

IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems

Sponsor

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of the
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Abstract: Practical instrumentation methods are presented for measuring the ac characteristics of large, extended or interconnected grounding systems. Measurements of impedance to remote earth, step and touch potentials, and current distributions are covered for grounding systems ranging in complexity from small grids (less than 900 m²), with only a few connected overhead or direct burial bare concentric (2) neutrals, to large grids (greater than 20 000 m²), with many connected neutrals, overhead ground wires (sky wires), counterpoises, grid tie conductors, cable shields, and metallic pipes. This standard addresses measurement safety; earth-return mutual errors; low-current measurements; power-system staged faults; communication and control cable transfer impedance; current distribution (current splits) in the grounding system; step, touch, mesh, and profile measurements; the foot-equivalent electrode earth resistance; and instrumentation characteristics and limitations.

Keywords: Grounding systems, impedance, safety

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Foreword

(This foreword is not a part of IEEE Std 81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems.)

During the late 1970's, in an effort to increase its usefulness, this guide was divided into two parts. The first part is entitled IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System. It covers the majority of field measurements that do not require special high-precision equipment and measuring, and that do not encounter unusual difficulties such as may be found with extensive grounding systems, abnormally high stray ac or dc currents, etc. IEEE Std 81 (Part I) has been extensively revised and updated. Part I was approved in 1983 and reaffirmed in 1991. This part of the guide (Part II) is entitled IEEE Std 81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems. This new part covers measurement of very low values of ground impedance (less than 1 Ω). The extensive use of specialized instrumentation, measuring techniques, and safety aspects are incorporated.

This guide was prepared by the Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems Working Group of the RLC Measurements Subcommittee of the Power Systems Instrumentation and Measurements Committee of the IEEE Power Engineering Society.

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IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems

1. Purpose

The purpose of this guide is to present practical instrumentation methods that may be used for the measurement of impedance to remote earth, step and touch potentials, and current distributions of large extended or interconnected grounding systems ranging in complexity from small grids (less than 900 m²), with only a few connected overhead or direct burial bare concentric neutrals, to large grids (greater than 20 000 m²), with many connected neutrals, overhead ground wires (sky wires), counterpoises, grid tie conductors, cable shields, and metallic pipes.

2. Scope

Test methods and instrumentation techniques used to measure the ac characteristics of large grounding systems include the following topics:

- 1) Measurement safety
- 2) Earth-return mutual errors
- 3) Low-current measurements
- 4) Power-system staged faults
- 5) Communication and control cable transfer impedance
- 6) Current distribution (current splits) in the grounding system
- 7) Step, touch, mesh, and profile measurements
- 8) The foot-equivalent electrode earth resistance
- 9) Instrumentation characteristics and limitations

Grounding electrodes consisting of a single ground rod, arrays of ground rods, tower footings, and many grids (if no external grounding is connected) can be measured, interference voltages permitting, with methods outlined in IEEE Std 81-1983 [2]¹. Even if a large grid has an impedance phase angle of 18° the resistance component will be only 5% lower than its impedance. However, for large grounding grids in low-resistive earth (<75 Ω-m) and for grounding

¹The numbers in brackets correspond to those of the references in Section 3.

systems that have numerous extended grounding conductors, the impedance could be significantly greater than the resistive component measured with the conventional test sets of IEEE Std 81-1983 [2].

Measurement of low-impedance grounding-system characteristics, with injection currents between 0.1–100 A, using techniques described in Section 8, is generally preferred. Or, grounding-system parameters may be measured or verified under power-system conditions with the staged-fault methods of Section 9. Due to the diversity in station grounding configurations and the variety of possible test connections, this guide cannot narrowly define the test method for each application. The user must take responsibility for the adequacy of the method selected (see Section 13, for a review of instrumentation components).

3. References

- [1] IEEE Std 80-1986 (Reaff 1991), IEEE Guide for Safety in AC Substation Grounding (ANSI)²
- [2] IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System (Part I).
- [3] IEEE Std 367-1987, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage From a Power Fault (ANSI).
- [4] IEEE Std 487-1992, IEEE Guide for the Protection of Wire Line Communications Facilities Serving Electric Power Stations (ANSI).
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²IEEE Publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[14] Velazquez, R., Reynolds, P.H., and Mukhedkar, D. "Earth-Return Mutual Coupling Effects in Ground Resistance, Measurements of Extended Grids," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, no. 6, pp. 1850–1857, Jun. 1983.

4. Safety Practices

The rules and procedures summarized in the following paragraphs are recommended to be used as reminders of possible hazards and to serve as guides in preparing safe test methods. Utilities should modify the suggested procedures to conform with their own conditions and safety regulations.

4.1 General Precautions

Test methods described in this guide require test connections between the grid and locations on the earth remote from the grid. Extended test leads, out-of-service transmission lines used in the current circuit, and the power system connected to the substation under test present a high degree of exposure to atmospheric disturbances or power system line-to-ground faults and ground potential rise (GPR). The following precautionary measures are recommended:

- 1) Do not schedule field measurements of either the power system grounding, during periods of forecast lightning activity, in areas (determined by conditions at each utility) that encompass the station being measured or of the power network connected to the station being measured.
- 2) Do not lay out test leads or connect test leads to out-of-service transmission lines during a period when lightning is prevalent.
- 3) When test procedures are not in progress, externally routed test leads should be disconnected and isolated from the grid and treated as being energized.
- 4) In the event lightning appears in the zone defined above when test procedures are underway, stop all testing, open the test connection to the out-of-service transmission line, and isolate from the grid any temporarily installed test conductors routed externally to the grid.

4.2 Safety Aspects of Test Preparations

Preparations for field measurements of system grounding leave participating personnel vulnerable to exposure caused by faults at or powered from the grounding under test, transferred potentials from remote test grounds, and inadvertent line energizations.

While the probability of the occurrence of one of these events is low, personal safety will, nevertheless, be enhanced by

- 1) Using high-voltage rated insulated gloves and boots, eye protection, and hard hats.
- 2) Working on clean, dry crushed rock or an insulating blanket.
- 3) Avoiding bare hand-to-hand contact between equipment and extended test leads.
- 4) Sufficiently insulating the voltage or current probe test conductor within the station and its close neighborhood.
- 5) Ensuring that the cable reel is well insulated or mounted on an insulated platform.
- 6) Connecting safety grounds (sized for fault levels) to all equipment frames.
- 7) Making connections to instrumentation only after cable-pulling personnel are in the clear (radio communication recommended).
- 8) Removing working grounds on the test circuit last.

It is recommended that test procedures, hazardous conditions, and the responsibilities of each person be discussed and understood by everyone taking part in the test.

Safety can be heightened by the use of a disconnect or switch to isolate the current source and the voltage-probe circuit when no measurement is being made. When grid rise exceeds several hundred volts, the measuring instrument should, if possible, be connected through instrument transformers or resistance voltage dividers. If a capacitor in series with the current circuit is employed, it should be located at the line entrance.

A current-injection high-voltage line must be earthed at both ends when the test is under preparation. The injection end cannot be grounded during the actual measurement. However, a safety spark gap or arrester with a sparkover voltage of 2 to 4 kV is advisable at the line entrance, in view of possible atmospheric overvoltages, fault-related ground rise, or inadvertent energizing of the line. Moreover, the circuit should not be touched after removal of the temporary grounding.

WARNING: *When the out-of-service transmission line shares a common right-of-way with energized lines, hazardous voltages may exist at the line termination due to induction.*

4.3 Safety Aspects of Test Measurements

After completion of the test set-up, it is essential that one person (usually the test supervisor) coordinate all switching operations, maintain control of connections made to all externally routed circuits, and authorize all test energizations. No personnel shall be permitted to work on or touch the test circuit without clearance from the test coordinator. During modifications of the test circuit, it is recommended that all safety practices outlined in 4.1 and 4.2 be followed along with those additional rules instituted by each utility.

From the standpoint of safety rules, a test that applies the 10 to 100 A current injection method should be considered as corresponding to a prolonged earth fault; and an earth-fault test should be considered as corresponding to a fast-tripped earth fault. Thus, the test currents should be such that the rules with regard to the touch-voltage, transferred-potential, and induced-potential limits for earth faults are respected.

It is recommended that all personnel present in the substation under study be informed of the nature of the tests, in particular of the consequences of current circulating in the ground.

Measurement of a grounding system with low impedance will require higher magnitude test currents to have an adequate signal-to-noise level and improved sensitivity. When tower footings, guy anchors, or ground rods are used for the injection-current remote electrodes, the possibility that their potentials could be hazardous must be considered. Selection of higher test currents (above 40 mA) raises the questions of safety for measurement personnel, the public, and domestic animals that could come in contact with remote-current-electrode potentials. Where temporary ground rods are used, every effort should be made to reduce the current-electrode resistance, e.g., paralleling several rods, salting, and using longer rods. Nevertheless, in high-resistivity earth, it may not be possible to reduce the current-probe resistance to less than 200 Ω . Even at 0.5 A, this would result in a 100 V probe rise. For current-probe voltages above some minimal value (20–40 V), it is recommended that a safety watcher and temporary fencing be provided during test energization.

5. Factors Effecting Grounding System Measurements

Measurement of grounding system impedance less than 0.5 Ω with injected test currents 0.1–100 A in conjunction with energized substations and transmission lines has numerous characteristics that introduce complications and impose constraints on the measurement technique:

- 1) Background voltage and noise resulting from conductive coupling
 - a) Unbalanced load-current flow through the grounding impedance.

- b) Harmonic-current flow through the grounding impedance.
- c) Induced currents in extended ground conductors circulating through grid.
- d) Impulse-type noise induced into the grounding system.
- e) Telluric stray currents.
- 2) Electromagnetic interference resulting from mutual coupling
 - a) Induced voltages in the test circuit due to paralleling with a current-carrying bus and/or lines (magnetic coupling).
 - b) Induced voltages in the test circuit due to proximity with an energized bus and/or lines (capacitive coupling).
- 3) Measurement considerations
 - a) For measuring the 60 Hz grounding-system impedance, the test-current frequency should be between 50–70 Hz.
 - b) For the grounding impedance of the grounded-wye shunt capacitor energization in-rush currents, the single-frequency test current should be between 300–600 Hz.
 - c) Mutual coupling between the current test conductor and the potential test conductor will introduce an error in the measured impedance (see Section 7.).
 - d) Mutual coupling between extended ground conductors that conduct the test current to earth and the potential test conductor will give a lower measured impedance.
 - e) Locating the current or potential remote test electrode near grounded metal structures, buried neutrals, aerial neutral grounds, or buried ground conductors that connect to the grounding system under test will result in a lower measured impedance. In urban areas, these components effectively enlarge the power-system grounding and make it difficult to reach remote earth.
 - f) Earth voltage drops for electrodes in the grounding system are linear with current because the voltage gradients appearing during power-system faults are well below the breakdown level of earth.
 - g) High resistance or corroded connections between grid and grounding system components, the current nonlinearity of steel overhead ground conductors (sky wires) when connected to the grid, and the nonlinearity of mechanical joints connecting overhead ground wires to tower can give a high measured impedance (see 14.4).
 - h) When a transmission line with a continuous overhead ground wire (grounded to grids at both ends and each tower) is used as a current path between the ground system under test and the remote current electrode (grid), consideration of the mutual coupling (shielding) between transmission line and sky wire is required in order to determine the portion of the test current that flows through the grounding system to earth (see 6.3 and Section 10.).
 - i) All components of the grounding system should be connected.
 - j) Out-of-service transmission lines should be grounded to the grid.

In the presence of background and interference voltages, the measurement accuracy will depend mainly on the length and routing of the test conductors, the magnitude of the test current (and the resulting voltage drop across grounding impedance), and the selectivity and sensitivity of the method used to measure the potential magnitude and its phase angle relative to the current. In general, high background levels, broad instrumentation frequency response, low grounding impedance, and/or tests at the power-system frequency will require the larger test currents. High interference levels can overload or even damage electronic equipment.

Because changing weather, power system load variations, and system switching modify many of the above factors, the test environment can change hour-to-hour.

The inductive component of impedance, mutual coupling, and earthing resistance of buried conductors does not necessarily change linearly with frequency. Therefore, to minimize errors in correcting for frequency, a test-current frequency near that of the power system is recommended [see item (3) above].

In those grounding systems containing nonlinear elements, such as steel overhead ground wires and corroded or high-resistance connections [see item (3) above], test currents high enough to produce 10 V or more across the grounding

impedance may overcome these nonlinearities and improve measurement accuracies, see [B25]³ and [B44]. Overhead ground wires that do not have bolted connections to towers will require the highest voltage drop.

6. Preliminary Planning and Procedures

Test voltage sources used for injecting current into the grounding system introduce many ramifications to the accurate measurement of impedance, safety characteristics, and current distributions in the grounding system. Consideration of the following items will be necessary before undertaking the test set-up or making test measurements.

6.1 Distance to Current and Potential Test Electrodes

Accuracy of grounding resistance/impedance measurement depends on locating test electrodes at remote earth. The minimum distance to test probes that will have an approximate measurement accuracy of 95% may be estimated by 6.5 times the extent of the grounding system (see 8.1). The extent of a grounding system for an isolated grid is its maximum diagonal distance. Or, when external buried conductors are connected, it may be approximated by the maximum grid dimension plus the effective length of a buried conductor if in one direction, or plus each buried conductor length if in opposite directions. Note that the effective length of a buried conductor, which was estimated from lossy transmission line formulas for 60 Hz, depends on earth resistivity and is approximately 500 m for 100 Ω -m earth, and 3 km for 10 000 Ω -m earth (see Appendix C).

6.2 Selection of Test-Conductor Routing and Test-Probe Locations

The current and potential test conductor routings and the location of current and potential remote electrodes should be determined; and test conductor lengths should be estimated from the station plot plan and area maps that show transmission lines, neutrals, buried conductors, communication cables, and piping locations.

To minimize measurement errors due to ac mutual coupling, the test potential conductor should be routed at 90° to the test current conductor. In grounding systems, in order to avoid mutual coupling with extended ground conductors and in-service transmission lines, it may be necessary to route at angles other than 90°. (See Section 7. for a discussion of mutual coupling errors between current and potential test conductors.)

Practically, when access is limited or when the grounding system includes a large number of extended conductors leaving the grid in diverse directions, test routings can only be selected so as to minimize these mutual couplings.

If existing duct-runs are used in the routing of the current and potential test conductors from the current injection point to the external test electrodes, it should be verified that there are no parallel sections.

If a telephone cable pair is to be used as a test conductor, it should be verified that it does not parallel overhead ground wires, power system neutrals, or extended grid conductors. If using a telephone cable pair or other test lead in a cable with a grounded shield, particular care should be taken that the test lead is connected to a low-resistance ground at the far end to avoid a possible erroneous measurement from the cable capacitance acting as a termination. *A telephone cable pair with its shield grounded should not be used within one grid diagonal of the grid or when its leakage resistance is less than 10 k Ω .* When, in addition to the ground-system impedance, measurements are being made for the purpose of designing protection of the telephone cable serving the power station, the use of a cable pair in that cable as a potential test lead may be desirable to measure the exposure (see Section 11.).

³The numbers in brackets, when preceded by the letter “B,” correspond to the Bibliography in Section 15.

6.3 Determining the Effect of Overhead-Ground-Wire Shielding on Test Current Distribution

When the current injection line parallels a branch of the grounding system extending from the grid, mutual coupling will induce a voltage in the paralleling branch that increases current flow in the branch. This induced current component will reduce the ground-system voltage rise and will have to be subtracted from the injected current to determine current flow through the grounding-system impedance. Refer to Section 10. for a discussion of current distribution in the grounding system.

6.4 Estimating Grounding Grid Impedance

The grounding system consists of the grid and all other extended grounding conductors connected to it. Grid resistance should be estimated using the IEEE Std 80-1986 [1] formula, the earth resistivity survey, and grid design drawings. Impedance of large grids ($>40\,000\text{ m}^2$) buried in low-resistivity earth ($<75\ \Omega\text{-m}$) with no extended grounds connected may be higher than the estimated resistance. Or, when extended ground conductors are connected to the grid, grounding-system impedance will be less than estimated grid resistance [B31].

Formulas and calculator programs of EPRI EL-904 [7] give methods for calculating the input impedance of extended buried conductor with or without a terminating impedance. As the buried conductor length is increased, input impedance approaches the characteristic impedance, and the impedance phase angle will be in the 35° to 40° range. Refer to Appendix C for examples of buried conductor impedance. Overhead ground wires that connect to towers and grids will have impedance angles in the 50° to 85° range (see Eq 37).

6.5 Estimating Minimum Test Current

The background noise on the grid should be measured with a spectrum analyzer or frequency-selective voltmeter. The nearest frequencies above and below power-system frequency with lowest background levels should be determined. The bandwidth of the measuring instruments will determine their ability to attenuate background voltages. However, background levels are not locked in with the test frequency and may produce variations in the tunable voltmeter reading. If voltage swings at the selected frequency are averaged and background levels at the selected frequency remain constant, impedance measurements may be made when the grid voltage due to test current is above the background levels. Averaging is done automatically by the dual channel signal analyzer (see 8.2.2), in which case noise levels may be higher than test signals. When the grid rise due to the test current must be high enough to overcome poor connections or nonlinearities in the grounding system, (test current) (estimated impedance) should be made at least equal to 10 V (see 13.1[(5) *sine wave network analyzer*], 14.4, [B25] and [B44]).

6.6 Test Current Sources

Low-impedance large grounding systems used in high-voltage power systems may require higher test current than the built-in 5–40 mA source provided by ground testers. Current magnitude, 0.1–100 A, and frequency selection will depend on the above requirements and the test method used. The following sources (see Section 13.) have been used to successfully measure grounding impedances:

- 1) Low-power, random-noise source with amplifier (0.1–10 A), frequency range 10–600 Hz
- 2) Oscillator-amplifier with matching adjustable transformer (0.1–10 A), frequencies above and below the power system frequency
- 3) Power-system station service with auxiliary matching transformer (1–100 A) (current reversal method)
- 4) Portable power generator (50 to 100 A), frequencies above and below the power system frequency
- 5) Power-system staged fault

6.7 Estimating Test-Current Source Requirements

Output voltampere requirements for the test-current source can be estimated from:

$$VA = (\text{maximum test current required})^2 \cdot [(\text{estimated current-probe resistance}) + (\text{current-test-conductor impedance})]$$

When test current magnitudes are large (50–100 A), the current injection line is long (<20 km), and the current-circuit impedance has a large X/R ratio (2 to 20), test-current-source apparent power (in VA) requirements can be reduced for fixed test-current frequencies by using an appropriately voltage-rated capacitor bank in series with the test line to cancel the reactive portion of the injection circuit impedance. Equipment with a 60 Hz VA rating can be reduced with test energization times of 10–30 s and off times of 5–15 min by utilizing the short-time thermal rating of the matching auxiliary transformer and the overvoltage rating of the capacitor bank.

NOTE — The test-current-conductor minimum size will depend on the test-current magnitude, the test duration, and the maximum allowable cable-probe impedance.

6.8 Remote Rod Electrode Current Capacity

When a test ground rod or an array of ground rods are temporarily installed for the remote current electrode, and test currents are in the range 1.0–10 A, consideration must be given to the earth's temperature rise, consequential moisture evaporation, and increasing electrode resistance. Increasing resistance results in more heating, higher probe potential, and possibly an inability to maintain a desired test current. The current-carrying capacity of a test rod may be estimated from its spherical equivalent and formulas derived by Rudenberg [B35].

Table 1 summarizes both continuous and short-time current ratings of a test rod for a 60 °C earth temperature rise as a function of earth resistivity and rod resistance.

Table 1—Current Rating of Test Ground Rods

Rod Depth m	Diameter mm	Earth Resistivity		Rod Resistance	
		Continuous A	1 min A	Continuous A	1 min A
0.3 (12 in)	15.9 (5/8 in)	$5.7/\sqrt{\rho}$	$23.7/\sqrt{\rho}$	$12.0/\sqrt{R}$	$49.9/\sqrt{R}$
0.6 (24 in)	15.9 (5/8 in)	$9.7/\sqrt{\rho}$	$69.2/\sqrt{\rho}$	$12.0/\sqrt{R}$	$85.4/\sqrt{R}$
1.0 (40 in)	15.9 (5/8 in)	$14.4/\sqrt{\rho}$	$152.5/\sqrt{\rho}$	$12.0/\sqrt{R}$	$126.7/\sqrt{R}$
3.0 (10 ft)	19.1 (3/4 in)	$36.8/\sqrt{\rho}$	$1019/\sqrt{\rho}$	$11.8/\sqrt{R}$	$327.5/\sqrt{R}$

where

$$R = (\rho/2\pi L) [\ln(8L/D) - 1]$$

R = rod earth resistance, in Ω
 ρ = earth resistivity, in $\Omega\cdot\text{m}$
 L = rod depth, in m
 D = rod diameter, in m

The current capability of a ground rod can be estimated with Table 1 by either knowing the earth resistivity or by measuring the rod's earth resistance. Current capacity increases with rod depth, inversely with test duration, inversely with the square root of resistivity or the rod earth resistance. Increased test current for short durations will require off times of 5–10 min to allow earth temperatures to cool. Current capacity can be increased with an array of ground rods. However, to reduce mutual effects and to equalize current distribution in each rod, rod spacing should be at least five times rod depth. When it is desirable to reduce the watt capacity of the current test source, rod earth resistance can be

lowered by pouring a water-salt solution into the rod's hole. Lowering-rod earth resistance will increase rod current capacity.

6.9 Potential Input Impedance

The input impedance of the potential measuring device, for 1% accuracy, must be 100 times or more the potential-cable impedance plus the potential-test-probe resistance. The resistance of the test conductor and potential electrode can be measured to the grid.

6.10 Determining Grounding System Connection Condition

Prior to the grounding-system impedance measurements, the connection integrity of the major grounding components connected to the grid should be established, either by inspection, by 10–100 A microvolt or millivolt drop dc tests, or by a micro-ohmmeter. This is especially important in older grounding systems in which low-resistance connections to the grid may have been destroyed by corrosion or system fault currents. Resistance measurements are made by injecting a dc current between the test point and a remote point on the grid 30 m or more away. Even if the connection under test is open, current flow may be by conductors that parallel the test connection. However, the potential between the injection point and the nearest point on the grid (2 to 10 m) 90° to 270° from the current injection line should be comparable with the estimated voltage drop of the tested section ($R = V_{dc}/I_{dc}$). Open or reduced connections in the grid are difficult to detect because of paralleling grid conductors.

The measurement of current in the grounding system branches during current injection can be used to verify the integrity of each extended grounding system branch (see Section 10.).

6.11 Establishing the Measurement Point on a Grounding System

It should be established, by a dc test method recommended in 6.10, that the test connection point to the grid has low resistance.

The point to which the current injection circuit is connected on the grounding system and the point of connection of the potential measurement circuit should be the same or very close together to avoid an unrealistically low measurement due to not measuring the voltage drop produced by the entire injected current. This is particularly true for large or distributed grounding systems.

It should be verified that the connection point is in the main body of the grounding system rather than some lightly connected peripheral grounding element such as a perimeter fence. Do not use a common lead to connect the current and potential measurement connections to the grounding system. These precautions are necessary to avoid unrealistically high measurements due to the impedance of the common connecting lead being in series with the true grounding impedance.

7. Earth-Return Mutual Effects When Measuring Grounding-System Impedance

7.1 Introduction

Fall-of-potential test methods described in this guide require an ac test source with frequencies near or at that of the power system to measure the grounding-system impedance (see Sections 5. and 6.). These test methods inherently can introduce three possible errors in the measured grounding-system impedance: (1) earth mutual resistance due to current flow through earth from the grid to the current probe, (2) ac mutual coupling between the current test lead and the potential test lead, and (3) ac mutual coupling between the extended ground conductor and the potential test lead.

7.2 Measurement Error Due to Earth Mutual Resistances

Errors of measurement of the grounding-system impedance result from the mutual resistance between the grid and the potential probe, the mutual resistance between the current probe and the potential probe, and the mutual resistance between the current probe and the grid. These mutuals were described in Appendix C of IEEE Std 81-1983 [2]. Mutual resistance errors can be mitigated by adequate spacing between grid to potential probe, grid to current probe, and current probe to potential probe (see 6.1).

In homogenous earth and for probe spacings one grid diagonal or greater, the measurement error, R_e , due to earth resistance mutuals is given by

$$R_e = \frac{\rho}{2\pi} \left[\frac{1}{\sqrt{C_1^2 + P_1^2 - 2C_1P_1\cos\Phi_1}} - \frac{1}{C_1} - \frac{1}{P_1} \right] \quad (1)$$

where

- C_1 = distance grid center to current electrode, in m
- P_1 = distance grid center to potential electrode, in m
- Φ_1 = angle between C_1 and P_1 (in Fig 7-1, Φ_{1a} , Φ_{1b} , Φ_{1c}), in degrees
- ρ = earth resistivity, in Ω -m

The grid resistance, R_g , in Ω , is given by

$$R_g = R_s - R_e \quad (2)$$

where

- R_s = the measured grid resistance, in Ω

The mutual earth resistance, R_e , will reduce to zero for a grid installed in homogeneous earth, when

- P_1 and C_1 > maximum grid dimension, and
- $P_1 = 0.618 C_1$ and $\Phi_1 = 0^\circ$, or
- $P_1 = 1.618 C_1$ and $\Phi_1 = 0^\circ$ or
- $P_1 = C_1$ and $\Phi_1 = 29^\circ$

However, for a grid or grounding system buried in heterogeneous earth, containing externally routed ground conductors connected to the grid, these simplifying conditions are, at best, only approximate.

7.3 Measurement Error Due to AC Mutual Coupling

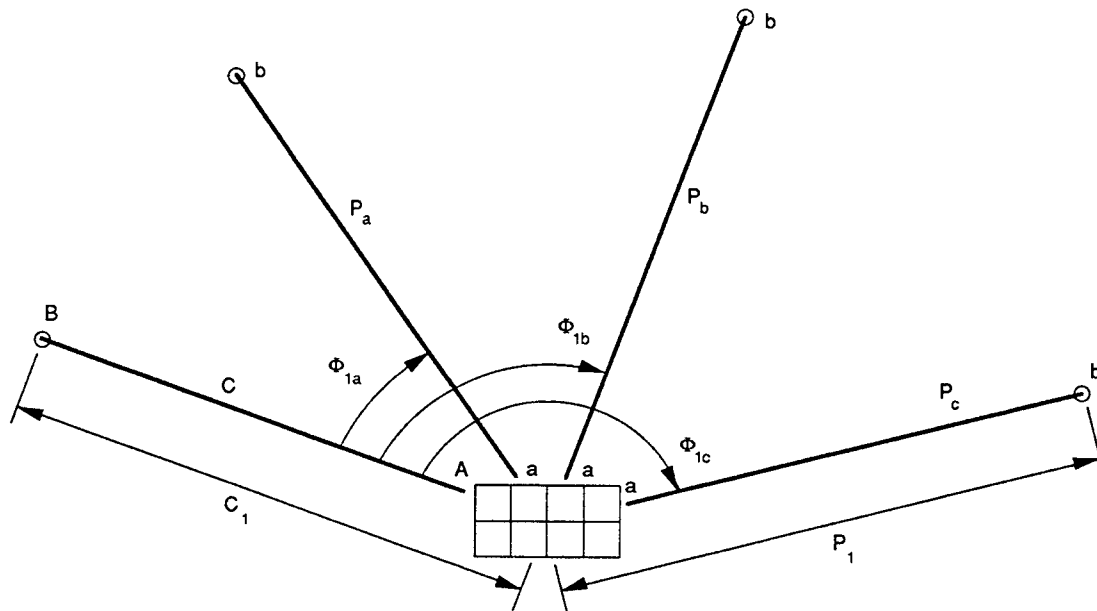
A second source of measurement error is the inductive coupling between the current and potential leads. This mutual coupling causes the ac test current in the current test lead to induce a voltage into the potential test lead that adds vectorially to the actual grid voltage.

Mutual impedance errors will be the largest when test conductors are paralleled. When the mutual impedance magnitude is equal to or greater than the grounding impedance, an error in calculating the mutual impedance components can result in a large error in the ground impedance determination. For this reason, it is recommended that large grounding systems be measured by angled conductors.

Ideally, if the angle between P and C is 90° , there is no ac mutual coupling. However, when performing field measurements, it is not always possible or practical to orient the test wires at a right angle. With an angle less than 90° ,

any voltage produced in the potential lead, P , due to the coupling from current flowing in the current lead, C , is additive to the desired measured voltage and produces a measurement error. With angles greater than 90° , the opposite effect is present, namely; the mutually coupled voltage is negative and results in a reduction in the measured impedance. Because the mutual coupling is less in magnitude, orientations of 90° – 180° and 180° – 270° are preferred over those of 0° – 90° and 270° – 360° .

In Fig 7-1, the earth grid potential rise measured with the potential conductor, P_b , will not be effected by mutual coupling from the current conductor. However, the measured grid potential rise using either P_a or P_c will be altered by mutual coupling from the current conductor.



P_a = POTENTIAL TEST LEAD LESS THAN 90° FROM CURRENT TEST LEAD
 P_b = POTENTIAL TEST LEAD 90° FROM CURRENT TEST LEAD
 P_c = POTENTIAL TEST LEAD GREATER THAN 90° FROM CURRENT TEST

Figure 7-1—Possible Potential Test Lead Routings Relative to That of the Current Test Lead

When measuring grid impedance, the combined errors of earth mutual resistances and ac mutual coupling are expressed by the equation for measured impedance

$$Z_s = Z_g + R_e + Z_M \quad (3)$$

where

$$\begin{aligned} Z_g &= \text{actual grid impedance, in } \Omega \\ Z_M &= R_M + jX_M \text{ mutual coupling between } C \text{ and } P, \text{ in } \Omega \\ Z_s &= \text{measured impedance and impedance angle, in } \Omega \text{ and degrees} \end{aligned} \quad (4)$$

or, grid impedance

$$Z_g = Z_s - R_e - Z_M \quad (5)$$

Mutual impedance errors resulting from the parallel orientation of test conductors can be approximated by Carson's formula for infinite conductors. However, the accuracy will depend on the length of the parallel conductor spacing, the frequency, and the earth resistivity approximation.

Formulas used to calculate the mutual impedance components of Eq 4 for finite length conductors of equal and unequal length, oriented either parallel or angled, are included in Appendixes A and B.

7.4 Mutual Coupling to Potential Lead From Extended Ground Conductors

Large grounding systems, besides the grid, may include buried neutrals, overhead neutrals, overhead ground wires, control and communication shields, buried bare grid-tie conductors, water pipes, gas lines, and railroad tracks. The extended nature of these components makes it difficult to route the potential test lead at right angles to each external pathway, thus introducing additional measurement error. The extended nature of these ground circuits requires longer test leads to reach remote earth.

If the grid conducts the bulk of the current to earth, or if the major portion of the external current flows in one direction, mutual coupling to the potential lead can be minimized by paralleling extended ground conductors with the least current. Major current paths in the grounding system can be either estimated from grounding configurations or established during current distribution measurements described in Section 10.

8. Measurement of Low-Impedance Grounding Systems by Test-Current Injection

8.1 Introduction

The fall-of-potential method is the fundamental method for measuring the ground impedance of large grounding systems (see 8.2.1.5 of IEEE Std 81-1983 [2]). As illustrated in Fig 8-1, this method of measuring ground impedance requires circulating a test current, I_s , between the ground system under study and a remote current electrode, C , while at the same time measuring the voltage, V_s , of the ground system relative to a reference potential electrode, P . In addition to the impedance, it is possible to measure the current distribution in the grounding system, the mutual impedance to the paralleling utility facilities, and step, touch, and profile voltages. Note that, to eliminate the measurement error due to the voltage drop in the test lead, as shown in Fig 8-1 and all following measurement schematics, a separate test lead is used for connecting the current loop and the potential circuit to the grid (see 6.11). Refer to 13.20 for a description of transient voltages that may be present during test measurements in energized substations.

The voltage, V_s , caused by the current, I_s , is measured by means of a high-impedance meter and an insulated probe wire extended from the ground system to a potential electrode some distance away. Preferably, this potential probe wire should be extended at an angle of 90° with respect to the current injection line to minimize mutual coupling between them. When the angle between the potential and the current test conductors is not 90° , the mutual-impedance correction methods of Section 7. require measurement of the phase angle between V_s and I_s of Fig 8-1.

As discussed in 6.1, locating the current and the potential probes approximately 6.5 times the extent of the grounding system will measure 95% of the grounding impedance. Then, to find the maximum value of V_s used to determine the grounding system impedance, the potential of the ground system should be measured with reference to a test-potential electrode placed at increasing distances from the ground system until the difference between two or three successive voltage readings is negligible (assuming the test current is held constant). Next, the current-probe distance should be increased significantly, and the potential measuring procedures should be repeated. Even under ideal conditions of perfectly homogeneous earth and no extended ground connections, a probe spacing extended to 50 times the maximum grounding system dimensions will give an expected measurement accuracy of only 98.5%. These measurement accuracies are estimated from Eqs 1 and 2 and the approximate grid resistance formula of IEEE Std 80-1986 [1].

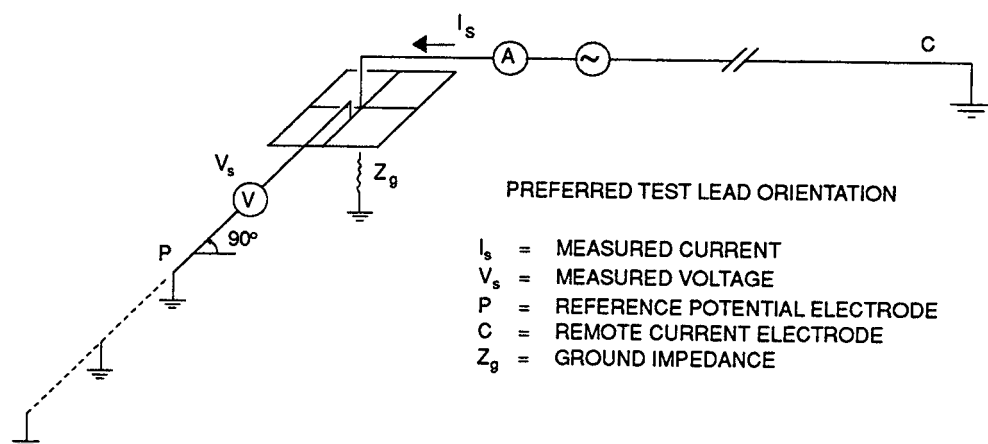


Figure 8-1—Impedance Measurement of the Grounding System

With the current and potential electrodes at remote earth, and assuming that the measurements are not influenced by mutual coupling or other interference, the grounding impedance may be found by Eq 6.

$$Z_g = \frac{V_s}{I_s} \quad (6)$$

Sources of current injection include either a signal generator plus power amplifier, a portable power generator, or an auxiliary matching transformer energized from a substation low-voltage source. Several signal detection techniques, described in this section, could be used with each of these test sources, although the current range is limited to 0.1 to 10 A. The signal generator source and power amplifier allow test frequencies to range from 50 to 600 Hz. The second and third methods allow higher currents (10 to 100 A or more) but are restricted to the power system frequency or frequencies close to the power system (50 to 70 Hz). Other combinations of current source and signal detector can be selected from the options detailed in Section 13.

8.2 Signal Generator and Power Amplifier Source

8.2.1 Tunable Voltmeter Method

One of the simplest instrumentation techniques used for impedance measurement, which utilizes equipment found in most utility test laboratories, is the tunable voltmeter method. In this method, an ac current (0.1–10 A) with a frequency close to the power-system frequency is used to measure the impedance, see [B46]. As shown in Fig 8-2, test equipment may consist of a 1:1 isolation transformer, a stable oscillator, a power amplifier with an internal or external matching transformer, M , a frequency-selective (tunable) voltmeter, and a resistive shunt, r_s . The test current may be measured by either the ammeter, A , the tunable voltmeter using the resistive shunt, r_s , or a current probe that converts milliamperes to millivolts. Measuring the current with the voltmeter is particularly useful in assuring that the oscillator and voltmeter frequencies have not drifted apart. It also improves the accuracy by using the same meter for both current and potential measurements. As mentioned in 6.7, current-source power requirements are determined by the test current magnitude, the current test-cable impedance, and the remote current-electrode (test probe) resistance. For a given test current, the power requirement can be directly lowered by the reduction of cable and probe resistance. Generally, a 100 W, 50–70 Hz source will suffice. However, in most cases, currents to 10 A can be obtained with amplifiers of 1.5 kW rating that are commercially available.

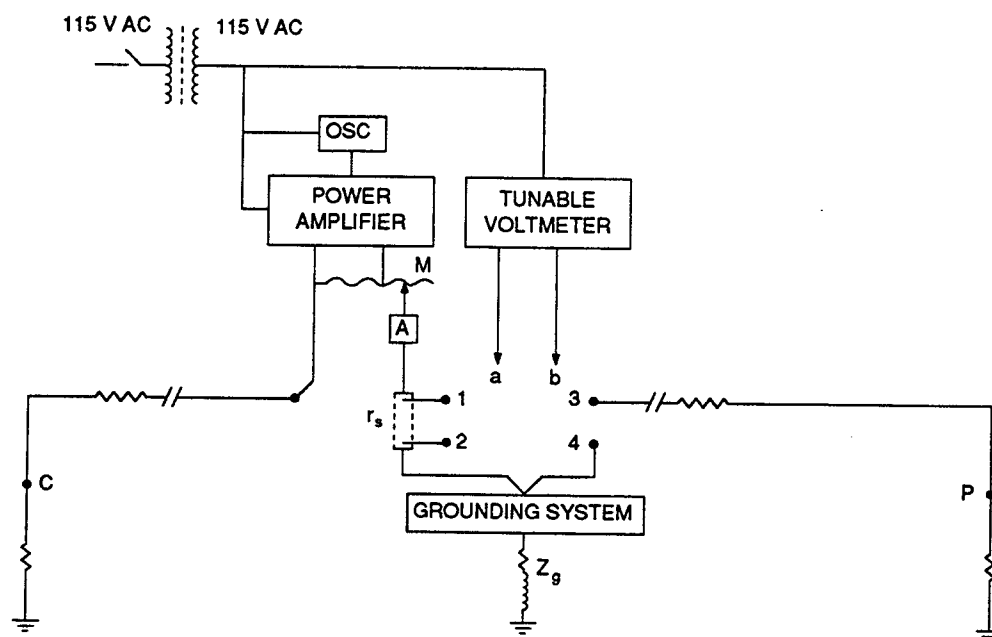


Figure 8-2—Tunable Voltmeter Method of Measuring Impedance

Measurement of only the magnitude of I_s and V_s , as above, permits calculation of only the magnitude of Z_g , and gives no information about the phase angle of the impedance. When a correction for mutual impedance errors (see Section 7.) is required, the phase angle between V_s and I_s can be determined by the three-voltmeter technique shown in Fig 8-3. The measurement error in this determination can be minimized by selecting the resistance value of shunt, r_s , which gives approximately equal values for V_s and V_r .

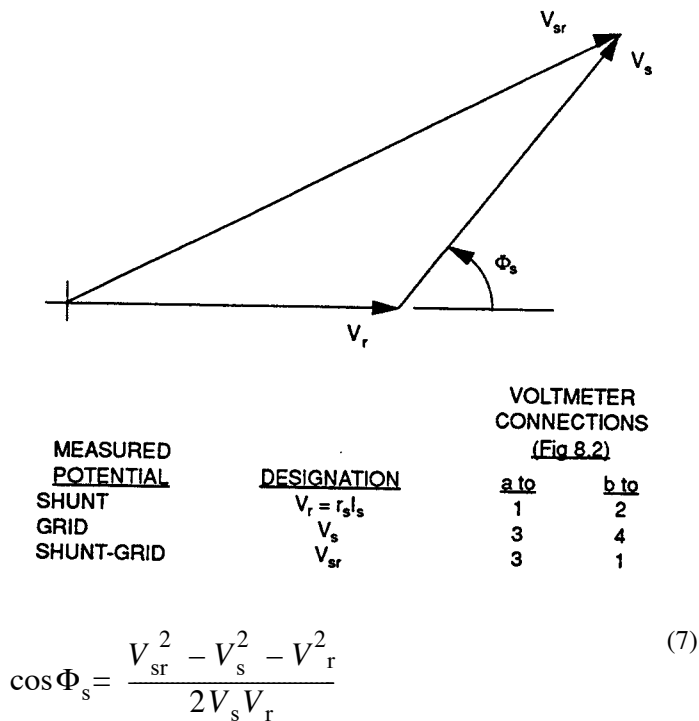
If conditions permit, it is recommended that the impedance be measured at a test frequency both above and below the power-system frequency. Then by interpolation, the ground-system impedance at power system frequency can be determined. After a test setup similar to Fig 8-2 is completed, and with the current test probe at remote earth, the following test procedures are recommended:

- 1) Scan the frequency band above and below (± 10 Hz) the power-system frequency to find a low-noise “window” in the ambient noise. Some users of this method have found such a window in the range of 65–68 Hz, see [B46].
- 2) Set the oscillator frequency at the selected frequency. Tune the frequency-selective voltmeter to the oscillator frequency.
- 3) Adjust the amplifier output to the selected current (measure the potential from point 1 to point 2 with the voltmeter; a current of 0.5 A is often suitable). In order to obtain the rated output of the amplifier, it may be necessary to use an adjustable matching transformer (M in Fig 8-2) between the amplifier and the current test circuit.
- 4) Measure the potential between the grounding system (grid) and the remote potential electrode, i.e., between points 3 and 4.

NOTE — A power-frequency rejection filter may be required ahead of the tunable voltmeter if the grid and the remote potential leads have high ambient power-system voltages.

- 5) Repeat steps (1) through (4) for the other more distant remote potential electrode locations until an asymptotic value of Z_g has been obtained.

- 6) If an impedance angle is required, the voltages across points 1–2, 3–4, and 3–1 (Figs 8-2 and 8-3) can be measured during steps (3) and (4) and the phase angle (Φ_s) between V_s and I_s calculated with Eq 7.
- 7) Any drift in the oscillator frequency or in the tunable voltmeter response between readings will result in large measurement errors. For field use in cold weather, it is advisable to provide an enclosure with auxiliary heat to maintain a warm, stable ambient temperature for the test instruments.



and Φ_s is the grounding system impedance angle

Figure 8-3—Phasor Diagram for the Three-Voltmeter Method of Impedance Angle Determination

8.2.2 Dual-Channel Network Analyzer Method

The signal analyzer method (see [B8], [B26], and [B37]) determines automatically, from current and potential measurements, the grounding-system impedance and impedance angle using a frequency-scanning technique. This method allows for a complete plot of the impedance and phase angle over a frequency range that may be selected to encompass both the power system frequency and switching transient frequencies conducted by the grid to earth.

The instrumentation connections shown in Fig 8-4 are similar in principle to those of Fig 8-1, and will require all of the considerations discussed earlier. The current source may consist of either a sinusoidal generator or a pseudo-random noise generator, a noise conditioning filter, and a power amplifier of about 1.5 kW. As an example, the bandwidth of the noise source can be set from 0 Hz to 400 Hz. An external filter would be used to limit the noise signal to a range of 10 to 400 Hz in order to protect the power amplifier output transformer and the power transistors from the effects of low-frequency saturation. The current and voltage signals are first filtered, then digitized, and transformed into the frequency domain through a Fast Fourier Transform (FFT) routine. Using the transfer function of the spectrum

analyzer, the display (either CRT or X-Y plotter) shows the impedance magnitude and phase angle over the selected frequency range. To reduce the effect of background voltages and improve measurement accuracy, the FFT analyzer is programmed to make repeated measurements, which are added and averaged several times to obtain the final impedance and phase-angle plot. Additional applications for the signal analyzer are included in 13.5.

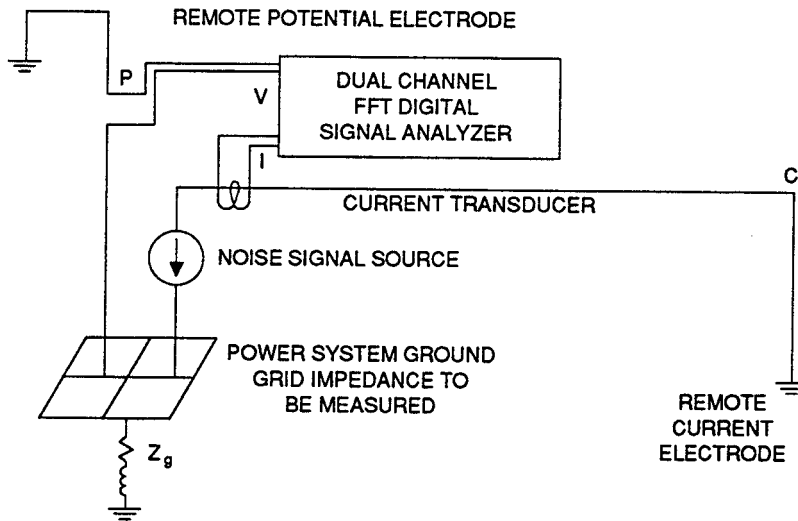


Figure 8-4—Dual-Channel Signal Analyzer Method of Measuring Impedance

8.3 Portable Power-Generator Source

The grounding system impedance may be measured with current levels of 10 to 100 A using a portable power generator with test current frequencies offset from the power-system frequency. Interference voltage from the power system can be avoided by using a test current frequency with at least 5 Hz difference from the system frequency, and by using measuring instruments of the selective-frequency type. A deviation of more than 10 Hz could introduce a significant error when shield wires and cable sheaths form an important part of the ground impedance. Or, if interference levels remain constant during the test period, the grounding-system impedance can be measured by the “beat frequency method” with a test-current frequency slightly offset (0.1 to 0.5 Hz) from the power-system frequency.

A portable power source can be an ac welding set, a truck-mounted recreational generator, or a portable 120 V ac generator carried by hand. Thus the power and current levels from about 1–50 kW and 10–100 A are feasible depending on the current-circuit impedance. The governor is adjusted to offset the test frequency from the power frequency. If the test results are thought to be sensitive to this frequency shift, measurements taken above and below the power frequency can be averaged.

At the higher test-current levels, the use of an out-of-service transmission line with phase conductors connected in parallel will simulate zero sequence current flow in the grounding system occurring during line-to-ground faults and will reduce current-circuit impedance. The remote current electrode may be a neighboring station grid (using ground switches closed on the test circuit) or a convenient transmission line tower. A spark gap or surge arrester should be provided across the generator in the event of lightning or system faults. Similarly, the frame of the generator and other instrumentation should be well bonded to the station grid.

For normal levels of interference, the portable power generator source with its lower current makes a continuous test practical since system regulation, hazardous potentials, and drying out of soil are not usually a problem. Continuous tests allow one detector to measure a large number of current splits and potentials.

For a simple grounding system where measured current and potential magnitudes can be used to determine grounding impedance magnitudes, the beat-frequency method or a tunable voltmeter detector will suffice. The magnitude-phase nuller method (see 8.3.2) can be used to measure both the magnitude and phase angle quantities. However, in the more extensive grounding system with numerous measuring points, the dual-channel network analyzer, which automatically measures the phase angle between and the ratio of two quantities, is more flexible during the continuous test energization as it allows one channel to determine the ratio and phase angle of a large number of current splits and potentials compared with a reference input current.

8.3.1 The Beat-Frequency Method (See [B25] and [B37])

This method involves an asynchronous test current and consists of a separate power supply, usually a mobile ac generator (frequency 0.1–0.5 Hz above or below the power frequency), an out-of-service transmission line, and a series capacitor inserted in series with the current loop to reduce the impedance of the current circuit (see Fig 8-5). Due to the frequency difference between the injected current, I_s , and the interference current, I_i , caused by the network during normal operation, the beat-frequency maxima and minima will occur in the test line as well as in the measured potential. When the maxima and minima values ($I_{\max}$, $I_{\min}$, $V_{\max}$, and $V_{\min}$) are measured, the residual voltage and current, V_i and I_i , should also be measured, as a check, before and after injecting the test current. Then, calculate:

$$I_s = \frac{I_{\max} + I_{\min}}{2} \quad \text{for } I_s > I_i \quad (8)$$

$$V_s = \frac{V_{\max} + V_{\min}}{2} \quad \text{for } V_s > V_i \quad (9)$$

$$I_s = \frac{I_{\max} - I_{\min}}{2} \quad \text{for } I_s < I_i \quad (10)$$

$$V_s = \frac{V_{\max} - V_{\min}}{2} \quad \text{for } V_s < V_i \quad (11)$$

$$Z_g = \frac{V_s}{I_s} \quad (12)$$

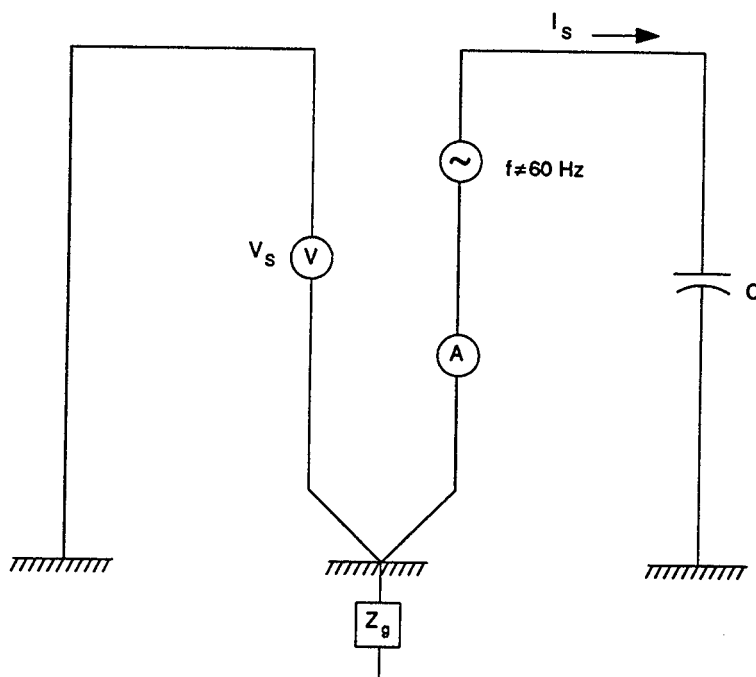


Figure 8-5—General Layout of the Beat-Frequency Method

8.3.2 Magnitude-Phase Nuller

This class of detector provides for separate nulling of magnitude and phase for measuring phasor impedances or current splits. As an example, the scheme shown in Fig 8-6 was configured, see [B9], for use with a welding generator source (67 Hz) where strong power-frequency noise was expected. With switch *S* in position 1, the oscilloscope positive (differential) input receives the test signal with the notch filter removing some power-frequency noise. The reference current signal from the CT is phase shifted and attenuated by the oscillator so as to null the test signal using the oscilloscope negative input. Through triggering of the oscilloscope by the line frequency, the noise represents a stationary waveform while the test signal provides a moving pattern that can be hulled with great sensitivity. Noise-free readings of the magnitude and phase are then made from the oscillator. With switch *S* in position 2, the procedure is repeated to measure the current reference signal. The ratio of the two results gives the test impedance with the amplitude and phase error in the notch filter cancelling.

Fig 8-7 shows a more simple alternative. A normal CT with shunt, R_s , provides a signal in phase with the test current. A split-core CT with an intentional air gap and high impedance burden provides a differential current signal leading by 90° . Calibrated potentiometers, P_r and P_x , are varied to bring about a null condition with the test signal, using the notch filter for additional noise reduction. The measured impedance is defined by the potentiometer settings as $P_r + jP_x$. The gapped CT is magnitude calibrated by separately measuring the voltage present across each potentiometer. In a similar manner, a variable mutual inductor and CT with secondary potentiometer may be used to null out the potential signal, which is superimposed on the 60 Hz plus harmonic interference voltages, see [5].

While these methods have good noise-rejection capability, nulling with two controls can be tedious in comparison with network analyzers.

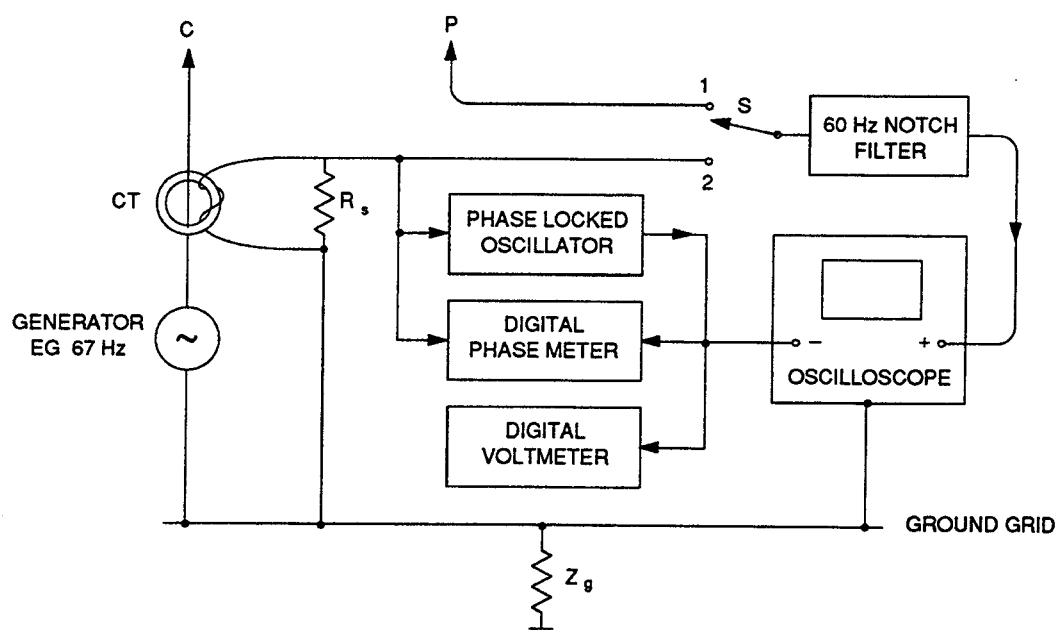


Figure 8-6—Magnitude-Phase Nuller Using Phase Locked Oscillator

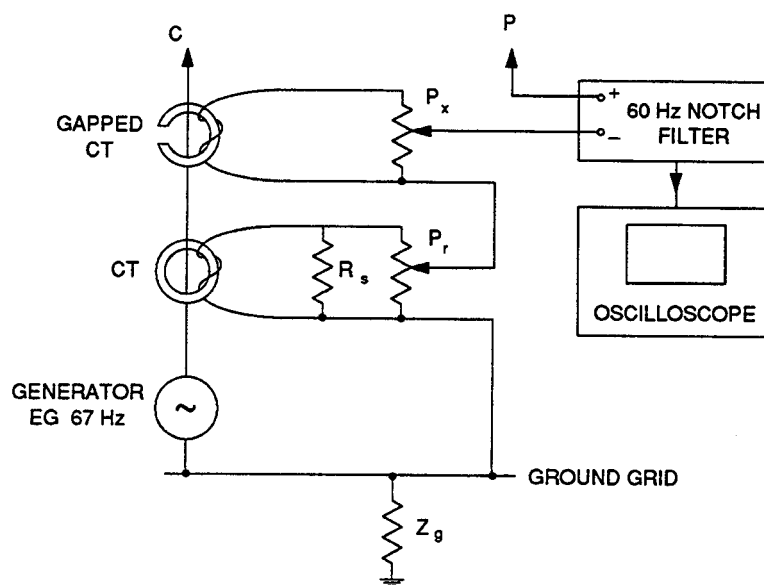


Figure 8-7—Magnitude-Phase Nuller Using Phase Differentiating CT

8.3.3 Dual-Channel Signal Analyzer

Grounding system multiple measurements can be made with a dual-channel network analyzer (DCNA), a portable generator (PG), and a step-up transformer (Tx) used to obtain the desired test current. The network analyzer, with an automatic averaging technique, calculates the ratio of the inputs to Channel 1 and Channel 2 and their phase angle difference. As shown in Fig 8-8, current transformers temporarily installed to measure current in each grounding branch have resistive shunts connected across their terminals. Shunt voltage drops, grid potentials, and cable conductor potentials are transmitted by shielded, twisted-pair cable to a central location (see 13.20). Then, each potential, in turn, can be compared with the output of the injection current CT.

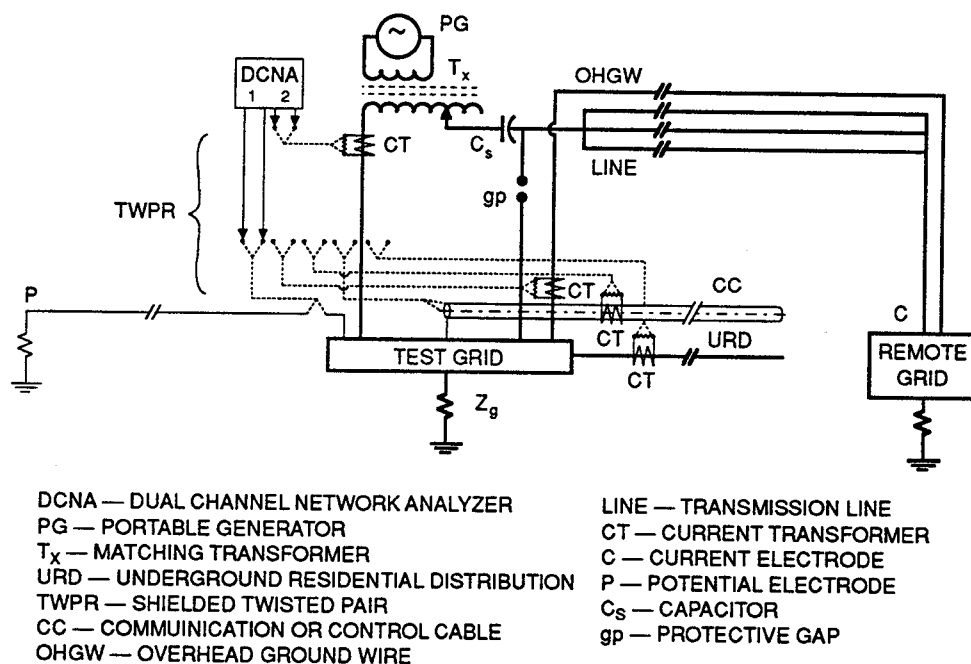


Figure 8-8—Grounding System Measurements With a Network Analyzer

A test current offset at 10 Hz or less from the power-system frequency may be injected into selected out-of-service lines while the normal power transmission is maintained on remaining lines. On the shorter lines (<10 km), in order to simulate the mutual impedance characteristics of a single-line-to-ground fault, only one phase conductor is used. The main objective is to determine the effective transfer impedance between a phase conductor and the communication and control cables with the beneficial effect of current flow in the grounding system. The latter is necessary to calculate the voltage stresses on these cables in the event of a power-system fault. On longer lines, in order to minimize injection circuit impedance, all three phases of the transmission line should be connected in parallel.

8.4 Power System Low-Voltage Source

The grounding system impedance may be measured with injected test currents taken from the power system low-voltage network, see [9], [B25], [B44], and [B40]. However, interference voltages present on the grounding conductors and induced on the test conductors will modify the measured currents and potentials. Measurement error can be reduced with test current magnitudes 50–100 A or higher, and fundamental and harmonic frequency errors can be minimized by the test-current reversal method and the interference compensation method (see 14.6).

8.4.1 Test-Current-Reversal Method (See [B13], [B25], and [B44])

The measurement of grounding impedance with test currents derived from a substation low-voltage source in the presence of an energized power system will add significant levels of fundamental and harmonic frequencies to the measured quantities. If the system conditions do not change during the test period, the interference will not change in magnitude, time, or phase relationships. Then, constant levels of background (fundamental and harmonic) frequencies present in the measured voltage and current can be cancelled out with the test-current-reversal method (see 14.6).

As shown in Fig 8-9, test equipment used for this method consists of the substation station-service source, an auxiliary adjustable matching transformer (Tx), an optional series capacitor (Cx) used to reduce current-circuit reactance, an out-of-service transmission line with either one phase used separately or three phases connected in parallel for impedance reduction, and an arrester or protective gap (gp) adjusted for 2–3 kV. The remote current electrode can be either the line termination grid or a low-resistance tower footing. Impedance magnitude and its resistance-reactance components can be calculated from measurements made with a wattmeter (W), ammeter (A), and voltmeter (V) of the electrodynamic type. A current transformer (CT) is used to reduce the test-current magnitude to within meter current coil ratings. These meters will give the true rms readings of waveforms containing harmonics. If the current in the wattmeter current coil has no distortion, only the fundamental frequency component of the potential waveform will produce active Power readings. Even if the current waveform has a slight (<5%) distortion, the active power produced by the harmonic content of the voltage will not significantly effect final results. Electrodynamic instruments of the moving-coil type are quite rugged; however, the input resistance of their potential circuits is low. If the resistance of the potential probe and the test lead, R_{probe} , is not at least 1/100 of the parallel voltmeter and wattmeter potential circuits, R_{meters} , then the voltmeter and wattmeter readings will be low and will require a correction multiplier: $(R_{meters} + R_{probe})/R_{meters}$. Meter potential circuit loading of the remote potential electrode circuit can be eliminated with a high-input-impedance, fixed-ratio amplifier (not shown in Fig 8-9) interposed between the meters and the test probe circuit. The optimum meter accuracy will be obtained if the amplified potentials are at least 50% of coil ratings. Then the actual active power and voltage will be found by dividing the measured values by the amplification factor.

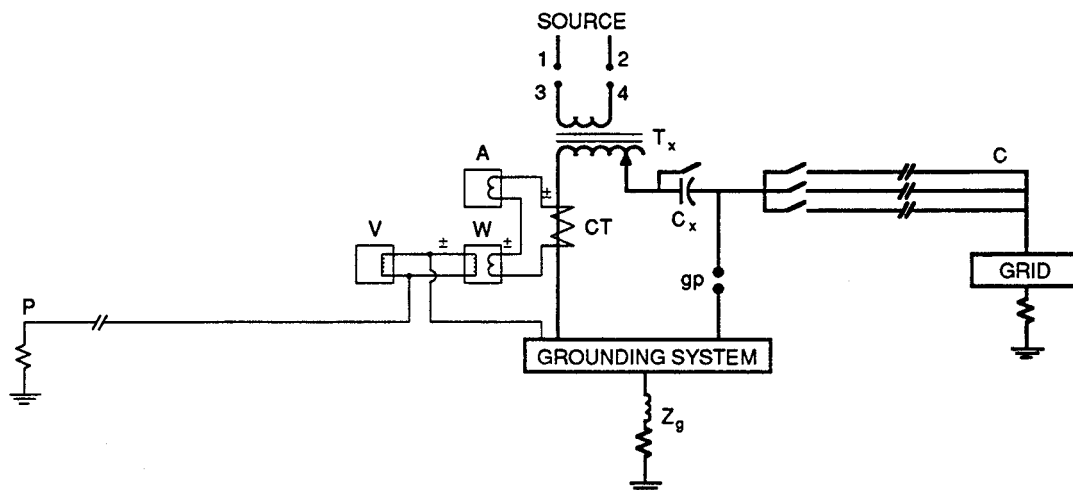


Figure 8-9—Substation Low-Voltage Source for Measuring Impedance

In the test-current-reversal method, referring to Fig 8-9, V_{sa} , I_{sa} , and P_{sa} are measured for connection 1 to 3 and 2 to 4; V_{sb} , I_{sb} , and P_{sb} are measured for connections 1 to 4 and 2 to 3; and, with 3 connected to 4 (1 and 2 open), V_i , I_i , and P_i are measured. If an initial current, I_i , exists in the injection line when the source of I_s is short-circuited (3 to 4), there will be a corresponding grid-rise voltage, V . To minimize errors caused by I_i and V_i , these quantities should be measured before and after the current injection test-current-reversal method. Then, I_s , V_s , and P_s can be calculated with the following equations:

$$I_s = \sqrt{\frac{I_{sa}^2 + I_{sb}^2}{2} - I_i^2} \quad (13)$$

$$V_s = \sqrt{\frac{V_{sa}^2 + V_{sb}^2}{2} - V_i^2} \quad (14)$$

$$P_s = \frac{P_{sa} + P_{sb}}{2} - P_i \quad (15)$$

and the impedance magnitude, resistance, reactance, and phase angle:

$$Z_g = \frac{V_s}{I_s} \quad (16)$$

$$R_g = \frac{P_s}{I_s^2} \quad (17)$$

$$X_g = \sqrt{Z_g^2 - R_g^2} \quad (18)$$

$$\cos \Phi_s = \frac{P_s}{V_s I_s} \quad (19)$$

where

Φ_s is the angle between V_s and I_s .

In conjunction with the test-current-reversal method, to improve measurement accuracy, it may be desirable to use the interference compensation method (see 8.4.2) to reduce any fundamental frequency interference voltage present in the potential-probe circuit. The advantages of using the power-system low-voltage source are:

- 1) Impedance is measured at power system frequency.
- 2) Equipment used for measurement is generally available in the utility.
- 3) Sufficient test current is used to overcome background voltages and any circuit nonlinearities such as connection resistances.

8.4.2 Interference Compensation Method (See [6], [B25], [B37], and, [B44])

The interference compensation method uses a power-frequency injection voltage to compensate the fundamental-frequency component of the residual voltage to zero with the current injection circuit open (see 13.8). After the compensation, the test current is injected by means of a current test circuit similar to that in Fig 8-10. Then, the selective-frequency voltmeter will measure the fundamental-frequency grid-voltage values. For the compensation, either a voltage source that is separately adjustable in magnitude and phase angle or two voltage sources shifted 90° apart that are independently adjustable maybe used. As an example of the latter, potentials may be obtained from a three-phase, four-wire source. The in-phase component can be obtained from *A* phase to *N*, and the 90° component from *B* to *C* phase (see Fig 8-10). The output impedance of the compensator should not exceed 0.5% of the potential measuring meter impedance.

If the out-of-service transmission line, used for current injection, parallels an energized line, the induced current alone could be used in conjunction with the interference compensation method to measure grounded-system impedance.

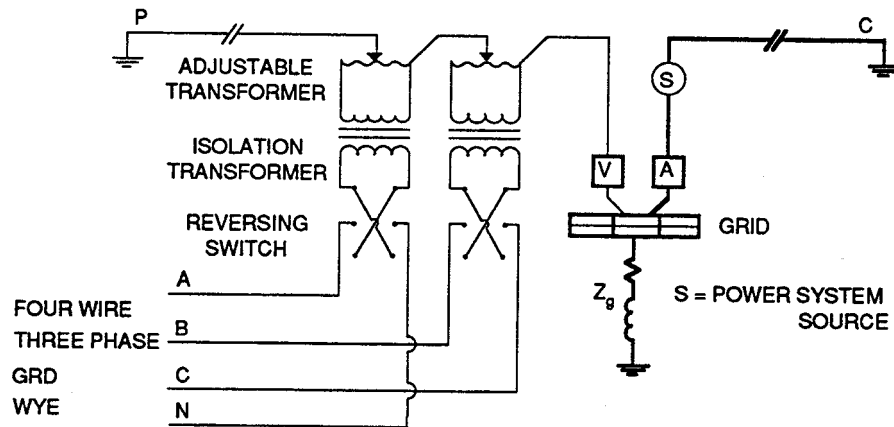


Figure 8-10—Potential Lead Interference Compensation Using a Three-Phase, Four-Wire Low-Voltage Source

9. Measurement of Low-Impedance Grounding Systems by Power System Staged Faults

9.1 Introduction

Grounding tests made under system conditions with full line-to-ground source voltage and high fault current provide a more exacting test of the grounding system. They make possible the determination of the grid potential rise, the fault current distribution in the grounding system, the phase angle difference between the voltage and current, the grid voltage profile, the voltages present on nearby buried metallic structures due to current flow through the earth, the induced voltages on paralleling utility facilities, and the effects of EMI generated by high-frequency current flow occurring at fault initiation and by system-frequency fault current flow (see 13.3 and 13.7). The staged fault test will not be required or desirable for every grounding grid. Normally, the current-injection test methods of Section 8. will be adequate, and only those grounding systems with special problems or marginal grid rise need be tested. Frequently, staged fault tests can be made jointly when system tests are conducted to determine circuit parameters, equipment performance, and protection characteristics. Fault testing of the grounding system will have a minimal effect on power-system operations, if performed during lightly loaded periods.

The projections of parameters to maximum expected fault current levels are necessary for grid safety, substation telephone service insulation requirements, interference voltages in paralleling control and communication circuits, and maximum effects on other utilities. Sub-station fault tests should be coordinated with interested telephone, pipeline, and customer engineering personnel.

Before undertaking measurement under power system conditions, it is recommended that safety practices of Section 4. be reviewed.

The following are additional precautions for power-system staged fault testing of grounding systems:

- 1) Cables used to measure the voltage rise must be considered live over their entire length at all times.
- 2) There should be no phone conversation during fault initiation.
- 3) Personnel should be warned not to establish any type of physical contact between two points at different potentials during tests.
- 4) A test sequence shall not be considered terminated until the opening of the test circuit is confirmed visually.