Testing and Evaluation of Grounding Systems: The Revision of the IEEE Std 81

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Grounding and Bonding is Fundamental for a Safe and Reliable Power System

Lightning and Surge Protection

Stabilize Circuit Potential and Assist in Proper Operation of:
- Communications
- Relaying
- Computers & Sensitive Electronic Equipment

Low Fault Circuit Path Impedance

Safety, Safety, Safety

Improve Quality of Power Service
Grounding, Bonding and Power Quality

“Recent studies indicate that as much as 80% of all failures of sensitive electronic equipment attributed to poor power quality may result from inadequate electrical grounding or wiring on the customer’s premises or from interactions with other loads within the premises.”

*Wiring and Grounding for Power Quality*
*EPRI CU-2026, March 1990*

“However, many power quality problems that occur within customer facilities are related to wiring and grounding practices. Up to 80% of all power quality problems reported by customers are related to wiring and grounding problems within a facility.”

*Power Quality Assessment Procedure*
*EPRI CU-7529, December 1991*
Over the Years Grounding Design Procedures Have Been Developed as Well as Appropriate Standards, Most Notable:


• National Electrical Code.

• National Electrical Safety Code.

• FIPS 94 and Derivatives.

For the Purpose of Verifying Designs, Testing Procedures have Been also Developed. Most Notable:


The History of IEEE Std 80

Guide for SAFETY IN ALTERNATING-CURRENT SUBSTATION GROUNDING
(Effective March 15, 1961)

Published by AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 West Thirty-ninth Street, New York 18, N. Y.

IEEE Guide for Safety in Substation Grounding

Published by The Institute of Electrical and Electronics Engineers, Inc. 345 East 47th Street, New York, NY 10017, USA
June 16, 1976
The History of IEEE Std 80
Basis of Standards: IEEE 80 & IEC

IEEE Std80
- Body Weight
  - 70 kg
  - 50 kg
- Body Current
  - IEEE (50 kg)
  - IEC (P=0.50%)

IEC
- Probability of Ventricular Fibrillation
  - 0.14 %
  - 0.50 %
  - 5.00 %
- Body Current
  - Let Go Cur.
  - 0.6121
- Shock Duration
  - 0.2014

WinIGS - Form: GRD_RP04 - Copyright © A. P. Meliopoulos 1998-2009
Value of Constant $k$ for Effective RMS Values of $I_B$:

$$k = I_b \sqrt{t_s}$$

$k_{50} = 0.116$ (Non-Fibrillating, 0.5%)
$k_{50} = 0.185$ (Fibrillating, 0.5%)
$k_{70} = 0.157$ (Non-Fibrillating, 0.5%)
$k_{70} = 0.263$ (Fibrillating, 0.5%)
Earth Current, Ground Potential Rise, Touch & Step

Basic Problems:
1. Determination of Soil Resistivities
2. Computation of Ground Potential Rise
3. Computation of Surface Voltages (touch and step)
4. Safety Assessment

\[ \tilde{I}_{\text{fault}} = \tilde{I}_{\text{shield}} + \tilde{I}_{\text{neutral}} + \tilde{I}_{\text{earth}} + \tilde{I}_{\text{counterpoise}} \]

\[ GPR = R_{\text{mat}} \tilde{I}_{\text{earth}} \]
Verification - Measurements

Key Fact:
Target Values Must be Determined in Design Phase
The History of the IEEE Std 81

First Edition:
IEEE Std 81 – 1962

Revision:
ANSI/IEEE Std 81-1983
IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

To Address Issues Related to Large Grounding Systems or Systems in Congested Areas:
IEEE Std 81.2-1991
IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems

All of Above Standards were sponsored by:

Power System Instrumentation and Measurement Committee
Of the
IEEE Power Engineering Society

In the period 2003-2004, I served as the Chair of the Substations Committee of the IEEE Power Engineering Society. I initiated and succeeded in transferring sponsorship of the standard to the Substations Committee with the plan to combine the two standards into one single standard. The unified standard has been developed in committee (working group E6, Chaired by Dennis DeCosta) and we expect to ballot it within the next 12 months.
ANSI/IEEE Std 81-1983
IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

1. Purpose
2. Scope
3. Objectives of Tests
4. Definitions.
5. Safety Precautions While Making Ground Tests
6. General Considerations of the Problems Related to Measurements
   6.1 Complexities
   6.2 Test Electrodes
   6.3 Stray Direct Currents
   6.4 Stray Alternating Currents
   6.5 Reactive Component of Impedance of a Large Grounding System
   6.6 Coupling Between Test Leads
   6.7 Buried Metallic Objects
7. Earth Resistivity
8. Ground Impedance
   8.1 General
   8.2 Methods of Measuring Ground Impedance
   8.3 Testing the Integrity of the Ground Grid
   8.4 Instrumentation
9. Earth Potential
   9.1 Equipotential Lines
   9.2 Potential Contour Surveys
   9.3 Step and Touch Voltages
10. Transient Impedance
11. Model Tests
12. Instrumentation
13. Practical Aspects of Measurements
Annex A Nonuniform Soils
Annex B Determination of an Earth Model
Annex C Theory of the Fall of Potential Method
Annex D Bibliography
IEEE Std 81.2-1991
IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems

1. Purpose
2. Scope
3. References
4. Safety Practices
5. Factors Effecting Grounding System Measurements
6. Preliminary Planning and Procedures
7. Earth-Return Mutual Effects When Measuring Grounding-System Impedance
   7.1 Introduction
   7.2 Measurement Error Due to Earth Mutual Resistances
   7.3 Measurement Error Due to AC Mutual Coupling
   7.4 Mutual Coupling to Potential Lead From Extended Ground Conductors
8. Measurement of Low-Impedance Grounding Systems by Test-Current Injection
   8.1 Introduction
   8.2 Signal Generator and Power Amplifier Source
   8.3 Portable Power-Generator Source
   8.4 Power System Low-Voltage Source
10. Current Distribution in Extended Grounding Systems
    10.1 Introduction
    10.2 Test Considerations
    10.3 Analysis of Current Distribution in a Grounding System
    10.4 Induced Current in the Angled Overhead Ground Wire
    10.5 Current Distribution During a Staged Fault Test
11. Transfer Impedances to Communication or Control Cables
12. Step, Touch, and Voltage-Profile Measurements
13. Instrumentation Components
    13.5 Fast Fourier Transform Analyzer
    13.6 Sine Wave Network Analyzer
    13.7 Staged Fault
    13.11 Low-Power Random Noise Source
    13.14 Pulse Generator
    13.15 Current Transformer (CT)
    13.16 Resistive Shunt
    13.17 Inductive Current Pickup
    13.18 Hall-Effect Probe
15. Bibliography

It was developed to address the special problems and issues associated with testing large interconnected grounding systems.
1. Overview
   1.1 Purpose
   1.2 Scope

2. References

3. Definitions

4. Test Objectives

5. Safety Precautions While Making Ground Tests
   5.1 Station Ground Tests
   5.2 Special Considerations

6. General Considerations on the Problems Related to Measurement

7. Earth Resistivity
   7.1 General
   7.2 Methods of Measuring Earth Resistivity
   7.3 Interpretation of Measurements
   7.4 Guidance on performing field measurements

8. Ground Impedance

9. Testing Local Potential Differences

10. Integrity of Grounding Systems

11. Current Splits

12. Transient Impedance of Grounding System

13. Other

ANNEX A (INFORMATIVE) SURFACE MATERIAL RESISTIVITY

ANNEX B - INSTRUMENTATION
   B.1. Megohm Meter
   B.2. Clamp-On Ground Tester
   B.3. Smart Ground Meter
   B.4. Transient Impedance Meter
Grounding System Measurements

• Ground Impedance Measurement Methods
  The 2-Point Method
  The 3-Point Method
  The Fall of Potential Method
  The 62% Rule
  The Ratio Method
  The Tag Slope Method
  The Intersecting Curve Method
  Staged Fault Tests
  Driving Point Impedance
  The SGM Method

• Continuity/Integrity Testing

• Soil Resistivity Measurements

• Touch and Step Voltages

• Other Tests (Tower/Pole Ground, Transfer V.)
Four Point – Wenner Method

\[ R = \frac{V}{I} \]

\[ \rho = \frac{4\pi aR}{2a + \frac{a}{\sqrt{a^2 + 4\ell^2} - \sqrt{a^2 + \ell^2}}} \approx 2\pi aR \]
Limitations of the Wenner Method

\[ V_m = RI - r_e aI - jx_e aI \]

\[ \frac{V_m}{I} = \frac{\rho}{2\pi a} - r_e a - jx_e a \]

Example: Soil of 10 Ohm.meter, separation 300 feet, measurements at 150 Hz. Compute error.
Basic Principles
Basic Arrangement

\[ R_g = \frac{V}{I} \]

Ground System Under Test
The Fall of Potential Method
The “62%” Rule
Optimal Voltage Probe Location – The 62% Rule

\[ V_a = \frac{I \rho}{2\pi} \left( \frac{1}{a} - \frac{1}{D} \right) \]
\[ V_p = \frac{I \rho}{2\pi} \left( \frac{1}{r} - \frac{1}{D-r} \right) \]

\[ R_a = \frac{V_a - V_p}{I} = \frac{\rho}{2\pi} \left( \frac{1}{a} - \frac{1}{D} - \frac{1}{r} + \frac{1}{D-r} \right) \]
Optimal Voltage Probe Location – The 62% Rule

\[
\begin{align*}
R_g &= \frac{V_a}{I} = \frac{\rho}{2\pi a} \\
R_a &= \frac{V_a - V_p}{I} = \frac{\rho}{2\pi} \left( \frac{1}{a} - \frac{1}{D} - \frac{1}{r} + \frac{1}{D - r} \right)
\end{align*}
\]

\[R_a = R_g\] requires that:
\[
\frac{1}{D} + \frac{1}{r} - \frac{1}{D - r} = 0
\]

Solving for \(r/D\) yields:
\[
\frac{r}{D} = \frac{-1 \pm \sqrt{5}}{2} = 0.618034
\]
The Fall of Potential Method – 62% Rule and Two Layer Soil

\[ K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \]
Ground Impedance Measurements
The Fall of Potential Method – Measurement Process

**THEORY**

![Diagram showing the measurement process]

- **Current Source**
- **Voltmeter**
- **Voltage Probe**
- **Ground Under Test**
- **Apparent Resistance**
- **Flat Curve Portion**
- **True Ground Resistance**
- **Distance from Ground Under Test**
The Fall of Potential Method
Earth Voltage Distribution - Actual Measurements
Contributor: American Electric Power

\[ R = \frac{V}{I} \]

Distance (feet)

Resistance (Ohms)

Volts

Current

Electrode

276 x 276 ft

2160 ft
The Fall of Potential Method

Factors Affecting Ground Impedance Measurement

- Difficulty reaching true remote earth reference voltage
- Effect of Auxiliary Electrode Location (Earth Current Return)
- Size and location of voltage probes
- Interaction Between Instrumentation Wires
- Interference from Overhead Lines and their Grounding
- Background 60 Hz Voltage and Harmonics
- Ground Impedance Magnitude
Fall of Potential Method Errors
Interaction between Instrumentation Wires

\[ M = l \frac{\mu_0}{2\pi} \ln\left(\frac{D_e}{d}\right) \]

where

\[ D_e = 2160 \sqrt{\frac{\rho}{f}} \]

(d,De in feet)
The Fall of Potential Method
Interaction between Instrumentation Wires

Induced Voltage Computation Example:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>500.00</td>
<td>feet</td>
</tr>
<tr>
<td>Current</td>
<td>1.00</td>
<td>Amperes</td>
</tr>
<tr>
<td>Rho</td>
<td>100.00</td>
<td>Ohm-meters</td>
</tr>
<tr>
<td>Frequency</td>
<td>90.00</td>
<td>Hz</td>
</tr>
<tr>
<td>d</td>
<td>10.00</td>
<td>feet</td>
</tr>
<tr>
<td>D_e</td>
<td>2276.84</td>
<td>feet</td>
</tr>
<tr>
<td>M</td>
<td>0.0001437</td>
<td>Henries</td>
</tr>
<tr>
<td>Voltage</td>
<td>0.081</td>
<td>Volts</td>
</tr>
</tbody>
</table>

Ground Mat Voltage: 
\[ V = RI(\omega) \]

Induced Voltage on Lead: 
\[ V_{md} = j\omega MI(\omega) \]

Measured Voltage: 
\[ V_m = V + V_{ind} \]

Measured Impedance: 
\[ Z_m = \frac{V_m}{I(\omega)} \]

Measurement Error: 
\[ \frac{Z_m - R}{R} \times 100\% \]
The Fall of Potential Method
Interaction between Instrumentation Wires

Induced Voltage Computation Example:

<table>
<thead>
<tr>
<th>Length</th>
<th>500.00</th>
<th>feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>1.00</td>
<td>Amperes</td>
</tr>
<tr>
<td>Rho</td>
<td>100.00</td>
<td>Ohm-meters</td>
</tr>
<tr>
<td>Frequency</td>
<td>90.00</td>
<td>Hz</td>
</tr>
<tr>
<td>d</td>
<td>10.00</td>
<td>feet</td>
</tr>
<tr>
<td>De</td>
<td>2276.84</td>
<td>feet</td>
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<td>Henries</td>
</tr>
<tr>
<td>Voltage</td>
<td>0.081</td>
<td>Volts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R</th>
<th>Magn. Error</th>
<th>Phase Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0.006%</td>
<td>0.65 Deg</td>
</tr>
<tr>
<td>1.0</td>
<td>0.6%</td>
<td>6.49 Deg</td>
</tr>
<tr>
<td>0.1</td>
<td>51%</td>
<td>48.68 Deg</td>
</tr>
</tbody>
</table>
Driving Point Impedance Meters: Hand-Held Meters
Easy to Use But Limited Applications

LEM GEO MODEL 15 - Ground Resistance Tester
Measurement Range: 0.025 ohms to 1500 ohms at 1.667 kHz
Hand-Held Meters

Diagram of a hand-held meter connected to a ground pole, showing the electrical connections and resistance values (Rn, Rm, Rt, Rx).
The Smart Ground Multimeter (SGM) Method: Model Based Measurement Instrument

Presently Available Functions

1. Ground (System) Impedance Meter
2. Touch Voltage Meter
3. Step Voltage Meter
4. Tower Ground Resistance Meter
5. Soil Resistivity Meter
6. Ground Mat Impedance
7. Transfer Voltage Meter
8. Low Impedance/Continuity Meter
9. Fall of Potential Method
10. Oscilloscopic Function
11. Pole Ground

User Selected 250V or 500V Internal Switchable Source
Smart Ground Multimeter
Ground Impedance Function
Illustration of Probe Placement and SGM Connections
60 Hz and Harmonic Interference Correction

Correction Method: Based on quadratic rational transfer function fitting

Minimize: \[ \sum_k W_k \left( \hat{H}(j\omega_k) - H(j\omega_k) \right)^2 \]

where: \( \hat{H}(s) = a_0 + a_1 s + a_2 s^2 \) or \( \hat{H}(s) = \frac{a_0 + a_1 s + a_2 s^2}{b_0 + b_1 s + b_2 s^2} \)
60 Hz and Harmonic Interference Example
Grounding System Audit: Objectives

- Verify Design Values
- Verify Safety and Ground Potential Rise
- Verify Construction or Determine Ground Integrity
- Verify Lightning Performance
- Investigate Possible Points of Danger
- Evaluate Possible Ground Enhancements (Cost/Benefit Analysis)
Grounding System Audit: Procedure

Part 1: Testing

- Create a Facility Model (per drawings)
- Ground System Impedance Measurement
- Facility Ground Resistance Measurement
- Soil Resistivity Measurement
- Point-to-Point Ground Measurements
- Transfer Potential Measurement (as needed)
- Oscilloscopic View of GPR
Grounding System Audit: Procedure

Part 2: Model Validation and Analysis

- Ground Model Validation (Compare Model to Measurements)
- Ground Conductor Size Adequacy Assessment
- Safety Assessment (IEEE Std 80 or IEC)
- Lightning Shielding Analysis and Risk Evaluation
- Evaluation of Remedial Measures (as needed)
Grounding System Audit – Testing
Detailed Grounding Model (3D)

- CAD Drawings
- Top Views
- Elevations
- Photographs
- On-Site Inspection
Grounding System Audit – Testing
Detailed Grounding Model

- CAD Drawings
- Top Views
- Elevations
- Photographs
- On-Site Inspection
Ground System Impedance Measurement

Smart Ground Multimeter – Grounding System + Voltage and Current Probe Model

Voltage Probes

Current Electrode

2000 ft
# Ground System Impedance Measurement

## Smart Ground Multimeter – Grounding System + Voltage and Current Probe Model

<table>
<thead>
<tr>
<th></th>
<th>Latitude</th>
<th>Longitude</th>
<th>Distance from SGM (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SGM</strong></td>
<td>N90</td>
<td>W11</td>
<td>51.8700</td>
</tr>
<tr>
<td><strong>Reference</strong></td>
<td>N90</td>
<td>W11</td>
<td>51.9080</td>
</tr>
<tr>
<td><strong>Current Return</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N90</td>
<td>1.71201</td>
<td>W11</td>
<td>51.67400</td>
</tr>
<tr>
<td>Probe 1Y</td>
<td>N90</td>
<td>W11</td>
<td>51.88800</td>
</tr>
<tr>
<td>Probe 2Y</td>
<td>N90</td>
<td>W11</td>
<td>51.88300</td>
</tr>
<tr>
<td>Probe 3Y</td>
<td>N90</td>
<td>W11</td>
<td>51.88500</td>
</tr>
<tr>
<td>Probe 1B</td>
<td>N90</td>
<td>W11</td>
<td>51.91100</td>
</tr>
<tr>
<td>Probe 2B</td>
<td>N90</td>
<td>W11</td>
<td>51.89800</td>
</tr>
<tr>
<td>Probe 3B</td>
<td>N90</td>
<td>W11</td>
<td>51.88900</td>
</tr>
</tbody>
</table>

Hood Patterson & Dewar  
Form GPS_COORD - Copyright © A. P. Meliopoulos 1992-2007

IEEE Industry Applications Society – Atlanta Chapter
January 19, 2010 Meeting
Grounding System Audit – Testing Soil Resistivity Measurement

Smart Ground Multimeter

• Based on extension of the four pin method

• Measures ground potential differences between six voltage

• Uses estimation based analysis to fit the measurements to the measurement system model

• Provides Measurement Interpretation (Two Layer Model)
Soil Resistivity Measurement
Soil Resistivity Measurement

**Smart Ground Multimeter**

**Soil Resistivity Report**

- **Case Name**: ALPHA_20FT_250V-X
- **Date and Time**: Monday, March 08, 2004 10:18 AM
- **Description**: 20 ft spacing, 250V, 40 deg fair.

**Soil Resistivity Model**

- **Upper Soil Resistivity**: 108.9 Ohm Meters
- **Lower Soil Resistivity**: 324.4 Ohm Meters
- **Upper Layer Thickness**: 16.3 Feet
- Results are valid to depth of 80.0 Feet

**Plot Cursors**

- **Error**
- **Confidence Level**

---

Hood Patterson & Dewar

Form SI_REP_1 - Copyright © A. P. Mellopoulos 1992-2007
Grounding System Audit – Testing Point-to-Point Ground Measurements

Testing & Calibration Unit

Separation (at least 20 ft)

Red

Yellow & Blue

Black & Green
### Grounding System Audit – Testing

#### Point-to-Point Ground Measurements

<table>
<thead>
<tr>
<th>Fig #</th>
<th>Test Point Locations</th>
<th>Computed Resistance (mΩ)</th>
<th>Measured Resistance (mΩ)</th>
<th>Measured Reactance (mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3</td>
<td>13 kV transformer to fence gate ground (points K01-K02)</td>
<td>1315</td>
<td>433.2</td>
<td>437.1</td>
</tr>
<tr>
<td>D4</td>
<td>13 kV transformer to fence pig-tail ground</td>
<td>1315</td>
<td>437.2</td>
<td>442.0</td>
</tr>
<tr>
<td>D5</td>
<td>13 kV transformer to TVA XFRM 2 (points K01-K03)</td>
<td>8.41</td>
<td>6.535</td>
<td>15.09</td>
</tr>
<tr>
<td>D6</td>
<td>Control House to Fence - Southeast Corner (points K04-K05)</td>
<td>1166.4</td>
<td>1619.2</td>
<td>1620.0</td>
</tr>
<tr>
<td>D7</td>
<td>Control House to Nixon Line PT - Phase C (points K04-K06)</td>
<td>6.77</td>
<td>8.704</td>
<td>15.18</td>
</tr>
<tr>
<td>D10</td>
<td>Control House to 161 kV Breaker #988 (points K04-K07)</td>
<td>7.29</td>
<td>8.196</td>
<td>15.28</td>
</tr>
<tr>
<td>D13</td>
<td>Control House to Breaker #968 (points K04-K08)</td>
<td>6.31</td>
<td>8.279</td>
<td>15.31</td>
</tr>
<tr>
<td>D17</td>
<td>Control House to Breaker #934 (points K04-K10)</td>
<td>7.71</td>
<td>8.209</td>
<td>14.08</td>
</tr>
<tr>
<td>D20</td>
<td>Control House to 161 kV Instrument PT - Phase B (points K04-K11)</td>
<td>6.87</td>
<td>8.475</td>
<td>14.50</td>
</tr>
<tr>
<td>D22</td>
<td>Control House to Breaker #954 (points K04-K09)</td>
<td>5.98</td>
<td>8.587</td>
<td>15.79</td>
</tr>
<tr>
<td>D26</td>
<td>Control House to Capacitor Bank Fence (points K04-K15)</td>
<td>5.70</td>
<td>117.9</td>
<td>130.6</td>
</tr>
<tr>
<td>D29</td>
<td>Control House to Capacitor Bank Sectionalizer Switch 2 Ground (points K04-K16)</td>
<td>9.48</td>
<td>12.99</td>
<td>33.36</td>
</tr>
<tr>
<td>D30</td>
<td>Control House to Capacitor Bank Sectionalizer Switch 3 Ground (points K04-K17)</td>
<td>12.21</td>
<td>13.21</td>
<td>34.51</td>
</tr>
</tbody>
</table>