Tutorial
IEEE Standard 81™ – 2012

IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System

IEEE POWER & ENERGY SOCIETY
2014 Annual Substation Committee Meeting
Portland, Oregon, USA
May 18, 2014

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THE INSTITUTE OF ELECTRICAL AND
ELECTRONICS ENGINEERS, Inc.

IEEE PES
Power & Energy Society™

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IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System

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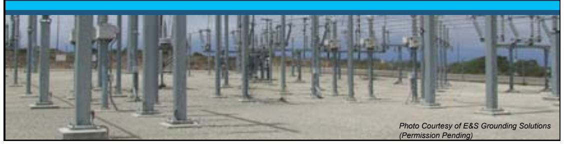

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Presented by

Bryan Beske, PE	American Transmission Co.
Carson Day, PE	NEETRAC/Georgia Tech
Dennis DeCosta, PE	Commonwealth Associates, Inc.
Lane Garrett	Commonwealth Associates, Inc.
Jeff Jowett	Megger
Carl Moller	CANA High Voltage
Steve Palmer	Safearth Consulting
Sashi Patel	NEETRAC/Georgia Tech
Will Sheh	TectoWeld Inc.
George Vlachos	AEMC Instruments

Key Objectives & Definitions

Will Sheh

Tectoweld, Inc.

PRESENTER TUTORIAL OBJECTIVE

What we want you to take away from this tutorial:

1. Understand the basic principles of measuring the electrical characteristics of grounding systems
2. Learn the basic methods of measuring earth resistivity, power frequency impedance to remote earth, step and touch voltages, and verifying the integrity of the grounding system
3. Identify various conditions and instrument limitations that can distort test measurements
4. Recognize that a lethal voltage can exist during testing and implement appropriate safety precautions

AUDIENCE TUTORIAL OBJECTIVE

Why are you here today?
&
What do we want you to take away from this tutorial?:

1. Professional development hours for PE License.
2. Introduce inexperienced engineers/designers to practical methods for ground testing.
3. Provide experienced engineers/designers with an enhanced knowledge of test methods and techniques used for measuring the electrical characteristics of grounding systems.

TUTORIAL OUTLINE

1. Introduction		
1.1 Test objectives & key definitions	Will Sheh	8:00 am
1.2 Safety considerations	George Vlachos & Jeff Jowett	8:10 am
1.3 Understanding the circuit being tested	George Vlachos & Jeff Jowett	8:20 am
1.4 Typical problems encountered during testing	Carl Moller	8:30 am
2. Test methods		
2.1 Earth resistivity	Lane Garrett	8:45 am
Break		***9:45 am***
2.2 Ground Impedance	Shashi Patel	10:00 am
2.3 Earth potentials and step & touch potentials	Carl Moller	11:00 am
Lunch	***12:00 pm***	
2.4 Ground integrity testing	Carson Day	1:00 am
2.5 Surface aggregate testing	Bryan Beske	1:30 pm
3. Test simulations		
3.1 Part 1	Steve Palmer	2:00 pm
Break		***3:30 pm***
3.2 Part 2	Steve Palmer	3:45 pm
3. Questions and answers		5:00 pm
4. Adjourn		***5:30 pm***

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QUESTIONS AND ANSWERS

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INTRODUCTION

Test Objectives

1. **Earth resistivity measurements**
   - 1.1 Estimate the ground impedance of a grounding system
   - 1.2 Estimate potential gradients including step & touch voltages
   - 1.3 Compute inductive coupling to nearby power & communication cables, pipelines and other metallic objects
   - 1.4 Design cathodic protection systems
2. **Impedance and potential gradient measurements**
   - 2.1 Verify the adequacy of the new grounding system
   - 2.2 Detect changes in an existing grounding system
   - 2.3 Identify hazardous step and touch voltages
   - 2.4 Determine the ground potential rise (GPR)

INTRODUCTION

Key Definitions

Coupling: The association of two or more circuits or systems in such a way that power or signal information is transferred from one to another.

Ground electrode: A conductor embedded in the earth and used for collecting ground current from or dissipating ground current into the earth.

Ground grid: A system of interconnected ground electrodes arranged in a pattern over a specified area and buried below the surface of the earth.

Ground impedance: The vector sum of resistance and reactance between a ground electrode, grid or system and remote earth.

Remote earth: A theoretical concept that refers to a ground electrode of zero impedance placed an infinite distance away from the ground under test. Remote earth is normally assumed to be at zero potential.

Soil (earth) resistivity: A measure of how much a volume of soil will resist an electric current and is usually expressed in Ω-m.

INTRODUCTION

Key Definitions (Continued)

Ground potential rise (GPR): The maximum electrical potential that a ground electrode, grid or system might attain relative to a distant grounding point assumed to be at the potential of remote earth.

Step voltage: The difference in surface potential that could be experienced by a person bridging a distance of 1 meter with the feet without contacting any grounded object.

Touch voltage: The potential difference between the GPR of a grounding grid or system and the surface potential where a person could be standing while at the same time having a hand in contact with a grounded structure or object. Touch voltage measurements can include or exclude the equivalent body resistance in the measurement circuit.

Transferred voltage: A special case of touch voltage where a voltage is transferred into or out of the vicinity of a ground electrode from or to a remove point external to the ground electrode.

Safety Considerations

George Vlachos, Jeff Jowett
AEMC Instruments Megger

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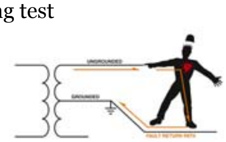
Safety considerations

Three Prime Safety Hazards

- Lethal voltage between electrode and ground
- Power-system fault during test
- Step & Touch Potentials



Safety considerations

Other Possible Hazards

- Ground Potential Rise
  - Can reach several thousand volts!
- Lightning Strokes (Strikes)

Safety considerations

- Create a test plan that includes Safety Rules
- Body prevented from closing circuit between points of potential difference
- Gloves and footwear
- Isolate exposed leads and electrodes
- Keep test signal application brief
- Leads and probes kept within sight
- Avoid induced voltages from overheads

Safety considerations

Surge Arrester Testing:

- Do not disconnect ground while primary remains connected to energized line!
- Lightning & switching currents can exceed 50 kA.
- If arrester fails during test, system fault risk.

Safety considerations

Disconnecting Neutral & Shield Wires:

- Avoid coupling

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Understanding The Circuit Being Tested

George Vlachos, Jeff Jowett
AEMC Instruments Megger

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Understanding the circuit being tested

- Distinctive complexities
- May need to plot multiple points
- Interference from stray voltages

Typical Problems Encountered During Testing

Carl Moller, P.Eng,
CANA High Voltage Ltd.

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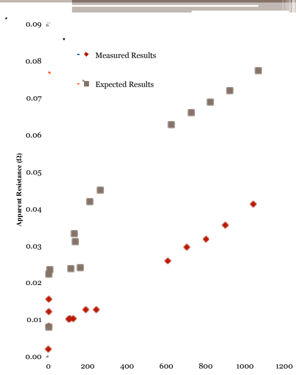
Not a Simple World

- Measurements always come with uncertainty
- The world isn't as simple as we'd like it to be
  - Variability in theory vs. actual installations
  - Trending over time -> clearer picture
  - Once installed, grounding systems can change over time
- Noise
  - Manifests itself in many ways
  - Noise can come and go temporally
  - Buried metallic structures
  - Nearby encroachment of utilities

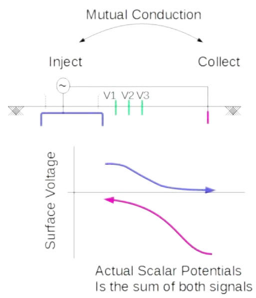
Measurements

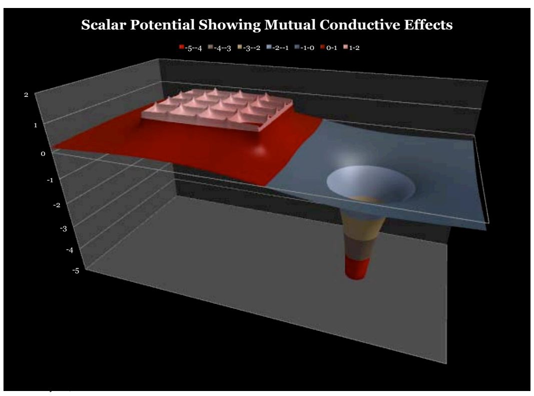
- My gear tells me the value is 0.012 Ohms...
  - Accuracy
  - Precision
  - Bias
- Seasonal Soil Variations
- What are affects of:
  - harmonics?
  - power frequencies?
  - DC noise?



Test Electrodes

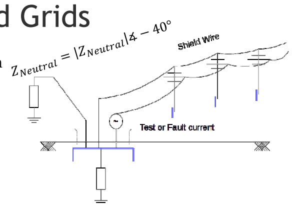
- Test electrodes can introduce mutual ground resistances
- For fall of potential testing the return electrodes can influence the voltage measurements by significant amounts
- Stray AC and DC currents will pick up through the electrodes
  - Test gear has to be able to reject this noise
  - Stray noise can be a significant safety concern
  - Telluric currents





Reactive Ground Grids

- Large ground grids (ie. 150m diagonal or larger)
- Multi-grounded neutrals
- HV Cable incomers
- Reactive components of impedances can become significant.
- DC meters will not help with this
- AC switchmode meters may not be able to reject the reactive component



$Z_{Ground\ Grid} = |Z_{Ground\ Grid}|\measuredangle -15°$

$|Z_{Ground\ Grid}| > |Z_{Neutral}|$

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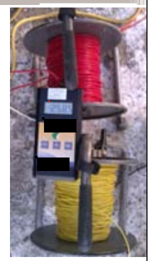
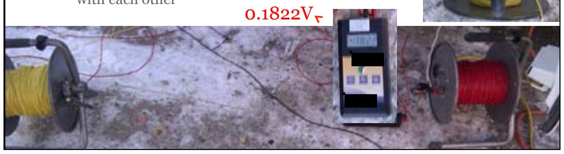
Test Lead Coupling

0.2585V

- Test leads may be inductively coupled
  - Close parallel leads for "zero degree" tests
  - Close parallel leads for long Wenner/Schlumberger soil resistivity Tests
- Coiling effects
  - Test lead current and potential reels can interfere with each other

0.1822V





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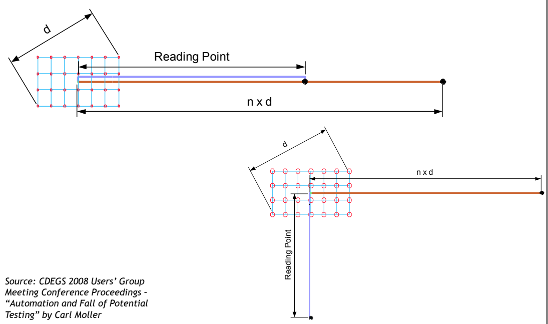
Test Lead Coupling



Source: CDEGS 2008 Users' Group Meeting Conference Proceedings - "Automation and Fall of Potential Testing" by Carl Moller

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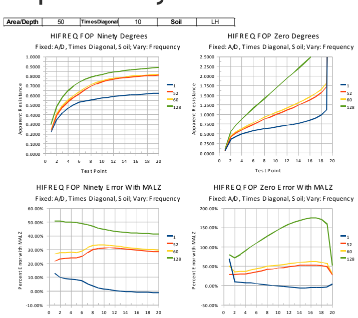
Frequency Dependency

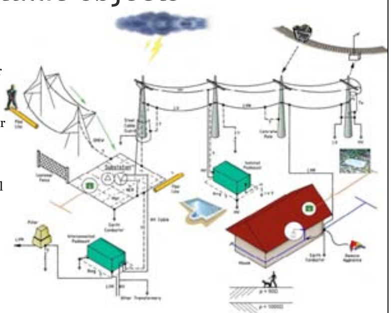
- Extend 10x diagonal of ground grid
- Vary frequency
- Up to 180% Error if not accounting for lead coupling
- Low over High resistivity soil



Source: CDEGS 2008 Users' Group Meeting Conference Proceedings - "Automation and Fall of Potential Testing" by Carl Moller

Buried metallic objects

- Pipelines (Cathodic Protection systems)
- Rail Lines
- Foundations with rebar
- Fences
- Geological variations
- Transmission line tower grounds
- Adjacent facility grounding systems
- Multi-grounded neutral networks
- Telephone/Cable grounds

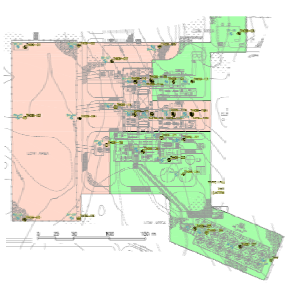


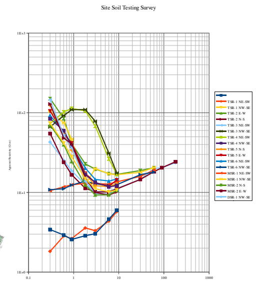
Source image courtesy of Dr. Bill Carman: DREC2012, 'Vt is not enough

Common Pitfalls

- Hiring an inexperienced contractor
- Not knowing what to do with the test data.
- Interpretation of questionable results
- Dealing with variability in expected measurements
- Forgetting to accurately record measurements or locations
- Not understanding the test circuit

How to Interpret this?





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Questions

TEST METHODS

Earth resistivity

Lane Garrett
Commonwealth Associates

- General: Safety, Circuit, Problems, Environmental
- How to perform/basic principles: Wenner, Schlumberger, Driven Rod, Computer-based Multi-meter
- Interferences
- Interpretation of results: During testing, Visual, Software

TEST METHODS

General

Safety
- PPE
  - Hard-soled (steel toe?) shoes
  - Safety glasses
  - Leather gloves
  - Traffic vest/cones
- Voltages/currents during testing
- Call before you dig (or drive rods into the ground)

TEST METHODS

General

Circuit
- Current source – circulate current into ground between two pins
- Voltmeter – measure voltage between two pins
- Wire – connects current source and voltmeter to various pins

TEST METHODS

General

Problems
- Access to site:
  - New site – grubbed, graded, final soil compaction
  - Existing site – where to test
- Injecting sufficient current – varies with instrument type
- Earth is not uniform
- Interferences

TEST METHODS

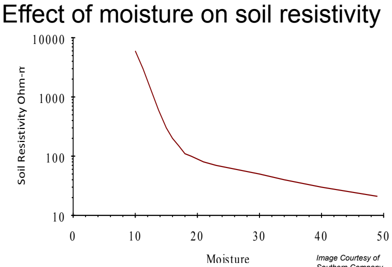
General

Environment
- See access to site
- Avoiding other construction activities
- Near roadway?
- When to test
  - Design schedule/materials delivery dictated?
  - When is site available?
  - Wait until final substation grading?
- Soil moisture and temperature

TEST METHODS

General

Effect of moisture on soil resistivity



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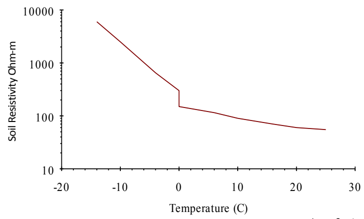
TEST METHODS

General

Effect of temperature on soil resistivity



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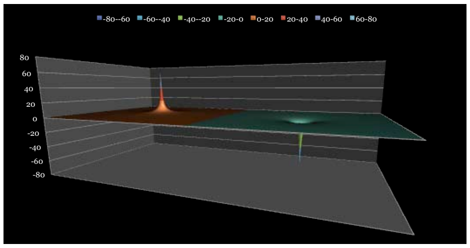
TEST METHODS

Basic Principles

- Inject current into earth to create potentials throughout the earth
- Measure voltage between two pins
- Apparent resistance is V/I
- From test geometry, derive formula to convert apparent resistance to apparent soil resistivity
  - Simple formulas assume uniform soil resistivity
  - Apparent soil resistivity: the equivalent, overall resistivity of a volume of soil with varying properties

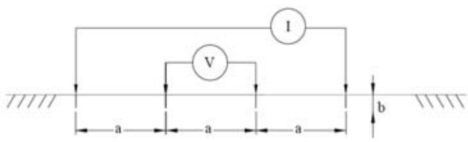
TEST METHODS

Basic Principles



TEST METHODS

Wenner 4-pin test



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

$$\rho_a = 2\pi a R$$

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TEST METHODS

Wenner 4-pin test

- Measure series of apparent resistivities by varying pin spacings along a straight line (profile)
- Run at least two profiles across the site in different directions
- For each profile, plot apparent resistivity vs. pin spacing
- Use visual method or computer programs to determine layered soil resistivity model
- Sample pin spacings: 2', 4', 6', 8', 16', 24' 32',...96' (or larger for very large substations or generating plants)

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TEST METHODS

Wenner 4-pin test - Good test location?

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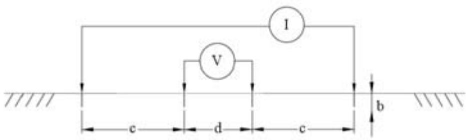
TEST METHODS

Schlumberger-Palmer test



$$\rho_a = \pi c(c+d)R/d$$

$$\text{“depth”} = (2c + d)/2$$

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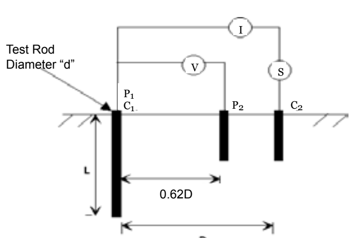
TEST METHODS

Schlumberger-Palmer test

- Vary potential (inner) pin separation, keeping distances between potential and current pins equal
- Can leave current pins in one place, moving only potential pins
  - Could speed up measurement process – move 2 pins instead of 4 pins
  - Might better detect changes in soil resistivity vs. depth
- Associate each apparent resistivity measurement with depth (spacing) computed using $(2c + d)/2$
- Run at least two profiles across the site in different directions
- For each profile, plot apparent resistivity vs. pin spacing
- Use visual method or computer programs to determine layered soil resistivity model

TEST METHODS

Driven-rod test



$$\rho_a = \frac{2\pi L R}{\ln\left(\frac{8L}{d} - 1\right)}$$

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TEST METHODS

Driven-rod test

- Drive ground rod to varying depths. For each depth:
  - Circulate current between ground rod and remote current pin
  - Measure voltage between ground rod and potential pin
  - Resistance is V/I
  - See section 2.2 for testing ground rod impedance
- Use simple (uniform soil assumption) formula to compute apparent resistivity
- Sample depths: 2', 4', 6', 8', 10', 15' 20',…100' (or refusal)
- Drive test rods at multiple locations across the site
- For each test rod location, plot apparent resistivity vs. pin spacing
- Use visual method or computer programs to determine layered soil resistivity model

TEST METHODS

Driven-rod test - Don't do this!

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TEST METHODS

Computer-based Multimeter

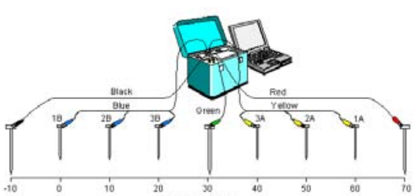


Image Courtesy of Advanced Grounding Concepts

TEST METHODS

Computer-based Multimeter

- Injects "white noise" current – as high as several Amperes
- Automatically switches between the multiple potential probes
- Each measurement is actually several Schlumberger-Palmer measurements
- Software automatically displays 2-layer soil and parameter errors

TEST METHODS

Errors due to limited probe spacing

Probe spacing (% grid length)	Error range (%)	
	Grid resistance	Touch and step voltage (in % of grid GPR)
40%	−50% to +30%	−20% to +110%
100%	−33% to +9%	−8% to +50%
300%	−17% to +9%	−8% to +20%

TEST METHODS

Interferences

- Any conductive "object" in the vicinity that can divert the test current or distort the soil potentials
  - Metal fences
  - Buried pipes (metal)
  - Grounding systems
  - Transmission or distribution pole grounds, especially if connected to other pole grounds
  - Distribution cables with bare concentric neutrals
- Any circuit that can induce voltages onto test leads
  - Transmission or distribution lines
  - Outside sources of current in the soil
- Lack of space to achieve desired maximum pin spacing

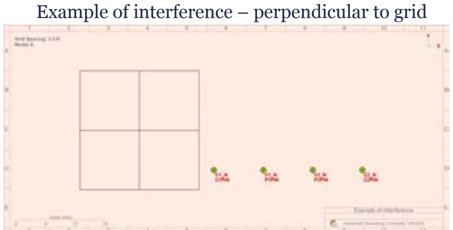
TEST METHODS

Example of interference – 3 ft parallel to grid

- 4-pin resistance at 10 ft spacing = 9.45
- Interference-free resistance = 15.11

TEST METHODS

Example of interference – perpendicular to grid

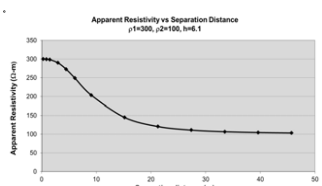


- 4-pin resistance at 10 ft spacing = 14.12
- Interference-free resistance = 15.11

TEST METHODS

Interpretation of results - software

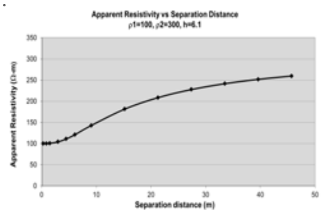
“Perfect 2-layer soil: $\rho_2 < \rho_1$



TEST METHODS

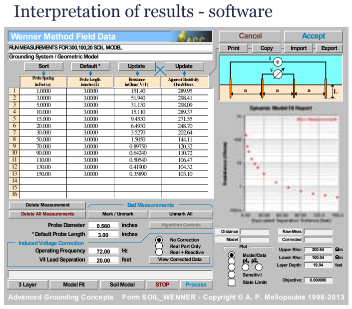
Interpretation of results - software

“Perfect 2-layer soil: $\rho_2 > \rho_1$



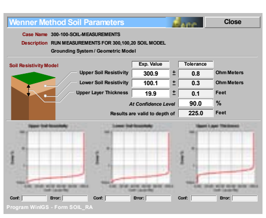
TEST METHODS

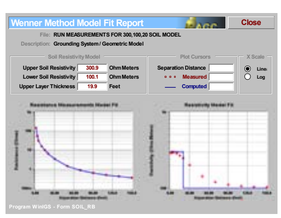
Interpretation of results - software



TEST METHODS

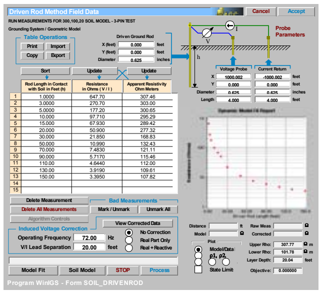
Interpretation of results - software





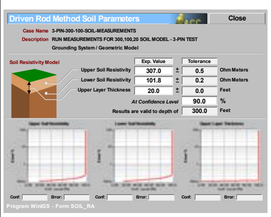
TEST METHODS

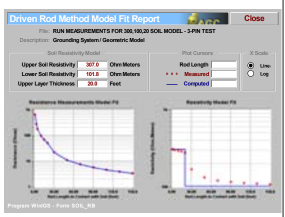
Interpretation of results - software



TEST METHODS

Interpretation of results - software





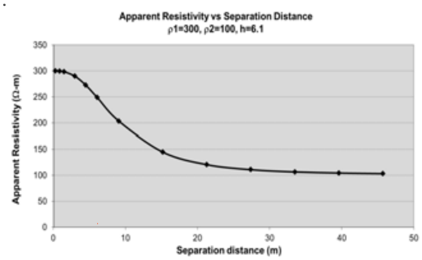
TEST METHODS

Interpretation of results - visual

- The computed apparent resistivities are always positive.
- As the actual resistivity increases or decreases with greater depth, the apparent resistivities also increase or decrease with greater probe spacings.
- The maximum change in apparent resistivity occurs at a spacing larger than the depth at which the corresponding change in actual resistivity occurs. Thus, the changes in apparent resistivity are always plotted to the right of the probe spacing corresponding to the change in actual resistivity.
- The amplitude of the curve is always less than or equal to the amplitude of the actual resistivity vs. depth curve.
- In a multi-layer model, a change in the actual resistivity of a thick layer results in a similar change in the apparent resistivity curve.

TEST METHODS

Interpretation of results - visual



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TEST METHODS

Interpretation of results – during testing

- If using software, input data in laptop while at site
- If using visual techniques, plot measurements by converting measured resistance to apparent resistivity
- Does apparent resistivity profile match expected based on soil type and environmental conditions?
- If results jump all over, check connections and/or look for interferences

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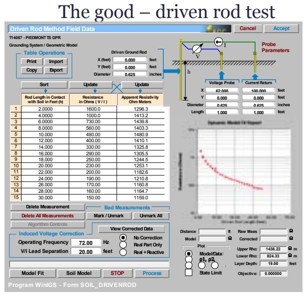
TEST METHODS

Interpretation of results – during testing
The good – driven rod test



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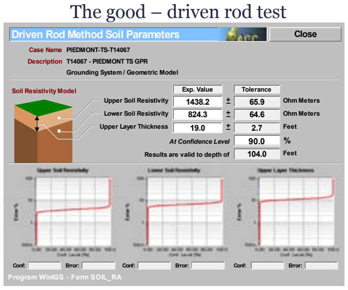
TEST METHODS

Interpretation of results – during testing
The good – driven rod test



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TEST METHODS

Interpretation of results – during testing
The bad – 4-pin test

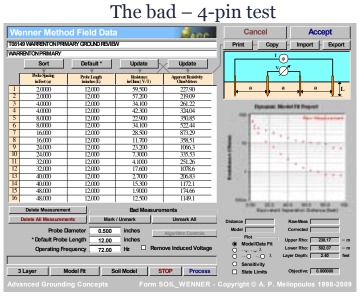

Image Courtesy of Southern Company

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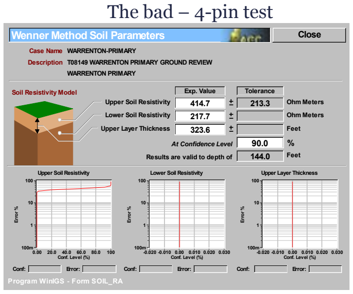
TEST METHODS

Interpretation of results – during testing
The bad – 4-pin test



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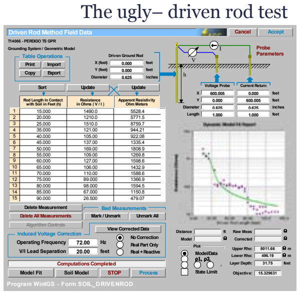
TEST METHODS

Interpretation of results – during testing
The ugly– driven rod test



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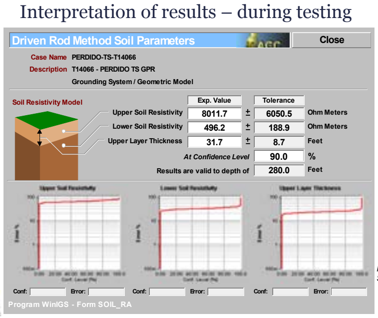
TEST METHODS

Interpretation of results – during testing



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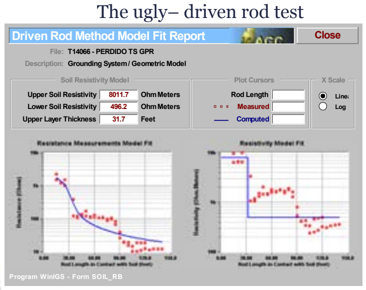
TEST METHODS

Interpretation of results – during testing
The ugly– driven rod test



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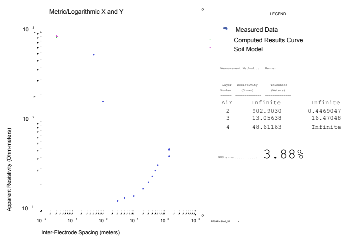
TEST METHODS

Interpretation of results – Sometimes good testing is masked by interpretation limitations



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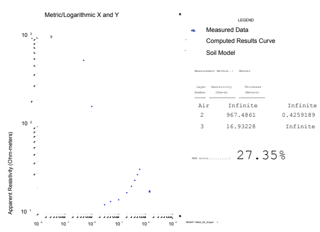
TEST METHODS

Interpretation of results – Same data with 2-layer limitation



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TEST METHODS

In the end, it is sometimes just a roll of the dice!

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QUESTIONS AND ANSWERS

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Ground Impedance

Shashi Patel
NEETRAC/ Georgia Tech

TEST METHODS

2.2 Ground Impedance

Shashi Patel

- General: Characteristics, Why Measure, Basic Tests, Safety, Problems
- How to perform/basic principles: Two Pin, Fall of Potential, Computer Based Grounding Multimeter, Current Injection, Clamp-on and FOP/Clamp-on
- Limitations: FOP, Computer Multimeter, Clamp-on
- Interferences: Conductive, Inductive
- Interpretations of results: Field Test Examples

General

Basic Characteristics

- Depends on soil resistivity and size of the grounding system (covered area)
- Components
  - Resistive component dominates for small isolated grounding systems
  - Inductive component increases with the ground grid size and specially when connected with multi grounded neutral/shield wires (interconnected grounding system)
- Changes in ground resistance
  - Reduces following initial installation due to settling of the soil
  - Seasonal variations particularly for grounds buried in a permafrost or over a high resistivity stratum such as rock bed

General

Why measure?

- Substations
  - Verify new design or additions
  - Existing ground grids –
    - Seasonal variations
    - Safety concerns for old substations
    - Fault or lightning events
  - Quick estimate of Ground Potential Rise (GPR)
    - GPR = I_{grid} x R_{grid} or I_{fault} x $Z_{interconnected\ system}$
    - Touch, step and transfer voltages depend on GPR
- Power line poles/structures (typical practice)
  - Limit resistance to a specified value
  - Install ground electrodes until the desired resistance value is obtained

General

Seasonal Variations of Grounding Parameters
North Georgia Weather
CI Method, CP @~12 mi, PP @~ 4000'

Date	Zg Ohms	GPR Volts	Igrid Amps	Vt(max) Volts
10/13/81	1.1	111	101	N/M
8/22/86	0.95	96	101	N/M
9/28/89 (Rain)	0.9+j0.04	140	156	23
2/26/90 (winter)	1.0+j0.05	155	155	30
8/21/90 Summer	0.76+j0.03	120	157	17

206'x186' ground grid (isolated), 10x5 meshes, 16' ground rods, soil ρ1=412 Ω-m, ρ2=87 Ω-m, h=16'
Source: EPRI TR-100863, July 1992 [R7]

General

Basic Tests

- Fall of Potential (FOP) or Three Pin Test– substation ground grids
  - Pass current between subject ground and current reference electrode (CP)
  - Measure voltage between the ground and voltage reference electrode (PP)
  - Ground impedance = V/I
- Clamp-on or Stakeless Test – power line poles or structures
  - Induce current in the loop made by the subject ground and multi grounded neutral or shield wire system
  - Measure the loop voltage
  - Ground impedance = V/I (assume zero impedance for the multi grounded neutral or shield wire system)

General

Safety

- High voltages around reference electrodes
  - Stray current
  - Fault current
  - Test instrument producing >50 volts
- Induced voltage on long test leads laid in parallel with energized power line(s)
- Measures
  - Personal protective equipment (PPE)
  - Take appropriate measures to protect general public

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General

Problems

- Test method limitations
- Interferences
  - Conductive
  - Inductive
- Testing in high soil resistivity areas
  - High resistance current electrode
    - Test current too low
  - High resistance voltage electrode
    - Measured voltage lower than the actual
- Reduce electrode resistance
  - Drive ground rod deeper or multiple ground rods
  - Distances between multiple ground rods no closer than their depths
  - Pour water around the ground electrodes

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How to Perform/Basic Principles

Two Pin Method

- Resistance is measured in series with a nearby low impedance grounding system such as power company's neutral system.
  - Impedance of the reference grounding system assumed negligible
  - Measured resistance represents the resistance of the ground
- Ground electrode under test
  - Isolated
  - High resistance value

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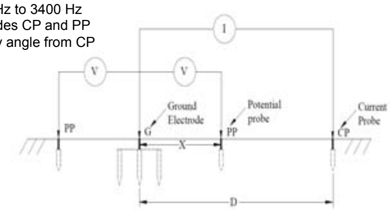
How to Perform/Basic Principles

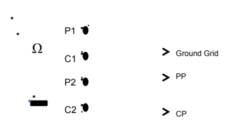
Fall of Potential (FOP) or Three Pin Method – Basic Circuit

- Widely accepted method
- Isolated or interconnected grounds
- Test current - 50 Hz to 3400 Hz
- Reference electrodes CP and PP
- PP direction at any angle from CP

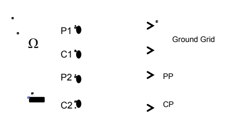


How to Perform/Basic Principles

Fall of Potential (FOP) or Three Pin Method – Instrument Connections



Resistance of Ground Grid Lead is Included in the Measurement

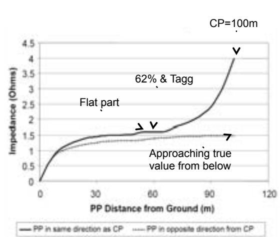


Resistances of Ground Grid Leads are not Included in the Measurement

How to Perform/Basic Principles

FOP Variations

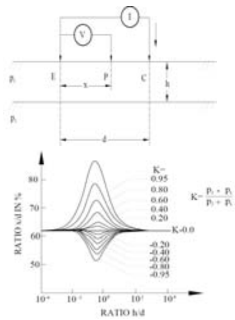
- PP in same direction as CP (solid line)
  - a) Flat part on the graph
  - b) 62% rule (PP @ 62m)
  - c) Tagg's slope method (PP @ 60m)
- PP in opposite direction (dotted line)
  - a) Approaching true value from below
- Assumptions
  - a) Small, isolated ground grid
  - b) Uniform Soil



How to Perform/Basic Principles

FOP Variations

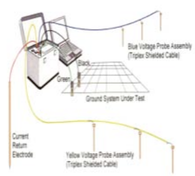
- Ground grid in single or two-layer soil
- Determine required PP location from Figure 8 (Guide81)
- Assumptions
  a) Small, isolated ground grid
  b) PP in same direction as CP

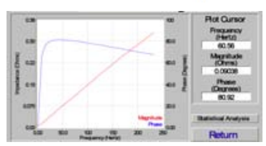


How to Perform/Basic Principles

Computer Based Multimeter

- One CP and six PPs
- Short duration current pulses (white noise)
- Input
  a) ground grid design
  b) X, Y co-ordinates of CP and six PPs
- Solving 2 x 6 matrix (weighted least square)
- Displays
  a) ground impedance vs. frequency
  b) magnitude and phase angle

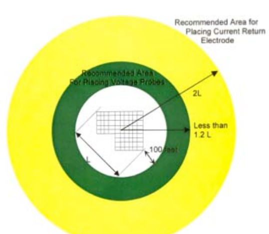




How to Perform/Basic Principles

Computer Based Multimeter – Recommended Locations for Reference Electrodes

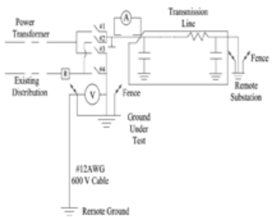
- CP (>2x L)
- 6 PPs (>100'<1.2L)



How to Perform/Basic principles

Current Injection Method (CI Method)

- Sometimes used for large substations
- Use of de-energized line
- High test current (100-200 amperes)
- Can test with substation energized
- Can Measure GPR and voltage gradients



How to Perform/Basic Principles

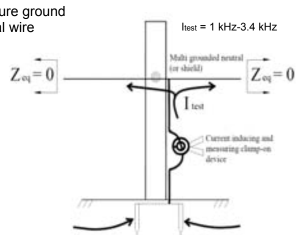
Staged Fault Test

- Rarely performed for grounding measurements
- More practical to use spare channels on existing recorders
- Attenuation circuits (CTs, VTs and Voltage dividers) are required due to high currents and voltages
- Safety – PPE

How to Perform/Basic Principles

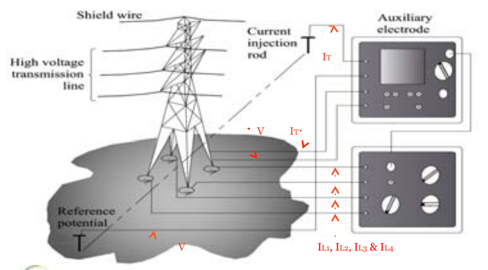
Clamp-on or Stakeless Method

- Widely used method for power line grounds
- Measures resistance of pole/structure ground without disconnecting shield/neutral wire
- Several limitations



How to Perform/Basic Principles

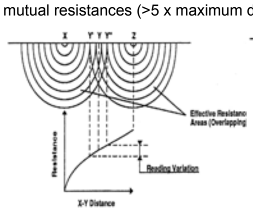
FOP/Clamp-on Method



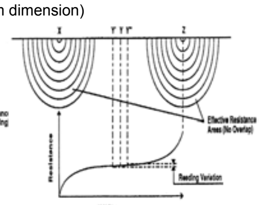
Limitations

FOP

- Current Probe (CP) must be far enough to eliminate interelectrode mutual resistances (>5 x maximum dimension)



Reference electrodes are close to ground electrode



Reference electrodes are far and clear of each other's mutual resistances

Limitations

Limitations Based on Theories of FOP Variations

- Flat slope, 62% ,Tagg and Figure 8 Plots
  - Small, isolated ground electrode system
    - Geometrical center same as electrical center
    - Must be represented by an equivalent hemispherical electrode
  - Only Tagg method allows measuring distances from a convenient point on the perimeter
  - Uniform soil structure
  - Only Figure 8 Plots allow non-uniform soil represented by a two layer model

Limitations

Computer Based Multimeter

- Also, measures impedance of standalone ground grid without disconnecting shield/neutral wires
- Shorter CP and PP distances
  - Compensation for CP location
  - Correction for induction of CP lead on PP lead
- No restriction for soil type
- Measured data may not be accurate
  - Large, irregular shaped substation ground grids
  - Interconnected grounding system
- Provides ±range for the impedance value

Limitations

Clamp-on Method

- Not suitable for grounding system connected at more than one point such as substation ground grid
- Resistance of subject ground must be significantly higher compared to multigrounded shield or neutral system
- Errors
  - Partially corroded neutral or shield wire
    - Device indicates open neutral or shield wire
  - High frequency current injection
  - Low signal/noise ratio for high resistance ground electrode

Interferences

- Conductive interference
  - CP and PP located near metallic objects that are connected to ground under test
    - Pole/structure grounds
    - Bare concentric cable neutrals
    - Pipes, fences etc
  - CP near metallic objects - current path altered
  - PP near metallic objects – soil potential altered
- Inductive interference
  - CP lead inducing voltage on PP lead when placed in proximity
    - Special problem – low impedance ground and long PP distances
  - CP and PP leads placed in proximity and parallel to metallic objects connected to the ground under test
  - Increases with the frequency

Interferences

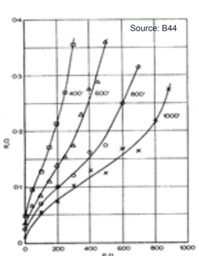
- Interferences can increase or decrease the true impedance value
- The best approach is to minimize interference
  - Keep reference electrodes away from interfering metallic objects
  - Keep PP lead away from the CP lead
  - Direction of PP at a large angle from that of CP

Interpretation of Results

- Finding the true impedance value is difficult
- Basic Requirements
  - Avoid or minimize interferences
  - Place CP as far as practical (>5xlargest dimension)
- Expect accurate results if test is performed within the limitations
- Try for best estimate in other cases
  - Non-uniform soil
  - Large or irregular shaped ground grids
  - Interconnected grounding systems

Interpretation of Results

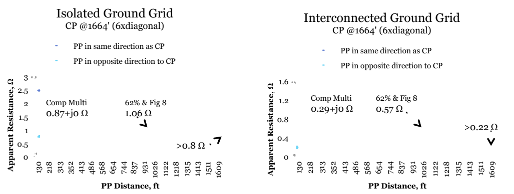
•Significance of increased CP distance
•Estimate based on a trend



300' x 250' Isolated Ground Grid (R_{true} =0.146 Ω) (soil resistivity not known)		
CP Distance ft	62% R_g Ω	Slope Method R_g Ω
400	0.215	0.215
600	0.18	0.166
800	0.165	0.152
1000	0.15	0.151

Interpretations of Results

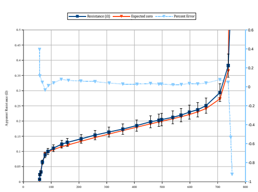
Non-Uniform Soil, Test Result Comparison

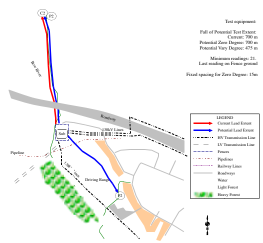


206'x186' substation, 10x5 meshes, 16' ground rods, two layer soil ρ1=412 Ω-m, ρ2=87 Ω-m, h=16'
Rg(computed, SGSYS)=1.13Ω
Source for the base graphs: EPRI unpublished data, 1994

Interpretations of Results

Matching between Test and Software Computed Data – PP in the Same Direction as CP (Interconnected Urban Substation)

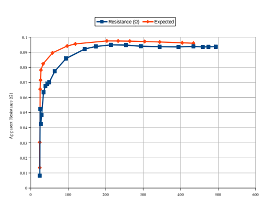


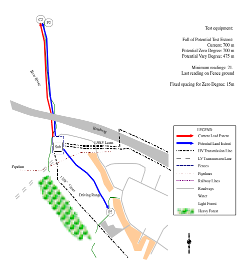


Source: CANA High Voltage

Interpretations of Results

Matching between Test and Software Computed Data – PP in Opposite Direction as CP (Interconnected Urban Substation)





Source: CANA High Voltage

Interpretations of Results

Test Method Comparison – Power Line Ground Electrodes

Line & Ground	FOP Methods (Neut or Sh Disconnected			Clamp on (N or Sh Conn) f=1667 Hz	FOP/ Clamp on (N or Sh Conn) f=128 Hz	Computer Method (N or Sh Disconn)
	Flat Slope	Tagg	62%			
46 kV TL 2- 35' CPs	*38.4 Ω	*39.9 Ω	*39.6 Ω	37.2 Ω	*30.7 Ω	31.0 @0.14°Ω ±12%
230 kV TL 2- 100' CPs	#58.0 Ω	#59.0 Ω	#59.4 Ω	56.0 Ω	#80.8 Ω	57.6 @0.5° Ω ±12%
25 kV DL 1-8' Rod	#199.0 Ω	#202.0 Ω	#201.0 Ω	240.0 Ω	#325.0 Ω	214.0@0.2°Ω ±16%
46 kV TL 1-8' Rod	*234.0 Ω	*>234.0 Ω	*234.0 Ω	310.0 Ω	*136.0 Ω	247.0@0.2°Ω ±8%

*CP=350', #CP=600'

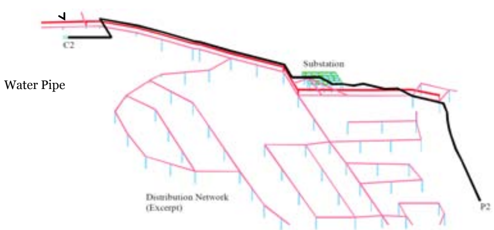
Source: NEETRAC Project 06-209

Appendix - A

Interferences - Examples

Interferences - Examples

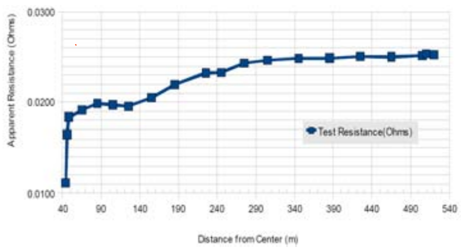
Urban Substation 1 – FOP Test Layout



Source: CANA High Voltage

Interferences - Examples

- US-1 - Altered Soil Potentials due to Buried Structures



Source: CANA High Voltage

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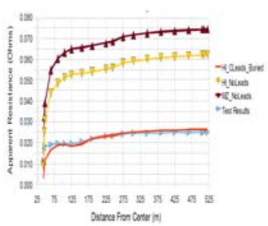
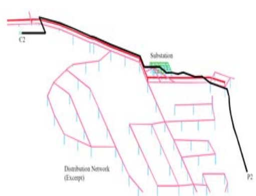
Interferences - Examples

- US-1 – Inductive and Conductive Interferences between Buried Structures and Test Current Circuit





Source: CANA High Voltage

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1

Surface Potentials, Touch and Step Voltages

Carl Moller, P.Eng,
CANA High Voltage Ltd.

May 18, 2014 IEEE PES Std 81-2012 Tutorial

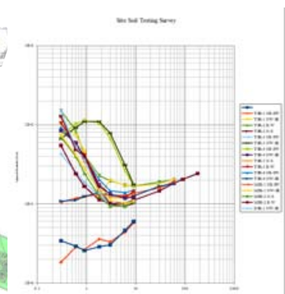
2

Variability in Grounding Design

- Many assumptions in grounding design
- Variability in Parameters of Design
  - Temperature
  - Moisture
  - Non-homogeneous
  - Site built-up,
  - Nearby cliffs etc.
- Reality has even more variables for which we can accurately account in our designs

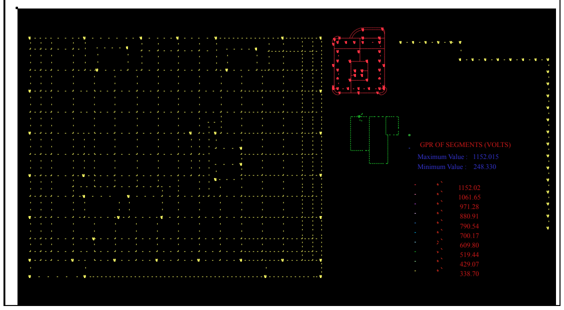
3

How to Interpret this?



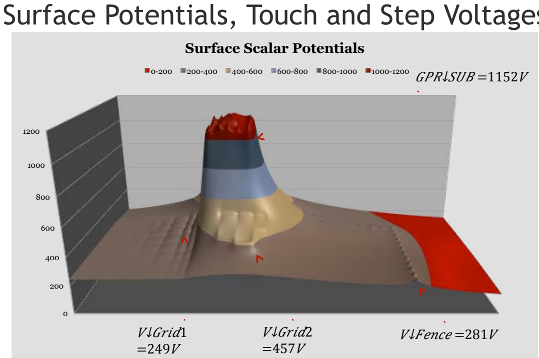
4

Fault at Substation



5

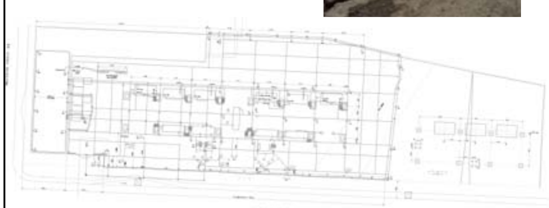
Surface Potentials, Touch and Step Voltages



6

What do we know?

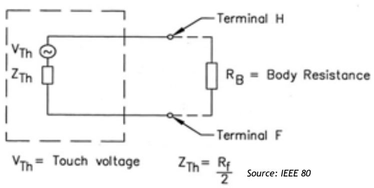
- When we install a ground grid, what have we achieved?
- Green-Field
- Brown-Field



Back to Basics

V=IR

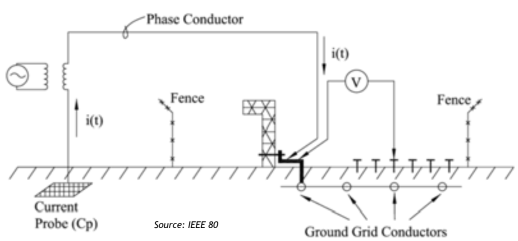
- Can we measure the performance of the ground grid?
- How might we measure scalar potentials
  - Transferred potentials?
  - Touch Potentials?
  - Step Potentials?
- Inject current into the grid
- Measure the soil scalar potentials.



Source: IEEE 80

Does this sound familiar?

- Similar concept to fall of potential testing.
- Characteristics of the current circuit
  - Current Generator Injection
  - Collection point remote from ground grid
- How far is far enough?



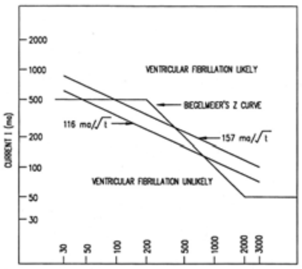
Source: IEEE 80

Variability in Design parameters

- Measure actual response of ground conductors
  - Non-homogeneous soil
  - Temperature – at time of test
  - Moisture – at time of test
  - Geology – Actual grid!
  - Nearby foundations, metallic structures, houses, industrial ground grids…all will be present under event conditions
- Many benefits to measuring actual Volts.

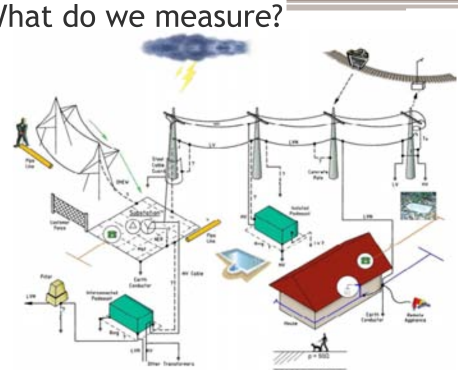
Measurements

- The actual grid response can be measured
- Measure, review and validate design compliance requirements
  - Compare measurements with tolerable limits
  - Measure open circuit conditions
  - Measure loaded circuit conditions (measure body current)



Source: IEEE 80

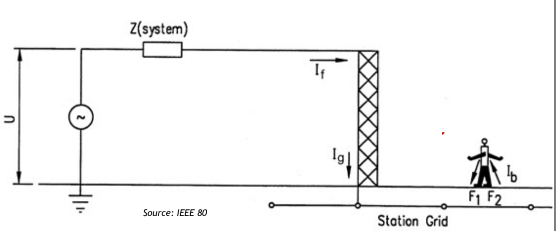
What do we measure?



Source image courtesy of Dr. Bill Carman: DREC2012, 'Vt is not enough

Step Voltage

- Lay definition: Voltage across your feet spaced 1m apart.
- Worst cases typically OUTSIDE substation where no insulating gravel is present
- Around sharp corners of ground conductors
- Significantly dependent on soil resistivity
- Around geological changes



Source: IEEE 80

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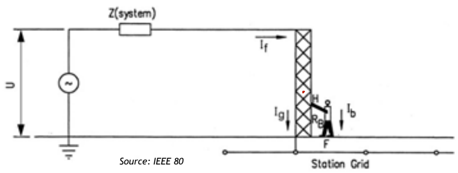
Touch Voltages

- Lay Definition: Voltage from your hand to two feet (typically 1m arm reach)
- What can you touch in a substation or nearby which might have a voltage difference?
- Metallic objects within the substation and the fence will be at the GPR of the site.
- What you are standing on will be a surface potential.



Source: IEEE 80

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Internal Transferred Voltages

- Internal
  - Extension cords
  - Cable sheaths bonded remotely
  - Water supplies
  - Gas supplies
  - Sewer services
  - Telephone networks
  - Railways
  - Pipelines

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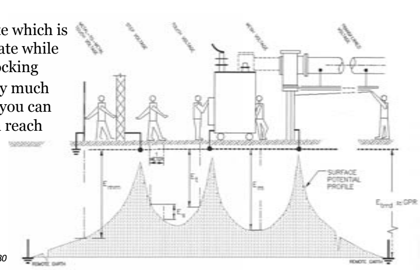
Typical Touch Voltage Exposure

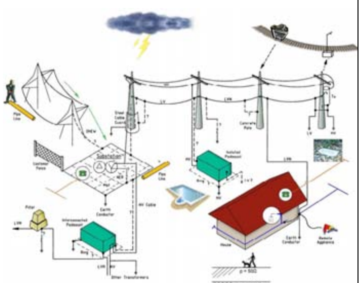
- Mesh: middle of ground grid loops
- Fence: 1m outside/inside edge of fence
- Gate: 1m off gate which is open. Also on gate while opening or unlocking
- Structure: pretty much everything else you can touch with a 1m reach



Source: Figure 12 - IEEE 80

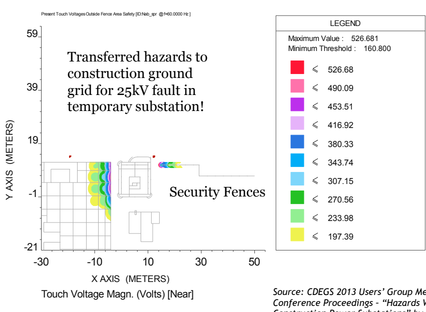
Remote Transferred Voltages

- Maximum voltage differential at 1m arm length:
  - Water faucets
  - Multi-grounded distribution neutral
  - Telephone and cable boxes
  - Fences
  - Gas lines
  - Cathodic Protection test points
  - Light standards etc.
  - Construction Power feeds



Source image courtesy of Dr. Bill Carman: DREC2012, 'Vt is not enough

Construction Power Hazards



Source: CDEGS 2013 Users' Group Meeting Conference Proceedings - "Hazards With Temporary Construction Power Substations" by Carl Moller

Methods of Measurements

- General Method:
  - Inject current
  - Measure voltage differentials

$I_{injection}$ ⇨ Voltage Response of Ground Grid ⇨ Measured soil potentials

- Touch Voltage:
  - Between metallic object and soil potential
- Step Voltage:
  - Between two soil potentials 1m apart
- Transferred:
  - Same as touch

Specific Methods

- Staged Fault
  - Actually fault the substation and measure touch and step voltages
  - Almost impossible to perform without extensive resources and extremely high speed multi-channel data collection systems
  - Some large utilities will perform these tests if the risks are sufficient enough.
- Current Injection Test
  - Overland Current Circuit
  - Transmission Line
  - Off-power frequency Generator, arc welder, Custom amplifier with frequency generator
- Currents will split down any interconnected shield wires
- Voltages are measured
  - Tuned volt meter (frequency selective)
  - RMS voltages with and without signal
  - Phase measurements can be significant.

Injection Test Current

- Current generator:
  - Conventional Generator (120/240V or 600V) with governor (frequency counter)
  - Mobile substation generator (engineered)
  - Amplifier with frequency generator. These can be commercially bought or made yourself.
    - RMS vs Switchmode

Current Injection

- Overland test leads
- Generator Current 2-200A
- Size Test Leads
- Return electrodes:
  - Array of Ground Rods in Soil
  - Minimize Mutual effects

- Transmission Line
- Injection: Generator 2-200A
- Return electrode:
  - Transmission Tower and shield wires
  - Measurement of phase angle is important

Measuring Voltages

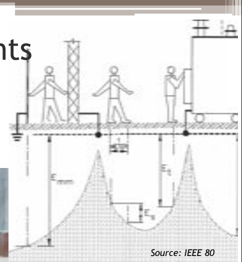
- Tuned Volt-meter (off-frequency)
- Commercial gear
- Measuring phase for voltages less important.
- Measuring the soil potentials
  - Small probe in contact with soil (thin metallic probe)
  - Small plate in contact with the soil (representing two feet)
- Touch Voltages
  - Measure between the metallic objects (using alligator clips or similar) and the soil potentials
- Step Voltages
  - Measure voltages between two points 1m apart
  - Where?

Voltage Measurements

- Probe
  - Unloaded (direct connection to volt-meter)
  - Loaded (connection in series with 1000 Ohm resistor)
- Plate
  - Unloaded
  - Loaded (Most realistic)
- Issues with Probes:
  - Does not represent a foot
  - Provide scalar touch potentials (as would be modeled in software)
- Issues with Plates:
  - Soil contact becomes significant
  - Use a bit of water to achieve good contact with crushed rock or soil
  - Provides realistic foot impedances in-situ

> Step Voltage

Voltage measurements

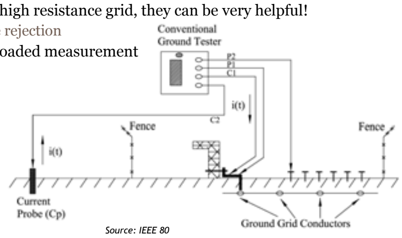


Source: IEEE 80

Touch Voltage Probe <

Conventional Gear

- Four pin resistance meter
  - Set up to measure a touch or step resistance
- In practice, touch and step resistance measurements are below the reliable range (ie. <0.03 Ohms)
- If you have a high resistance grid, they can be very helpful!
  - Great noise rejection
- Cannot take loaded measurement



Source: IEEE 80

Bias in measurements

- If other circuits are energized:
  - Imbalance "zero sequence" currents in the grid
  - Induction on current circuit
  - Stray DC currents
- Currents down unforeseen paths
- Conductive interference with return electrode ground grid

- Methods to overcome Noise (Section 9.4.2):
  - Take three measurements:
    - Standard Section 9.4.2
    - Follow equations
- Model the test scenario to apply correction factors
  - Advanced techniques required
  - Can provide expected values

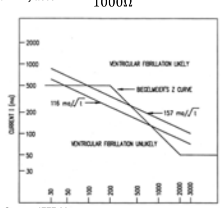
What to do with the measurements

- Injection Testing
  - Determine Current scaling factor
  - Multiply voltages by current scaling factor
  - Compare with IEEE 80 tolerable voltages
- Loaded voltages with plates:
  - Compare with body current tolerable current levels
  - Voltage across 1000 Ohm resistor is a scaled version of the current through the body

$$V_{touch} = S_{factor} V_{measured}$$

$$V_{step} = S_{factor} V_{measured}$$

$$I_{body\_m} = S_{factor} \frac{V_{measured\_loaded}}{1000\Omega}$$



Source: IEEE 80

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Conventional Meter

- Touch and step resistances
- Multiply by expected earth-return current to get respective unloaded touch and step voltage values
- Compare with IEEE 80 tolerable threshold voltages
- Use of only probes will not easily represent loaded touch voltage values

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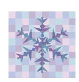
Other Issues

ΔT



- Seasonal Variations
  - Freezing
  - Drying out of soil
  - High ground-water table
  - Recent Rain
  - Recent hot weather
- Nearby geological changes
  - Encroaching MGN
  - Mining

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Only one slice of the pie

- You get an excellent picture of actual voltages.
- You have to decide whether seasonal variations are significant:
  - Urban
  - Rural
- It's only one slice of time.
- In Canada and US parts of the country must account for seasonal variations
- More engineering judgment is required.

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Gain Experience Testing

- Who is doing these tests?
- It is highly recommended to go out in the field and perform this test.
- Get as much experience as you can in the field.

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Questions

1

Ground Integrity Testing

Carson Day
NEETRAC/ Georgia Tech

TEST METHODS

Ground integrity testing

1. The Ground Grid
2. Test Methods
3. Test Result Interpretation
4. Safety Considerations

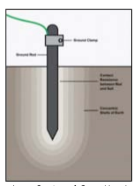


Image Courtesy of Ground Level Systems, LLC (Permission Pending)

The Ground Grid

- Consists of:
  - Buried ground conductors
  - Above ground risers that are attached to equipment and support structures
  - Control/relay house grounds
  - Equipment panel grounds
  - Equipment cabinet grounds
  - Cable trench grounds

The Ground Grid

- Protects personnel by limiting step and touch voltages in the yard during normal and abnormal conditions
- Protects equipment by limiting transient voltages

A Good Ground Grid

- Withstands available fault currents
- Limits touch and step potentials
- Limits transient voltages on I&C cables at equipment terminations.
- Provides shielding to I&C cables.

Ground Grid Testing - General

Verification that integrity of ground grid is intact

- No fully or partially corroded conductors or connections
- Can identify area of yard with relative high resistance

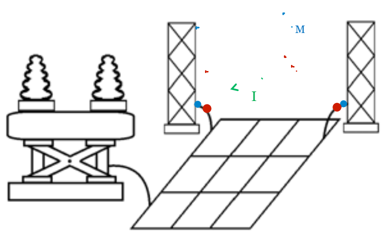
It does not measure the ground grid resistance to remote earth.

Methods in IEEE 81

- **Section 10.2** - High Current Test Method
- **Section 10.3** - Measurement of Resistance between two risers
- **Section 10.4** - Low impedance continuity measurement by computer-based grounding multimeter

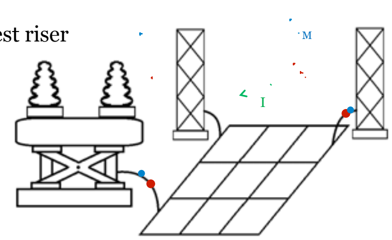
General Procedure

- Select a riser as a reference & connect source
- Connect second test lead to test riser
- Push current
- Measure



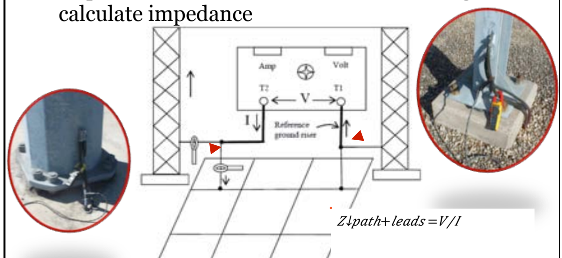
General Procedure

- Select a riser as a reference & connect source
- Connect second test lead to test riser
- Push current
- Measure
- Go to next test riser
- Repeat



High Current Test Method

- Impedance Measurement – measure voltage, calculate impedance



$Z_{path+leads} = V/I$

Figure 16 from IEEE81-2012

Measurement of Resistance between two risers

- Resistance Measurement – test equipment calculates resistance from V, I, and θ

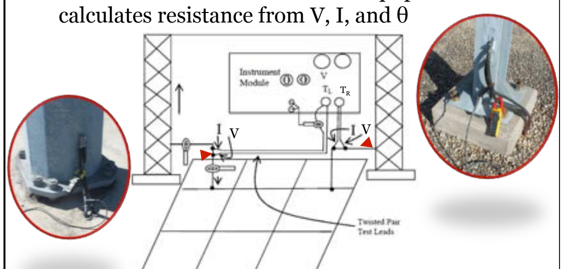


Figure 17 from IEEE81-2012

Measurement of Resistance between two risers – Resistance Calculation

$$R_{path} = V\cos\theta / I$$

Equation 11 from IEEE 81-2012

where

R_{path}	is the path(s) resistance between two risers
V	is the voltage across two risers
I	is the current in the risers
θ	is the phase angle between V and I

Low impedance continuity measurement by computer-based grounding multimeter

Provides a complete characterization of impedance (R+jX).

Rejects the influence of ambient currents

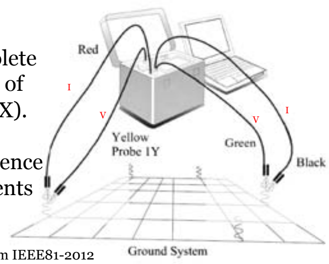


Figure 18 from IEEE81-2012

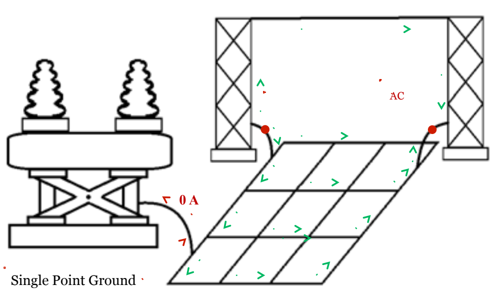
Interpretation of Results

- What is a good resistance value?
  - 1.5V per 15m? (i.e. 5mΩ at 300A)
  - Compare to adjacent readings, considering:
    - Distance between points
    - Ambient currents
    - Multiple paths

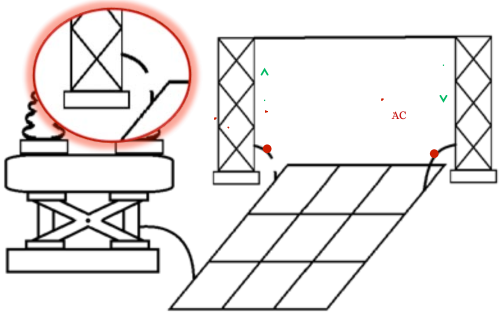
Other Considerations:

- Current Division
- Ambient Currents
- Test Lead Impedance

Current Division

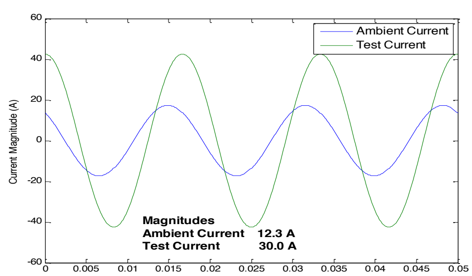


Current Division



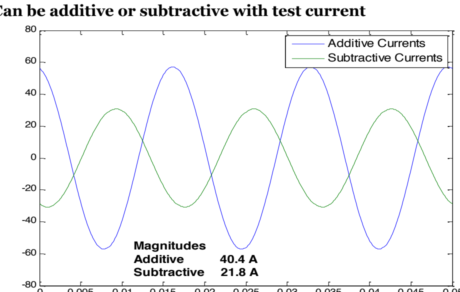
Ambient/Circulating Currents

- **Ambient currents usually exist**



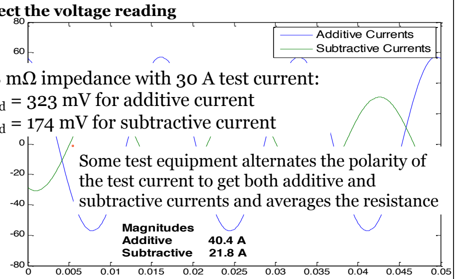
Ambient/Circulating Currents

- Ambient currents usually exist
- **Can be additive or subtractive with test current**



Ambient/Circulating Currents

- Ambient currents usually exist
- Can be additive or subtractive with test current
- **Will affect the voltage reading**



Assume 8 mΩ impedance with 30 A test current:

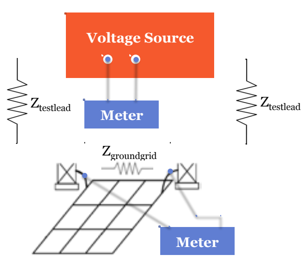
$V_{Measured}$ = 323 mV for additive current

$V_{Measured}$ = 174 mV for subtractive current

Some test equipment alternates the polarity of the test current to get both additive and subtractive currents and averages the resistance

Test Lead Resistance

Where you measure affects results!



1. Measurement includes test lead impedance
2. Measurement **does not** include test lead impedance

Safety Considerations

Generally

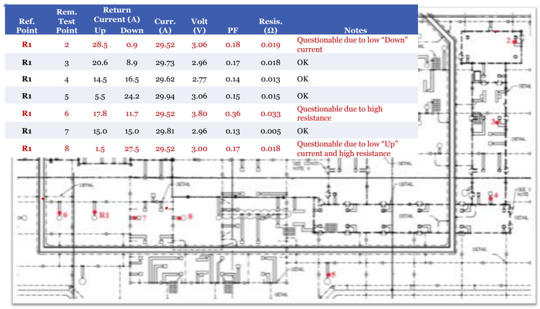
- Equipment safety - Voltage gradients across the ground grid conductors
- Personnel Safety - Touch and Step Voltages

Specific Examples

- When using high current, ensure that appropriate rated equipment is used (i.e. clamps, cables, transformers, etc.)
- A potentially dangerous voltage can exist on the remote test lead at the reference location

Resistance Method Example

Ref. Point	Rem. Test Point	Return Current (A) Up	Down	Curr. (A)	Volt (V)	PF	Resis. (Ω)	Notes
R1	2	28.5	0.9	29.52	3.06	0.18	0.019	Questionable due to low "Down" current
R1	3	20.6	8.9	29.73	2.96	0.17	0.018	OK
R1	4	14.5	16.5	29.62	2.77	0.14	0.013	OK
R1	5	5.5	24.2	29.94	3.06	0.15	0.015	OK
R1	6	17.8	11.7	29.52	3.80	0.36	0.033	Questionable due to high resistance
R1	7	15.0	15.0	29.81	2.96	0.13	0.005	OK
R1	8	1.5	27.5	29.52	3.00	0.17	0.018	Questionable due to low "Up" current and high resistance



Surface Aggregate Testing

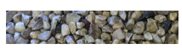
Bryan Beske
American Transmission Company

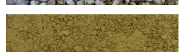
TEST METHODS

Surface Aggregate Testing

Bryan Beske

- General
- How to perform/basic principles
- Limitations
- Interpretation of results



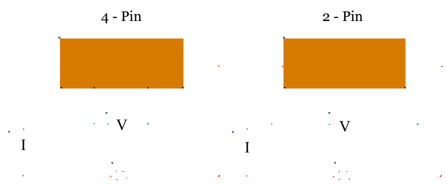


General - Background

- IEEE Std 80: Section 12.5 - Use of surface material layer
  - Table 7 – Typical surface material resistivities
  - Sentences at end of third and fourth paragraph…
    - "Thus, it is important that the resistivity of rock samples typical of the type being used in a given area be measured."
    - "Tests should be performed to determine the resistivity of the stone typically purchased by the utility."
- Problem – no standardized test method currently exists…
- …but it still can be done.

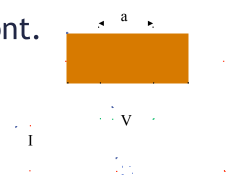
General – Understanding the Circuit

- Like other tests – comes down to the basics
  - injecting a current and measure a voltage



General - Circuit Cont.

$$\rho = R\frac{A}{a}$$



- Where:
  - ρ = Resistivity (Ωm)
  - R = Resistance (V/I) (Ω)
  - A = Cross sectional area of the container perpendicular to the current flow (m^2)
  - a = Probe inner spacing (m)

General - Safety

- Test doesn't require high current or voltage
- Field
  - Standard field safety items
    - Traffic, system faults…
- Lab
  - Standard lab safety items

General – Problems

- Meter capabilities
  - Does it have the resolution
    - Upper/lower
  - AC not DC
- Box Considerations
  - Large enough, non-conductive, easy to clean
  - Sturdy
    - Able to withstand repeated compaction of material
- Properly quantifying material properties

How to perform - Lab versus field

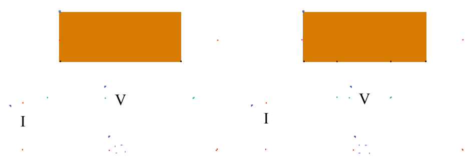
- Same
  - Two pin – four pin
  - Hard to replicate in-situ conditions
- Different
  - Quantifying material properties

Limitations

- Field testing
  - Reproducibility
  - Seasonal variations
  - Quantifying parameters
- Laboratory testing
  - Replicating field conditions

How to perform – Choose the method

- Two pin versus four pin



Choose the method – Calc Example

Box Dimensions (m)

Width	Height	Length	Pin Sep
0.06	0.05	0.40	0.20

Example Cont.

$$\rho = R\frac{A}{a}$$

Box Dimensions (m)

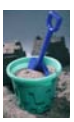
Width	Height	Length	Pin Sep
0.06	0.05	0.40	0.20

- A = (0.06)(0.05) = 0.0030
- a = 0.2
- $\rho = R(0.015)$
- $\rho = \frac{V}{I}0.015$

How to perform – Quantify parameters

- What parameters will impact the resistivity:
  - Sample size
  - Moisture content
  - Particle size
  - Compaction
  - Water resistivity

Quantify parameters - Sample size



- Vessel size: minimum of 3 times max particle diameter

Quantify parameters – Moisture Content

- ASTM C127, Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
- ASTM D2216, Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

Quantify parameters – Particulate Size


- ASTM C136, Sieve Analysis of Fine and Coarse Aggregates

Quantify parameters – Compaction

- ASTM C29, Bulk Density ("Unit Weight") and Voids in Aggregate
- ASTM D698, Laboratory Compaction Characteristics of Soil Using Standard Effort
- ASTM D1557, Laboratory Compaction Characteristics of Soil Using Modified Effort

Quantify parameters – Water Resistivity

- What to use
  - Tap water
    - Typical resistivity from 0.2Ωm to 200Ωm[1]
  - Rain Water
    - Typical resistivity from 100Ωm to 5,000Ωm[1]
  - Distilled water
    - Typical resistivity from 3,300Ωm to 20,000Ωm[2]
  - "Laboratory Modified" water
    - User determined

[1]Sanders, L.L., 1998, *A Manual of Field Hydrogeology*: Prentice-Hall, NJ, 381p.
[2]http://water.epa.gov/type/rsl/monitoring/vms59.cfm

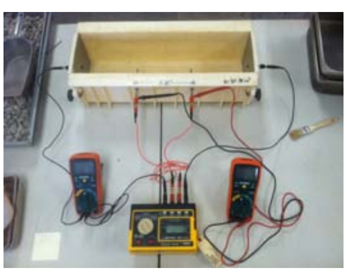
Interpretation of results

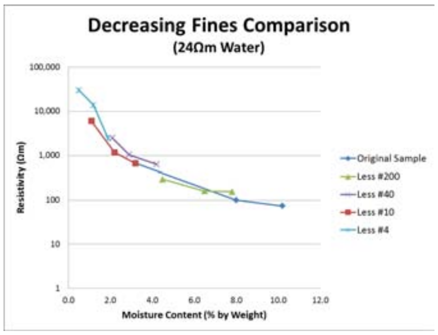
- During testing
  - Know the limitations of your equipment
- Considerations for acceptance
  - Conditions tested at vs those experienced in field
  - Comparison to other testing results
  - Historical testing performed

Utility Experience

- Current Practice
  - Existing Stations
    - Obtain representative sample and test
    - Evaluate ground grid using tested value
  - New Stations
    - Obtain sample from quarry and test
    - Design grid using tested value

Test setup being used

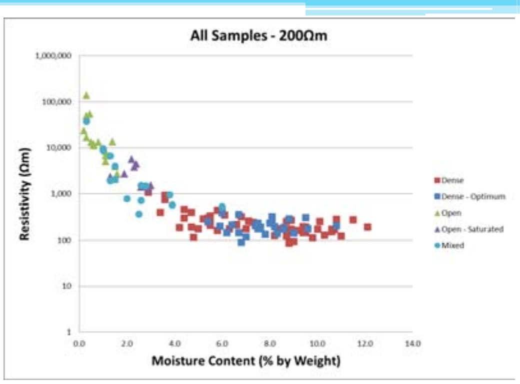




Effects of Compactions and Water Used

Sample 1 - Open Graded Aggregate								
Moisture	Tap Water			Distilled Water			% Diff Between Waters	
Content (%)	Compacted	Loose	% Diff	Compacted	Loose	% Diff	Compacted	Loose
0.5	21,728	24,881	15%	33,849	38,580	14%	56%	55%
1.2	5,157	5,624	9%	9,477	10,819	14%	84%	92%
2.3	1,748	2,094	20%	3,360	3,947	17%	92%	88%

Sample 2 - Dense Graded Aggregate								
Moisture	Tap Water			Distilled Water			% Diff Between Waters	
Content (%)	Compacted	Loose	% Diff	Compacted	Loose	% Diff	Compacted	Loose
5.0	224	538	140%	430	1,174	173%	92%	118%
5.8	196	376	92%	338	747	121%	72%	99%
7.6	145	254	75%	282	475	68%	94%	87%



- Presentation was based on the paper:

Edlebeck, J.E.; Beske, B., "Identifying and Quantifying Material Properties That Impact Aggregate Resistivity of Electrical Substation Surface Material," Power Delivery, IEEE Transactions on , vol.PP, no.99, pp.1,1
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Test Simulations and Field Examples

safearth.com

Presented by:
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TEST METHODS

Test Simulations & Field Examples

Session Overview

Topics:

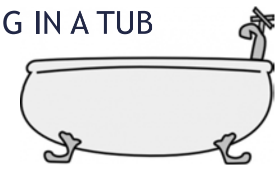
- Current Flow in Soil
- Electrode Resistance
- Interference
- Soil Resistivity
- 3-Point Impedance
- Current Injection
- Grid Integrity

Topics covered with a mix of theory, practical demo and video

May 18, 2014 IEEE PES Std 81-2014 Tutorial 2

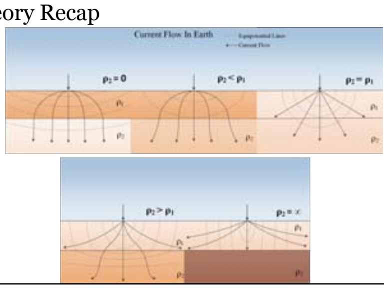
DEMO'S – TESTING IN A TUB

- Current Mechanism
- Scale
- Accuracy
- Limitations
  - Layers
  - Infrastructure



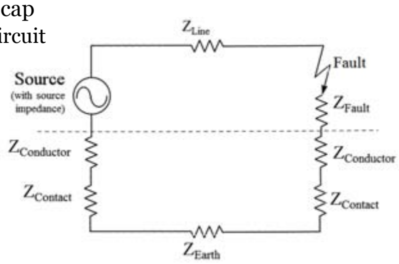
CURRENT FLOW IN SOIL

- Theory Recap



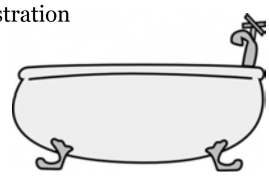
CURRENT FLOW IN SOIL

- Theory Recap
  - Fault Circuit



CURRENT FLOW IN SOIL

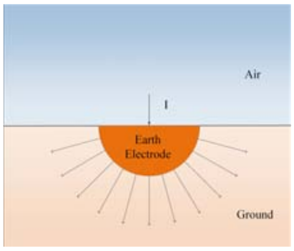
- Demonstration



ELECTRODE RESISTANCE

- Theory Recap

$$R_\infty = \frac{\rho}{2\pi r}$$



ELECTRODE RESISTANCE

- Theory Recap

$$R_R = \frac{\rho}{2\pi l}\left[\ln\frac{8l}{d} - 1\right] \quad [\Omega]$$

$$= \text{Resistance of driven rod} \quad [\Omega]$$

where :

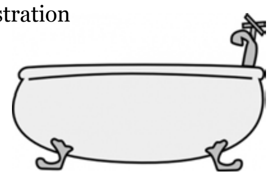
ρ = Earth resistivity $[\Omega m]$

l = Rod length $[m]$

d = Rod diameter $[m]$

ELECTRODE RESISTANCE

- Demonstration

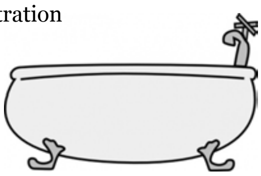


ELECTRODE RESISTANCE CLAMP-ON METHOD

- Theory Recap

ELECTRODE RESISTANCE CLAMP-ON METHOD

- Demonstration

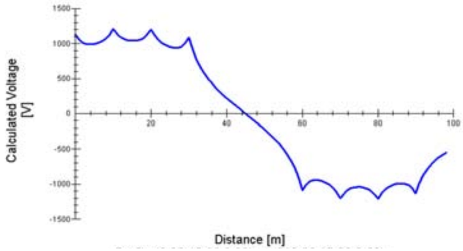


ELECTRODE RESISTANCE CLAMP ON METHOD

- Video

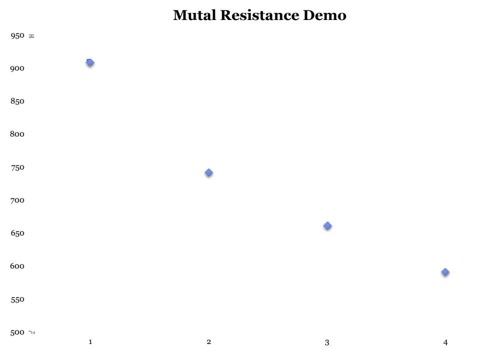
INTERFERENCE - Mutual Resistance / Proximity Effect

- Theory Recap

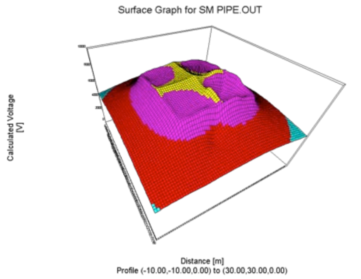


INTERFERENCE - Mutual Resistance / Proximity Effect

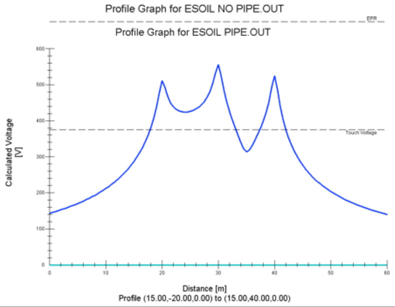
- Finger Puppets can help



INTERFERENCE - CONDUCTIVE

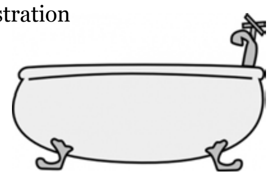


INTERFERENCE - CONDUCTIVE



INTERFERENCE - CONDUCTIVE

- Demonstration



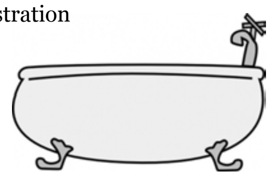
INTERFERENCE - STANDING VOLTAGES

Theory Recap

- What could cause a standing voltage?
- What difference could a standing voltage make?

INTERFERENCE - STANDING VOLTAGES

- Demonstration



INTERFERENCE - STANDING VOLTAGES

Theory Recap

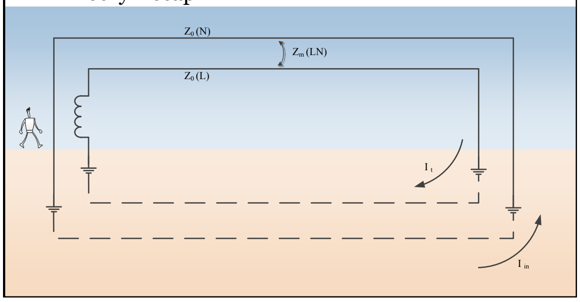
- Noise Immune Test Instruments should be OK
- Test Frequency Versus Noise Sources
- Signal to Noise Ratio

INTERFERENCE - INDUCTION

- Theory Recap

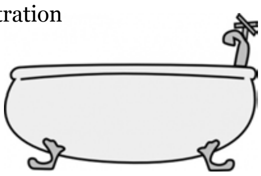
INTERFERENCE - INDUCTION

- Theory Recap



INTERFERENCE - INDUCTION

- Demonstration

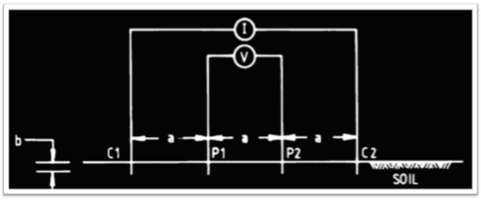


SOIL RESISTIVITY TESTING

- Wenner Method
- Schlumberger-Palmer Method
- Drilled Rod

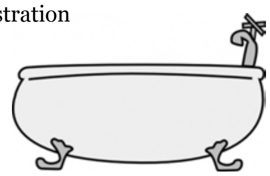
WENNER RESISTIVITY TEST

- Theory Recap



WENNER RESISTIVITY TEST

- Demonstration

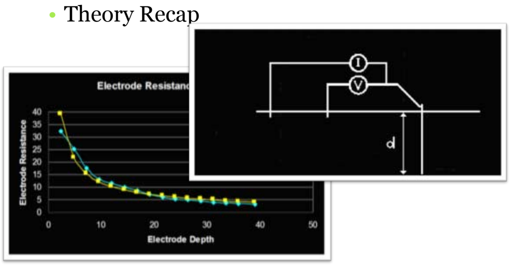


WENNER RESISTIVITY TEST

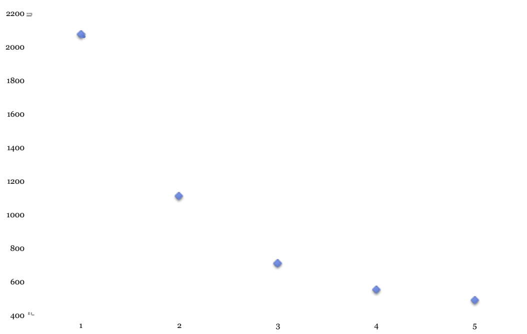
- Video

DRILLED OR DRIVEN ROD TEST

- Theory Recap



Driven Rod Res Test Demo

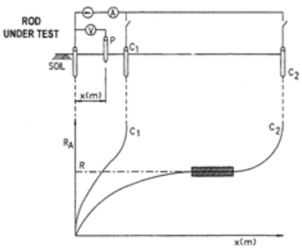


DRIVEN ROD TEST

- Video

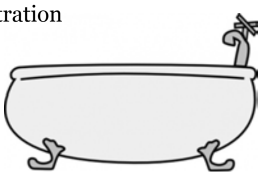
THREE-POINT IMPEDANCE

- Theory Recap
- 61.8% Rule



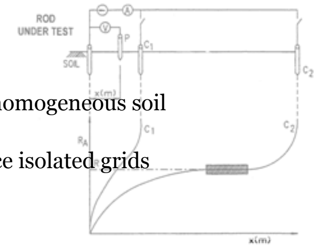
THREE-POINT IMPEDANCE

- Demonstration



THREE-POINT IMPEDANCE

- Theory Recap
- 61.8% Rule
- Works best for homogeneous soil
- Higher resistance isolated grids

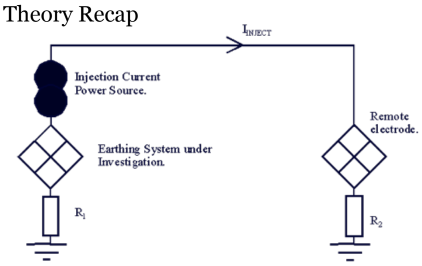


THREE-POINT IMPEDANCE

- Video

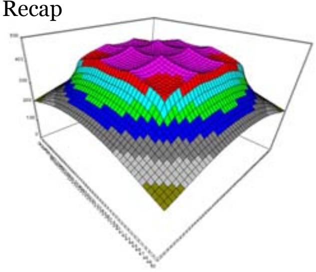
CURRENT INJECTION

- Theory Recap



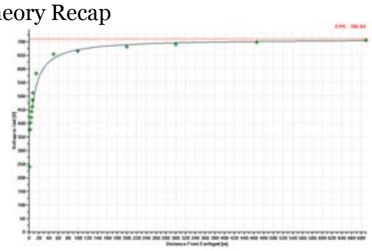
CURRENT INJECTION

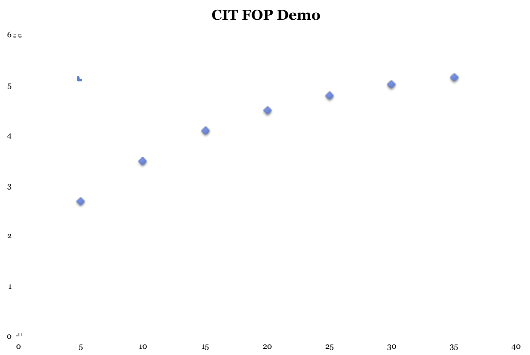
- Theory Recap



CURRENT INJECTION Fall-of-Potential

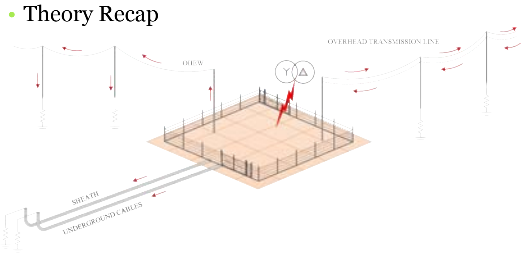
- Theory Recap





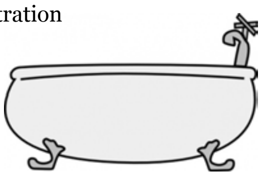
CURRENT INJECTION
Current Distribution

- Theory Recap



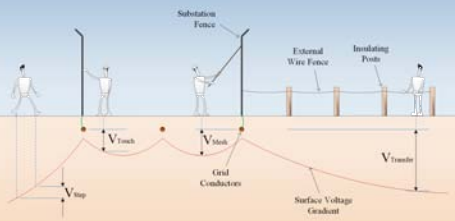
CURRENT INJECTION
Current Distribution

- Demonstration



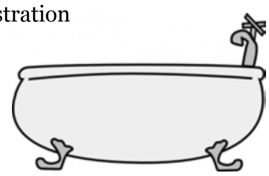
CURRENT INJECTION
Step/Touch Voltage

- Theory Recap



CURRENT INJECTION
Step/Touch Voltage

- Demonstration



CURRENT INJECTION

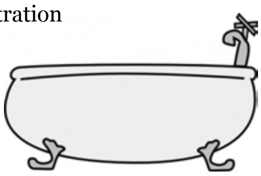
- Video

INTEGRITY TESTING

- Theory Recap

INTEGRITY TESTING

- Demonstration



INTEGRITY TESTING

- Video

TRICKS & TRAPS RECAP

QUESTIONS?