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Grounding Methods and Best Practices for High Voltage Transmission

WHITE PAPER

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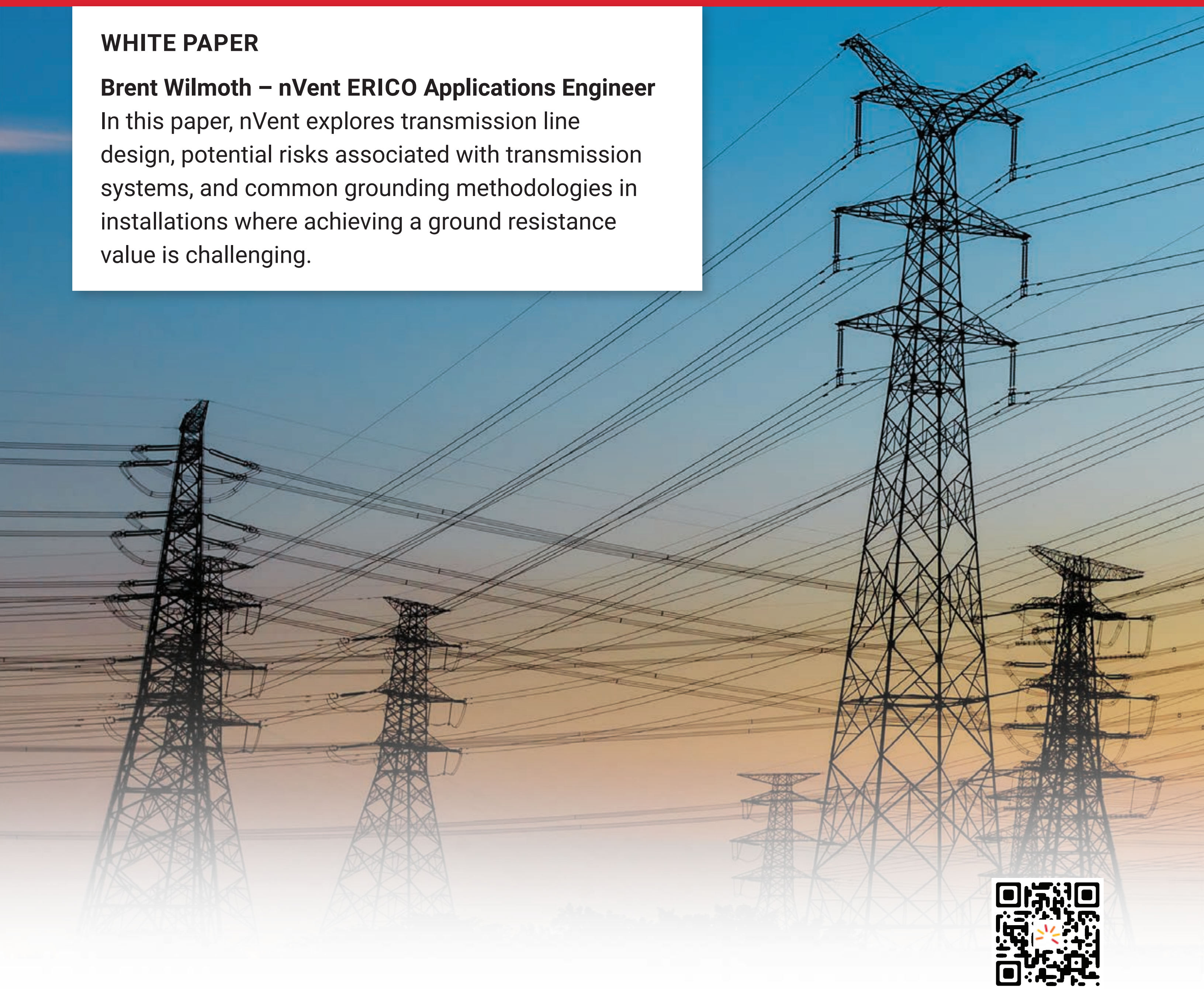
In this paper, nVent explores transmission line design, potential risks associated with transmission systems, and common grounding methodologies in installations where achieving a ground resistance value is challenging.



Introduction

The purpose of a grounding system is to establish a low impedance path to earth to clear electrical currents applied on the system to ensure personnel safety and protect equipment. Electrical infrastructure requires adequate grounding to safely dissipate fault current energy, primarily for the safety of utility personnel and the public. High-energy faults from lightning or over voltage transients can cause substantial damage to utilities. A well-designed grounding system mitigates outages and reduces costly damage to sensitive equipment.

With the rise of new utility projects due to the "electrification of everything" initiative, there is an increasing dependence on utilities for the safe and reliable distribution of power. Routine maintenance and inspection of grounding systems are essential for their effective operation. As reliance on the grid and usage increases, neglecting grounding—whether in design or maintenance—can significantly elevate risks of outages, equipment damage, and safety concerns. These issues are exacerbated when utility infrastructure exceeds its designed lifespan. However, in many cases, transmission lines are installed in locations where the soil resistivity is high or available space is limited, which makes obtaining a ground resistance value and therefore the grounding design challenging.

This paper aims to provide a general overview of transmission line design, the potential risks associated with transmission systems, and common grounding methodologies for these systems, particularly in installations where achieving a ground resistance value is challenging.

High Voltage Transmission Tower Design

Transmission systems carry high voltage AC power over long distances from generation plants to electrical substations to maximize efficiency and minimize line voltage drop. The power is transmitted either overhead, underground, or underwater. Each method faces its unique challenges, but the focus of this paper is on the most common method in the United States, overhead high voltage transmission lines, further referred to as plainly transmission lines.

High voltage transmission lines are supported by towers, now often composed of a steel lattice or a steel monopole. The towers support the phase conductors with long and highly rated insulators. The ratings of the insulators are selected based on the line voltage these conductors carry. At the top of the towers, there are one or more shield wires that are designed to protect the phase conductors from a lightning strike. The shield wires provide a theoretical radius of protection to defend the phase conductors from lightning.

When considering power transmission design, an understanding of the factors that cause outages is necessary [9]. Outages vary based on the location of the system. One factor to consider is severe weather, which can cause power outages either directly or indirectly through natural events such as high wind, tornadoes, fire, and lightning. Trees, especially when located near the lines and not maintained pose an increased risk during severe weather. To mitigate these risks, electrical utilities must invest in regular maintenance to control tree growth near the lines.

High Voltage AC Transmission Systems and Lightning

Lightning protection design is critical for utility power transmission. To protect against strikes, an understanding of what causes lightning is necessary. Lightning is an electrical phenomenon that often impacts power transmission because, generally, lightning will often attach to the tallest object. Lightning is created by atmospheric conditions in the clouds. Inside the clouds, water droplets interact with frozen particles. When these particles interact with each other, they generate a charge that causes the clouds to become polarized. Inside the cloud, the polarity is split, where at the top of the cloud carries a positive charge and a negative charge is generated at the bottom of the cloud.

Due to the charge separation, an electrical field is then created within the clouds and between the cloud and the earth. In the context of interactions between clouds and the Earth, the atmosphere functions as an insulator. When this insulator fails, an electrical discharge known as lightning takes place. This electrical discharge can take place between clouds, inside one cloud, or between the cloud and elements on the Earth. As the polarized cloud passes over the Earth, it repels the negatively charged electrons in the earth, causing the earth's surface to become positively charged. The difference in potential from the clouds to objects on Earth can be in the range of tens to hundreds of millions of volts. As downward leaders propagate from the cloud toward Earth, an opposite-charged upward leader propagates toward the downward leader. When both leaders collide, the bright flash we typically associate with lightning occurs.

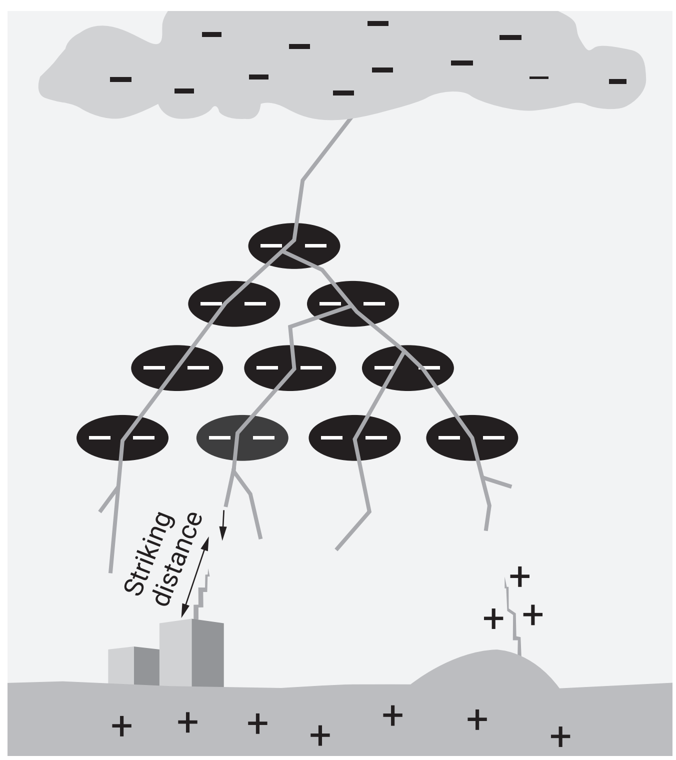


Figure 1: Principal of lightning generation

Lightning Protection and Transmission Towers

As polarized clouds pass over a transmission system, the proximity of the tower makes them a likely target of the downward leader propagating from the clouds.

Lightning can strike the shield wire, phase conductors, or the tower itself [1]. The shield wire is placed at the peak of the towers with the intent to prevent lightning from striking the phase conductors. Figure 2 illustrates the protection of phase conductors by the shield wire using a simplified shielding method known as the fixed angle method. It is common practice to use an optical ground wire (OPGW) as the shield wire, but it's use and implementation has its unique challenges. OPGW contains optical fibers shielded by layers of aluminum and/or steel. Utilizing OPGW for transmission lines has two major benefits. The first is that it can act as a shield wire to protect the phase conductors from a lightning strike. The second is the OPGW can be used to transmit date along the lines. Adding communication between the towers reduce outages for transmission systems. If there is a fault condition that causes an outage, relay data can be sent through the fiber cables to help determine where the outage occurs.

One negative of using OPGW though is the fibers in the cable are sensitive to damage from transient events. If the current sent down the OPGW is sufficiently large, overheating causes damage to the fibers. When most or all of the fibers are damaged, the damaged section of the OPGW requires to be replaced and therefore an added maintenance item for the electrical utility.

Using OPGW poses a unique challenge because the shield wire needs a specialized connector to bond with the tower ground. Standard compression connectors can crush the fiber cables, rendering them unusable for communication. Therefore, a specialized OPGW bonding connector is required to ensure electrical connection without damaging the fiber optics.

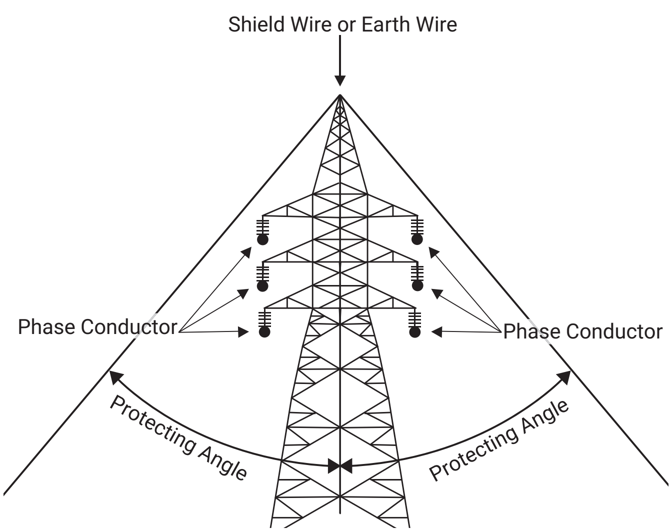


Figure 2: A General transmission tower layout

Severe Weather Considerations

Severe weather conditions are a critical consideration in the design of transmission line layouts. Utilizing the fixed angle method for the protection of phase conductors, it is essential to ensure that these conductors remain within the protection angle provided by the shield wire. Any deviation outside this protection angle increases their vulnerability to lightning strikes. Wind gusts combined with sagging conductors can cause the phase conductors to sway beyond the designated protection area. In colder climates, ice accumulation on the phase conductors and shield wire adds significant weight, impacting both tower support design and the protection zone of the shield wire. Special attention is required for older transmission lines experiencing increased capacity. As these lines near their maximum design loading, conductor sag becomes more pronounced. Direct lightning strikes to the phase conductors leading to flashovers to grounded poles can result in outages.

When lightning strikes the shield wire, the current propagates in both directions along the shield wires and the tower. The tower itself acts as an effective down conductor if they are electrically conductive. If the ground resistance is high, the current will not be able to efficiently dissipate into the earth. Rather the voltage buildup may be higher than the insulator's withstand voltage. If the voltage exceeds the insulator's withstand voltage a flashover occurs to the conductors. The potential difference between the shield wire and the phase conductors must be low, otherwise the possibility of a flashover increases. If the line to ground potential exceeds the designed value, a flashover and an outage will occur.

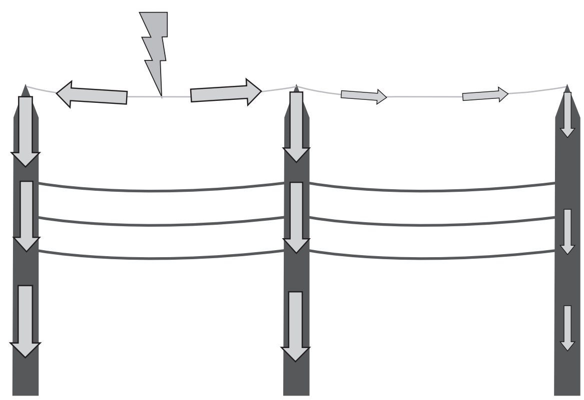


Figure 3: Diagram of lightning striking the shield wire

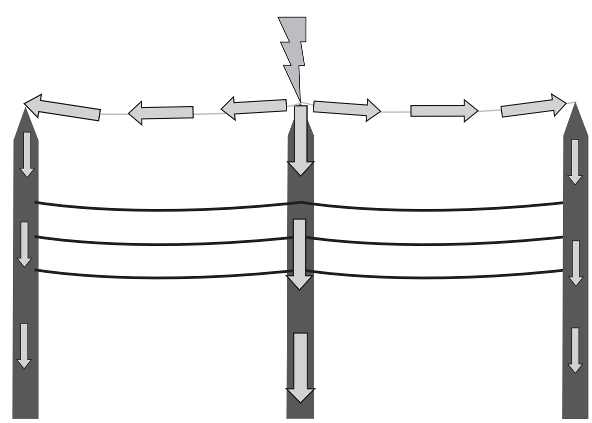


Figure 4: Diagram of lightning striking the tower

It is common that transmission systems are designed to be in service for 30 years. However, lines existing in the United States can far exceed this timeline. Exceeding the designed lifespan can be problematic. Many factors will impact the lifespan of the grounding system, such as damage related to corrosion, previous lightning events, or an increased loading on the line conductors. A best practice is to implement a maintenance routine that includes electrical ground resistance measurements to monitor the state of the grounding system.

High Voltage AC Transmission Systems and Grounding

A properly designed grounding system is intended to provide a low impedance path back to the source in order to clear fault currents, minimize ground potential rises, and most importantly maximize safety. A quality grounding design and implementation protect structures and equipment from damage while providing safety for personnel and the public. When possible during the installation of a transmission system, it is important to validate that the ground resistance meets a predetermined ohm requirement. Many transmission line designers in the United States reference the IEEE C2, National Electrical Safety Code (NESC) [6] to aid their design. Some designers reference the NESC for their grounding resistance requirement specifies for single-grounded systems, the ground resistance should not exceed 25 ohms. For multi-grounded systems, a ohm requirement is not stated, rather a minimum of 4 grounds for each mile. Depending on the proximity of the transmission system to the public and the importance of the line, a lower resistance value (such as 5–10 ohms) may be targeted. However in many regions of the United States, 25 ohms or lower may not be possible. In some locations the soil resistivity is high or the available area to install a transmission line is minimal, which reduces the area for grounding. For such cases, implementing a well designed grounding layout and the addition of other ground enhancement materials are recommended. Grounding techniques are covered later in this paper.

Ground measurements are an effective way to provide confirmation the grounding design was installed correctly. Deviation from the expected values may indicate a missing or damaged connection in the grounding system. A deviation may also indicate that the local soil is poor relative to other locations where measurements were taken. However, in urban and suburban areas, conducting ground measurements is often impractical - if not impossible - due to a lack of room to drive auxiliary probes into the soil or outside the influence of the local infrastructure. Consideration of highly specialized equipment, such as the EPRI Zed-Meter [8] or the AEMC 6474 Ground Resistance tester Kit may be considered. When availability of these types of equipment is not possible, careful consideration of the design and installation must be taken to best ensure the integrity of the grounding system.

Soil's Role in Grounding

The soil around a transmission tower is a major contributor to the grounding system design. The soil should be treated as a part of the grounding system as it supplements in dissipating fault currents injected into the system. High soil resistivity requires additional grounding electrodes to obtain the minimum ohm requirement when compared to a similar system in lower soil resistivities.

In general, moist soil is more capable of providing a low-impedance path than dry soil (Figure 5). The temperature of the soil is a critical factor and varies throughout the year. As temperatures reach below freezing, soil moisture freezes. Ice is generally a poor conductor therefore frozen soil has a higher resistivity. To minimize the impact that temperature variability has on a grounding system, investigation of the depth of the local frost line and installation of grounding components below this line should be followed. Figure 6 shows that as the soil temperature reaches freezing, the resistivity sharply increases. Soil type, compactness, and pH content are other factors to consider. Soil types varying from clay to bedrock will impact resistivity. Clay can retain moisture well whereas rocky soils such as bedrock will have high resistivity. An analysis of the composition of soluble salts, acids alkali, sulfides, chlorides and fluorides, and organic matter of the soil can reveal factors that contribute to soil resistivity and corrosive properties.

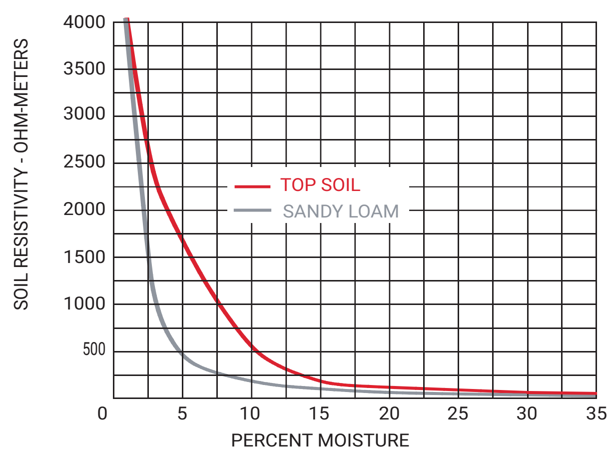


Figure 5: Chart showing the relationship between soil moisture and soil resistivity

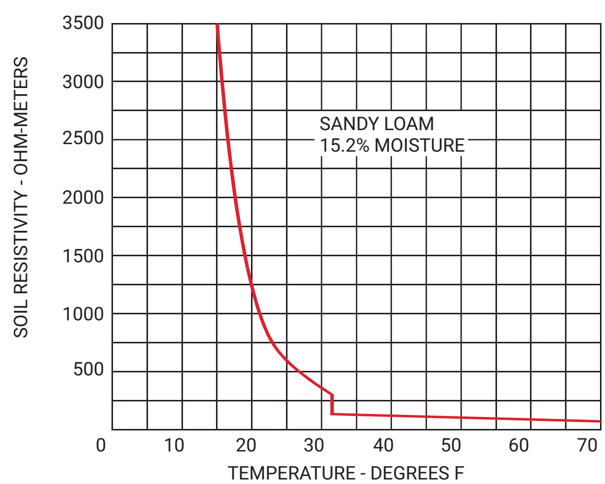


Figure 6: Chart showing the relationship between soil temperature and soil resistivity

Soil Type	Resistivity
Loam	1 to 50 ohm-m
Clay	20 to 100 ohm-m
Sand & Gravel	50 to 1,000 ohm-m
Surface Limestone	100 to 10,000 ohm-m
Shale	5 to 100 ohm-m
Sandstone	20 to 2,000 ohm-m
Granites, Basalt	10,000 ohm-m
Slates	10 to 100 ohm-m

Figure 7: Table showing expected ranges of resistivity based on soil type.

The Institute of Electrical and Electronics Engineers (IEEE) standard IEEE 81 IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System [4] details proper measurement techniques that should be followed in all grounding system designs. The most popular method to measure soil over a large area is the four-point (Wenner) method which utilizes a ground tester and four collinear, evenly spaced probes driven until sufficient contact with the soil is made (typically around 8 inches). The two outer probes inject a current while the two inner probes measure the voltage and a resistance is obtained. After each measurement, more data is obtained by increasing the probe spacing which helps to characterize the resistance values at different soil depths. The process is repeated at different probe spacing and orientations until the soil is properly mapped. Resistivity is given in IEEE 81 as:

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{(\sqrt{a^2 + 4b^2})} - \frac{a}{(\sqrt{a^2 + b^2})}}$$

Where:
ρ = Resistivity (ohm.meters)
a = Probe spacing (meters)
b = Probe depth (meters)
R = Measured Resistance

In the case that the probe depth is negligible relative to probe spacing such as 8" depth to greater than 120" spacing, then the equation can be simplified to:

$\rho = 2\pi a R$

Mapping of the soil resistivity before installation will help guide the location of the grounding system.

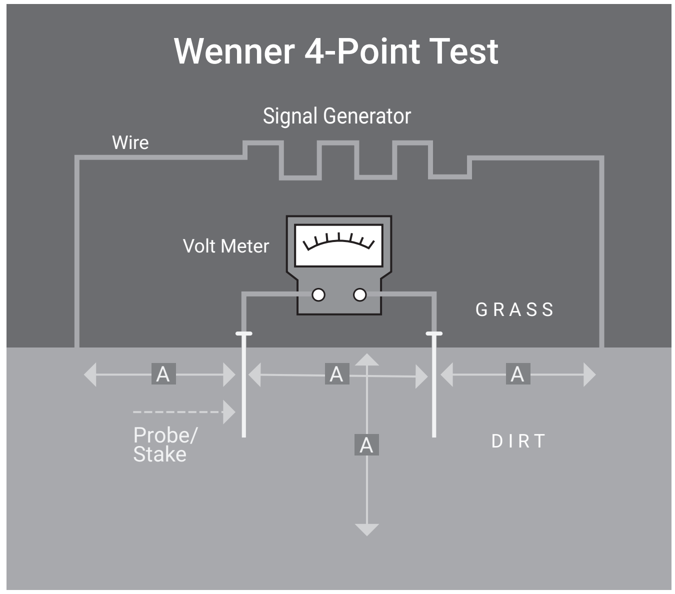


Figure 8: Wenner 4-point method for measuring soil resistivity

Tower Support and Grounding

A grounding system design is dependent on the support towers. If the transmission tower is a steel lattice design, the legs are supported by concrete footers in the soil. The concrete may be used as an effective grounding electrode, however, it should not be relied upon as the sole electrode to handle electrical faults. Concrete encased electrodes, also commonly referred to as Ufer grounds, effectively reduce ground resistance due to the presence of moisture and dissolved ions in concrete. Relying on Ufer grounds exclusively, however, is of concern because of the brittle nature of concrete. Concrete is porous and retains moisture in these pockets. When heated to a high temperature rapidly, that moisture turns into steam which generates enough force to crack the concrete. Left unrepaired, the effectiveness of the Ufer ground is significantly diminished and the damage to the concrete foundation may affect the structural integrity of the tower footing. It is recommended any concrete encased electrode be complemented with an external ground grid to minimize this effect.

Helical piles can also be used to support towers and can be used to complement the grounding design due to their metallic construction. However, an over dependence on helical piles for grounding can be problematic. Helical piles should be bonded to a grounding system but should not be the sole means of dissipating fault currents. Helical piles are typically hollow and galvanized, which may deteriorate quickly.

Utilizing Ground Rods and Other Ground Enhancement Techniques

A common method for grounding transmission towers is to keep adding ground rods to the grounding system until the target resistance is reached. This may not be possible however when space is limited around the tower. Another effective method is to utilize deep driven ground rods to reach lower resistivity soil. The length of the ground rods can be increased with the use of ground rod couplers. The installation depth and total length of the ground rods can be optimized by performing soil resistivity measurements.

Ground rod material selection is important to consider. Galvanized ground rods have a sacrificial layer of zinc protecting the steel core from corrosion. As the coating deteriorates, the steel core is then the next to break down. Another ground rod type is copper-bonded ground rods. They contain a steel core with an electro-plated copper exterior for superior corrosion resistance. Stainless steel ground rods are another ground rod type that is utilized in highly corrosive locations.

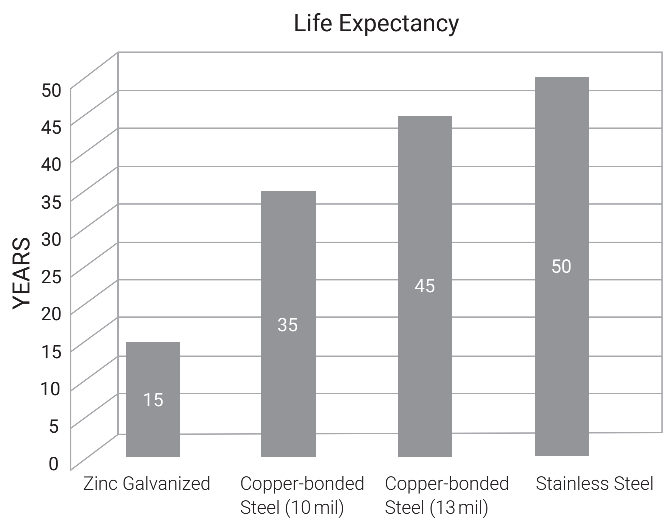


Figure 9: Life expectancy of ground rods

When the ground resistance target cannot be obtained utilizing only ground rods, then further ground enhancement components are used. These methods are often used when the soil resistivity is high or available space for the grounding system is limited.

Ground enhancement materials (GEM) is a conductive material used to lower ground resistance values. GEM is a Portland cement-based product, however, GEM should never be used for structural purposes as it has compressive strength far below what is needed for foundation footings. GEM is maintenance free and corrosion resistant.

Figure 10: An exhumed ground rod in ground enhancement material

Chemical ground rods are an effective way to provide a low impedance to ground in tough such as when rocky soil makes installation difficult to drive standard ground rods and the soil resistivity is sufficiently high. These ground electrodes are constructed with a hollow copper tube with small holes along the entire length. A salt mix are poured inside the tube which then during application interacts with moisture to leach into the earth. The chemical ground rod is typically back filled with ground enhancement material and a Bentonite clay. Pigtails come welded by the manufacturer to the copper tube to bond to the structure needing to be grounded. Chemical ground rods need to be periodically filled with the salt mix to maintain its effectiveness. Because of the cost and maintenance required for chemical ground rods, they are typically not used for transmission line grounding, but can be considered in extreme cases.

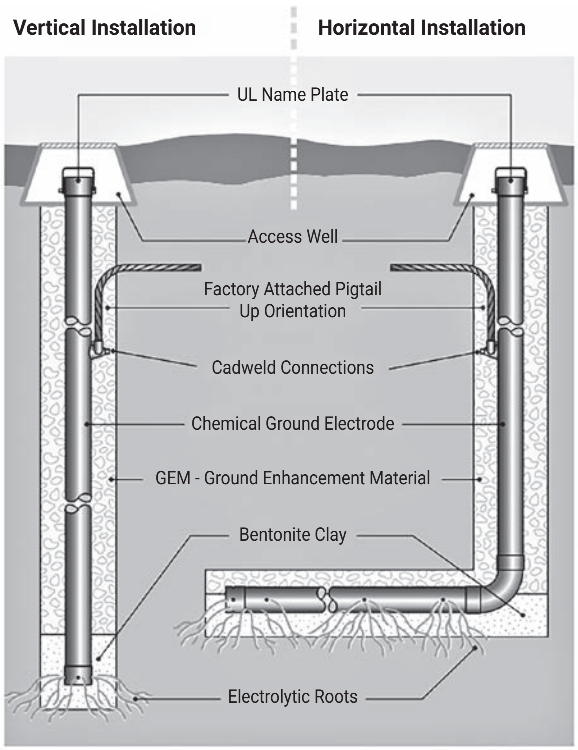


Figure 11: Representation of a chemical ground rod installation

The selection of grounding connectors is crucial to ensuring the longevity of the grounding system. Grounding connectors can be categorized into three types: bolted, compression, and exothermic. Bolted connections, such as acorn clamps or u-bolts, have a low upfront cost and are relatively simple to install. However, these connectors may degrade or loosen quickly due to inadequate surface contact. Alternatively, compression methods—whether achieved through specialized equipment or designed into the connector, such as interference fit or wedge—and exothermic connections provide enhanced surface contact. This improvement in contact quality contributes to an extended lifespan for the grounding system.

Other Grounding Design Techniques

Depending on the voltage level of the transmission systems, there may be different requirements for tower spacing. Higher voltage lines typically will have further spacing between towers. Regardless of tower spacing, to maximize safety it is recommended to provide supplementary grounding at each tower.

Transmission systems are always limited to installing within the easement ("right-of-way") of the lines. At the transmission tower, counterpoise grounding systems is an effective and efficient way to introduce grounding by limiting the grounding system footprint. A series of evenly spaced ground rods and conductors 6–10 feet radially spaced from the tower can be installed around and bonded to the transmission tower. If the target resistance remains high, another series of ground rods and conductors 12–24 feet radially spaced from the tower and bonded to the ground system would then be used. Combining concentric grounding, with other ground enhancement material is an efficient way to ground a system in high resistivity soils.

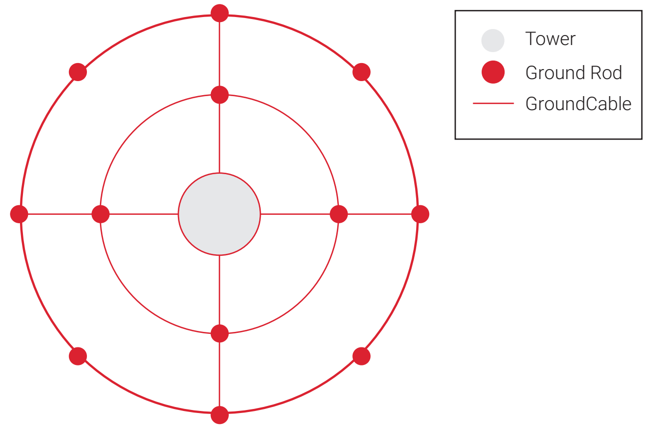


Figure 12: Concentric grounding example

Increasing Dependence on Electricity

There are a growing number of initiatives in the United States to push for more dependence on electricity, such as electric consumer and fleet vehicles, and the switch from gas to electric in common household appliances. According to a 2022 article from the Wall Street Journal [7], most of the transmission and distribution lines are between 25 and 50 years old. Transmission towers across the United States can exceed 50 years before there is consideration to replace - effectively doubling their expected service life. Climate change is increasing lightning activity and storm severity, with weather related outages continuing to grow. High voltage transmission lines are particularly in danger because of common grounding practices omitted at these installations. Transmission lines need to be designed to last a long time, therefore long lasting grounding components should be considered.

High voltage transmission lines can operate at voltages exceeding 345 kV. Transmission tower designs need to consider touch and step potentials when implementing a grounding design. During a fault condition, the tower and the local soil become energized at differing potentials. When the soil resistivity is high, and when there is a lack of grounding bonded to the tower, the faults could present a danger. The touch and step potentials at and around the tower can present a hazard to personnel and the general public. Touch potentials occur when there is a potential difference between where a person is standing and another surface that can be touched. If a person touches a tower that is at a different potential than the surface they are standing on and the potential difference is large enough, then the resulting shock may be fatal. Step potentials can also present a danger at the location around transmission systems. These potential differences occur when the soil under a person's right and left foot are at different potentials. Should the difference be large enough, the person again may experience a shock that could be fatal. Considering a lightning strike dissipating at a transmission tower without additional grounding installed, the potential gradient at the tower is significantly higher the closer you are to the tower and rapidly drops the with distance away. Some common methods to limit touch and step potentials in substation design, such as ground mats, high resistance gloves and shoes, and crushed at the surface, can be implemented at transmission towers to limit the danger. Another common practice is to install and connect counterpoise grounding around the base of the tower to minimize the effects of these potential risks.

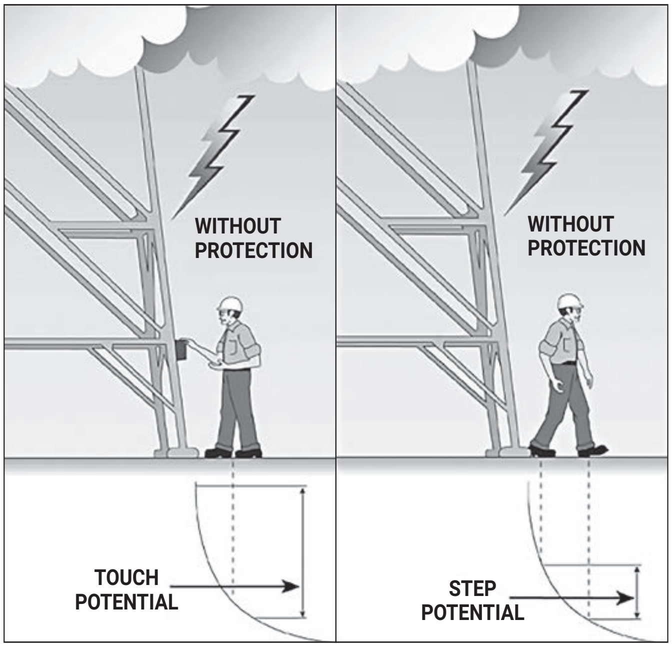


Figure 13 & 14: Touch & Step potential representation

Closing and Recommendations

Given the growing reliance on electricity and the aging transmission infrastructure, it is important to focus on effective grounding techniques for high voltage transmission lines. By utilizing counterpoise grounding and other supplementary grounding techniques to minimize the ground resistance of the transmission line, the risks associated with touch and step potentials can be significantly minimized. Regularly updating and maintaining grounding systems will help ensure the safety of both personnel and the public, as well as improve the reliability of transmission systems in response to climate change and increased lightning activity. Implementing these practices will contribute to a more resilient and secure electrical grid.

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