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How to Measure Ground Resistance and Optimize Grounding Grid

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1. Understanding Ground Resistance

The term ground is specified as a conducting link by which a circuit or device is connected to the earth. The link is used for establishing and keeping as closely as possible the potential of the ground on the circuit or device linked to it. A ground consists of a grounding conductor, a bonding connector, its grounding electrode(s), and the soil which is in contact with the electrode. Grounds have few basic protection applications. For natural phenomena, such as lightning, grounds are used to secure a discharge path for the current to decrease shock hazard to staff and to avoid damage to equipment and property.

For induced potentials due to failures in electric power systems with earth returns, grounds help in ensuring quick operation of the protection relays by giving low resistance fault current paths. This allows clearing the induced potential as fast as possible. The earth has to drain the induced potential before staff is injured and the power or communications equipment is damaged. In ideal conditions, to keep a reference potential for instrument safety, to protect against static electricity, and limit the equipment earth voltage for operator safety, an earth resistance needs to be 0 Ω. However, in reality, this value cannot be reached. Also, low earth resistance is demanded by NEC, OSHA, and other electrical safety codes and regulations.

2. Grounding Electrode Resistance

Grounding rod (electrode) is presented in Figure 1. Grounding resistance is comprised of the following elements:

1. Electrode resistance and resistance of its connection.

2. Ground resistance immediately surrounding the grounding electrode or resistivity of ground. Typically, this is the major factor.

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3. Contact resistance of the surrounding ground to the electrode.

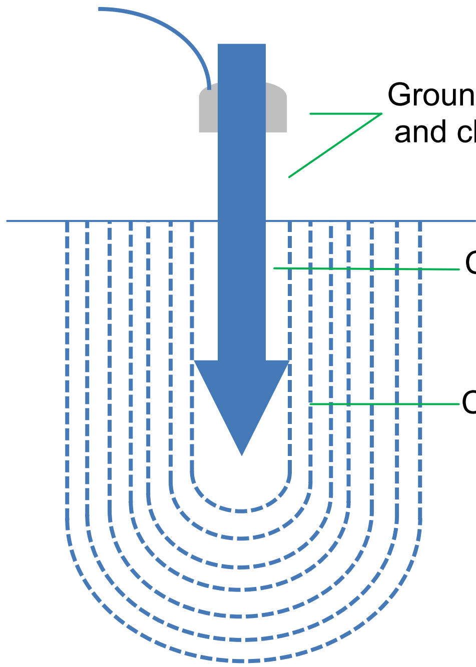

Figure 1. Schematic drawing of grounding electrode

Typically, grounding electrodes are made of a very conductive metal (usually copper or copper clad) with sufficient cross sections so that the overall resistance can be neglected. The resistance between the grounding electrode and the surrounding ground can be neglected if the electrode does not contain paint, grease, or other coating, and if the soil is compactly packed. The only element that remains is the resistance of the surrounding ground. The electrode can be looked at as being surrounded by concentric shells of ground, all of the same thickness. The closer the shell to the grounding electrode, its surface area is smaller. Therefore, its resistance is higher. The farther away the shells are from the grounding electrode, the surface of the shell is bigger. Therefore, the resistance is lower. Finally, adding shells at a distance from the grounding electrode will no longer noticeably impact the total ground resistance surrounding the electrode. The distance at which this effect happens is known as the effective resistance area and it directly depends on the depth of the grounding electrode.

When ground fault current goes from a ground rod to earth, it dissipates in all directions through a series of concentric spheres or shells. These are known as effective cylinders of ground, surrounding the rod. The resistance of the closest sphere to the ground rod is the highest since it is the smallest sphere.

As the distance from the ground rod increases, the resistance becomes lower since the sphere becomes larger. Finally, a distance from the electrode is reached where the sphere resistance becomes zero. Hence, in any ground resistance measurement only the part of ground resistance is considered that contributes a major part of the resistance. In theory, the ground resistance needs to be measured up to infinite distance from the ground rod. Nevertheless, for practical purposes, the effective cylinder of ground (shells) that contributes the major portion of the ground resistance is two times the length of the ground rod. Theoretically, the ground resistance can be calculated using the general equation:

$$R = \rho \frac{L}{A} \qquad (1)$$

Where:

- R is the ground resistance
- ρ is the soil resistivity
- L is the grounding electrode length
- A is the surface area

This equation shows why resistance of concentric ground shells decreases the farther they are from the ground rod:

$$R = Resistivity\ of\ soil \times \frac{thickness\ of\ shell}{area} \qquad (2)$$

In the case of ground resistance, uniform soil resistivity throughout the volume is assumed, even though this is rarely the case in nature. The mathematic formulas for systems of electrodes are very complex and typically expressed only as approximations. The most typically used equation for single-ground electrode arrangement is:

$$R = \frac{\rho}{2\pi L} \times \frac{[(ln4L)-1]}{r} \qquad (3)$$

Where:

- R is the ground rod resistance (Ω)

- L is the length of the grounding electrode

- r is the grounding electrode radius

- ρ is the average soil resistivity(Ω-cm)

3. Effects of Electrode Size and Depth on Grounding Resistance

Size: Increasing the rod diameter does not reduce its resistance. Doubling ground rod diameter decreases resistance by less than 10%, as shown in Figure 2.

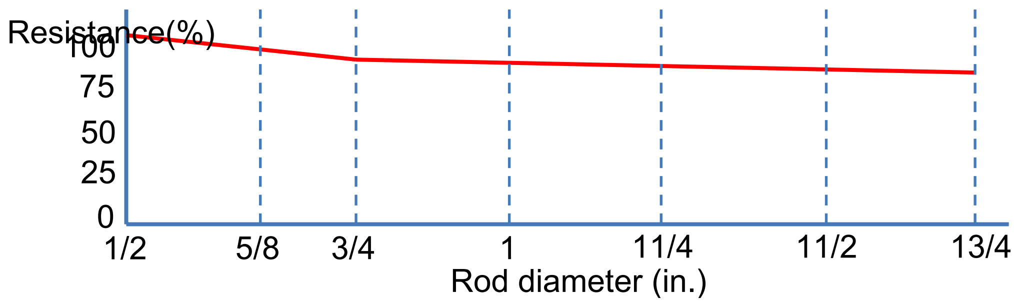

Figure 2. Ground resistance vs. rod diameter

Depth: Since a ground rod is driven deeper into the ground, its resistance is substantially decreased. Typically, doubling the rod length decreases the resistance by extra 40%, as presented in Figure 3. The NEC demands a minimum of 8 ft. (2.4 m) to be in contact with the soil. The most typically used is a 10 ft. (3 m) cylindrical rod which meets the NEC code. A minimum diameter of 5/8 in. (1.59 cm) is needed for steel rods and 1/2 in. (1.27 cm) for copper rods.

Minimum practical diameter for driving limitations for 10 ft. (3 m) rods is 1/2 in. (1.27 cm) in average soil. Also these values can be:

- 3/4 in. (1.91 cm) in hard soil or more than 10 ft. driving depths

- 5/8 in. (1.59 cm) in moist soil

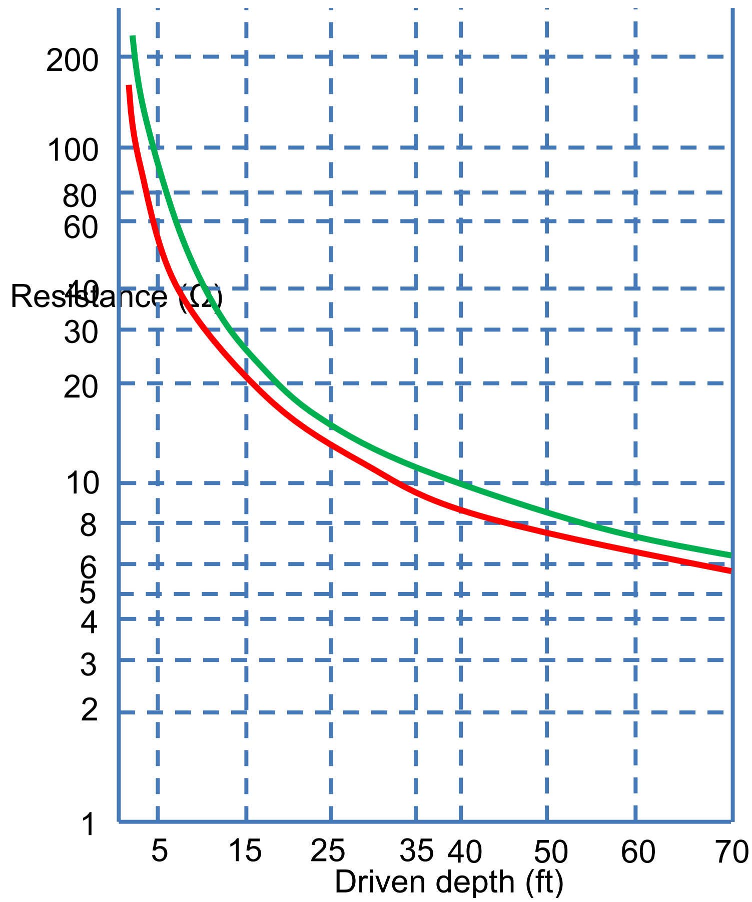

Figure 3. Ground resistance vs. depth of ground rod

4. Soil Resistivity Effect on Ground Electrode Resistance

Resistance of grounding electrodes depends not only on the depth and surface area of grounding electrodes, but also on soil resistivity. Soil resistivity is the major factor that affects what the resistance of a grounding electrode will be, and to what depth it must be driven to get low ground resistance. The soil resistivity changes widely throughout the world and changes seasonally. Soil resistivity is largely affected by its content of electrolytes that consist of moisture, minerals, and dissolved salts. A dry soil has big resistivity if it contains no soluble salts, as indicated in Table 1.

Table 1. Cross comparison of different soil resistivity

	Resistivity (Ω-cm)		
	Minimum	Average	Maximum
Loam, gumbo, clay	340	4060	16300
Cinders, waste, ashes, brine	590	2370	7000

Same, with varying proportions of sand and gravel	1020	15800	135000
Gravel, sand, stones with little clay or loam	59000	94000	458000

5. Factors that Affect Soil Resistivity

Two soil samples, when completely dry, can become very good insulators, having a resistivity higher than 109 Ω-cm. Soil sample resistivity changes fast until roughly 20% or higher moisture content is reached as shown in Table 2. The soil resistivity is also affected by temperature. Table 3 presents the variation of resistivity of sandy loam that contains 15.2% moisture, with temperature changes from 20°C to –15°C. Resistivity changes from 7,200 to 330,000 Ω-cm in this temperature range. Since soil resistivity directly relates to moisture content and temperature, it can be assumed that the resistance of any grounding system will change throughout the different seasons of the year. These variations are presented in Figure 4.

Table 2. Moisture effects on soil resistivity

Moisture content (% by weight)	Resistivity (Ω-cm)	
	Top soil	Sandy Loam
0	<109	<109
2.5	250000	150000
5.0	165000	43000
10.0	53000	18500
15.0	19000	10500
20.0	12000	6300
30.0	6400	4200

Table 3. Temperature effects on soil resistivity

Temperature		Resistivity (Ω-cm)
°C	°F	
20	68	7200
10	50	9900
0	32 (water)	13800
0	32 (ice)	30000
-5	23	79000
-15	14	330000

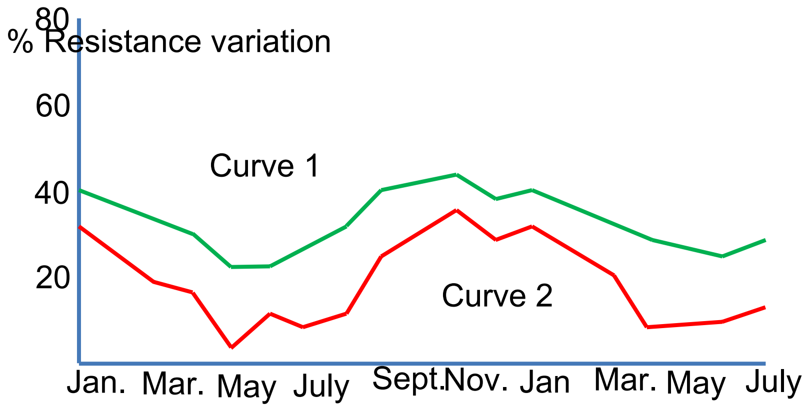

Figure 4. ¾ in electrode ground resistance seasonal change. Depth of electrode in ground is 3ft. for curve 1, and 10ft. for curve 2

Since temperature and moisture content are more stable at greater distances below the ground surface, it means that a grounding system needs to be made with the ground rod driven down a considerable distance below the surface of the ground. The best results are obtained if the ground rod reaches the water table.

In certain areas, ground resistivity is so high that low-resistance grounding can be accomplished only at high expense and with an elaborate grounding arrangement. In these cases, it may be beneficial to use a ground rod system of limited size and to decrease the ground resistivity by periodically increasing soil soluble chemical content. Table 4 presents the substantial resistivity reduction of sandy loam by an increase in chemical salt content.

Table 4. Impact of salt content on the soil resistivity

Added salt (% by weight of moisture)	Soil resistivity (Ω-cm)
0	10700
0.1	1800
1	460
5	190
10	130
20	100

Chemically treated soil is also exposed to considerable change of resistivity with temperature variations, as presented Table 5. If salt treatment is used, it is mandatory to use ground rods that can resist corrosion.

Table 5. Temperature impact on the resistivity of soil containing salt

Temperature (°C)	Soil resistivity (Ω-cm)
20	110
10	142
0	190
-5	312
-13	1440

6. Impact of Ground Electrode Depth on Resistance

In determining the approximate ground rod depth needed to get a desired resistance, a grounding nomograph can be used. The nomograph, presented in Figure 5, shows that to get a grounding resistance of 20 Ω in a soil with a resistivity of 10,000 Ω-cm, a 5/8 in. OD rod needs to be driven 20 ft. Values shown on the nomograph are based on the assumption that the soil is homogenous and, hence, has uniform resistivity. The nomograph value is a rough approximation.

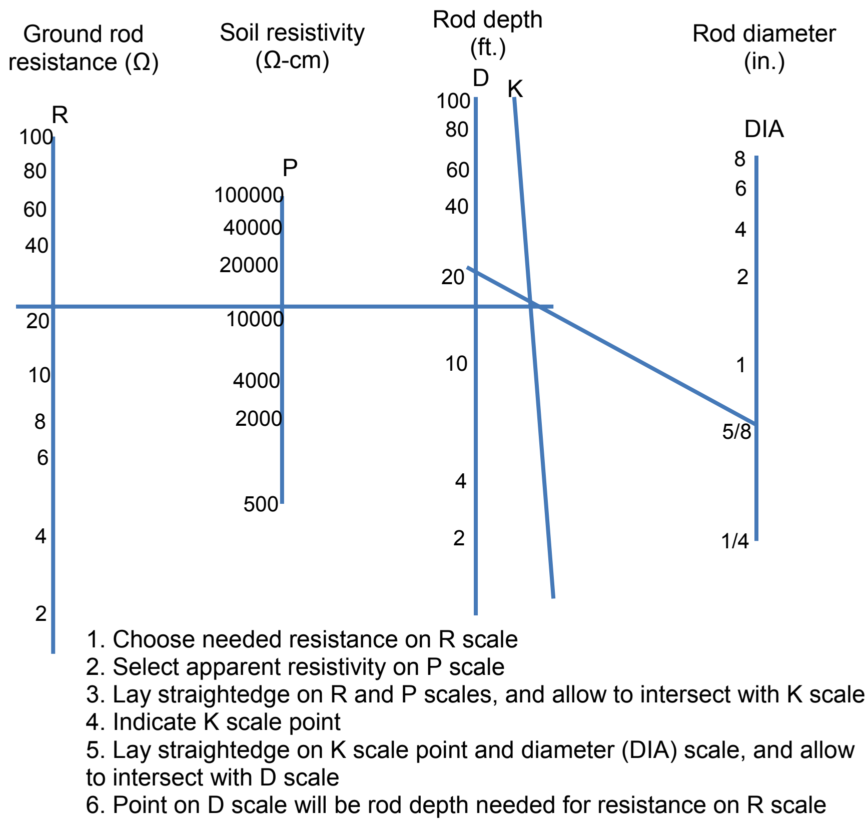

Figure 5. A nomograph displaying ground electrode depth versus ground electrode resistance

7. Ground Resistance Values

The NEC code suggests that the resistance to ground shall not surpass 25 **Ω**. This is the maximum value of ground resistance and in most situations considerably lower ground resistance is needed.

"How low a ground resistance needs to be?" An answer to this question is rather difficult. The lower the ground resistance, the safer, and for adequate protection of staff and equipment, it is worth the effort to go for less than 1 **Ω**. Typically, it is not practical to reach such a low resistance along a distribution system or a transmission line or in small substations. In certain areas, resistances of 5 **Ω** or less may be reached without any issues. In other locations, it may be challenging to lower resistance of driven grounds below 100 **Ω**.

Relevant industry standards suggest that transmission substations need to be designed not to surpass 1 Ω resistance. In distribution substations, the maximum suggested resistance is 5 Ω or even 1 Ω. In majority of applications, the buried grid system of any substation will provide the needed resistance. In light industrial or in telecommunication central offices, 5 Ω is typically sufficient value. For lighting protection, the arrestors need to be coupled with a maximum ground resistance of 1 Ω. Table 6 presents typical ground resistance values for different installation types.

Table 6. Typical grounding resistance values for different installation types

Installation	Type	Substation maximum grounding resistance values (directly grounded systems)
Commercial	Metallic buildings	≤25 Ω (per NEC)
	Wet wells, etc.	
	Homes	
Utilities	Generating stations	1 Ω*
	Large substation	1 Ω
	District substations	1.5-5 Ω
	Small substations	5 Ω
Industrial	General facilities	5 Ω
	Chemical	3 Ω
	Computer	<1-3 Ω
	High-speed loading facilities for chemical	<1 Ω

Grounding parameters can typically be met with the correct application of basic grounding theory. However, there will always be situations which will make it challenging to obtain the ground resistance demanded by the NEC or other safety regulations. In such situations, several techniques for lowering the ground resistance can be used. These include parallel rod systems, deep-driven rod systems using sectional rods and chemical soil treatment. Other techniques include buried plates, buried conductors, electrically connected building steel, and electrically connected concrete reinforced steel. Electrically connecting to water and gas distribution network was typically considered to yield low ground resistance. Nevertheless, recent design modifications utilizing non-metallic pipes and insulating joints have made this technique questionable and, in many situations, unacceptable.

8. Measurement of Ground Resistance

To keep sufficiently low resistance values of grounding systems, periodic inspection is needed. Inspection involves measurement to make sure that they do not surpass design limits. Ground and soil resistance and measurement techniques are:

- Two-point method
- Fall-of-potential method
- Three-point method
- Four-point method
- Clamp-on method
- Ratio method
- Touch potential measurements

Ground resistance measurement can only be done with specially designed test devices. The typical technique for measuring ground resistance uses the fall-of-potential method of alternating current of 60 Hz or some higher frequency that circulates between an auxiliary electrode and the ground electrode that is tested. The reading will be provided in ohms and represents the resistance of the ground electrode to the surrounding soil.

9. Two-Point Method

This technique can be used to measure the resistance of a single driven ground rod. It uses an auxiliary ground rod. Its resistance is known. The resistance value of the auxiliary ground rod also must be very small in comparison with the resistance of the driven ground rod so that the measured value can be assumed to be wholly contributed by the driven ground rod. For instance, this method is applicable for resistance measurement in the case of residential buildings in congested areas where finding space to drive two auxiliary rods may be an issue.

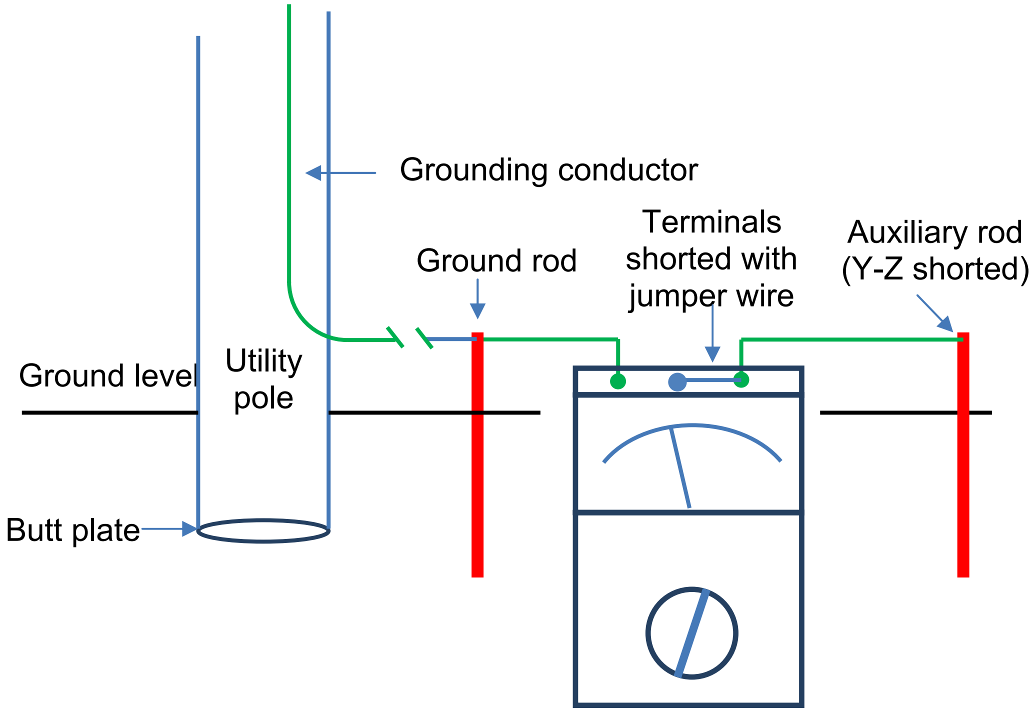

Figure 6. Two-point ground resistance measurement technique

In this particular arrangement, metallic water supply line can be treated as the auxiliary ground rod with resistance value of 1 Ω or less. This value is rather small in comparison to the value of a single driven ground rod. Its resistance is in the order of 25 Ω. The reading obtained is that of the two grounds in series. The lead resistances will also be measured and it needs to be subtracted from the overall measurements. This technique is typically appropriate in situations when a go, no-go type of test is needed. The connections for this test technique are presented in Figure 6.

10. Three-Point Method

This technique is very similar to the two-point technique except it uses two auxiliary rods. To get precise values of resistance measurements, the resistance of the auxiliary electrodes needs to be roughly equal to or less than that of the tested electrode. The connections for the three-point method are shown in Figure 7.

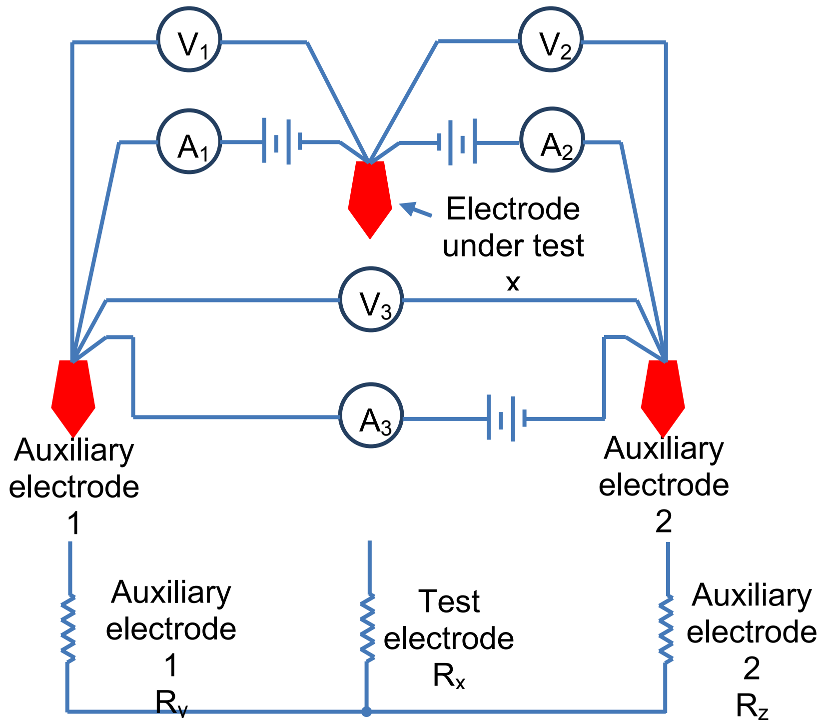

Figure 7. Three-point test technique and its equivalent network

AC (60 Hz) or DC can be used for this test. The benefit of using AC is that it minimizes the impacts of stray currents on measurement readings. Nevertheless, if stray currents have the same frequency, there will be an error. The use of DC current for this test will completely eliminate the AC stray currents. Nevertheless, stray DC and formation of gas around the electrodes will generate reading error when using DC for this test. The impact of stray DCs can be lowered by taking readings with current in the opposite direction. The average of the two readings will provide correct test value. Currents should be applied only long enough to collect readings. The test electrode resistance can be computed as:

$$R_1 = R_x + R_y = \frac{V_1}{A_1}$$

$$R_2 = R_x + R_z = \frac{V_2}{A_2}$$

$$R_3 + R_y + R_z = \frac{V_3}{A_3}$$

After these three formulas are solved, following is obtained:

$$R_y = R_3 - R_z$$

$$R_x = R_1 - R_y = R_1 - R_3 + R_z$$

Also:

$$R_x = R_2 - R_z$$

For which

$$2R_x = R_1 + R_2 - R_3$$

Or

$$R_x = \frac{R_1 - R_2 - R_3}{2}$$

11. Fall-of-Potential Method

This technique measures grounding electrode resistance based upon the principle of potential drop across the resistance. This technique also uses two auxiliary electrodes (one current rod and a potential rod) that are installed with sufficient spacing from the test electrodes. A current of known magnitude is injected in the tested electrode and one of the auxiliary electrodes (current rod). The drop in potential between the tested electrode and the second auxiliary electrode (potential rod) is obtained. The ratio of voltage drop (V) to the known current (I) will show grounding circuit resistance. DC or AC voltage sources can be used for this test. Few issues and errors may be encountered with this technique, such as

- Stray currents in ground may cause voltmeter readings to be either high or low

- Resistance of auxiliary electrode and electrical leads may introduce errors in the voltmeter reading. This error can be decreased by using a voltmeter with high impedance. This technique can be used with either a separate voltmeter and ammeter or a single device that gives a reading directly in ohms. To measure grounding electrode resistance, the current electrode is installed at a suitable distance from the tested grounding electrode. As presented in Figure 8, the potential difference between rods X and Y is measured by a voltmeter, and the current flow between rods X and Z is measured by an ammeter. Using Ohm's law E = RI or R = E/I. Ground electrode resistance R, can be calculated using this formula. If E = 30 V and I = 1 A, then

$$R = \frac{E}{I} = \frac{30}{1} = 30\Omega$$

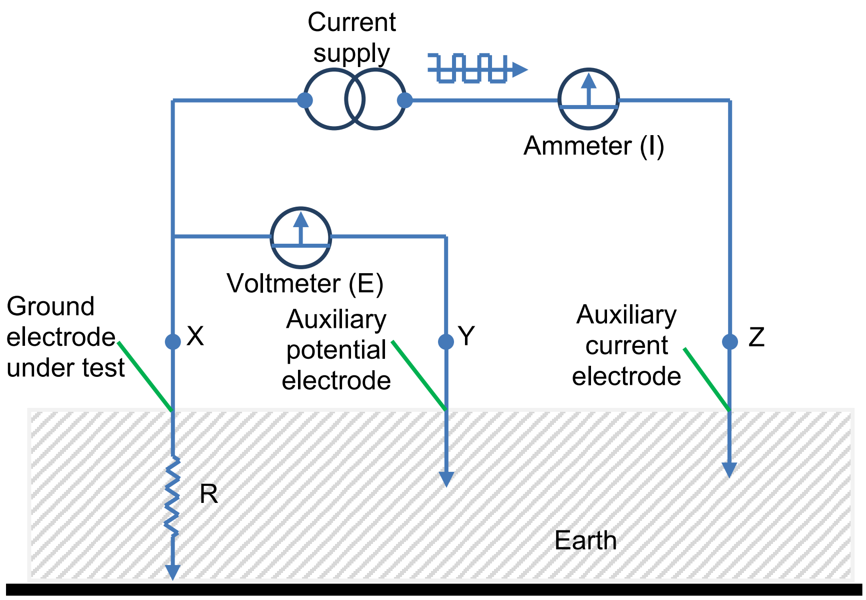

Figure 8. Fall of potential technique

12.Auxiliary Electrodes Positions during Measurements

Installing the auxiliary current electrode Z far enough from the tested ground electrode so that the auxiliary potential electrode Y will be outside of the effective resistance areas (effective cylinder of ground) of both the ground electrode is the main issue in precisely measuring the resistance to ground.

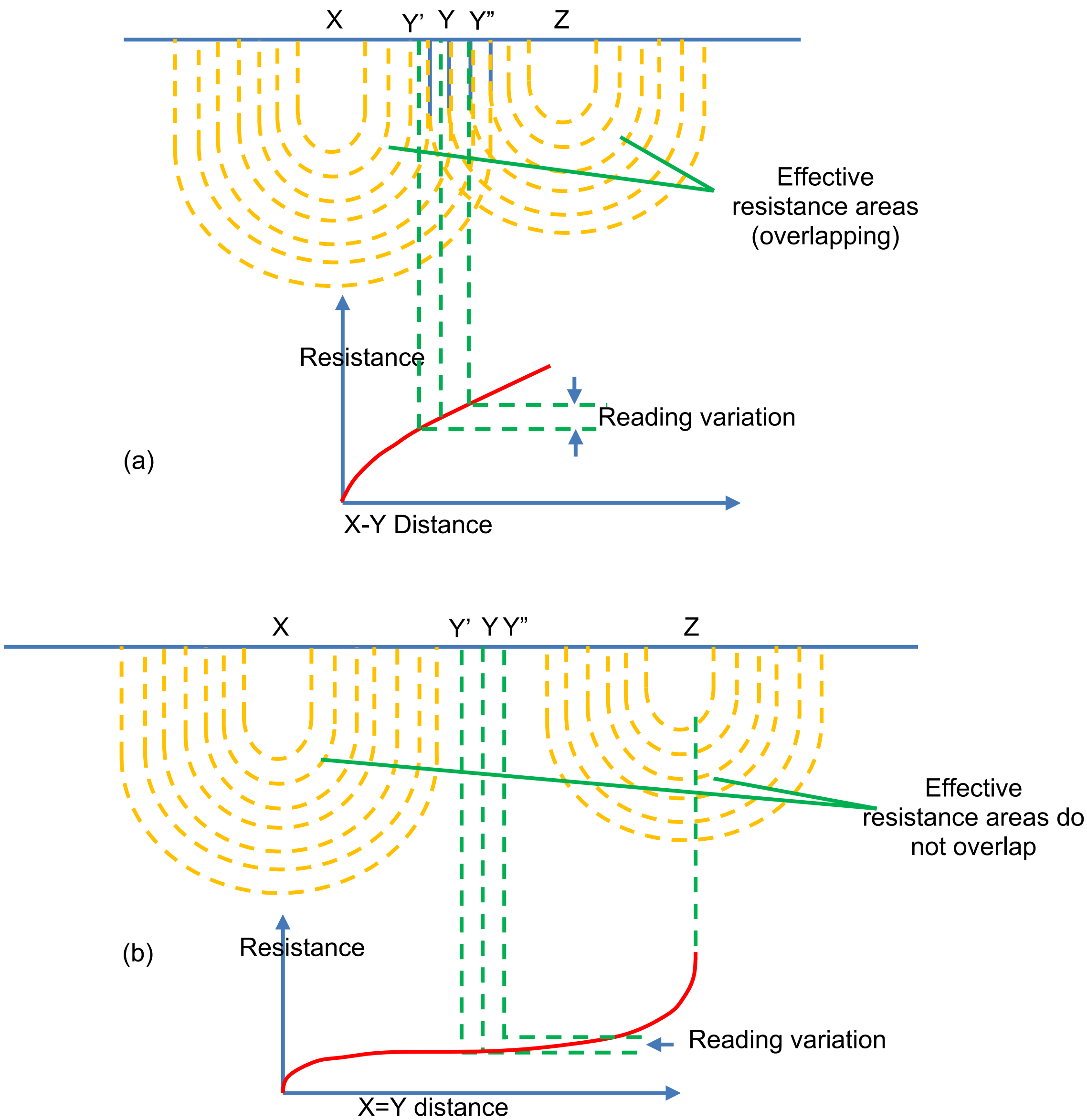

Figure 9. Effective resistance areas (cylinders of ground) (a) overlapping and (b) not overlapping

The most effective method to determine if the auxiliary potential rod Y is outside the effective resistance areas is to move it between X and Z and to record measurement at each location. In the case auxiliary potential rod Y is in an effective resistance area (or in both in the case they overlap as in Figure 9 (a)), by displacing it collected readings will noticeably differ. In this situation, no exact value for the resistance to ground may be determined. In the case auxiliary potential rod Y is located outside of the effective resistance areas, as shown in Figure 9 (b), as Y is moved back and forth the reading change is minimal.

Collected readings should be relatively close to each other, and are the best values for the resistance to ground of the ground X. Collected readings need to be plotted to make sure that they lie in a "plateau" region as displayed in Figure 9 (b). The region is typically referred to as the 62% area.

13. Ground Electrode Resistance Measurement (62% Technique)

The 62% technique is an extension of the fall-of-potential technique and has been adopted after graphical consideration and after real measurement. It is the most precise technique but is limited by the fact that the tested ground is a single unit. This technique applies only when all three electrodes are in a straight line and the ground is a single electrode, pipe, or plate as presented in Figure 10.

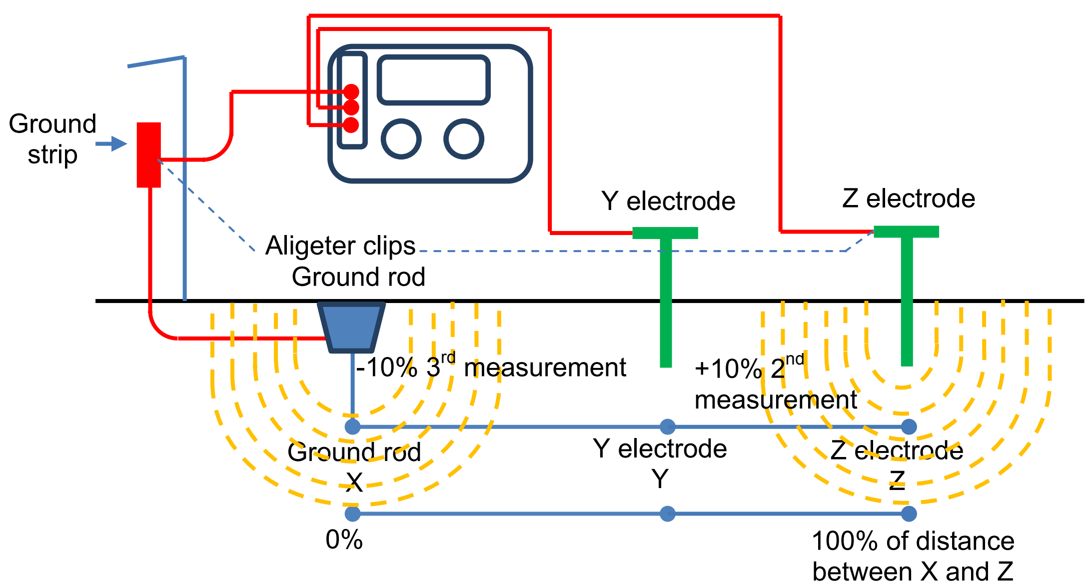

Figure 10. Fall of potential technique displaying potential rod location at 62% distance from the tested electrode

Let us observe Figure 11, which displays the effective resistance areas (concentric shells) of the ground electrode X and of the auxiliary current electrode Z. The effective cylinders of earth of the X and Z rods do overlap. If readings were collected by moving the auxiliary potential electrode Y toward either X or Z, the reading differences would be high and one could not get a reading within a reasonable tolerance band.

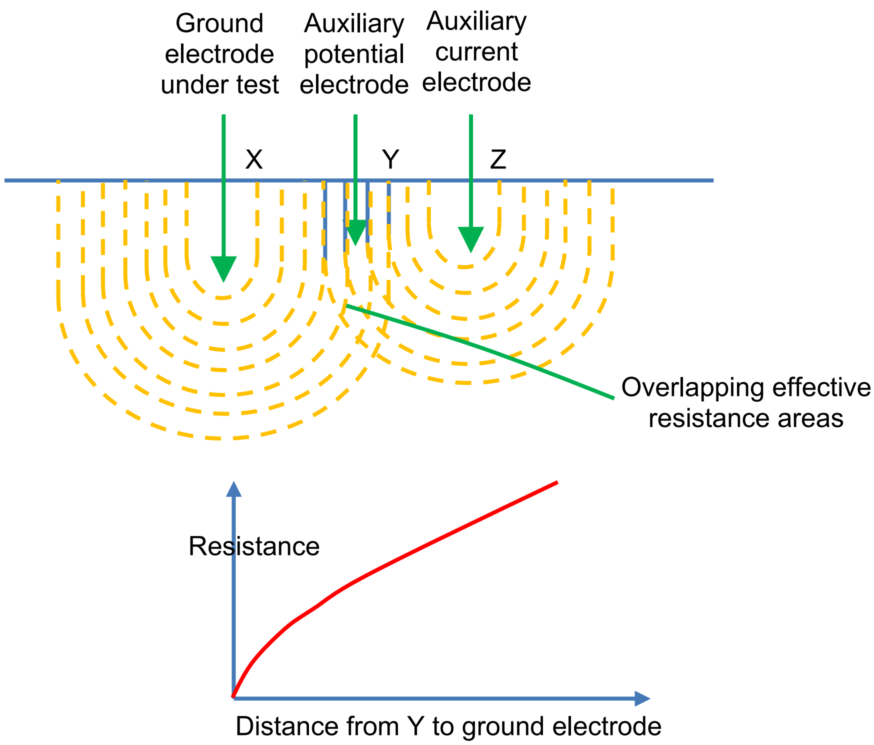

Figure 11. Effective resistance areas overlap

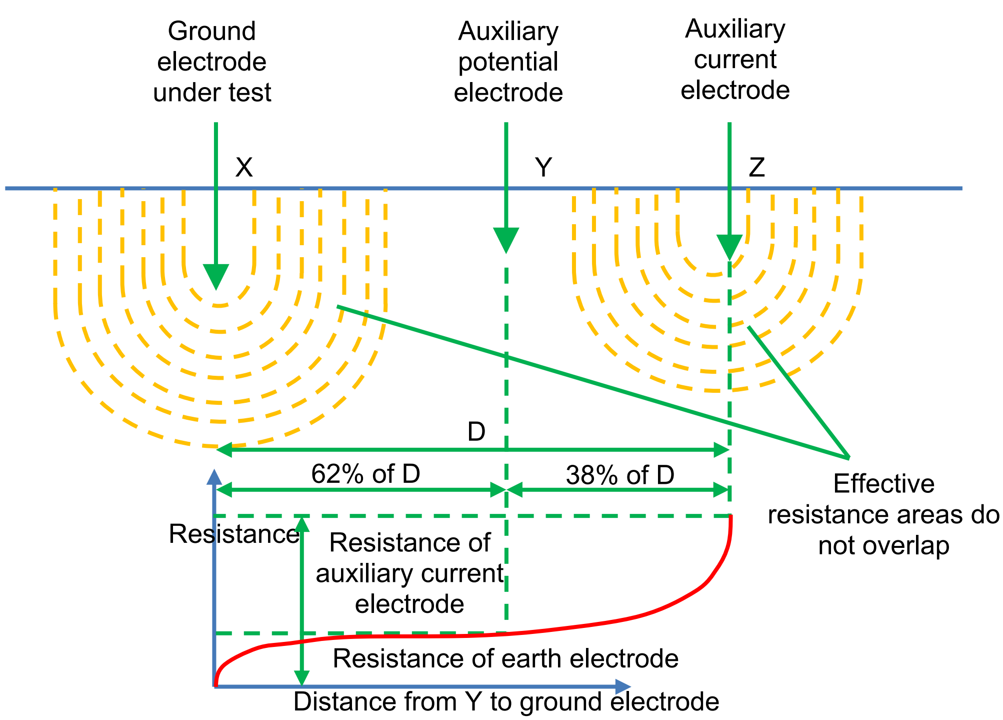

Figure 12. Effective resistance areas do not overlap

The sensitive areas overlap and constantly tend to increase resistance as Y is moved away from X. Now let us consider Figure 12, where the X and Z electrodes are considerably spaced so that the areas of effective resistance do not overlap. In the case collected resistance reading is plotted, the measurements level off when Y is installed at 62% of the distance from X to Z, and that the readings on either side of the initial Y setting are most likely to be within the established tolerance band. This tolerance band is determined by the user and shown as a percent of the first reading: ±2%, ±5%, ±10%, etc.

14.Spacing of Auxiliary Electrodes

No definite distance between X and Z can be provided, since this distance is relative to the diameter of the tested electrode, its length, the homogeneity of the tested soil, and especially, the effective resistance areas. Nevertheless, rough distance may be obtained from Table 7, which is provided for a homogeneous soil and an electrode of 1 in. in diameter. It is suggested that the ground electrode resistance test is completed for each season of the year. Collected reading should be retained for each season for cross comparison and assessment. Considerable deviation of the test data from previous years, other than seasonal variations, could indicate electrode corrosion.

Table 7. Rough distance (ft.) to auxiliary electrodes using the 62% technique

Driven depth	Distance to Y	Distance to Z
6	45	72
8	50	80
10	55	88
12	60	96
18	71	115
20	74	120
30	86	140

15.Multiple Electrode Arrangement

A single driven ground electrode is an economical and straightforward technique of making a good ground arrangement. However, sometimes a single rod will not give low resistance. In those situations, several ground electrodes should be driven and connected in parallel by a cable. When two, three, or four ground electrodes are used, they are driven in a straight line. When four or more are used, a hollow square arrangement is used and the ground electrodes are connected in parallel and equally spaced as presented in Figure 13. In multiple electrode systems, the 62% technique electrode spacing may no longer be directly used (as shown in Table 8). In this situation, the distance of the auxiliary electrodes is based on the maximum grid distance.

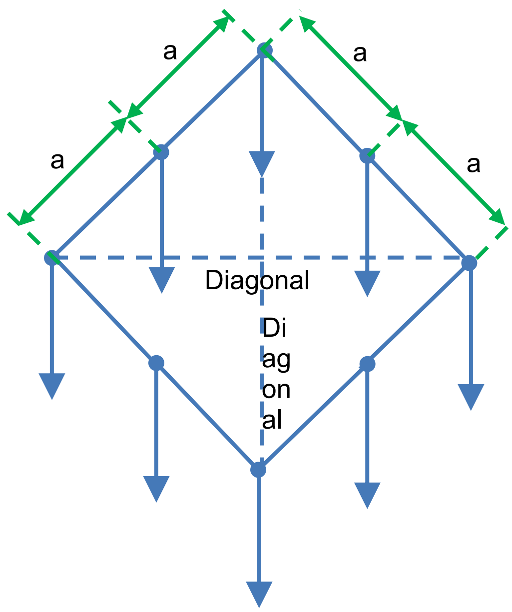

Figure 13. Multiple electrode system (ground grid)

Table 8. Multiple electrode system distance (ft.)

Maximum grid Distance	Distance to Y	Distance to Z
6	78	125
8	87	140
10	100	160
12	105	170
14	118	190
16	124	200
18	130	210
20	136	220
30	161	260
40	186	300
50	211	340
60	230	370

80	273	440
100	310	500
120	341	550
140	372	600
160	390	630
180	434	700
200	453	730

16.Excessive noise

Excessive noise may interfere with testing process since long leads are used to perform a fall-of-potential test. A voltmeter can be used to discover this problem. X, Y, and Z cables need to be connected to the auxiliary electrodes as for a standard ground resistance test. Voltmeter needs to be used to test the voltage across terminals X and Z as presented in Figure 14.

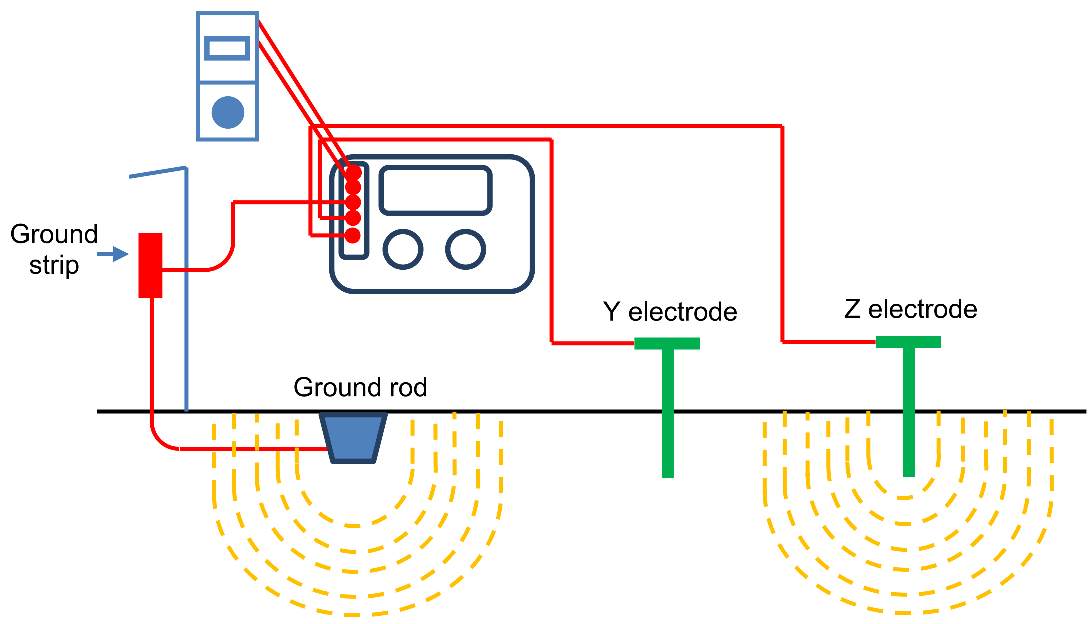

Figure 14. Stray voltage inspection

Collected reading needs to be within the stray voltage tolerances that are acceptable to the used ground tester. If the test surpasses this figure, following should be tried:

1. Braid the auxiliary cables together. Typically, this has the effect of cancelling out the common mode voltages between two conductors.

2. If the previous technique does not give results, try changing the alignment of the auxiliary cables so that they are not parallel to power lines above or below the earth.

3. In the case a satisfactory low voltage value is still not obtained, application of shielded cables may be needed. The shield acts to protect the inner conductor by capturing the voltage and draining it to ground, as presented in Figure 15.

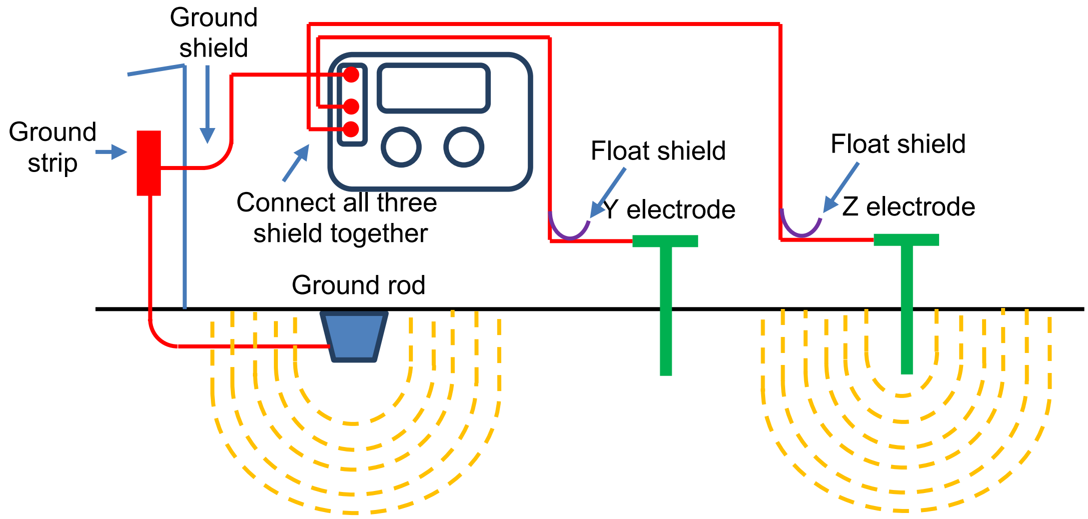

Figure 15. Application of shielded cables to minimize stray voltages

17.Excessive resistance of auxiliary rod

The inherent feature of a fall-of-potential ground testers is to inject a constant current into the ground and measure the voltage drop by means of auxiliary electrodes. Extra resistance of one or both auxiliary electrodes can inhibit this function. This is caused by high soil resistivity or poor contact between the auxiliary electrode and the surrounding dirt. To make sure proper contact with the ground is established, stamp down the soil directly around the auxiliary electrode to remove air gaps that are made when installing the rod. In the case soil resistivity is an issue, pour water around the auxiliary electrodes. This decreases the auxiliary electrode's contact resistance without impacting the measurement process and accuracy.

18.Tar or concrete mat

In some situations test must be completed on a ground rod that is surrounded by a tar or concrete mat. In those cases auxiliary electrodes cannot be installed easily. If such situation is encountered, metal screens and water can be used to replace auxiliary electrodes, as presented in Figure 16.

Put the screens on the floor at the same distance from the tested ground rod as you would put auxiliary electrodes in a standard fall-of-potential test. Pour water on the screens and let it soak in. These screens will complete the same function as would driven auxiliary electrodes.

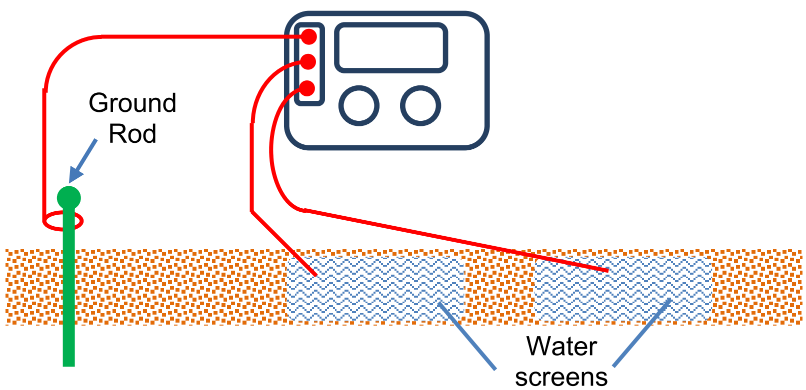

Figure 16. Application of screens as auxiliary electrodes

19.Ratio Technique

This technique uses a Wheatstone bridge or an ohmmeter to measure the grounding and auxiliary electrodes' series resistance. The test connections are presented in Figure 17. A slide wire potentiometer is used with a Wheatstone bridge for this test. The potentiometer is installed across the tested grounding electrode and the first auxiliary electrode. The potentiometer's sliding contact is connected to the second auxiliary electrode through a detector for recording the null point. The test and auxiliary electrodes' resistance is measured first by the Wheatstone bridge or ohmmeter. Then, using the potentiometer and Wheatstone bridge, a new null point is determined with the second electrode in the test circuit. Grounding electrode resistance is the ratio of the test electrode resistance to the total resistance of the two in series. The process and formulas are as follows:

1. Measure Rx + Ry by means of a Wheatstone bridge or ohmmeter

2. Calculate from the potentiometer the ratio of RA/(RA + RB)

3. Install second auxiliary electrode (Rz) in test circuit and get null point

$$\frac{R_x}{R_A} = \frac{R_x + R_y}{R_A + R_B} \quad or \quad R_x = (R_x + R_y)\left(\frac{R_A}{R_A + R_B}\right)$$

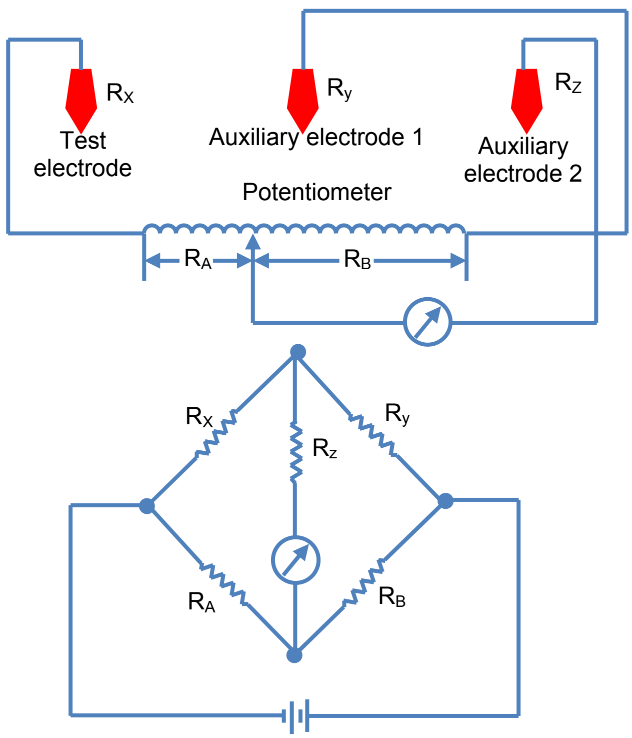

Figure 17. Ground resistance ratio measuring technique

20.Four-Point Soil Resistivity Measurement Technique

The objective of soil resistivity measurements is threefold. First, such information is used to make subsurface geophysical surveys as an aid in identifying ore areas, depth to bedrock, and other geological characteristics. Second, resistivity has a direct effect on the corrosion degree of underground pipelines. A decrease in resistivity relates to an increase in corrosion activity. Hence, it dictates the protective treatment that needs to be used. Third, soil resistivity directly impacts the design of a grounding arrangement. When designing an extensive grounding arrangement, it is suggested to locate the area of lowest soil resistivity in order to get the most economical grounding installation.

The two methods of resistivity measurements are two-point technique and four-point technique. The two-point technique is simply the resistance measured between two points. For most usages, the most precise technique is the four-point technique. The four-point technique, as the name suggests, requires the installation of four equally spaced, and in-line, electrodes into the test location. A known current from a constant current generator is passed between the outermost electrodes. The potential drop is then measured across the two innermost electrodes. The ground resistivity is determined with the equation given below and the meter is calibrated to read directly in ohms. This value is the ground average resistivity at a depth equivalent to the distance A between two electrodes.

$$\rho = \frac{4\pi AR}{1 + \left(2A/\left(\sqrt{A^2 + B^2}\right)\right) - \left(2A/\left(\sqrt{4A^2 + 4B^2}\right)\right)}$$

Where:

- A is the spacing between the electrodes (cm)
- B is the electrode depth (cm)
- R is the ohmic value as measured by four-terminal ground tester

In the case, A > 20B, the equation becomes:

$$\rho = 2\pi AR \quad (with\ A\ in\ cm)$$

$$\rho = 191.5AR \quad (with\ A\ in\ ft)$$

$$\rho = soil\ resistivity\ (\Omega - cm)$$

21. Touch Potential Measurements

The main reason for completing ground resistance measurements is to provide electrical safety for personnel and equipment. Occasional ground electrode or grid resistance inspections are suggested when:

1. The electrode/grid is rather small and can be conveniently disconnected

2. Corrosion caused by low soil resistivity or galvanic action is suspected

3. Ground faults are unlikely to happen near the tested ground

In certain situations, the degree of electrical safety can be assessed from a different perspective. Voltage gradient are a safety issue in large high voltage switchyards and substations. Hence, the ground grid arrangement of these facilities is made to make sure that the voltage gradients due to induced or fault currents stay at low value and not introduce a danger to staff or equipment. The maximum voltage limit for these gradients is determined in terms of the following:

Touch potential: Touch potential is the voltage difference between a person's arm and the feet, created by the voltage gradient due to fault or induced current. It is believed that the current goes through the heart and hence this potential needs to be kept near zero to safeguard personnel who might come in contact with equipment and structures in a switchyard or substations.

Step potential: Step potential is the voltage difference between a person's feet, created by the voltage gradient due to fault or induced current. It is believed that the current goes through the legs and hence this potential needs to be kept near zero to safeguard staff. Touch potential measurements are suggested when the following factors are present.

1. It is impossible to disconnect the ground to be inspected.

2. Ground faults could reasonably be expected to happen near the ground to be tested, or near equipment grounded by the ground to be tested.

3. The footprint of grounded equipment is comparable to the size of the ground to be tested. (The footprint is the outline of the part of equipment in contact with the ground.)

When doing touch potential inspections, a four-pole ground resistance tester is used. During the inspection, the instrument creates a low-level fault into the ground at some proximity to the subject ground. The instrument shows touch potential in volts per ampere of fault current. The displayed figure is then multiplied by the highest expected ground fault current to get the worst case touch potential for a given arrangement. For example, if the instrument showed a figure of 0.100 when connected to a system where the maximum fault current was anticipated to be 5000 A, the maximum touch potential would be 500 V. Touch potential inspections are similar to fall-of-potential measurements in that both measurements demand installation of auxiliary electrodes into or on the ground. Spacing the auxiliary electrodes during touch potential inspections differs from fall-of-potential electrode spacing, as presented in Figure 18.

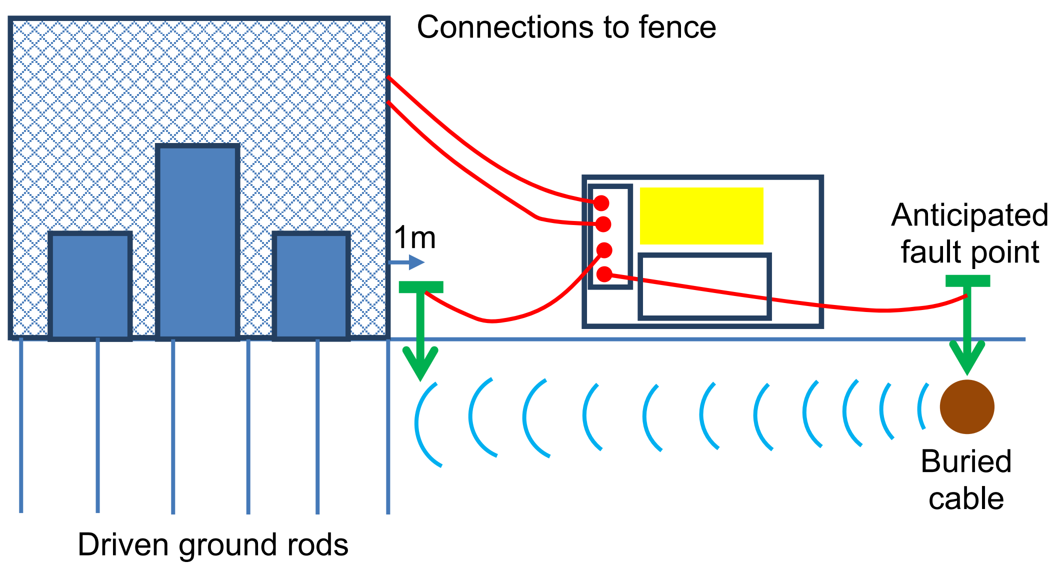

Figure 18. Touch potential inspections

Case Scenario: In the case buried cable shown in Figure 18 experienced an insulation breakdown near the substation, fault currents would go through the ground toward the substation ground, producing a voltage gradient. It may be dangerous or potentially lethal to staff who came in touch with the affected ground. To examine approximate touch potential values in this case, following needs to be done. Connect cables between the substation fence and C1 and P1 of the four-pole ground resistance tester. Place an electrode in the ground at the point at which the ground fault is expected to happen, and connect it to C2. In a straight line between the substation fence and the expected fault location, place an auxiliary electrode into the ground 1 m away from the substation fence, and connect it to P2. Switch on the instrument, select the 10 mA current range, and look at the measurement. Multiply the displayed reading by the maximum fault current of the expected fault. By installing the P2 electrode at different positions around the fence adjacent to the expected fault line, a voltage gradient map may be obtained.

22. Clamp-On Ground Resistance Measurement

This measurement technique is new and relatively unique. It provides the possibility to measure the resistance without disconnecting the ground. This measurement technique also offers the benefit of including the bonding to ground and the overall grounding connection resistances.

23. Operation Method

Typically, a grounded distribution line can be presented as a simple circuit as displayed in Figure 19, or an equivalent circuit as displayed in Figure 20. In the case voltage E is applied to any measured grounding pole R_x through a special transformer, current travels through the circuit, establishing the following formula:

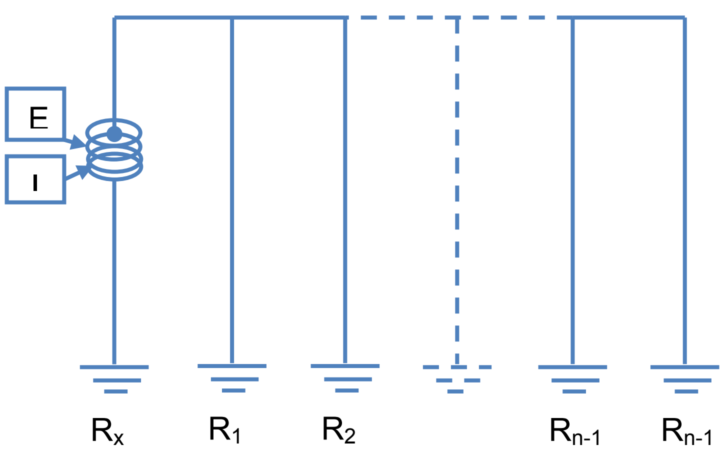

Figure 19. Simple circuit of grounded distribution system

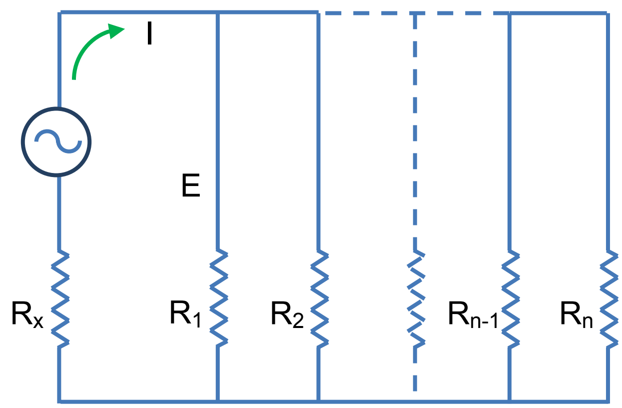

Figure 20. Equivalent circuit of grounded distribution system

$$\frac{E}{I} = R_x + \frac{1}{\sum_{k=1}^{n}(1/R_k)}$$

where typically:

$$R_x \gg \frac{1}{\sum_{k=1}^{n}(1/R_k)}$$

Hence, $E/I=R_x$ is established. If current is discovered while E is kept constant, measured grounding pole resistance can be measured. Please, observe Figures 19 and 20. Current is directed to a special transformer via a power amplifier from a 1.6 kHz constant-voltage oscillator. Current is sensed by a detection current transformer (CT). Only the 1.6 kHz signal frequency is amplified by a filter amplifier before being directed into analog/digital (A/D)-converter, and after synchronous rectification it is shown on the LCD screen.

The filter amplifier is used to cut off ground current at commercial frequency and high-frequency noise. Voltage is sensed by coils placed around the injection CT and then amplified and rectified to be cross compared by a level comparator.

24.Field Measurements

Following section discussed ground resistance measurements in field:

Pole-mounted transformer: Remove any protection covering the ground conductor, and make adequate space for the jaws of the clamp-on ground tester. The jaws must be securely closed around the ground conductor. The jaws can also be put around the ground rod itself.

Note: The clamp must be installed so that the jaws are in electrical path from the system neutral or ground wire to the ground rod or rods. Clamp onto the ground conductor and measure the ground current. Typically, the maximum range is 30 A. If the ground current surpasses 30 A, ground resistance measurements cannot be done and there is no need to proceed with any further measurements. Once ground current is measured, choose the ground resistance range Ω and measure the resistance directly. Measurement reading does not only indicate rod resistance, but also resistance of the connection to the system neutral and all bonding connections between the neutral and the rod. Note that in Figure 21, there is a butt plate and a ground rod. In this arrangement, it is mandatory to install the tester jaws above the bond so that both grounds are included in the test.

Note: A high resistance reading suggests one or more of the following: Poor ground rod. Open ground conductor. High resistance bonds on the rod or splices on the conductor; and hammer-on connections.

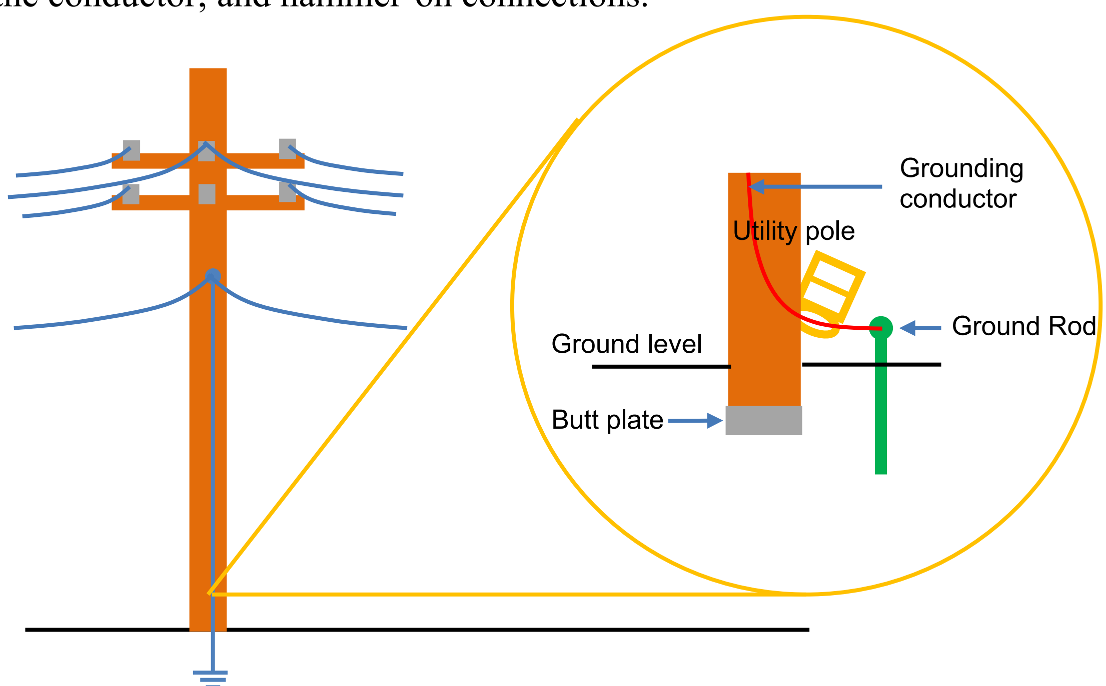

Figure 21. Pole-mounted transformer ground resistance measurement

Service entrance or meter: Same procedure as in the first example needs to be followed. Figure 22 presents the possibility of multiple ground rods and in Figure

23, the ground rods have been replaced with a water pipe ground. Both of them can act as a ground. In these situations, it is mandatory to complete measurements between the service neutral and both grounded points.

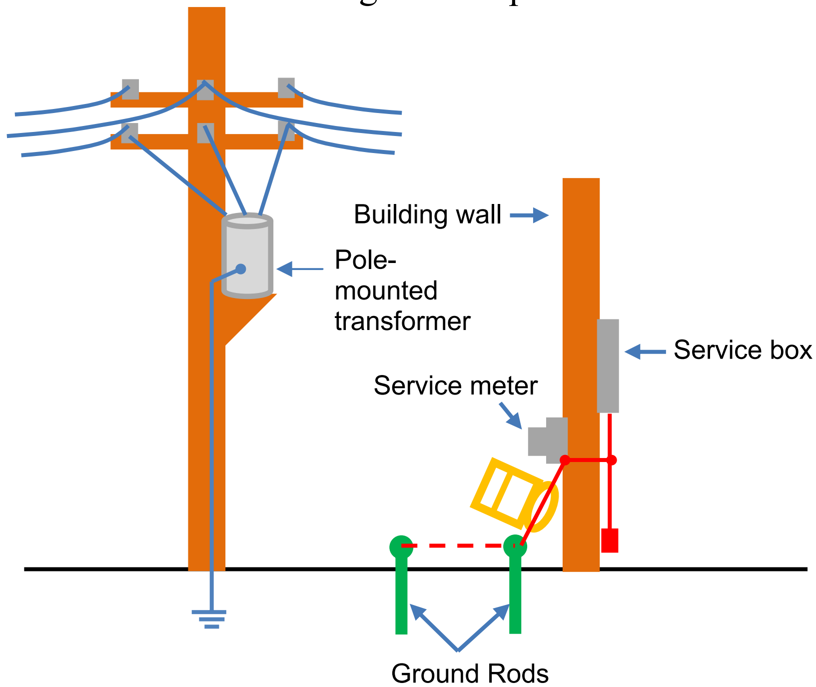

Figure 22. Service entrance with multiple ground rods - ground resistance measurement

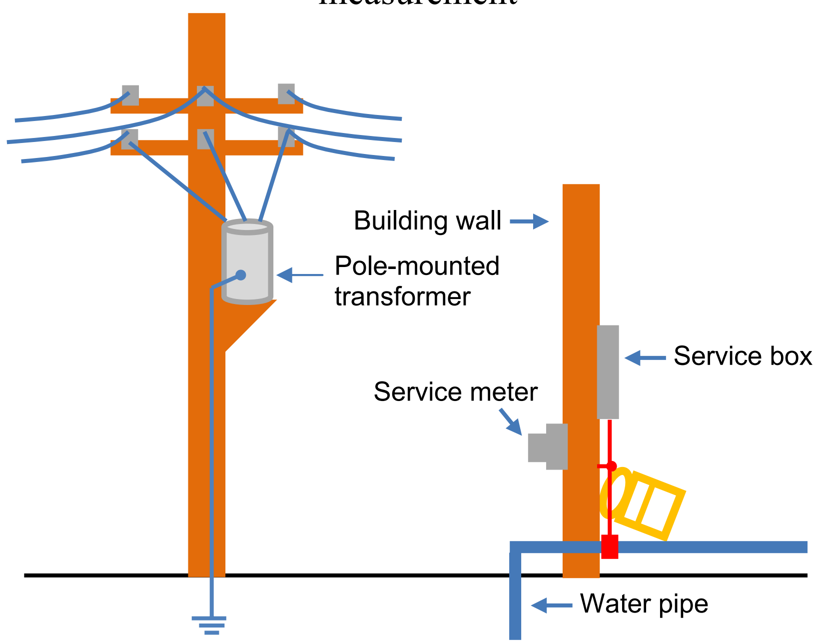

Figure 23. Service entrance with water pipe ground - ground resistance measurement

25.Pad-mounted transformer

In the case of pad-mounted transformer it is important to remember not to open transformer enclosures since they are the property of electrical utility. In the case ground test has to be completed with the utility transformer, coordinate with the utility staff for such a test.

Find and number all rods (typically there is only one rod). In the case the ground rods are inside the enclosure, look at Figure 24 otherwise refer to Figure 25.

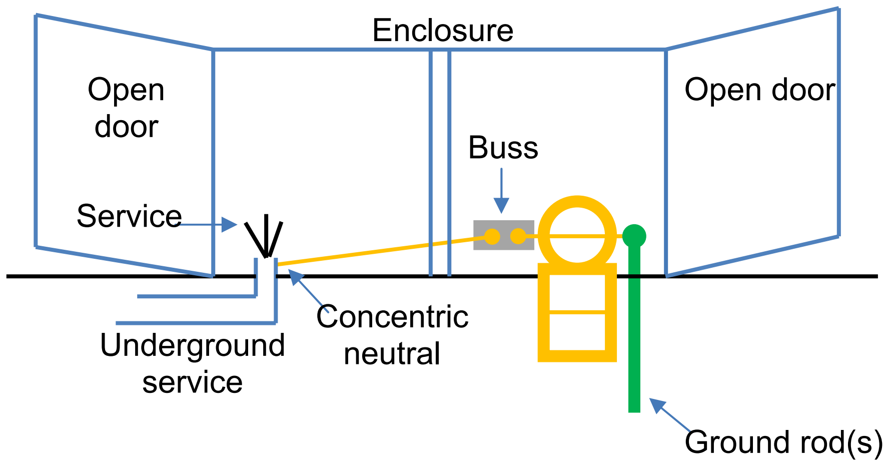

Figure 24. Pad-mounted transformer with ground rods inside the transformer enclosure - ground resistance measurement

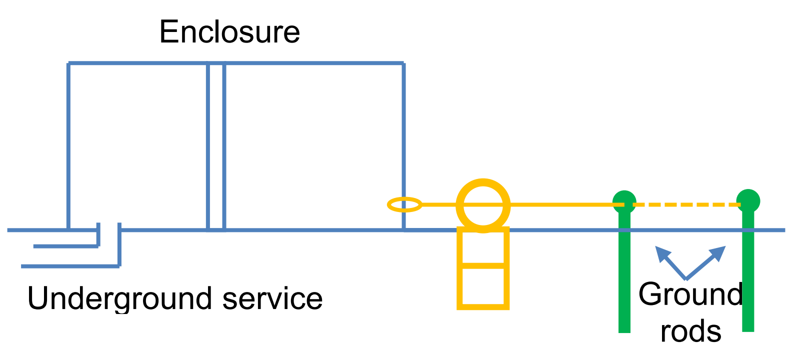

Figure 25. Pad-mounted transformer with ground rods outside the transformer enclosure - ground resistance measurement

In the case there is a single rod within the enclosure, the measurement needs to be conducted on the conductor just before the bond on the ground rod. Typically, more than one ground conductor is connected to this clamp, looping back to the enclosure or neutral. In many situations, the best reading can be obtained by installing the instrument onto the ground rod itself, below the point when the ground conductors are attached to the rod, so that ground circuit is measured. Attention has to be taken to find a conductor with only one return path to the neutral. Typically, a very low reading suggests that there is a loop and test closer to the rod needs to be repeated. In Figure 25, the ground rod is placed outside the enclosure. Clamp at the indicated measuring point to get the correct measurement. In the case, more than one rod exists at different comers of the enclosure, it will be mandatory to figure out how they are connected to correctly measure the ground resistance.

26.Transmission Towers

Find the ground conductor at the base of the tower. Figure 26 presents a single leg placed on a concrete pad with an external ground conductor. The point at which the ground tester is installed needs to be above all splices and connections which allow for multiple rods, butt wraps, or butt plates.

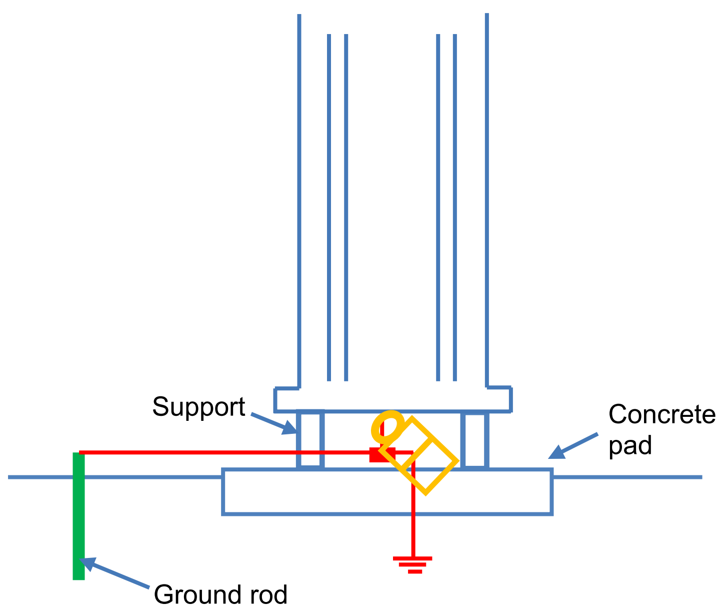

Figure 26. Transmission tower with a single leg placed on a concrete pad with an external ground conductor - ground resistance measurement

27.Central Office Locations

Typically, the main ground conductor from ground window or ground plane is too big to clamp around. Depending on the wiring practices, there could be many locations at which water pipe can be found within the building. Typically, an effective location is at the ground buss in the power room, or near the backup generator. By measuring at several points and cross comparing the measurements, discovering neutral loops, utility grounds, and central office grounds can be done. The measurement is efficient and precise because the ground window is typically connected to the utility ground at only one point.

28.Ground Grid Integrity Inspections

Ground resistance measurements and touch potential measurements do not give information on the ability of grounding conductors and connections to transfer ground fault currents safely to ground. Ground fault current can cause considerable damage to equipment and pose safety hazard to staff in the case it does not find a low- impedance path to the ground grid. Hence, it makes sense to occasionally inspect and verify the integrity of the ground grid connections.

The purpose of this inspection is to determine if the equipment, frame, structures, or enclosure grounds are connected to the grounding electrode or ground grid with low resistance. The resistance value of such connections should be very low (100 μΩ or less). The most effective way to complete ground grid connections integrity tests is to use a large but practical current and some way of measuring the voltage drop caused by this current. There is a test set to conduct this measurement using AC current. This test method is known as the high-current test technique. This method includes passing 300 A through the ground grid between a reference ground (typically a transformer neutral) and the tested ground (conductor and connections). The voltage drop and the current magnitude and direction are observed to check the integrity of the ground connections. The test connections for completing this test are presented in Figure 27. The below listed points are provided when using the high-current method of testing the continuity of ground grids and grounds. Nevertheless, it needs to be remembered that these are only suggestions since each ground has to be considered on its own merits relative to other grounds in the immediate vicinity.

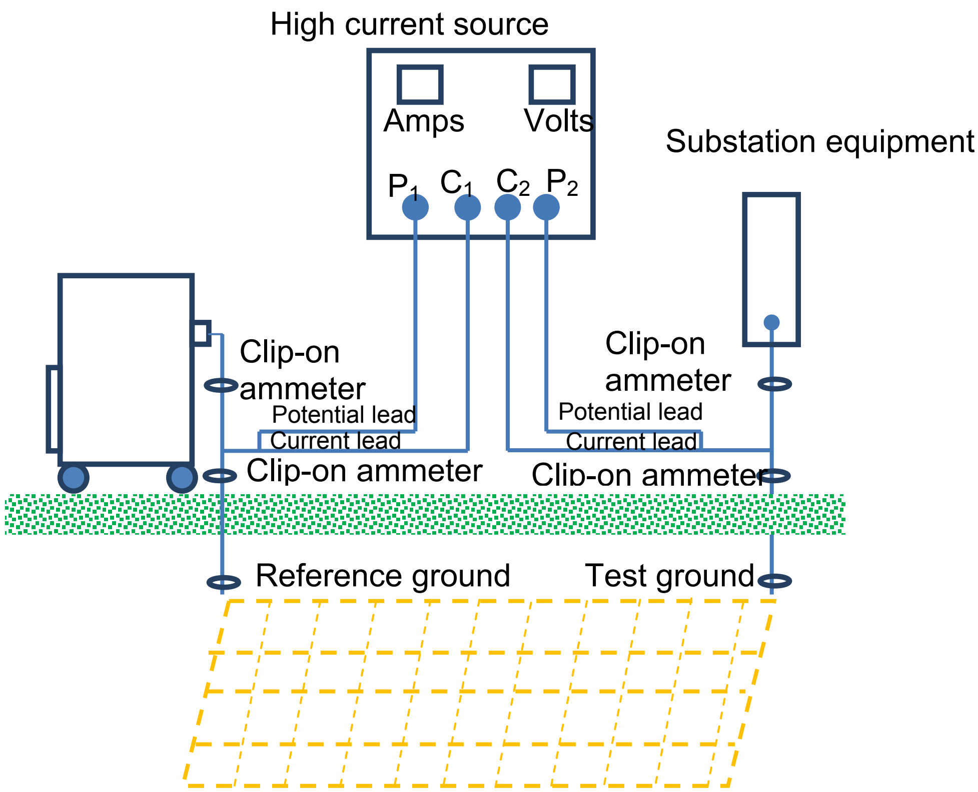

Figure 27. High-current technique for testing ground grid integrity

1. The voltage drop of the ground grid increases roughly 1 V for each 50 ft. of straight distance from the reference point.

2. On equipment with single ground the ground can be considered as acceptable if the voltage drop is in line with item 1 above and at least 200 A goes to the ground conductor. On majority of similar equipment, 300 A will flow to the grid. Nevertheless, in some situations current will also go through foundation bolts and or conduits.

3. On equipment with multi-grounds, a ground can be considered as acceptable if the voltage drop is in line with item 1 above and at least 150 A goes to the ground conductor. In the case the current to the grid is lower than 150 A, the ground needs to be disconnected from the equipment and 300 A again needs to be passed through the ground. In the case, ground passes the 300 A and the voltage drop does not increase more than 0.5 V over the previous level, the ground can be considered as acceptable.

4. To test transformer neutral or reference point pass 300 A through the transformer neutral at a point above grade but below any bonding connections or clamps on the tank. In the case, at least 150 A goes to the ground grid, the reference point can be considered as acceptable.

5. Make a reference ground, preferably a transformer neutral. From a high-current AC source connect one test lead to tested ground as shown in Figure 27. Connect the test lead at a point above grade but below the bonding connections or clamps. Pass 300 A through the ground grid and measure the voltage drop across the grid. Using an ammeter, measure the amount of test current going above (to the equipment) and below (to the grid) the test lead. The voltage drop needs to be in line with item 1 above. The test amperes need to be in line with items 2 and 3 above.