) will occur between the conductor and fitting or between hardware bolts and body of the hardware. Hardware that is loose and causing static arcing will have corrosion or pitting and/or will be darkened from the ionized material. Good construction methods, hardware tightening, and proper hardware selection are the best defenses for static noise.

- Loose hardware on pole grounds can also cause pole fires. As poles age, they can dry and shrink, loosening the staples. Using longer staples and staples with barbs can help eliminate loose ground wires. Compression hardware can be used in place of bolted hardware to eliminate troublesome fittings.

Climbing/Bucket Truck Inspections

- **Above Ground Inspection.** Although this type of inspection can be very labor-intensive, it also offers the ability for up-close observation and repair of above ground problems, including damage or wear of all components and connections at the shield wire. Depending on bucket truck height (relative to the height of the structure) and the slope of the terrain, locating the bucket truck perpendicular to the structure will allow the best vantage point for inspection.

Other Inspection Methods/Considerations

- **Drone, Helicopter, Fixed Wing Aircraft , or UAV (Unmanned Aerial Vehicle) Inspections.** This type of inspection has increased in popularity of late as imaging technology has improved to the point where very detailed examinations of structure are possible along the entire length of a transmission line. Similar to bucket truck inspections, this method will also allow a detailed examination of hardware and assemblies at the top of the structure and is especially well-suited for finding broken or damaged bonding at the shield wire, with the added advantage of not exposing personnel to potential safety hazards.
- **Inspection Using Infrared Camera.** Thermography is the use of an infrared imaging and measurement camera to see and measure thermal energy emitted from an object. The higher the object's temperature, the greater the heat radiation, providing an indication of incipient failure if the contrast with a normal operating temperature is significantly higher. The infrared camera can be used to inspect overhead conductors, leads, and other mechanical connections in real time to locate hot spots.

  Poor grounding connections will generally be difficult to spot using this method, but, if a hot spot is located, corrective action can be taken before a full failure. Summer or winter peak load periods are usually the best time to schedule these inspections, as operating conditions during this timeframe stress the transmission system and the differential resolution between operating temperatures and ambient temperatures will help highlight problem areas.
- **Corrosion of Ground Rods.** The earth's resistance is by far the major component of resistance in a grounding system. From an electrical standpoint, galvanized and copper-clad rods are nearly identical. However, an installed ground rod should resist corrosion well enough to provide a sufficient metallic cross-section throughout its anticipated life. If the ground rod appears to be in poor condition, further testing should be performed to verify it has not deteriorated to the point where it is no longer functioning properly.
- **When to Increase Inspections.** Obviously, if you start having an increased number of flashovers in a particular area, you should increase the frequency of inspections there. Broken or kinked grounding conductors above what might be expected for the age of the

line would also be an indication of the need for more frequent inspections. When commodity prices for copper increases, copper theft (by removing grounds) will unfortunately also be likely to increase. Numerous instances in a close proximity can indicate a problem that should be monitored. One option to deal with this issue would be to replace standard copper wire grounds with a ground wire called a copperweld ground. In addition to providing an increased measure of fatigue prevention due to the presence of steel, these grounds are much more difficult to remove and are essentially worthless to a recycling company.

MAINTENANCE SCHEDULE

A periodic inspection of the grounding system on transmission lines will pay a future dividend in preventing failures and reducing outage time when storms or other events occur. An annual inspection is a good overall benchmark, especially if the transmission line is exposed to a wide variety of weather or other environmental conditions, but higher voltage or system critical lines may require more frequent and/or more detailed inspections. In coastal areas or localized areas with high amounts of contaminants that degrade hardware quickly, a more frequent inspection may be needed. In other areas such as mountainous regions or areas not frequently exposed to severe weather, a longer inspection cycle may be perfectly adequate. The schedule listed in Table 12 is intended as a typical—but proactive—guide for a ground patrol.

Table 12: Maintenance and Inspection Schedule

Equipment	Inspection, Maintenance, and Tests	Frequency/Remarks
Wood Poles	Check leaning, washout, splitting damage to ground connection due to lightning or other reasons, staples loose or missing from grounds	Annual patrol Visual inspection Binoculars or a UAV with digital imaging capability will be helpful
Lightning Arrester	Loose or broken ground lead connection	Annual inspection Binoculars are needed if a UAV is not available
Conductors	Broken strands, blisters, or burned loose connection, clearances	Annual inspection Binoculars are needed if a UAV is not available
Mechanical Hardware and Connections	Looseness, corrosion, evidence of overheating or de-coloring due to excessive heat	Annual inspection Binoculars are needed if a UAV is not available

TROUBLESHOOTING

Grounding-related problems are often difficult to trace, given the small timeframe in which the transients occur and the unpredictability of when a problem may become apparent. Damage to equipment is often the first indication that you may have a grounding issue. The best way to prevent a grounding problem from reoccurring is first to make sure that your connections are still good and provide a solid path to ground.

Table 13: Symptoms, Possible Causes, and Remedies for Ground-Related Failures

Symptoms	Possible Cause	Remedy
Wood Pole Fire	Poor grounding connections Inadequate clearances High-magnitude lightning strike	Provide solid grounding connections Check clearances
Damage to Steel Pole	Poor grounding connection Lightning strike	Repair or replace grounding connections
Discolored Pole	Poor grounding connection Poor connection with foundation steel	Repair or replace grounding connection

TESTING GROUNDING OF TRANSMISSION POLES

If you suspect a problem at or near a certain location based on fault data, testing the grounding system at a representative group of poles may help give you an indication of where your problem might be. (You could even include placing a metal tag on the pole with the date and test results for future reference.) If you wanted to be certain that you have completely evaluated the grounding system, you could test the ground resistivity at every pole along the line and run a computer simulation of the line.

Computer Simulations

Tower ground resistance has a major effect on the lightning flashover rate of a line, but the actual calculation is complicated and is a nonlinear function (affected by annual frequencies of thunderstorms in a given area, earth resistivities, and stroke current magnitudes). The range of available software varies from programs that perform simple analysis to give a rough estimate of line lightning performance to programs that also include an economic analysis of various ground electrode designs and line geometries. It may also be worth obtaining a ground flash density map (try an internet search for North American Lightning Detection Network) for the area in which the line is located for comparison purposes to the performance of other lines of similar construction.

Considerations for various test methods include the clamp-on and counterpoise tests.

Clamp-On Test

- **Advantages.** Quick and easy test, no probes need to be driven, ground rod does not need to be disconnected, the reading from a clamp-on can also tell you fairly quickly whether you have a loose connection.
- **Disadvantages.** Only effective with multiple grounds in parallel, so it will not work well where the grounds have been isolated due to damage.
- Pointers

  - Open the jaws of the meter clamp and make sure that the surfaces fit together properly and are free of dust, dirt, or any foreign substances that could give you a false or incorrect value.
  - The self-calibration should work properly, but, if it does not, check the jaw surfaces for dust or dirt and try again.
  - Wait for self-calibration to finish before making measurements.
  - For concrete poles, make sure that you don't attach the clamp-on meter above where the pole ground is bonded to the steel tendons in the pole; otherwise, you'll get an incorrectly low reading due to the ground loop in the pole.

Counterpoise Test

- **Advantages.** Can achieve good results in most locations.
- **Disadvantages.** Requires quite a bit of installation work to perform the test.
- Pointers
  - Install a ground conductor laid horizontally in the ground and parallel (or at some other symmetrical angle) to the line at a depth of 2-3' below the surface.
  - If you can't go very far due to rock or some other obstacle, try spreading out multiple counterpoise wires on opposite sides of the structure (each wire can be assumed to have the same length and electrical response).
  - Use a high-current, low-resistance ohmmeter to verify complete electrical continuity across bonds, welds, clamps, and other conductive elements from the pole to the buried electrode.
  - In theory, the test results should be essentially the same at all points, but it's a good idea to repeat the test in various directions to average out any localized variations.
  - Clamp-on testing is not well-suited for testing counterpoise grounding systems due to the high-frequency impedance associated with a counterpoise.

Examples of wood, steel, and concrete poles with good ground connections are shown in Figures 44 through 47.

Figure 44: Wooden Pole with Good Ground Connection

Figure 45: Steel Pole with Good Ground Connection

Figure 46: Concrete Pole with Good Ground Connection

Figure 47: Steel Pole with Good Ground Connection

10. SPECIAL CONSIDERATIONS

In addition to the topics listed in the previous sections, it is also possible that you may run into some unusual grounding related challenges that may require additional studies or consultation with others who are familiar with the issue(s) at hand. A few of these possible items are listed below, along with potential electrical utility system equipment additions or other suggested action plans to consider.

LIGHTNING ARRESTER APPLICATIONS

Below are reasons why you might want to add transmission line arresters:

- Existing transmission line is a three-wire system with no lightning protection,
- Existing transmission line is a shielded system which has a number of momentary outages due to being in a high isokeraunic area with higher ground resistance,
- To reduce transient overvoltages for live-line work,
- To reduce insulator flashover due to high switching surges, and
- Improved protection in areas where grounding is poor (ledge rock areas).

Theory of Operation

Lightning or switching events cause a traveling surge down the transmission line (if shielded line, the surge may come down the ground wire) which will result in a flashover of the insulator if the surge is higher than the withstand level of the insulator or approximately 85% of the critical flashover value. If the lightning surge flashes over the insulator, a backflash happens, with the power frequency current requiring a circuit breaker or other interrupting device to break the fault current, resulting in a momentary outage.

Figure 48: Transmission Line Surge Arrester

When an arrester is applied to the insulator, the lightning surge is transferred to the grounding system, eliminating the operation of the breaker (therefore, no momentary outage). If the transmission line is shielded and the grounding system is high, the lightning surge may travel down the ground wire and cause a backflash to the lower or middle insulators.

The first response to improve performance will be to add more grounding to the structure. However, if grounding is difficult, lightning arresters can be added to improve reliability. There will be instances where the lightning current will exceed the rating of the arrester and will result in operation of the disconnect device on the arrester. The arrester will fail in open mode.[15]

Polymer Surge Arresters

In most cases, high-voltage surge arresters are generally equipped with polymer housing. Surge arresters housed with polymer provide several advantages over the porcelain-housed units. First of all, polymer surge arresters have a better mechanical behavior and, thus, a higher safety level in the case of a failure. In addition, polymer arresters are much lighter in weight and generally offer superior protection in polluted environments.

SURGE ARRESTER CHARACTERISTICS

Metal-oxide varistor (MOV) surge arresters have nonlinear volt-ampere characteristics in order to perform as a blocking device at lower voltages and as a good conducting device at higher voltages. A typical volt-ampere characteristic of an MOV arrester is shown in Figure 49. The important operating features of such a surge arrester are:

- Very small leakage current at the operating voltage,
- Maximum continuous operating voltage (MCOV) level in between the operating voltage and rated voltage,
- Temporary overvoltage (TOV) at a current of around 10 A,
- Switching surge capability with a current of up to 1 kA, and
- Lightning surge conduction capability of 10 kA.

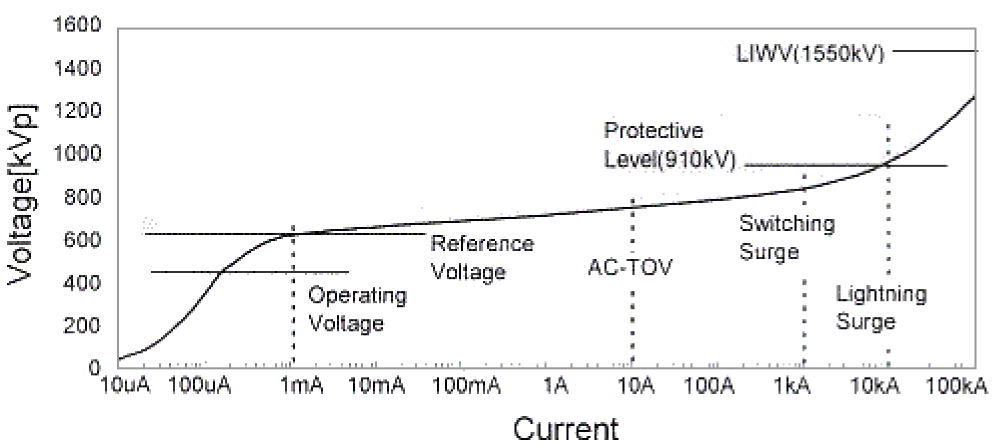


Figure 49: Volt-Ampere Characteristics of an MOV Surge Arrester

The allowable time durations for various operating points are different and are defined accordingly below.

[15] For more information, see IEEE 1243-1997, Guide on Lightning Improvement of Transmission Lines.

- **Rated Voltage.** The rated voltage of a surge arrester is presented as a line-to-line voltage. This voltage rating must be higher than the system voltage in order to withstand the voltage rise during system fault conditions.
- **Temporary Overvoltage (TOV)**. The common source of temporary overvoltage rise on unfaulted phases during line-to-ground faults depends on the type of grounding. On a delta-connected system, a single line-to-ground fault produces line-to-line voltage on the unfaulted phases. If the surge arrester is connected phase-to-ground, such arresters will experience 1.732 times the phase voltage. In a solidly grounded, effectively grounded, wye-connected system during a single-line-to-ground fault, the arresters will experience up to 1.38 times the phase voltage on the unfaulted phases.
- **Maximum Continuous Operating Voltage (MCOV).** The MCOV rating of a surge arrester is the maximum rms value of the power frequency voltage that may be applied continuously between the terminals of the surge arrester.
- **Front-of-Wave Protective Level (FOW).** This is the discharge voltage for a faster (0.6 × 1.5 microsecond), typical 10 kA impulse current, which results in a voltage wave cresting at 0.5 microsecond.
- **Switching Surge Protective Level**. The switching surge discharge voltage of a surge arrester increases as current increases. A switching surge coordination current of 3 kA (45 × 90 microseconds) is used for ratings of 54 kV to 588 kV.
- **Impulse Discharge Voltage.** The resultant voltage using an 8 × 20 microsecond wave across the surge arrester, due to the forced current, is usually presented for various current levels.
- **Magnitude of Discharge Currents**. The discharge current through a surge arrester depends on the flashover voltage of the insulation, surge impedance of the incoming line, and the type of grounding. For effectively shielded installations, the discharge current will vary from 1 kA to 20 kA, depending on the system voltage.

LOCATION OF SURGE ARRESTER

It is always a good practice to locate the surge arresters very close to the equipment to be protected. In the case of effectively shielded substations, where the chances of direct stroke to the equipment are minimal, the surge impedance limits the discharge current. Therefore, sometimes a surge arrester can protect more than one piece of equipment. In noneffectively shielded substations, surge arresters should be installed at the terminals of the equipment to be protected.

Separation Effect

It is sometimes impractical to install surge arresters at equipment terminals. In such cases, a cable is used to connect the equipment to the surge arrester. A traveling wave coming into the substation is limited in magnitude at the surge arrester location to the value of discharge voltage. When a surge arrester is separated from the protected equipment by leads of significant length, oscillations occur, which result in higher than the arrester voltage at the equipment.[16]

[16] Natarajan, Ramasamy. *Power System Capacitors*. CRC Press, March 30, 2005.

The effect of separation distance on the voltage at the equipment is shown in Figure 50 for different incoming waves. In addition to the reflected wave, it is always possible that still higher peak voltages can occur at the equipment due to the oscillations caused by the inductance of the cable between the surge arrester and the protected equipment.

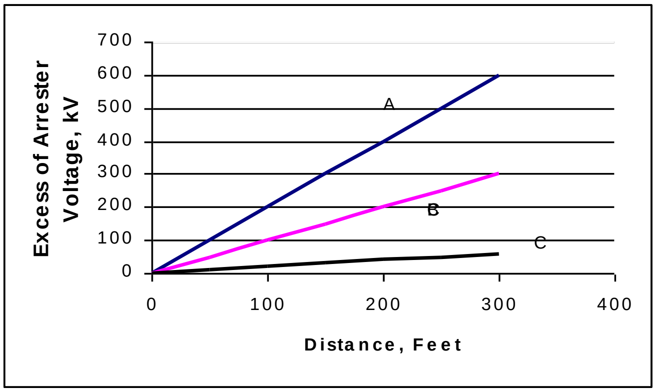


Figure 50: The Separation Effect

Grounding of Surge Arrester in a Distribution Underbuild System

The use of a surge arrester in a high-voltage system for line protection is very rare. If there are high-resistivity soil issues, then surge arresters are employed on high-voltage systems. The grounding arrangement of a typical surge arrester in a distribution underbuild system is shown in Figure 51. When three surge arresters are used, all three ground connections are joined to a common point and then to the ground conductor.

MOV Summary

Surge arresters are used in power systems for surge protection. The overvoltages are produced due to lightning surges and switching operations. The important characteristics of the metal oxide varistor type of surge arresters are presented in this section. The separation effect is discussed when there is a significant lead length used in connecting the surge arrester.

In areas where structure grounding is difficult to achieve, or the lightning performance of an existing transmission line needs to be improved, Metal Oxide Varistor (MOV) line arresters can be installed. These arresters should be coordinated with the substation station class arresters for proper performance. The engineer should determine the size of the substation arresters and choose a slightly higher Maximum Continuous Overvoltage (MCOV) rating on the transmission line to prevent the line arresters from taking all of the flashover duty. (Values in Table 14 are taken from Ohio Brass® Proteca*Lite® catalog tables courtesy of Hubbell Power Systems, Inc.)

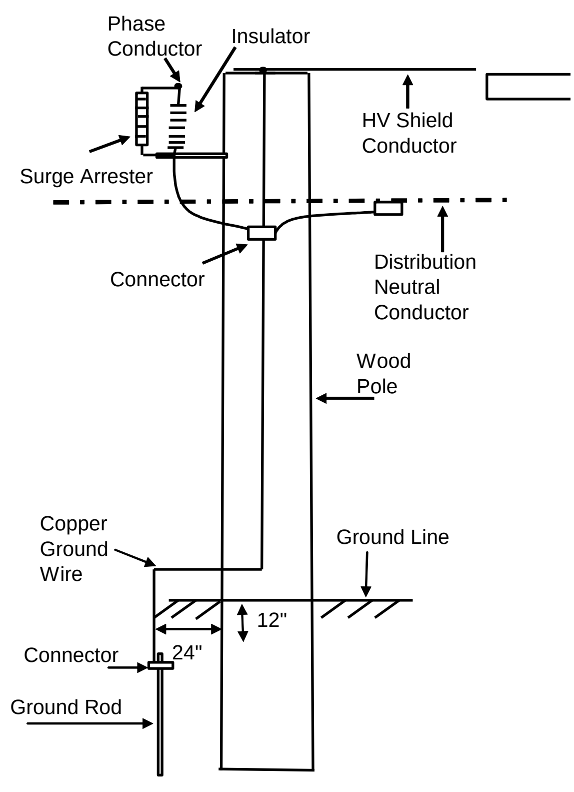


Figure 51: Grounding of a Surge Arrester in Distribution Underbuild

Table 14: MCOV Recommendations Based on System Voltage

System Line to Line Voltage in kV *(Nominal)*	System Line to Line Voltage in kV *(Maximum 5% over nominal)*	Effectively Grounded Neutral Circuit *(Minimum MCOV in kV)*	Effectively Grounded Duty Cycle Rating kV	Temporarily Ungrounded, Impedance Grounded or Ungrounded *(Minimum MCOV in kV)*	Ungrounded Duty Cycle Rating kV
23	24.2	15.3	18	22	27
34.5	36.2	22	27	36.5	45
46	48.3	29	36	48	60
69	72.5	42	54	70	90
115	121	70	90	115	144
138	145	84	108	131	168
161	169	98	120	152	-
230	242	140	172	220	-

Figure 52: High-Voltage Polymer Surge Arrester

*Ohio Brass® Proteca*Lite® systems courtesy of Hubbell Power Systems, Inc.*

On a triangular three-wire design, adding an arrester to the top phase of every structure will typically give some shield angle protection to the other phases. For best performance, the arrester should be tied to a grounding system with 10 ohms or less of resistance. If good grounding is not available, the borrower should consider adding lightning arresters to all three phases. Lightning arresters can also be installed on shielded lines to minimize back flashover where good grounding is difficult. The engineer should design for phase-to-phase clearances between the failed arrester, open position, and other phase wires since the arrester may drop near the other energized phase position.

GROUND-FAULT NEUTRALIZER

If the transmission line is connected to a ground-fault neutralizer (GFN), otherwise known as a "Petersen Coil," the transmission line needs to be considered ungrounded. Petersen Coils are neutral grounding reactors installed at the substation with inductive reactance values which are tuned to cancel the capacitive reactance values to ground current during single line to ground faults. This will limit the fault current to a value that will not sustain an arc. This technology has been primarily used in Europe since the 1930s; however, it has also been used on some three-wire systems in the United States.

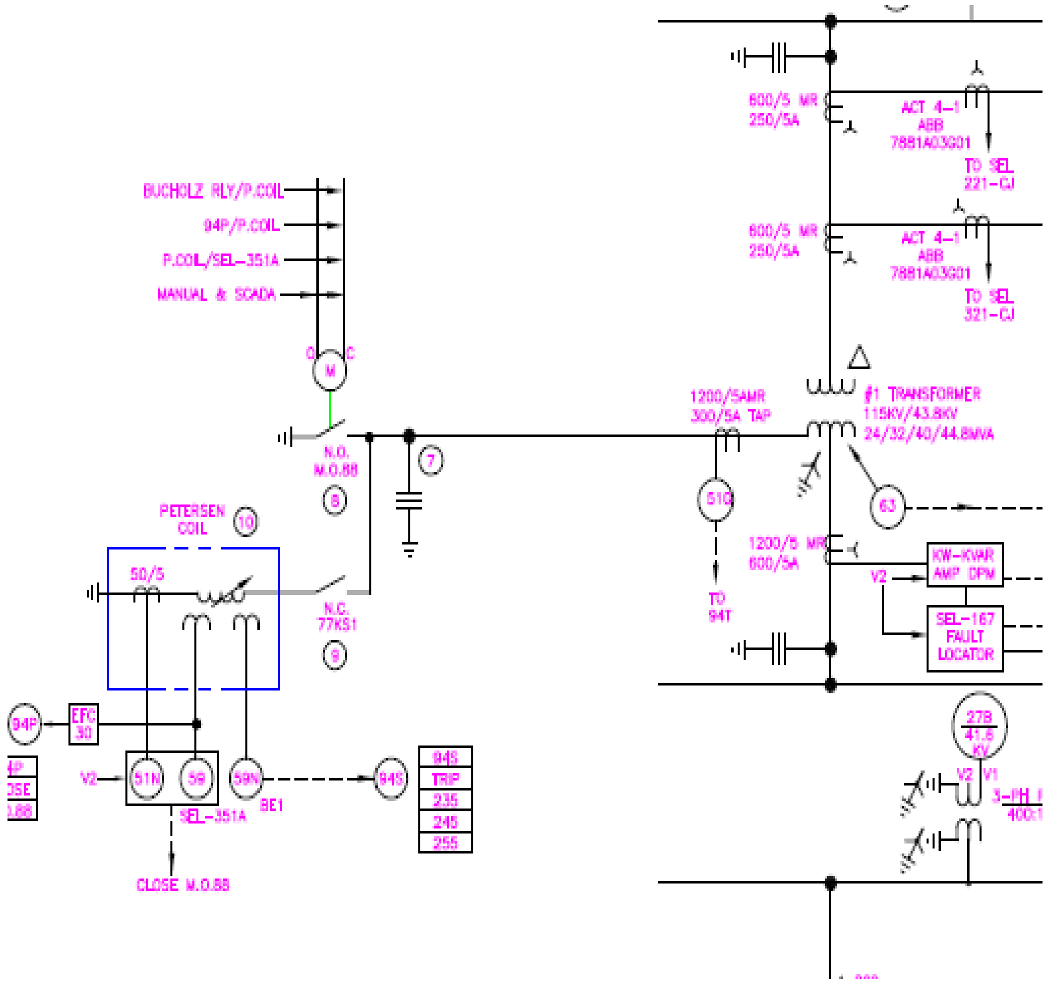


Figure 53: Ground Fault Neutralizer in One-Line Diagram

The Petersen Coil will not work on effectively grounded systems. As commonly used, a Petersen Coil is simply a reactor with taps connected between a substation transformer neutral and ground. When one phase of the system is faulted to ground, a lagging reactive current will flow from the coil through the transformer to the fault and then to ground; at the same time, the line capacitance current will flow from line to ground.

The lagging current from the coil and the leading current from line capacitance will be practically 180 degrees out of phase; therefore, the actual current to ground at the fault is equal to the difference between the two. By properly tuning the coil (adjusting to the right tap), the two currents can be made almost equal, resulting in a cancellation of the reactive current to nearly zero. Under this condition, the fault current is theoretically small enough that the arc cannot maintain itself and the fault is extinguished. Lightning arresters will need to be sized for ungrounded neutral systems. The arresters will mitigate impulse overvoltages on the transmission line and will reduce the duty cycle of the Petersen Coil.

Figure 54: Photo of Ground Fault Neutralizer

RETROFITTING TRANSMISSION LINES WITH ARRESTERS

When retrofitting three-wire transmission lines with lightning arrester protection, an evaluation of the pole ground system should be reviewed. Old designs used butt wraps for grounding purposes, which will not be adequate for grounding of the arrester. A copper-type ground wire, with an attachment to a separate ground rod with an effective ground resistance, is recommended. If the ground resistance is too high due to soil resistivity, then the utility should add lightning arresters to all three phases. If there is no ground wire, or the ground wire is severed, the lightning surge can cause a pole fire.

Figure 55: Lightning Arrester on Three-Wire System

LIST OF MATERIALS

REF.	REQD	DESCRIPTION
1	1	ARRESTER, 31.5KV MCOV ASSEMBLY PROTECTA-LITE, W/O INSUL
2	1	CONNECTOR, COMP, CRIMPED, CU #6 SOL 4-STRD

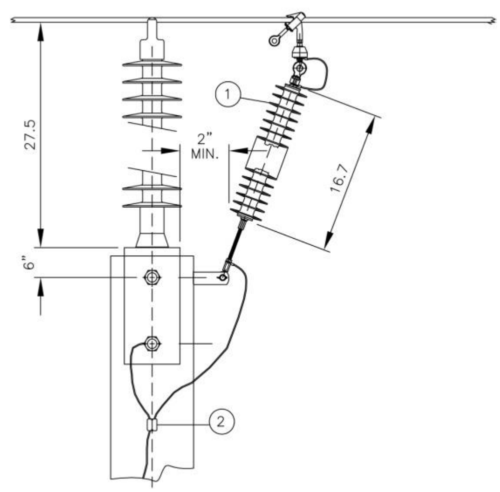


Figure 56: Drawing of Lightning Arrester Installation

SWITCH PLATFORM AND GROUNDING—1-WAY, 2-WAY, 3-WAY (WITH DRAWINGS)

Switch platform grounding is recommended primarily for lineworker safety during operation of the switches. It is recommended that the ground grid be no more than 10 ohms, with a minimum of 1/0 stranded copper wire attached from the operating pipe to the ground plate. The ground connection should be visible to ensure line personnel of proper connection during switching. A loop from the operating pipe to the ground platform back to the pipe will provide proper continuity of the ground connection. All underground connections are exothermic-type connections to be applied to the ground rods attached to the switch platform (see Figure 57 below as an example). All personnel are required to wear rubber gloves when operating any air break switches.

NOTES:
1. ON EXISTING SWITCH INSTALLATIONS THAT HAVE AN INSULATOR INSTALLED IN THE SWITCH OPERATING PIPE AND NO EXISTING GROUNDWIRE RUNNING UP THE POLE. DO NOT INSTALL A GROUND LEAD UP THE POLE OR REMOVE THE INSULATOR FROM THE OPERATING PIPE.

2. THIS UNIT MAY BE USED ON WOOD AND LAMINATED WOOD SWITCH POLES.

3. THE RESISTANCE OF THE GROUND RODS SHALL BE DETERMINED BEFORE THEY ARE CONNECTED TO THE GROUND GRID. GROUND RODS SHALL BE DRIVEN AT LEAST 20 FEET DEEP OR UNTIL A READING OF 10 OHMS OR LESS IS OBTAINED. THE INSPECTOR SHALL REVIEW ALL READINGS AND DETERMINE WHETHER ADDITIONAL GROUND RODS SHALL BE INSTALLED. REFER TO, ADDITION TO GROUNDING ASSEMBLY, UNIT NUMBER TM10.

REF.	REQD	DESCRIPTION
1	75	WIRE, COPPER #1/0 7- STRD SD BARE
2	4	STAPLES, 2" X 1/2" X 0.162", SLASH POINT, GALV
3	3	CLAMP, TOWER #4 TO 300 TO FLAT SINGLE CONDUCTOR
4	4	ROD, CW GROUND 5/8" X 10' THREADLESS, ONE END POINTED
5	2	COUPLING, BRONZE FOR 5/8" X 10 THREADLESS SECTIONAL GND
6	2	CLAMP, 5/8 TO 3/4IN ROD TO #6 TO 2/0 CABLE BRONZE BOLTED
7	10	CONNECTOR, 1/0-2/0 COPPER WIRE E-Z GROUNDING COMPRESSION
8	8	TAP LUG, BRONZE #6-250 CU 1- BOLT
9	5	PLATE, SW GROUNDING 1-1/4" x 3' x 4', GALV
10	3	STRAP, GROUND, BRAIDED FLEXIBLE, CU 9-1/2" LONG
11	4	CONNECTOR, SPLIT BOLT 1/0 STR CU
12	3	PADLOCK, SHACKLE 3/8" DIA X 7/8"

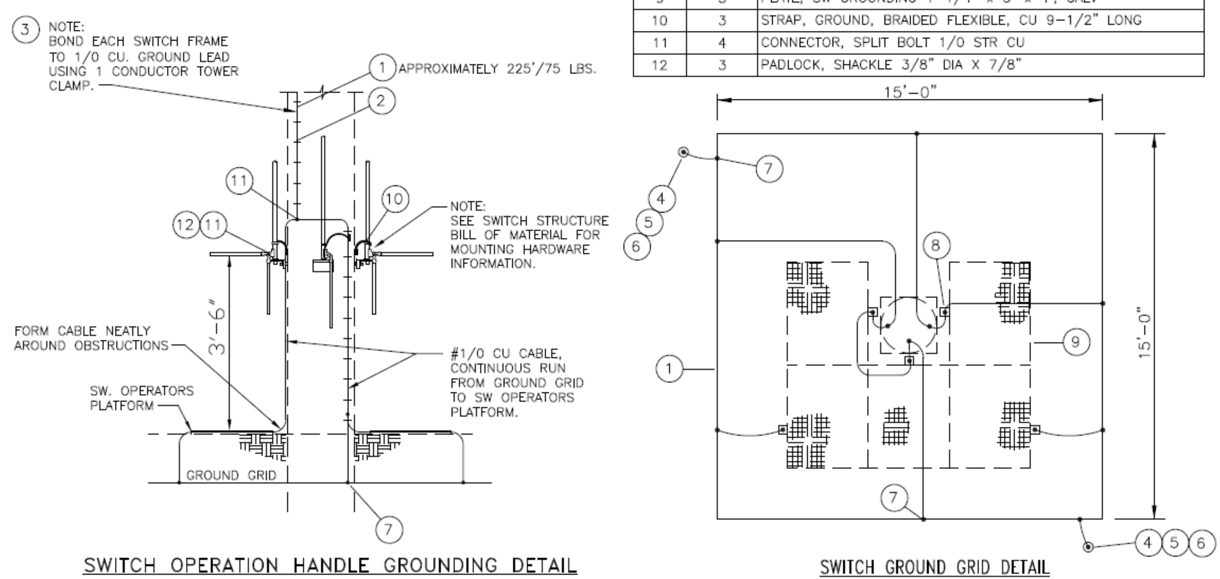


Figure 57: Three-Way Line Switch Grounding Detail

GUYING NEAR SUBSTATION GROUND GRID

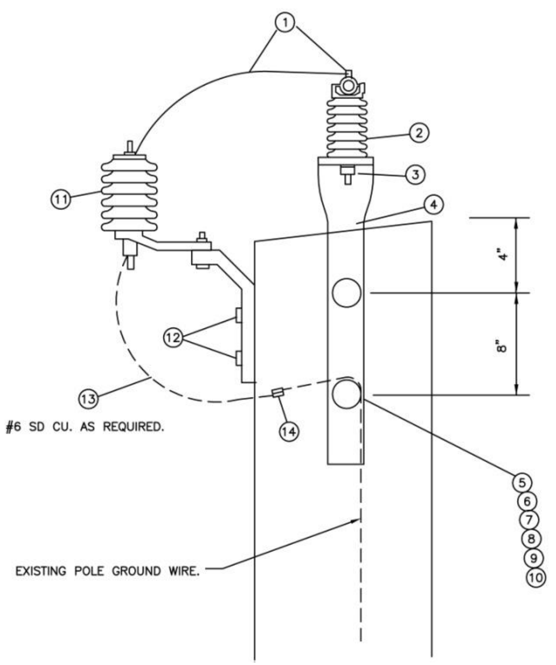
Substations have a tremendous amount of copper used for grounding purposes. This could cause premature corrosion of the transmission line anchoring system which is nearby. The designer should consider using insulated guys on structures near substations to prevent this corrosion. The pole ground and shield wire should be sized to meet fault current requirements and any step potential concerns.

Insulated Fiber (ADSS) Underbuild

An All-Dielectric Self-Supporting (ADSS) type of fiber can be installed in the conductor space if maintained by the transmission line provider. The designer may want to consider grounding the attachment bolts to the grounding conductor to eliminate any radio or television interference and any inductive discharge from the electric field of the conductor.

Insulated Shield Wire

When a transmission line is routed near a communications antenna, the owner may be requested to insulate the shield wire to mitigate interference or degradation of the communications signal. An insulator with a distribution-type insulator can be used to mitigate the steady state interference issue and still provide a path for lightning during storms. See Figure 58.



LIST OF MATERIALS

REF.	REQD	DESCRIPTION
1	1	CLAMP, SINGLE SUPPORT ASSY. FOR OPGW. DIA RANGE .512 –.536
2	1	INSULATOR, VERTICAL LINE POST, 69KV, POLY, 1–3/4" DIA ROD
3	1	STUD, LINE POST, 3/4" X 1–3/4" LONG
4	1	BRACKET, LINE POST INS 66KV, 13/16" STUD MOUNTING HOLE W/
5	3	BOLT, MACHINE, 5/8" X 14"
6	3	NUT, 5/8" SQ M–F LOCK, GALV
7	3	WASHER, SPRING, 5/8", GALV
8	4	WASHER, SQ CURVED, 11/16" HOLE, 1/4" x 3" x 3", FOR 5/8"
9	2	NUT, GALV 5/8" SQUARE
10	1	CLAMP, IRON CABLE FOR BONDING GROUND WIRE TO STATIC SUPPORT
11	1	ARRESTER, SURGE 10KV, 8.40 KV MCOV, HEAVY DUTY RISER POLE
12	2	SCREW, LAG, 1/2" X 5"
13	1	WIRE, COPPER #6 BARE SD WYR, SOL
14	1	CRIMPIT, COPPER #6 SOL. #4 STR

Figure 58: Distribution-Type Insulator

ELECTROMAGNETIC INTERFERENCE

Fault current or electromagnetic induction may result in safety issues for railroads or pipelines which parallel the transmission line. An independent study may be required to evaluate the parallel facility. If interference is confirmed, possible solutions include:

- Underground cable with conductivity specified by a qualified engineering study;
- Underbuild or additional shield wires, with the conductor sized with the proper conductivity, specified by a qualified engineering study;
- Additional separation from the affected facility; or
- Technical solutions by the affected facility, new signal technology, additional grounding, etc.

NESC rule 95B2 states that no ground electrode can be closer than 10' from a high-pressure transmission (flammable liquids or gas) pipeline which is operating at a pressure of 150 lb/in^2 or greater unless they are electrically interconnected and cathodically protected as a single unit. Pipeline companies have concerns with worker safety and corrosion of their infrastructure. Fault currents can be induced on pipelines during construction or where an existing pipeline corridor is physically close to a proposed transmission line. A fault analysis may be requested on a case-by-case basis when either a new transmission line is being constructed or a new pipeline is near the transmission line easement. Fault currents can be mitigated by additional cables either installed on the transmission line or buried underground in a strategic location to reduce the current injection.

In addition to fault current concerns, induced ac currents can cause pitting of the iron pipeline due to galvanic reactions caused by various soil conditions (lower resistivity soils are more corrosive, see RUS Bulletin 1751P-670, Table 2). A potential survey profile (using copper-copper sulfate half-cell) of the pipeline voltages can be done to determine if mitigation is required. Steel behaves as a sacrificial anode to other metals such as copper; half-cell dc voltages greater than –0.10 volts could indicate potential corrosion activity (RUS Bulletin 61-11). Mitigation includes adding anode or ac rectifiers to the pipeline to counteract galvanic reactions.

Railroads will have similar concerns as described above; however, their concern is the safe operation of the railway system. Interference can cause misoperation of their signaling systems. Railroad companies are concerned with the safety of their personnel during maintenance operations. Some companies will require an induction study as a condition of license agreements to determine if any mitigation is required, per their standards. Mitigation will include adding neutral cables either overhead or buried along parallel construction. In addition, a railroad may require a utility to pay for mitigation equipment on the rails as well.

Adding mitigation overhead cables on the transmission line may cause an interference of nearby AM radio station transmitters, possibly also requiring the addition of detuning equipment. This should be analyzed prior to commitment of any overhead neutral solution.

Table 15: Recommended Fence Grounding Intervals (Feet)
(from REA 62-4, Electrostatic and Electromagnetic Effects of Overhead Transmission Lines)

Fault Current (Amperes)	69 kV	115 kV	138 kV	161 & 230 kV	345 kV
1,000	4,976	6,976	6,990	7,004	9,760
5,000	995	1,395	1,398	1,401	1,952
10,000	498	698	699	700	976
20,000	249	349	350	350	488
30,000	166	233	233	233	325
40,000	125	175	175	175	244
50,000	100	140	140	140	195

Metal fences or buildings along the right of way—*i.e.*, under or within the influence of a high-voltage transmission line—should be grounded at proper intervals (typically every 200') to mitigate shock currents along the facility. A farmer with an electric fence may have the complaint that the fence is still energized after the fence power is shut off. This may have resulted from electromagnetic induction from the parallel transmission line. A filter (or "choke") can be installed on the fence per Figure 59 to bleed off the ac current to ground and allow the dc current to remain. Table 15 is the recommended fence grounding interval (feet) for a single line-to-ground fault for voltages levels of 69 kV to 345 kV.

Grounding intervals are based on a 50 kilogram (110 pound) person experiencing a 0.5% probability of ventricular fibrillation. Values are based on typical NESC clearances, typical phase separation, soil resistivity of 100 ohm-meters, fence lateral distance of 30' from 69 kV, 50' from 115 kV to 230 kV, 75' from 345 kV centerline (taken from RUS Bulletin 62-4).

Buildings should be outside of the power line easement; however, buildings within 75' to 215' from the energized conductor should be grounded per Table 16 (based on RUS Bulletin 62-4).

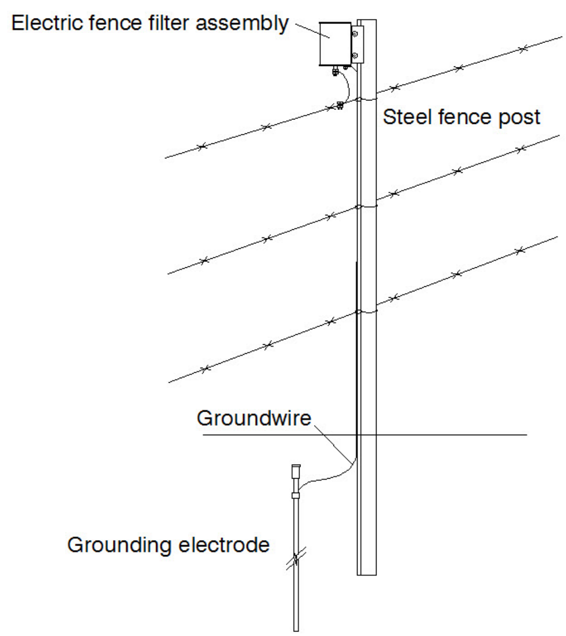


Figure 59: Electric Fence Filter

Table 16: Building Grounding Recommendations

Line Voltage	Object Horizontal Distance from Outside Conductor (ft.)	Minimum Area of Metallic Surface Requiring Grounding (sq. ft.)	Minimum Length of Gutter Requiring Grounding (ft.)
345	Within 75	*	*
345	Between 75 and 100 (Min.)	2,000	150
500	Within 100	*	*
500	Between 100 and 150 (Min.)	2,000	150
765	Within 130	*	*
765	Between 130 and 215 (Min.)	2,000	150

** No minimums are specified. Consideration should be given to grounding of any insulated metallic object.*

If the building stores flammable materials and is within 250' of the outer conductor, add ground rods to the metal parts per above.[17]

Anyone operating large farm vehicles which are continually under extra-high-voltage transmission lines should consider adding chains to the vehicle to minimize nuisance shocks.

[17] Appendix I–Living and Working Safely Around High-Voltage Power Lines, Bonneville Power Administration