Evaluation of Ground Grid Performance: Testing and Maintenance

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Outline

- Ground Grid Components
- Ground Grid Modelling/Design
- Basic Shock Situations (Step and Touch)
- Tolerable Body Limit
- Ground Grid Under Fault Conditions
- Zero Sequence Analysis
- Evaluating the Grid Performance
  - Current Injection Test
    - Soil Resistivity Testing
    - Ground Grid Resistance
    - Current Injection Testing
    - Step and Touch Potentials
  - Integrity Tests

Applicable Standards

- IEEE Std 80-2013 - Guide for Safety in AC Substation Grounding
- IEEE Std 81-2012 - Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System
- IEEE Std 367-2012 - Recommended Practice for Determining the Electric Power Substation Ground Potential Rise and Induced Voltage from a Power Fault
- IEEE Std 487-2015 - Recommended Practice for the Protection of Wire-Line Communication Facilities Serving Electric Supply Locations
- IEEE Std 665-1995 - Guide for Generating Station Grounding
- IEEE Std 837-2014 - Standard for Qualifying Permanent Connections Use in Substation Grounding
- IEC Std 60479-1 - Effects of Current on Human Beings
- NFPA Publication 70 - The National Electric Code
- NFPA 780 - Standard for Installation of Lightning Protection System
- CSA Std. B72 - Installation Code for Lightning Protection Systems

Terminology

- Bonding: To provide a permanent low impedance path, with adequate current rating and redundancy, between an object and the ground grid.

- Grounding: To provide a permanent low impedance path, with adequate current rating, between objects and remote earth.

Terminology

- Ground Electrode: Buried conductors that dissipate ground current into the earth.
- Grounding System: All conductors that facilitate grounding.
- Ground Fault: An insulation failure between an energized phase conductor and the grounding system.

Terminology

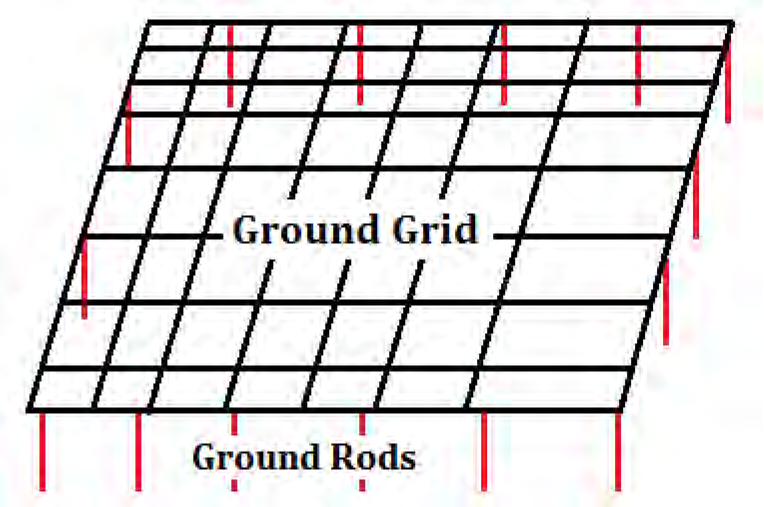
- Ground Current: The current that enters a grounding system.
- Ground Potential Rise (GPR): The voltage between a grounding system and remote earth during a ground fault.
- Remote Earth: A potential reference point sufficiently distant from the fault to experience negligible potential rise.

Terminology

- Step Potential: The open circuit foot-to-foot voltage during a ground fault.
- Touch Potential: The open circuit hand-to-foot voltage during a ground fault.
- Mesh potential: The maximum touch voltage experienced while standing within a mesh of a ground grid and touching a grounding object.
- Transferred Potential: The voltage between local soil and a grounded object that extends exterior to a station.

Grounding System Components

- Ground Grid: A meshed system of buried conductors used to provide contact with the underlying earth.
- Ground Rods: Ground rods are vertical rods used to facilitate the conduction of fault current from the ground grid to the deeper soil layer in the underlying earth



Grounding System Components

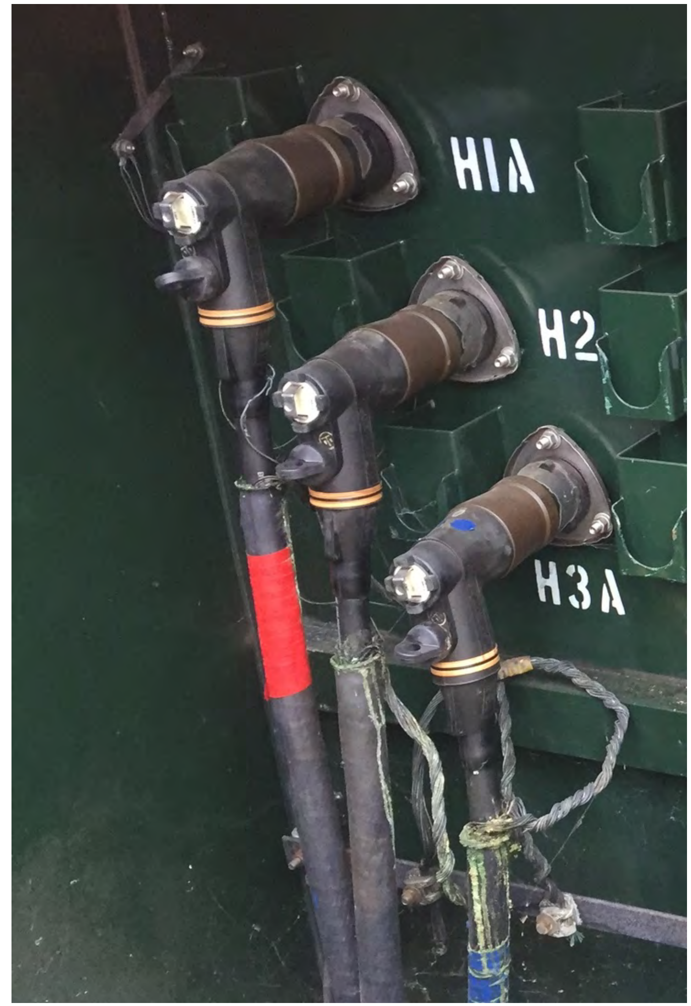
Overhead Ground Wires:

Ground conductors located above phase conductors on transmission lines used to shield the overhead high voltage conductors from lightning strikes.

Grounding System Components

OHGW Connection to Ground Grid

Distribution/Concentric Neutral



Objectives of Grounding

Primary objectives of grounding are to:

1. Protect life from the danger of electric shocks by limiting potential differences between touchable objects during normal or fault conditions
2. Isolate faults as soon as possible by providing a low impedance path to ground in order to activate protection
3. Redirect fault current and lightning away from equipment and property susceptible to damage
4. Minimize electrical interference

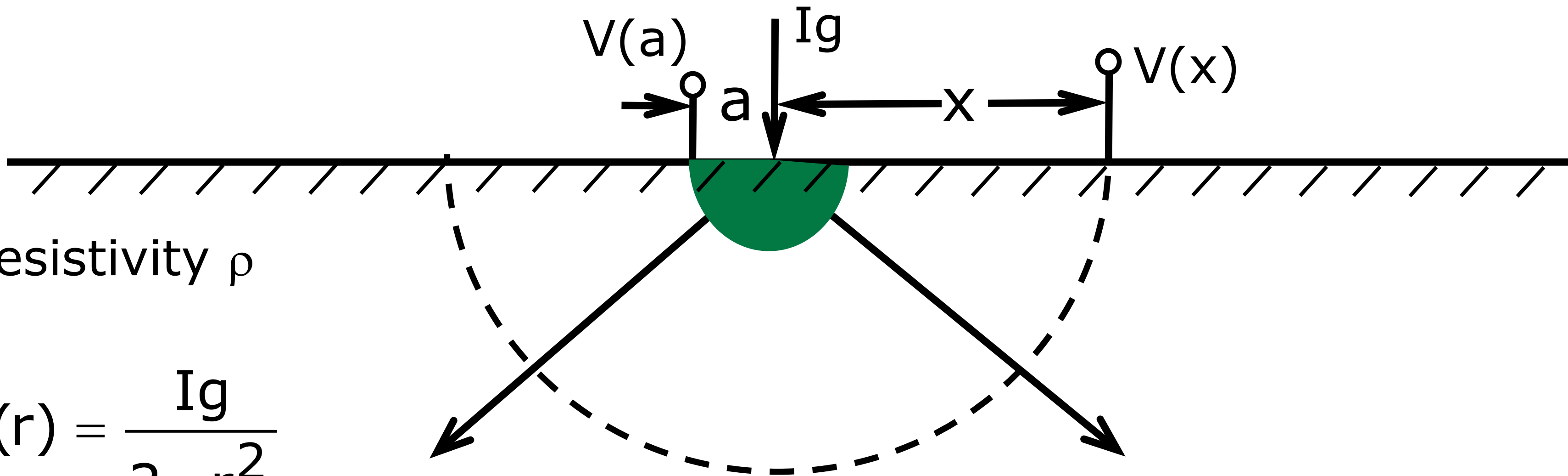
Calculating Ground Grid Parameters: Simplified Scenarios

- See how simple grounding formulas are derived
- Understanding the concept of remote earth resistance
- Relation between resistance and soil resistivity
- Show how image methods handle multilayer soil

Why Modelling is Important?

- Analytical understanding
- Predicts performance before construction
- Allows optimizing use of copper
- Usually less expensive than testing
- Many different modelling tools available
- Results can easily be rechecked

Mutual Resistance Rm(x), Half Sphere Rg



Resistivity ρ

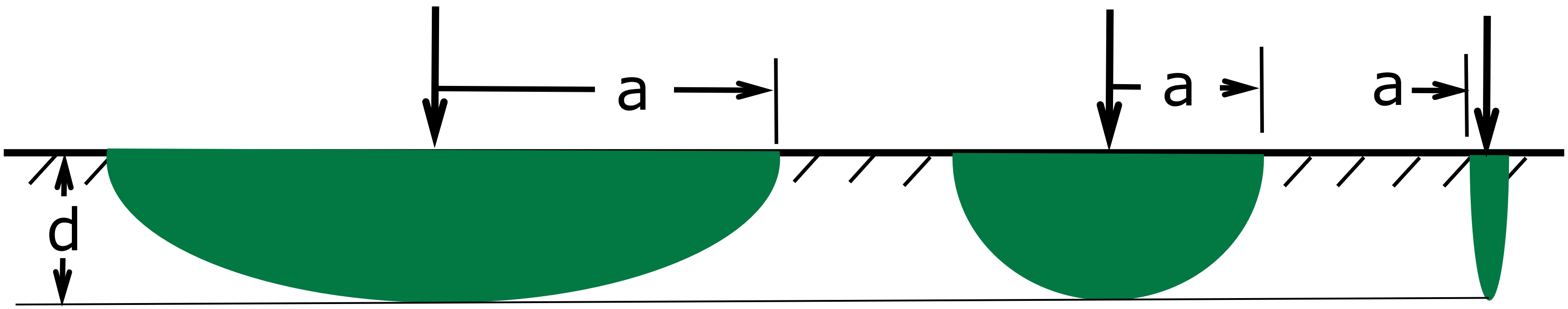
$$J(r) = \frac{Ig}{2\pi r^2}$$

$$E(r) = \rho\, J(r)$$

$$V(x) = \int E(r)\, dr = \left.\frac{\rho\, Ig}{2\pi r}\right]_x^{\infty} = \frac{\rho\, Ig}{2\pi x}$$

$$\text{Mutual } \; Rm(x) = \frac{\rho}{2\pi x} \qquad Rg = \frac{\rho}{2\pi a}$$

Sunde (1949) Ellipsoids of Revolution



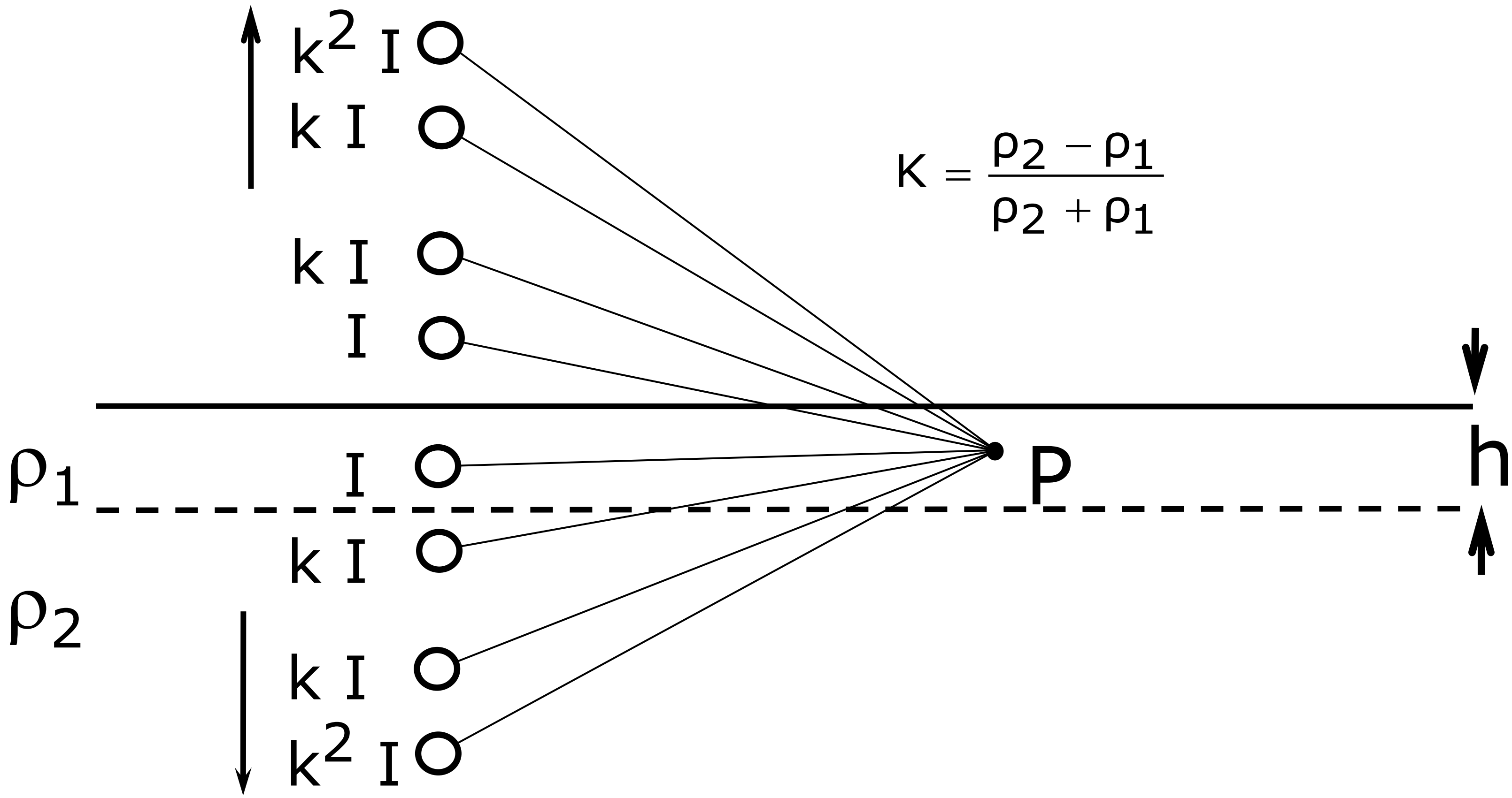
Disk $Rg = \frac{\rho}{4a}$

Sphere $Rg = \frac{\rho}{2\pi a}$

Rod $Rg = \frac{\rho}{2\pi d} \ln \frac{2d}{a}$

E.D. Sunde, “Earth Conduction Effects of Transmission Systems”, Van Nostrand, 1949, p 71

Two Layer Soil Gives Multiple Images



$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

$$Rm(x) = \frac{\rho_1}{2\pi x} + \frac{\rho_1}{\pi} \sum_{n=1}^{\infty} \frac{K^n}{\sqrt{x^2 + (2nh)^2}}$$

Importance of Soil Information

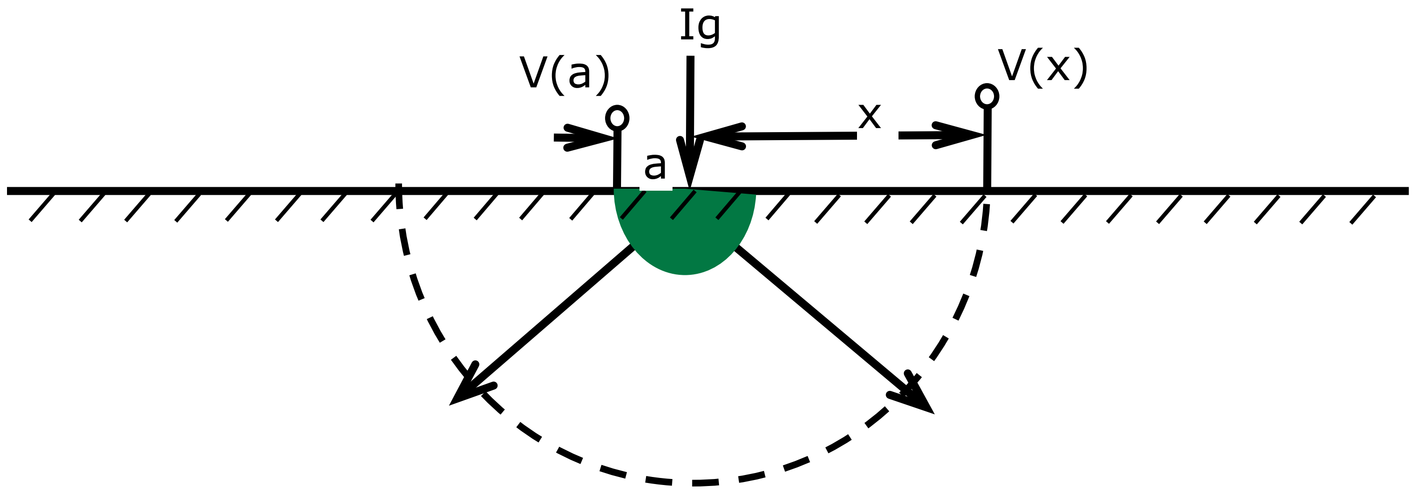
- The grid resistance if directly proportional to soil resistivity.

$$\text{Disk Rg} = \frac{\rho}{4a}$$

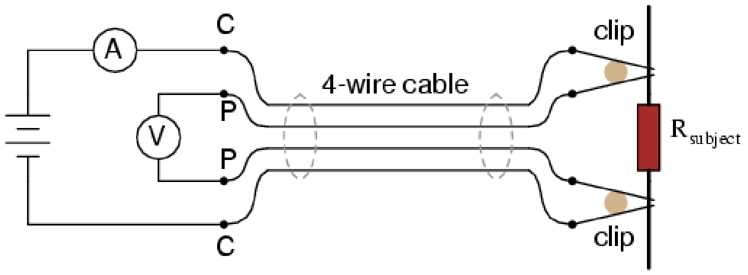
- Similar grid arrangements in different soils have completely different performances

Grounding Perspectives

- Concept of Remote Electrode, Earth Resistance

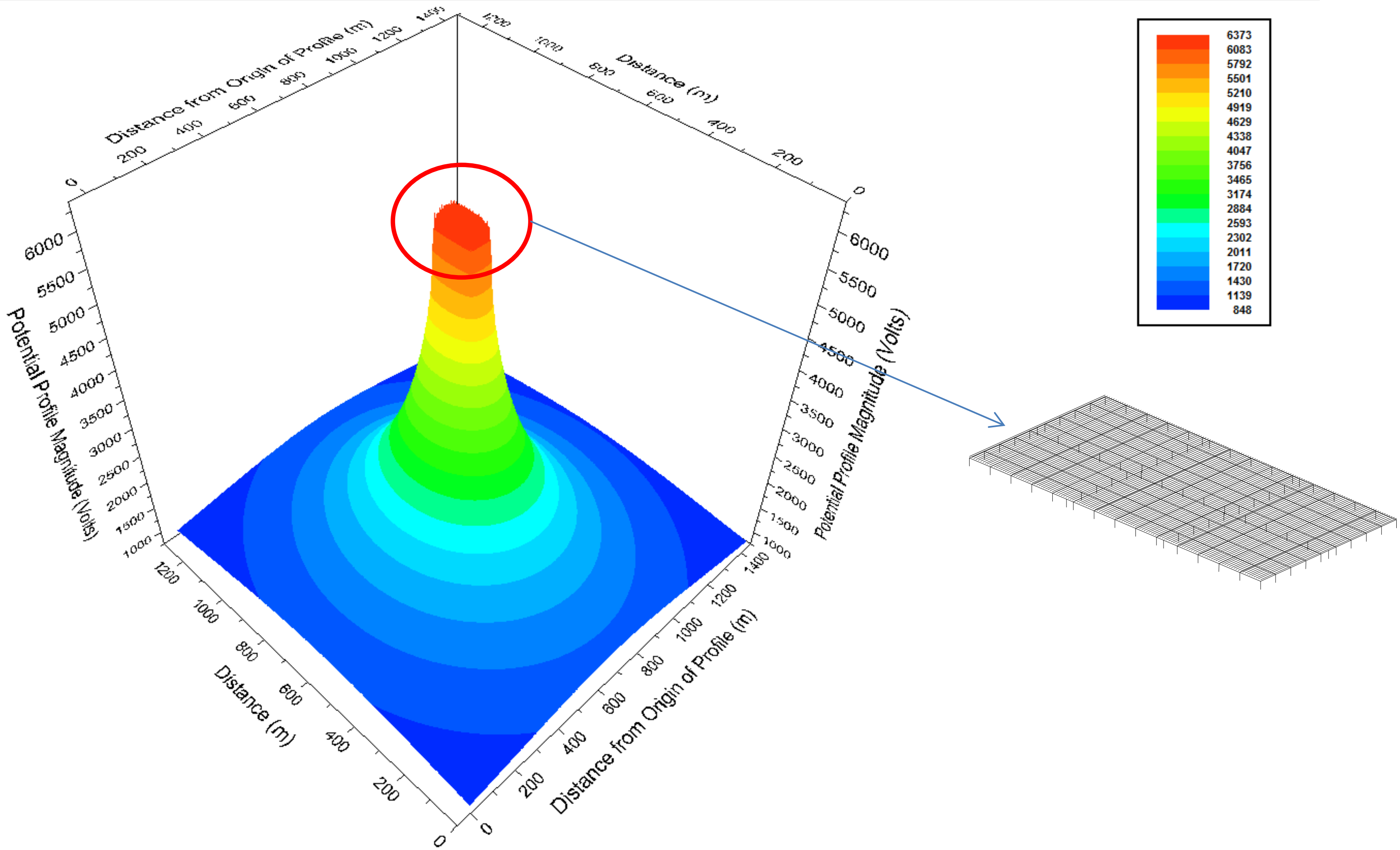


- Integrity, Bonding, 4 point resistance measurement

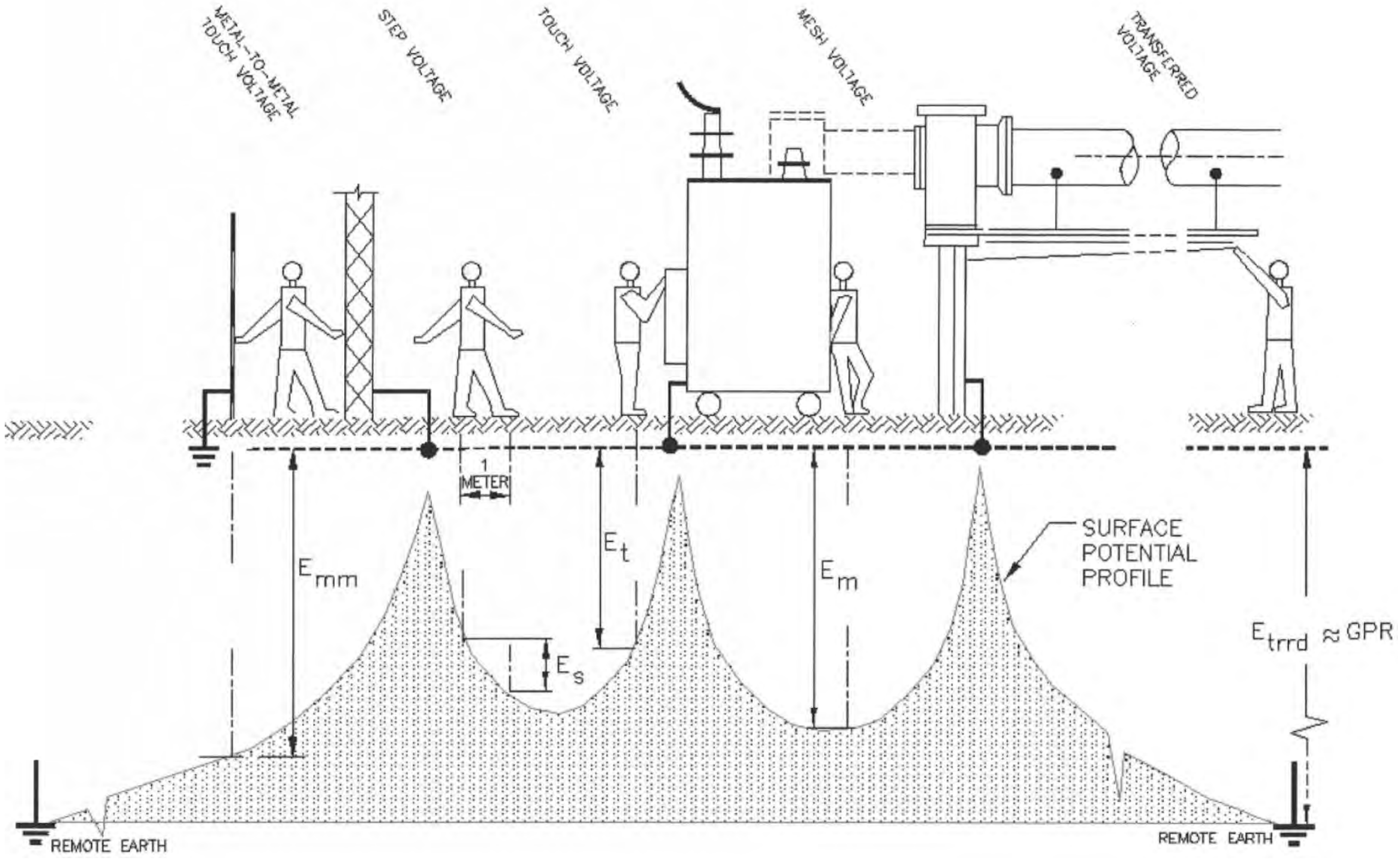


$$R_{subject} = \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}$$

Soil Potential during Fault



Basic Shock Situations



Source: IEEE Std 80

Touch Voltage Modelling

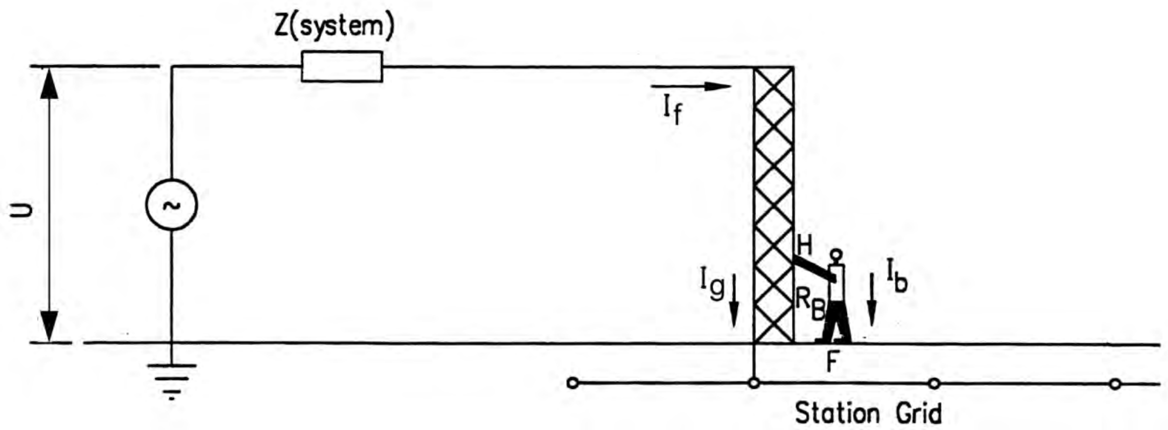


Figure 6—Exposure to touch voltage

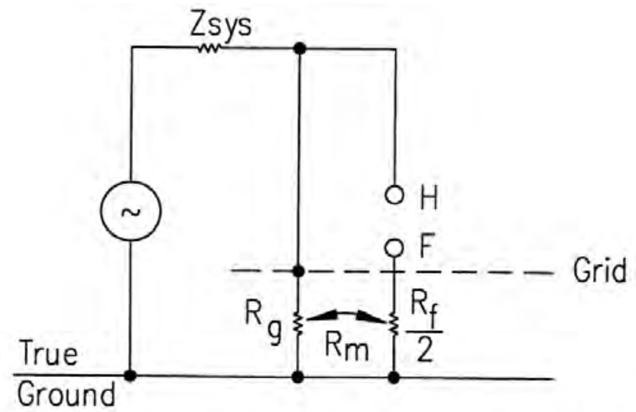


Figure 7—Impedances to touch voltage circuit

Source: IEEE Std 80

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Open Circuit Touch Voltage

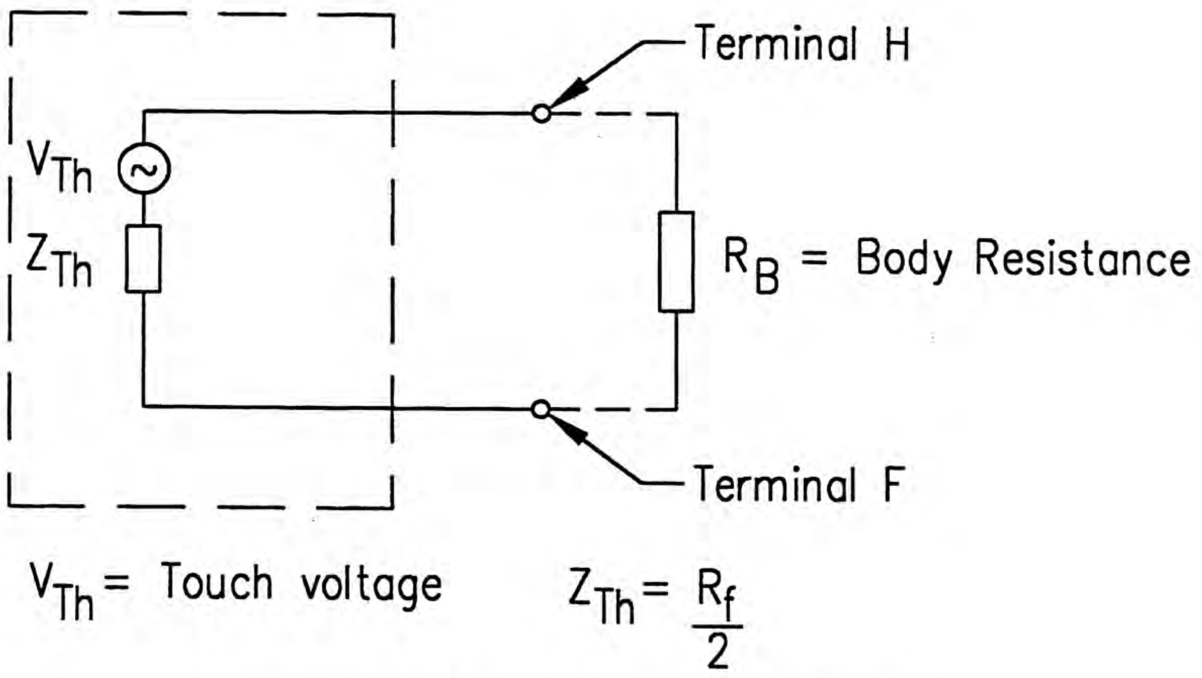


Figure 8—Touch voltage circuit

Source: IEEE Std 80

Open Circuit Step Voltage

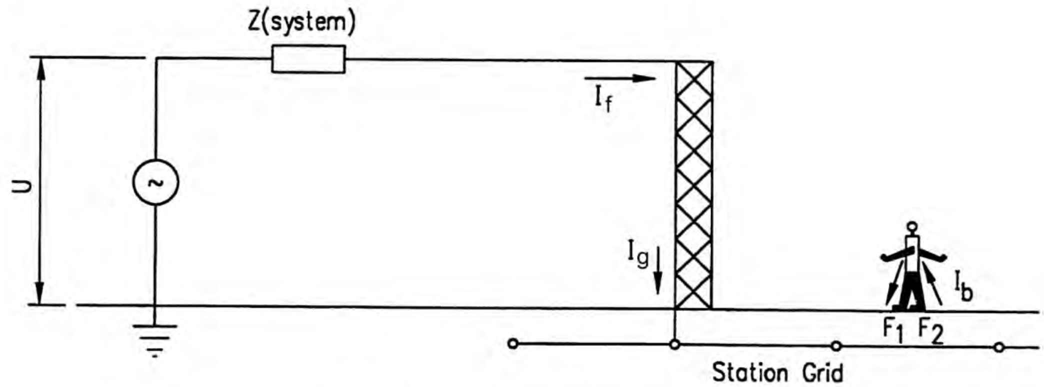


Figure 9—Exposure to step voltage

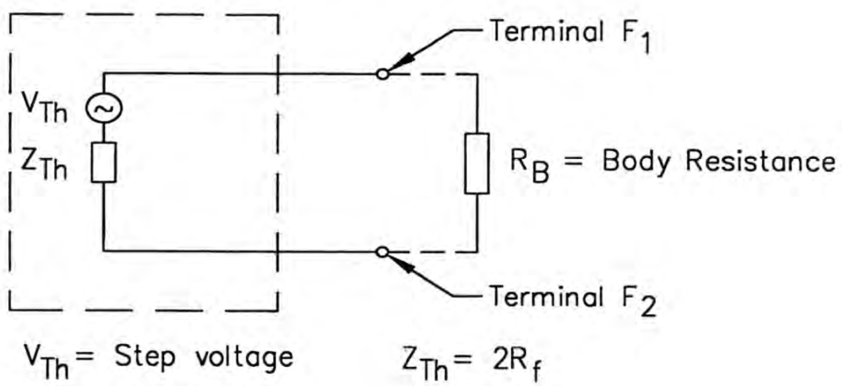


Figure 10—Step voltage circuit

Source: IEEE Std 80

Resistance of one foot

$$R_f = \frac{\rho}{4 \times b}$$

Model foot resistance by a disk with radius of 8 cm (b=0.08 m)

$$R_f = \frac{\rho}{4 \times 0.08} \cong 3\rho$$

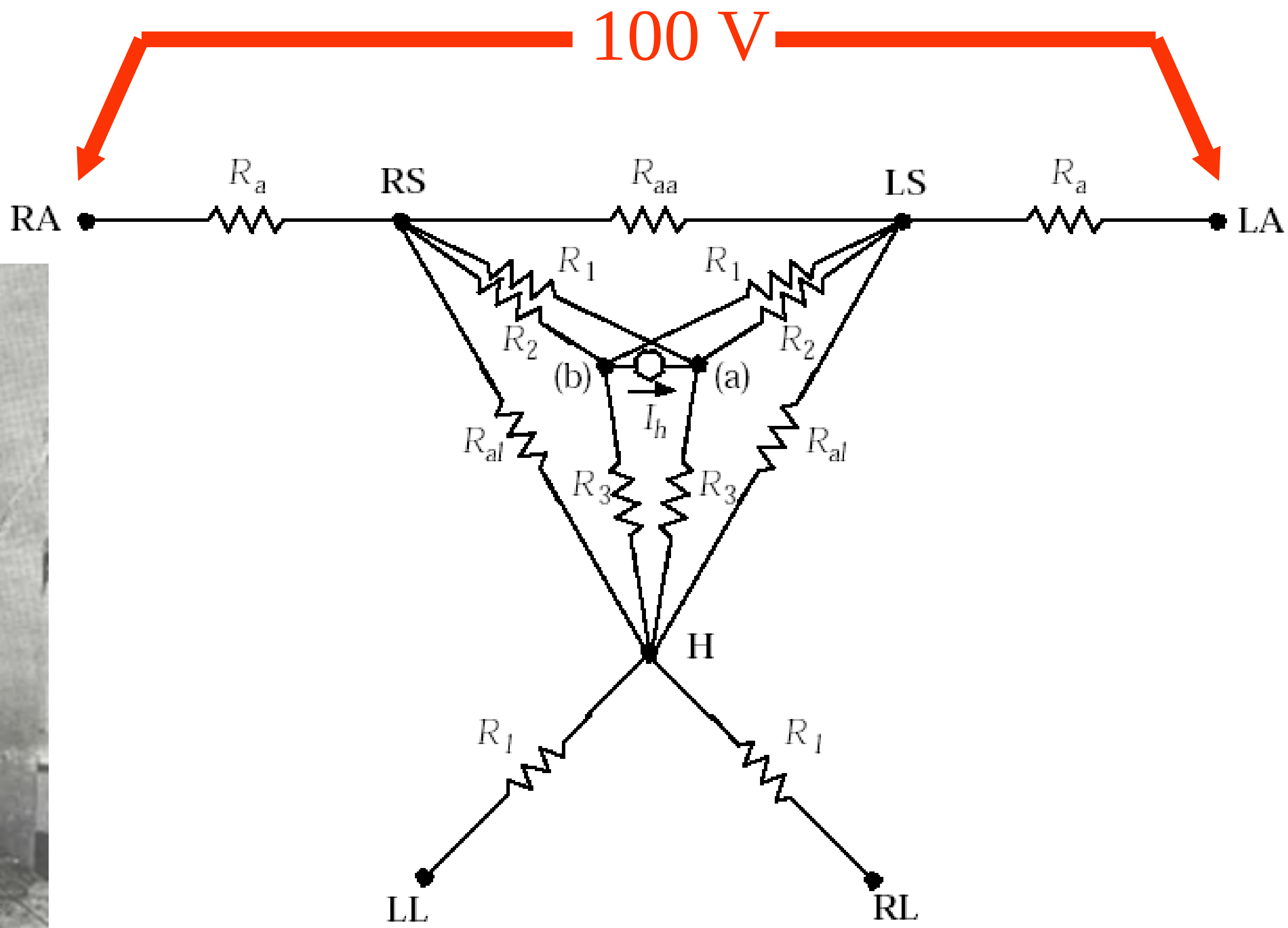
For Touch $\quad Z_{th} = 1.5 \times \rho$

For Step $\quad Z_{th} = 6 \times \rho$

Maximum Voltage Threshold

- $V_{Threshold} = (R_{Body} + Z_{th}) \times I_{max}$
  - R_{Body} (Body Resistance)
  - I_{max} (Electrocution Current)

Body Impedance Model - Einthoven



Body Impedance Model - Einthoven

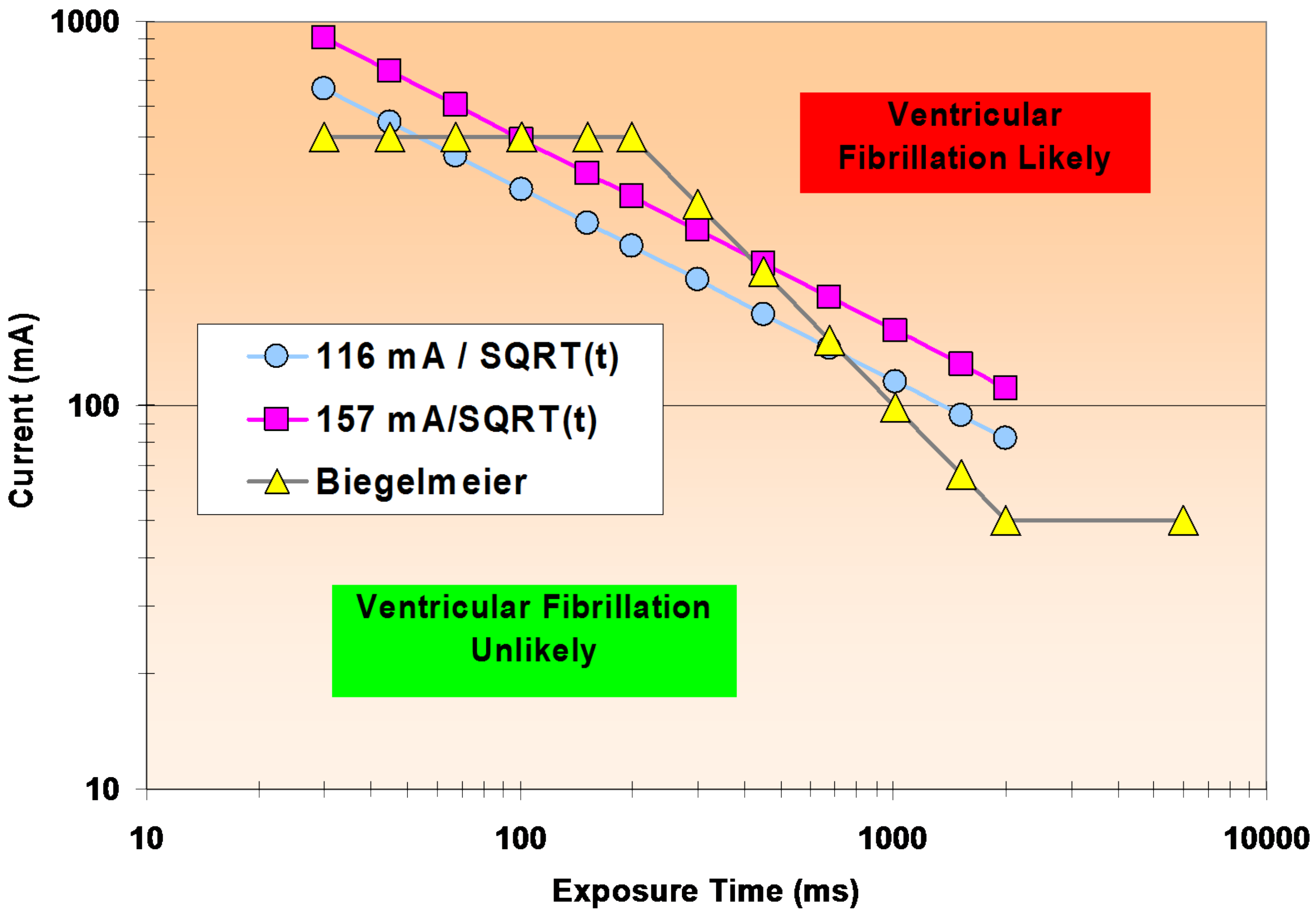
Resistance terms

R_a arm resistance	250 Ω
R_l leg resistance	325 Ω
R_{aa} peripheral torso resistance arm-arm	40 Ω
R_{al} peripheral torso resistance arm-leg	80Ω
R_1 internal resistance 1	26 Ω
R_2 internal resistance 2	24 Ω
R_3 internal resistance 3	25 Ω

Body Resistance – IEEE 80

- Dalziel [1953] performed extensive testing using saltwater to wet hands/feet to measure let-go current.
  - Conclusion $\boldsymbol{R_{body} = 1000\ \Omega}$
- Neglects:
  - Contact resistance
  - Glove/shoe resistance
  - Skin Puncture

Electrocution Current: IEC 60749 to IEEE 80



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Effect of Crushed Stone

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- Increases the foot resistance

$$V_{Threshold} = (R_{Body} + Z_{th}) \times I_{max}$$

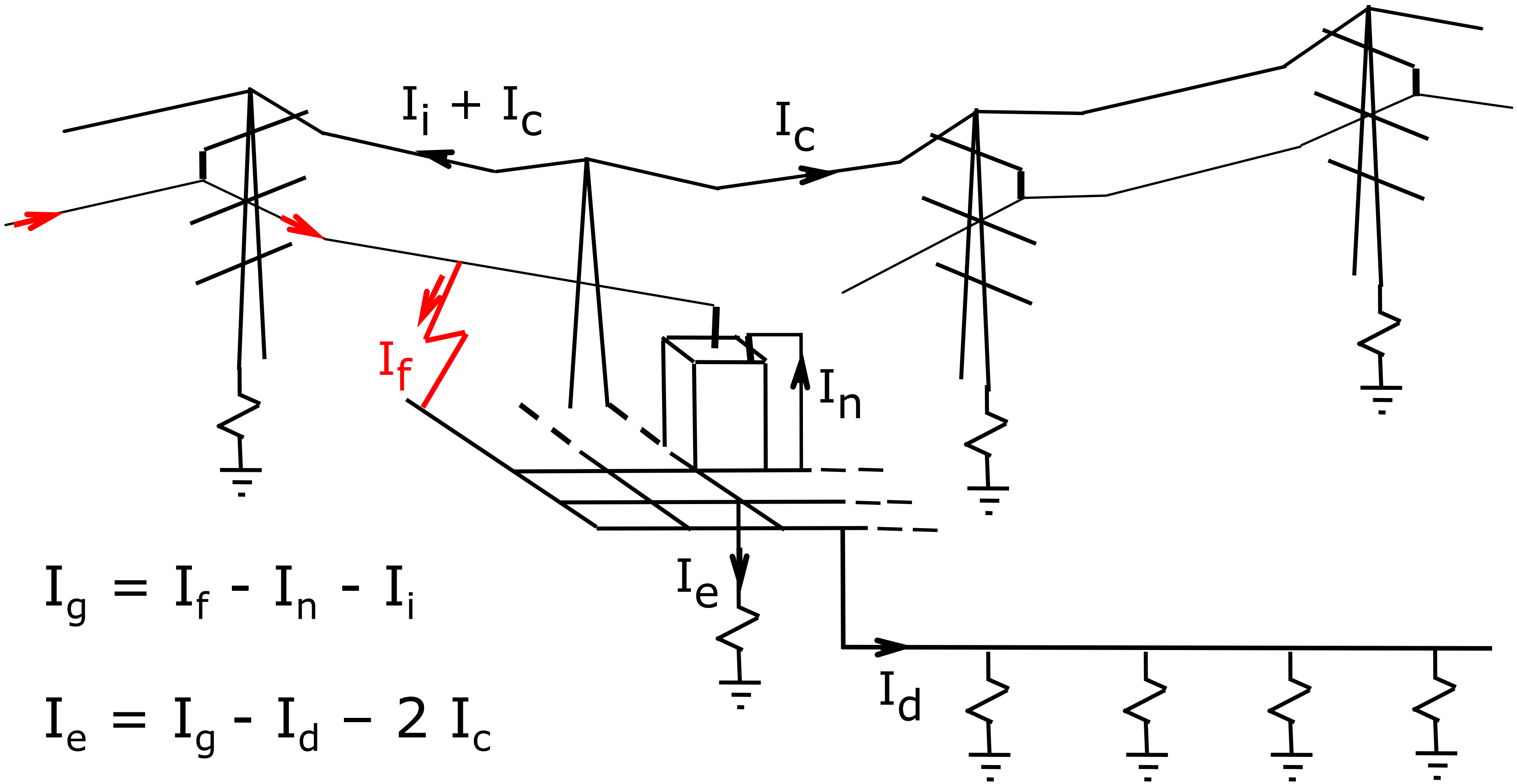
- Therefore, higher tolerable limit

$$R_f = \frac{\rho_{stone}}{4 \times b} \times C_s$$

Safety Assumptions	Clearing time of 0.5 sec , X/R = 20, 50 kg worker	
Surface Material	80 mm of 3,000 Ωm Crushed Stone	Native soil of 100 Ωm
Touch Voltage Safe Limit	622.4 V	180.4 V
Step Voltage Safe Limit	2,021.8 V	253.5 V

Ground Grid Under Fault Conditions

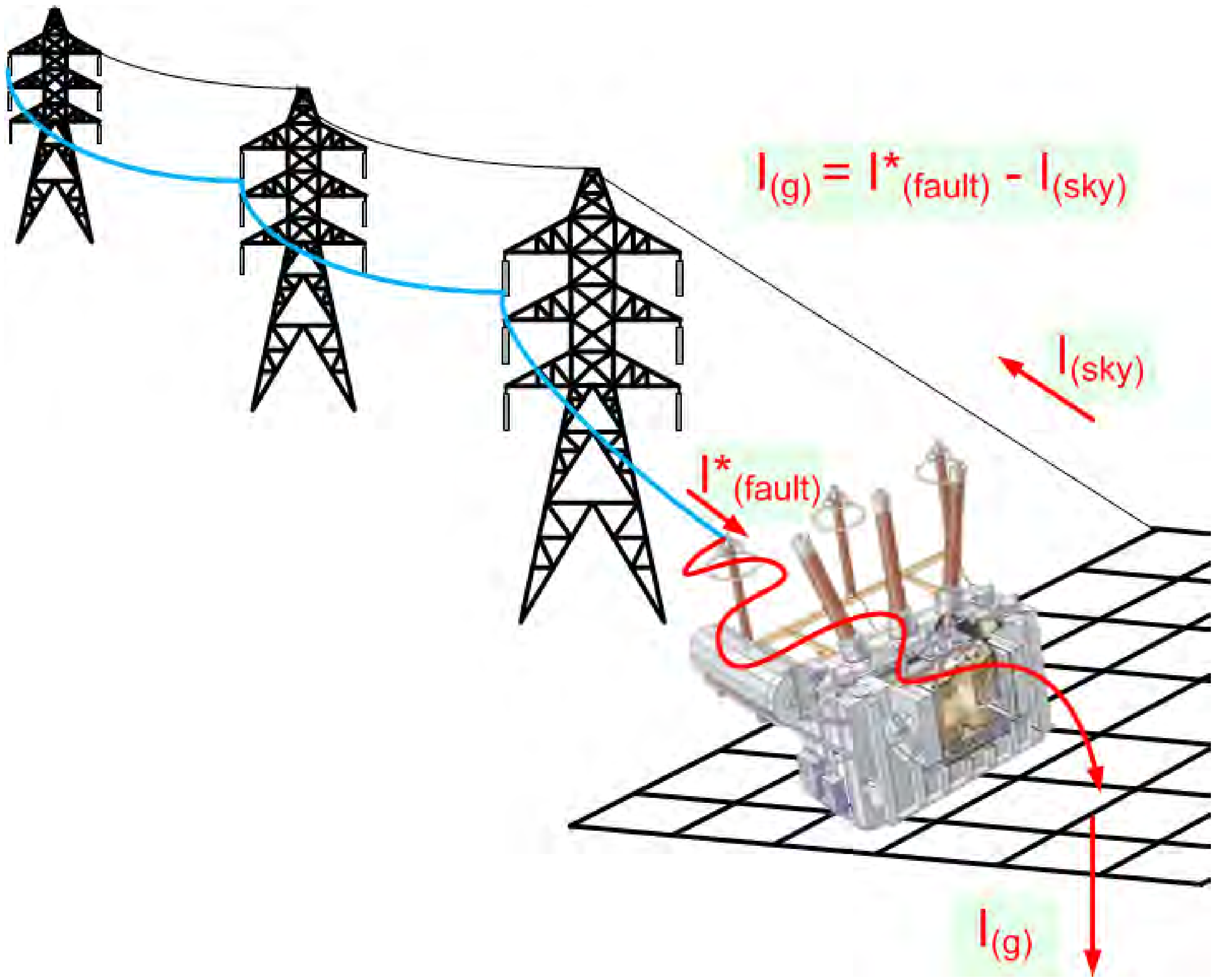
Fault Current From Remote Source



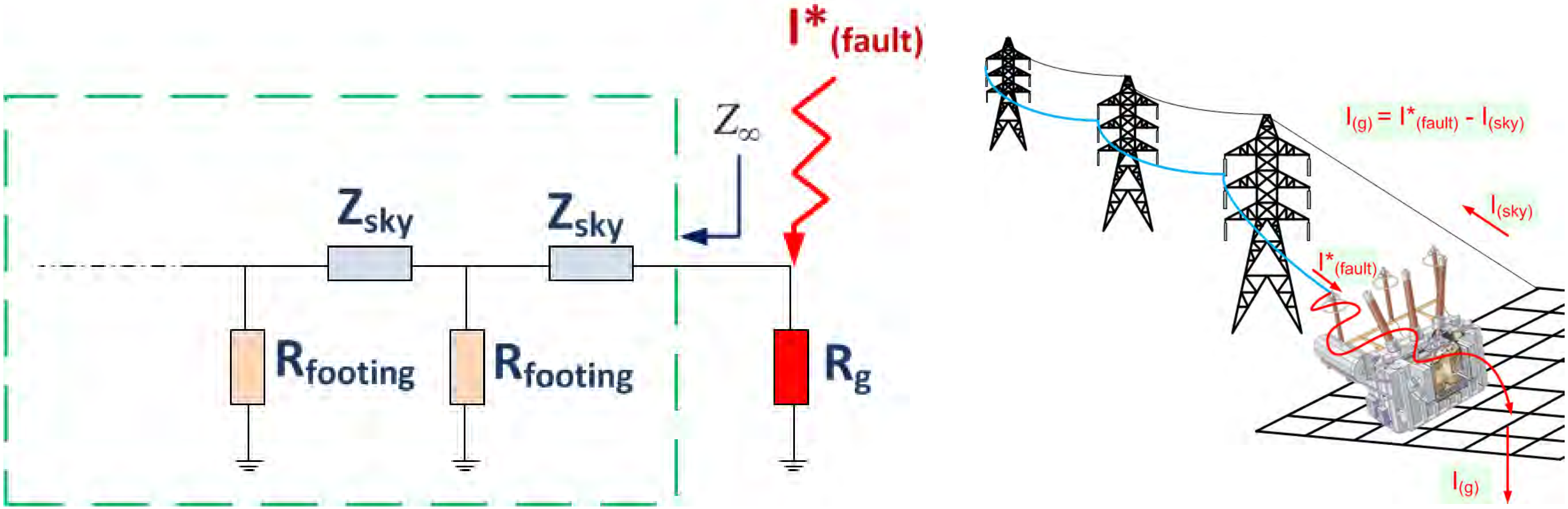
$$I_g = I_f - I_n - I_i$$

$$I_e = I_g - I_d - 2\,I_c$$

Simplified Scenario



Problem Formulation



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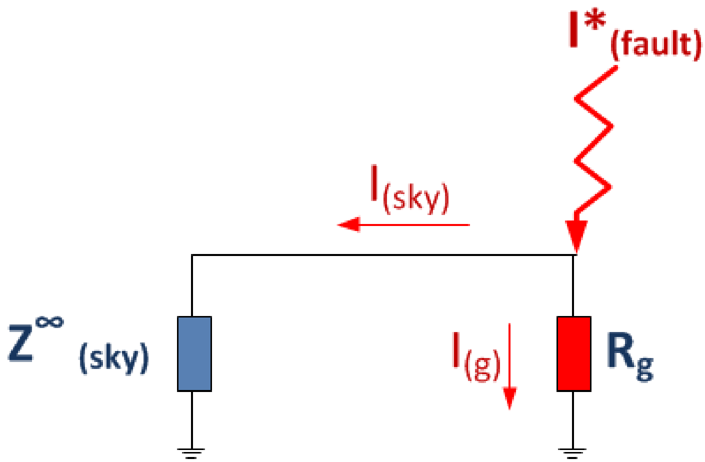
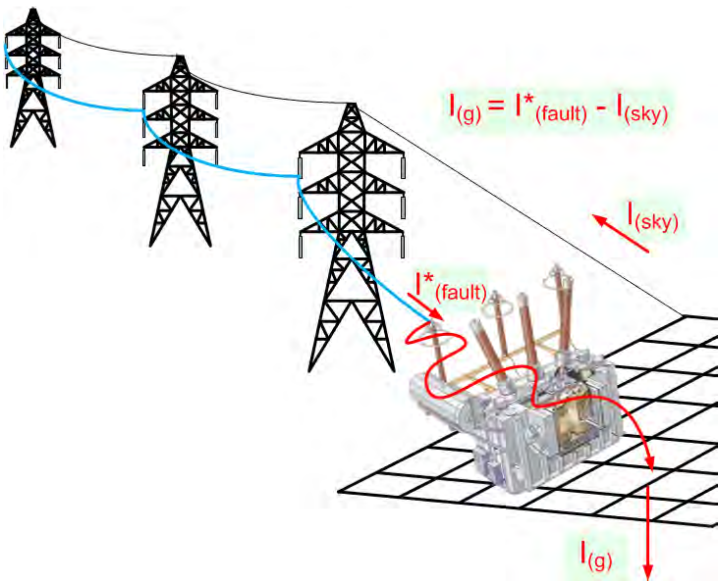
Split Factor

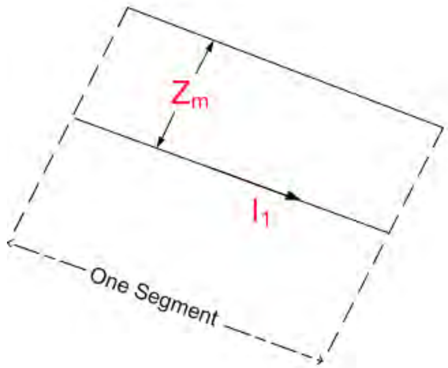


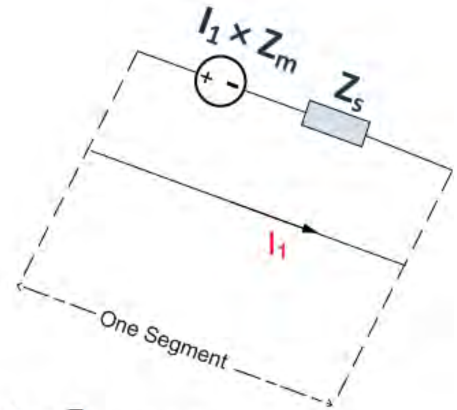
$$GPR = R_g \times I_{(g)} = Z^{\infty}_{(sky)} \times I_{(sky)} = \left(R_g \,||\, Z^{\infty}_{(sky)}\right) \times I^{*}_{(fault)}$$

$$= R_g \times \underbrace{\frac{Z^{\infty}_{(sky)}}{R_g + Z^{\infty}_{(sky)}}}_{\text{Split Factor}} \times I^{*}_{(fault)}$$

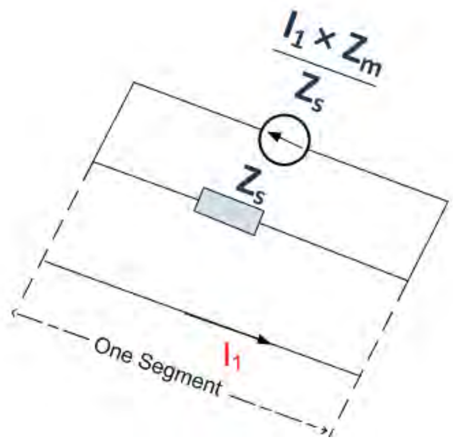


Shielding Factor

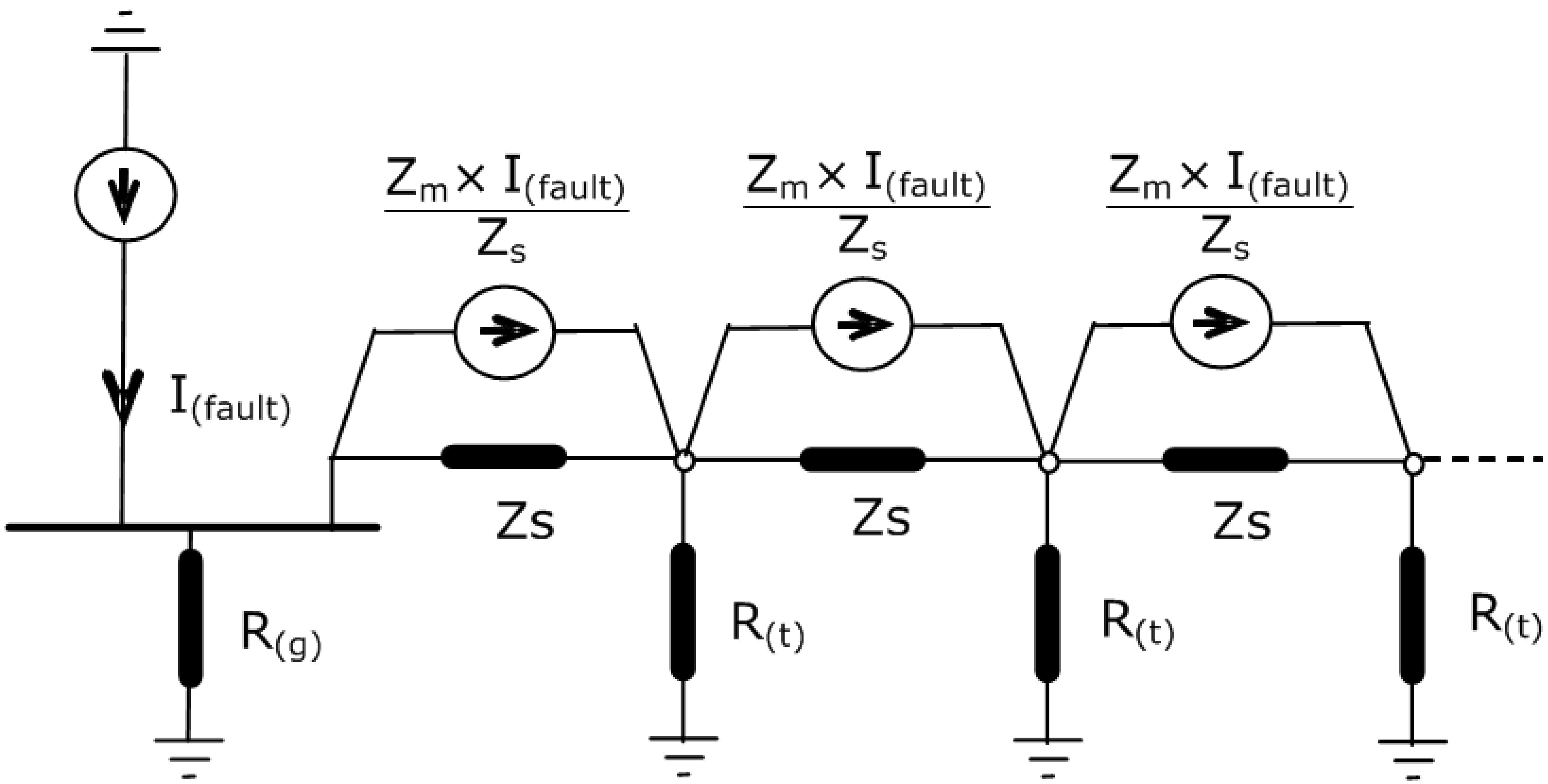




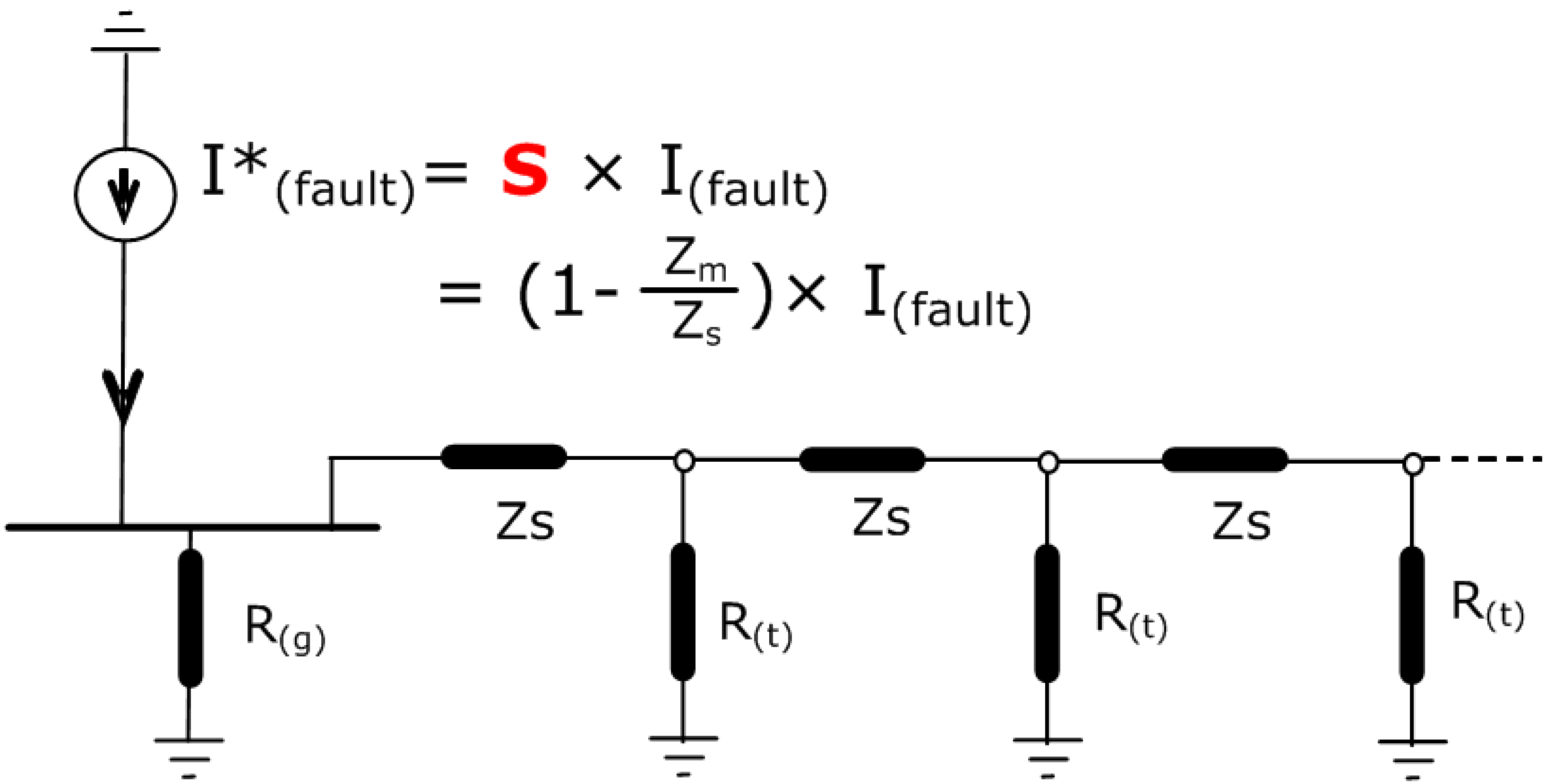
$$Z_m = 0.059 + j\ 0.0377 \ln\left[\frac{8440\,\rho}{d^2}\right] \quad \Omega / km$$



Shielding factor: Norton Equivalent



Shielding factor: De-coupled



$$I^*_{(fault)} = \mathbf{S} \times I_{(fault)}$$

$$= \left(1 - \frac{Z_m}{Z_s}\right) \times I_{(fault)}$$

Circulating Current within the Transformer

- Some of the fault current will be circulating within the transformer
- The circulating current will not return to remote earth and therefore will not cause any GPR
- To properly account for the circulating current, transformer winding configuration as well as the impedance model must be known

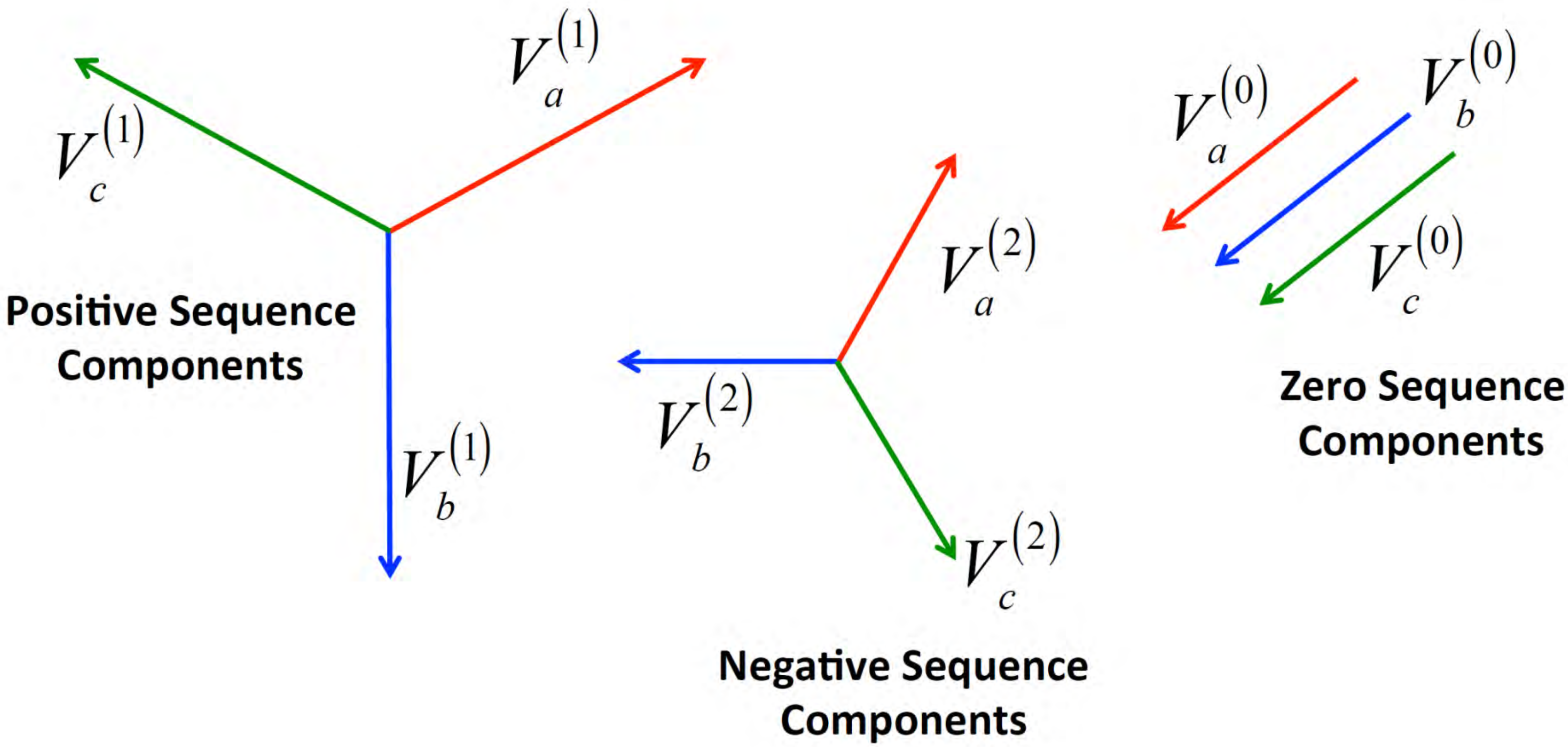
Sequence Network Theory

(Fortescue's Theorem 1918) Three unbalanced phasors of a three phase system can be mapped into three balanced systems of phasors.

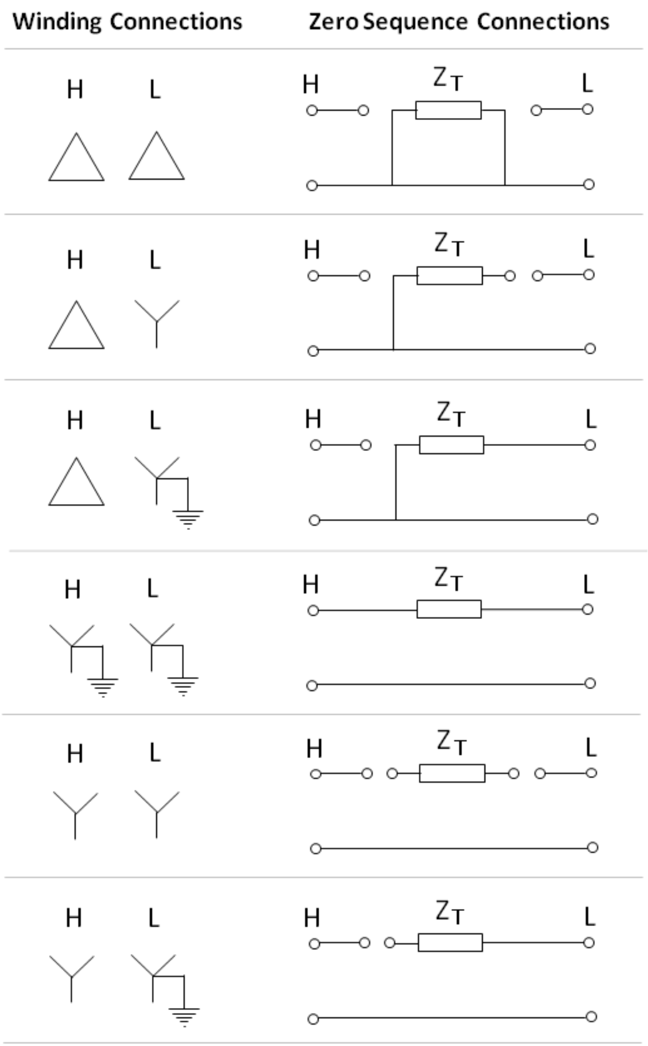
The balanced sets of components are:

- **Positive sequence components:** consisting of three phasors equal in magnitude, 120^o apart in phase, but have the same phase sequence as the original phasors.
- **Negative sequence components:** consisting of three phasors equal in magnitude, 120^o apart in phase, and have the opposite phase sequence as the original phasors.
- **Zero sequence components:** consisting of three phasors equal in magnitude and with zero phase displacement from each other.

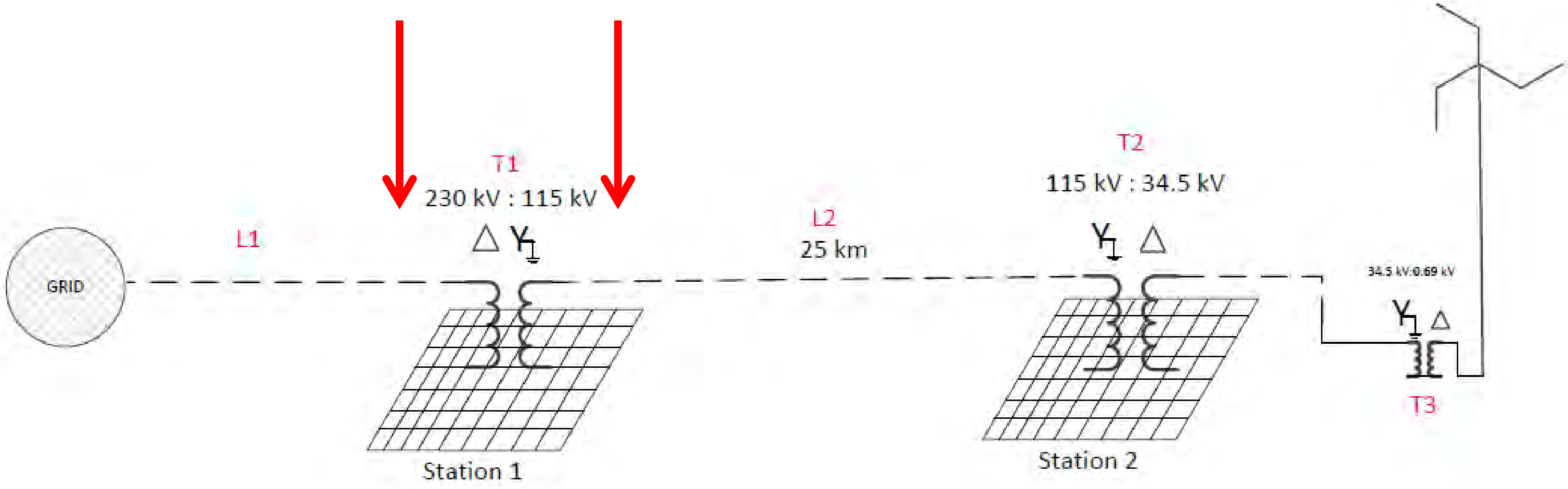
Sequence Network Theory



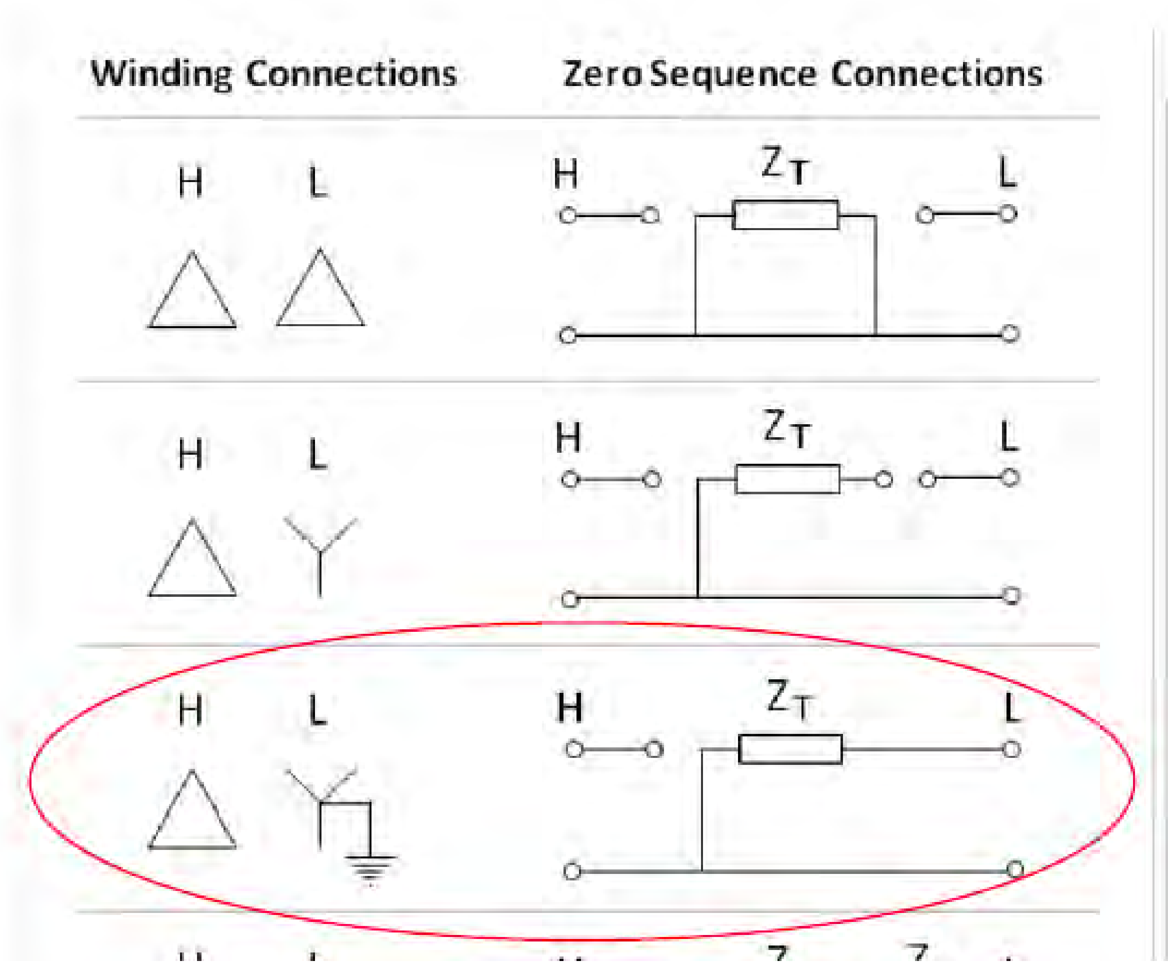
Transformer Winding Configurations



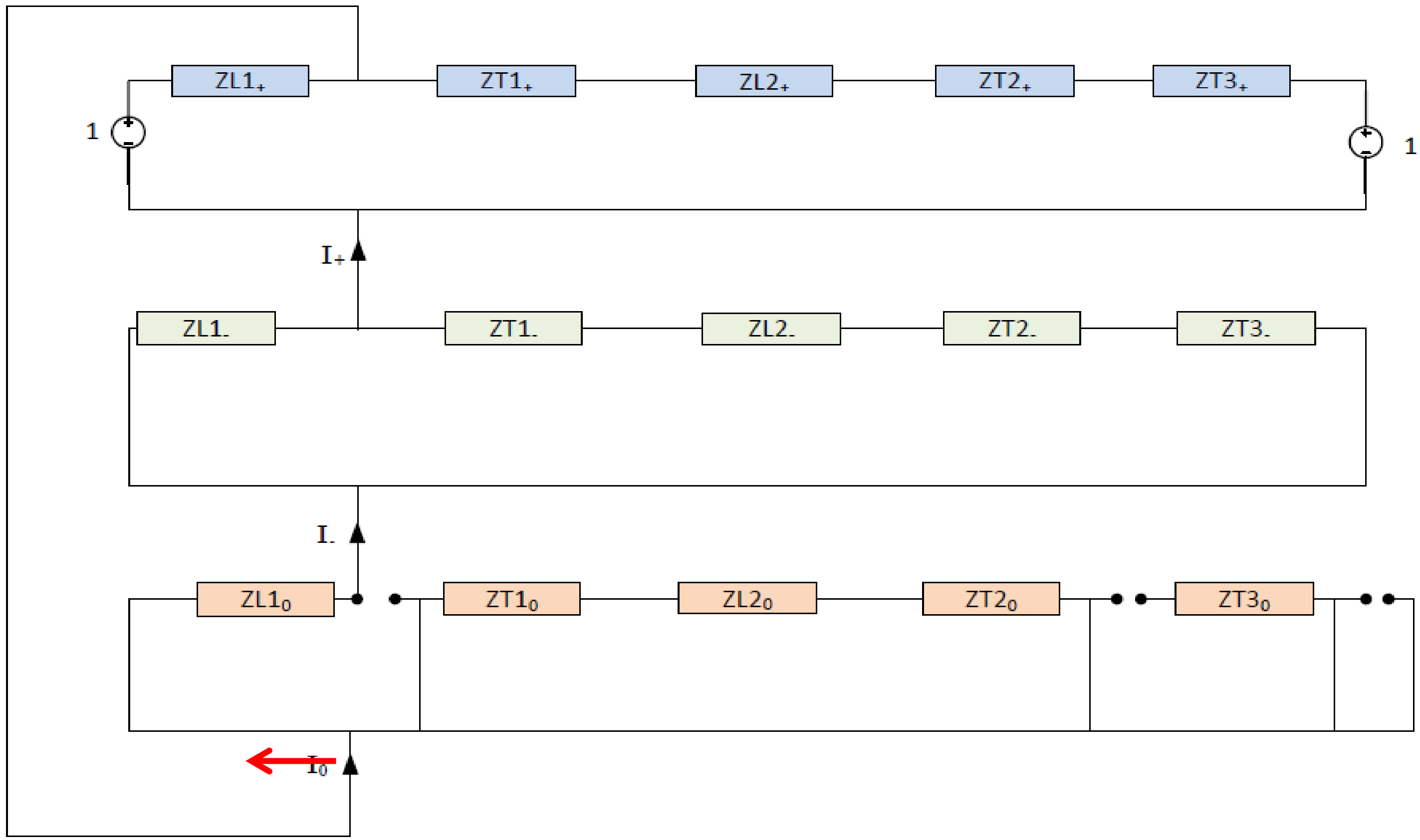
Calculating Zero Sequence Fault

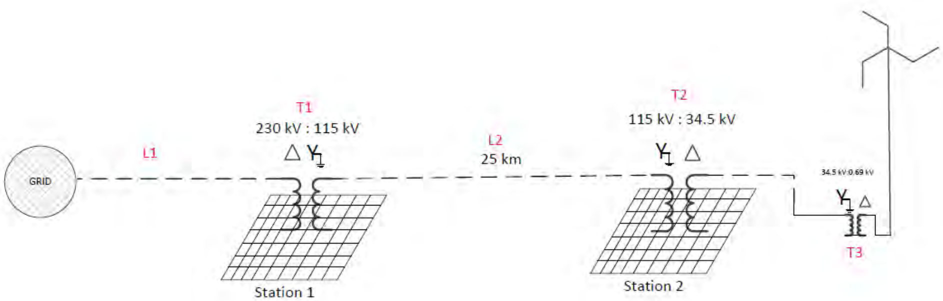


Zero Sequence Model of Transformers

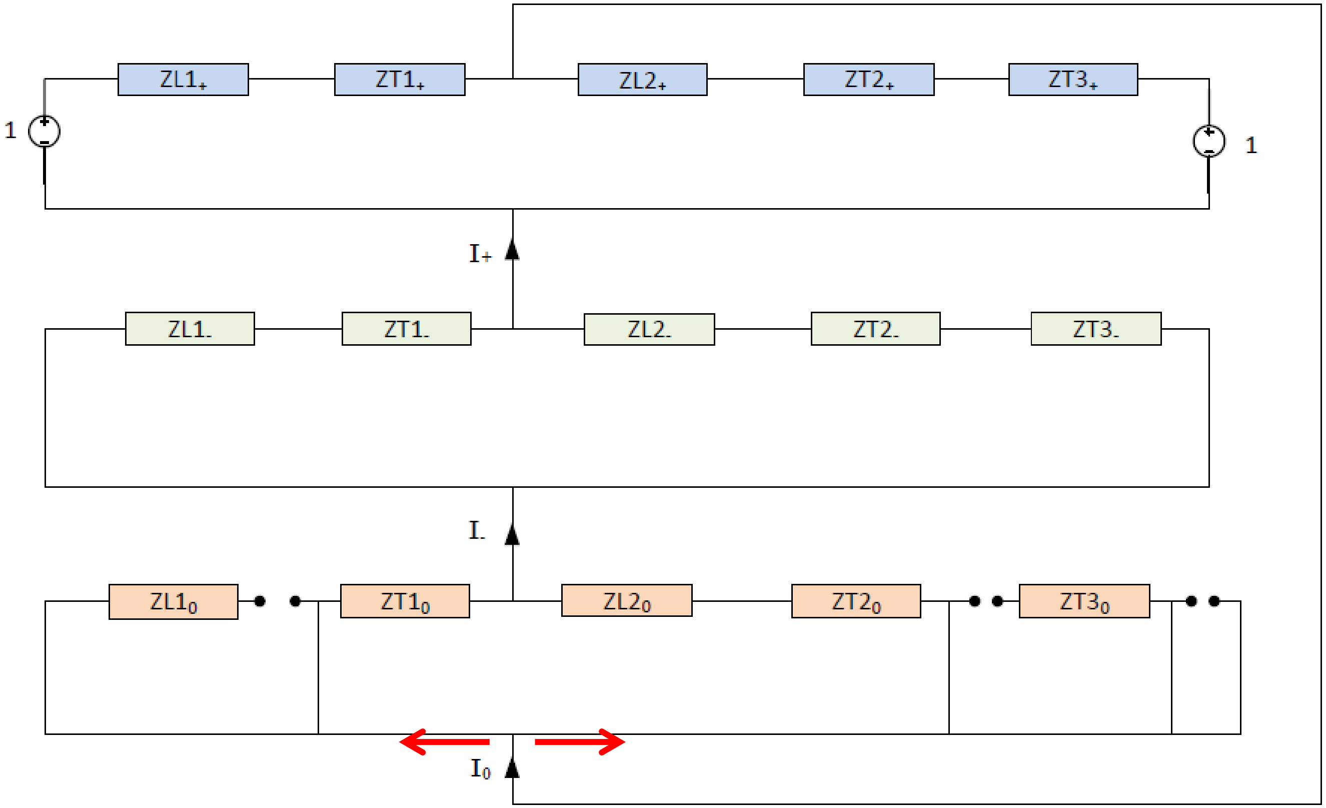


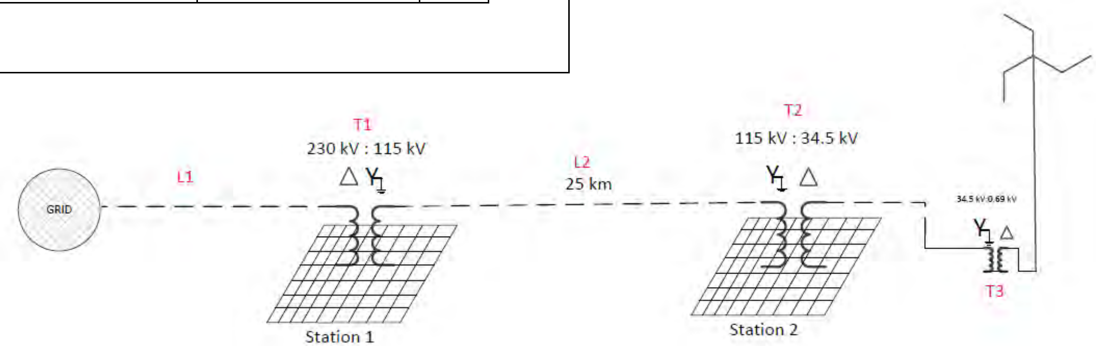
Fault at the HV side



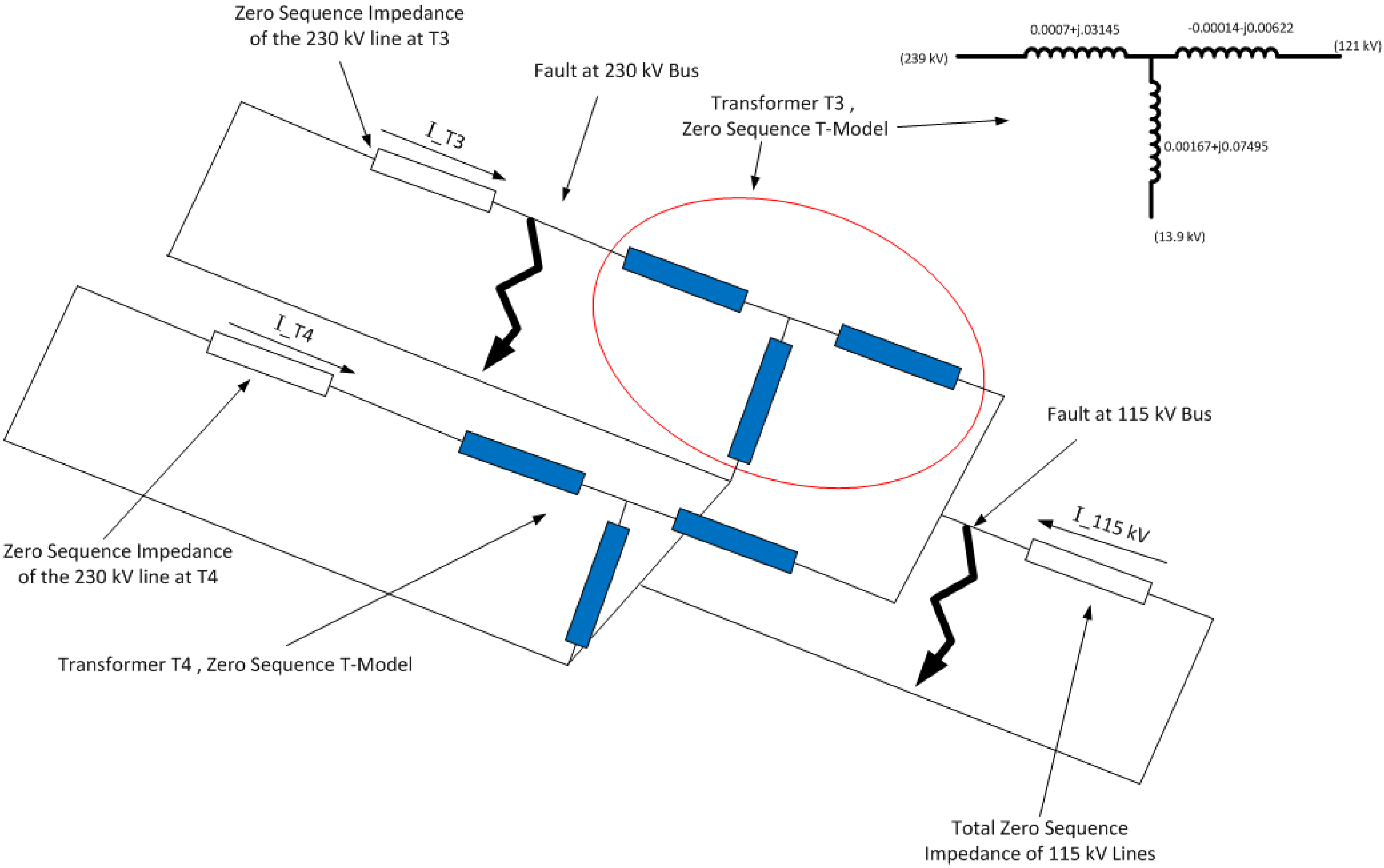


Fault at LV Side





Three Winding Transformers



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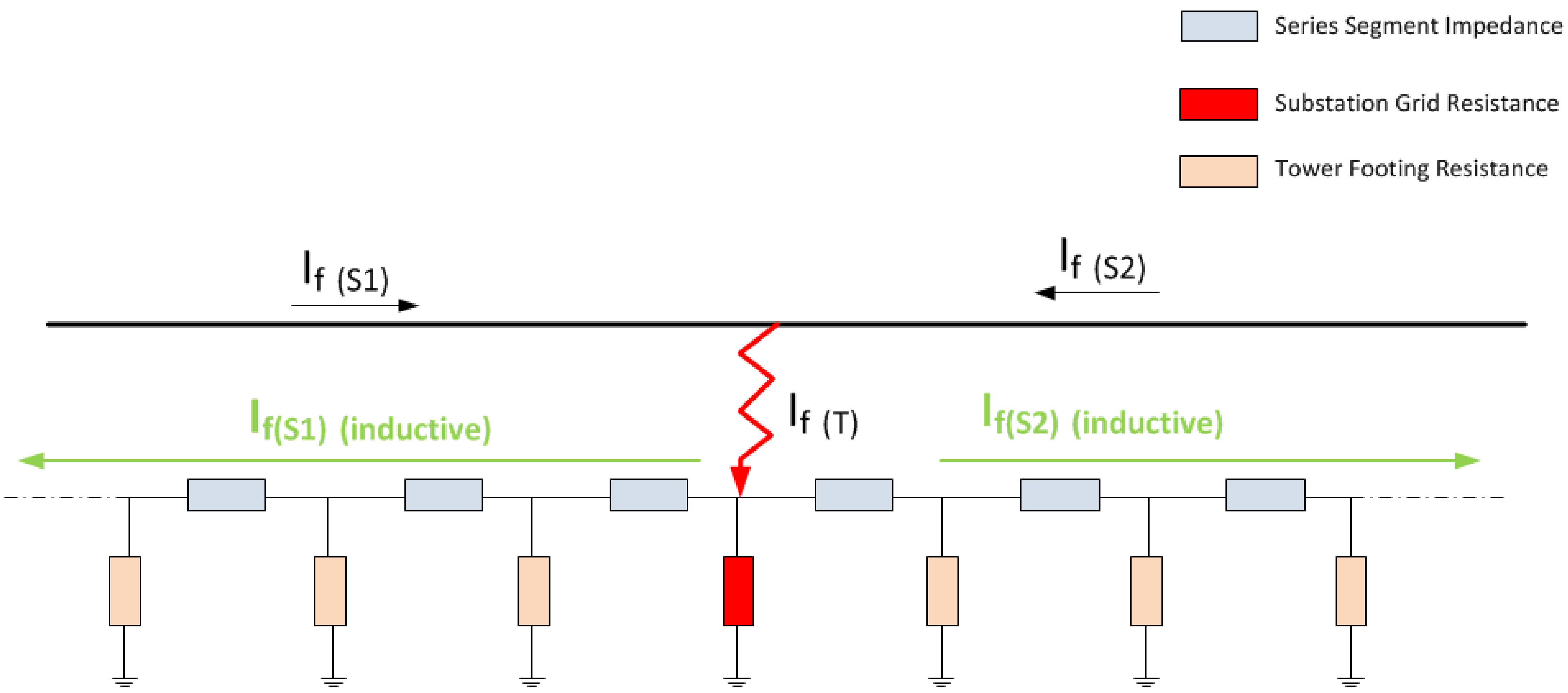
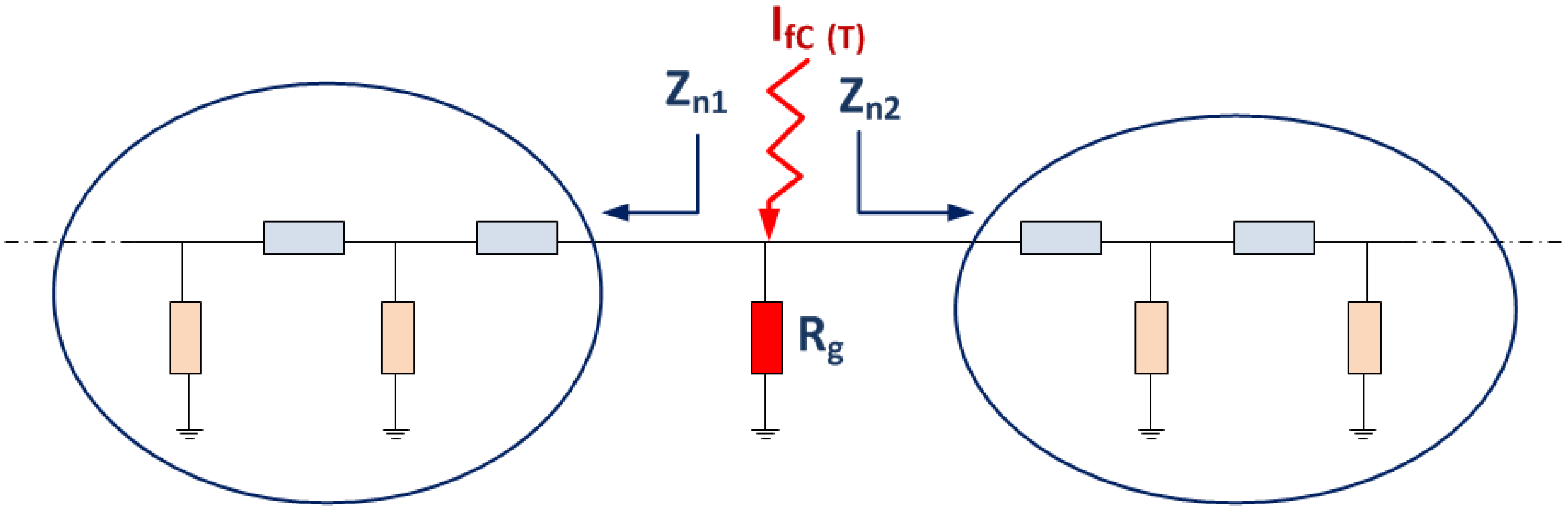
Summary – Fault Analysis

Problem Formulation



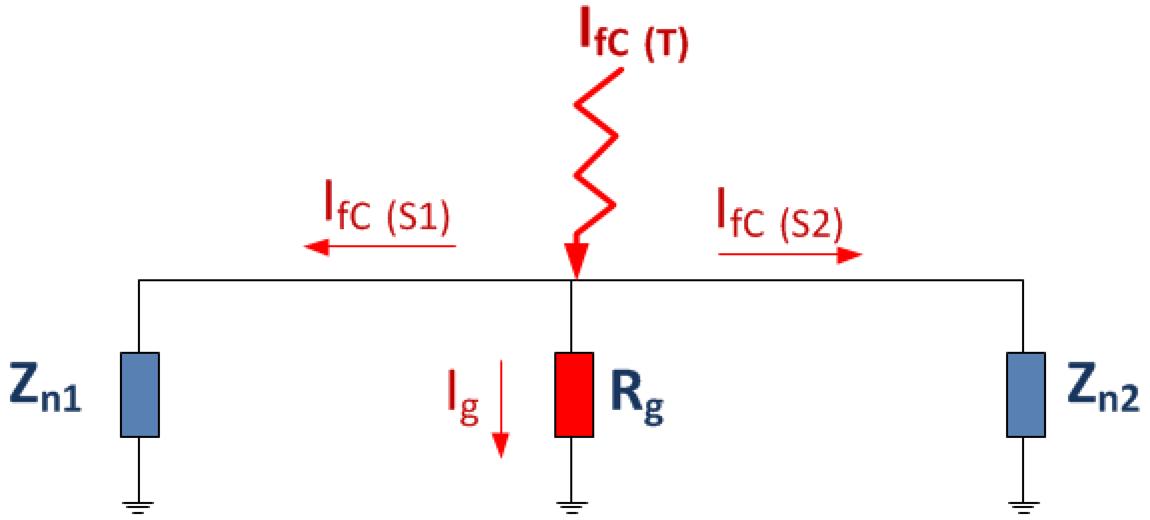
Driving Point Impedance - Decoupling



$I_{fC\ (T)} = I_{f\ (T)} - I_{f(S2)\ (inductive)} - I_{f(S1)\ (inductive)}$

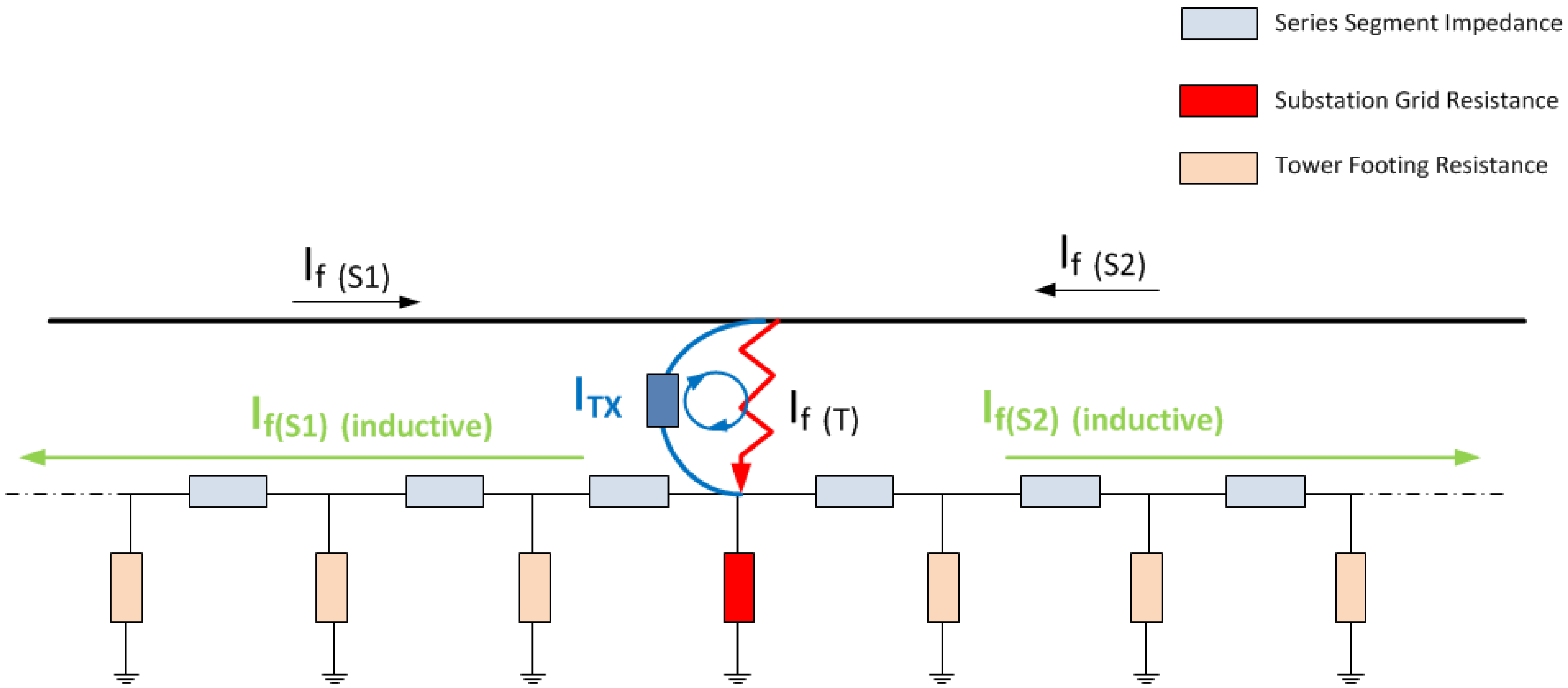
Z_n = Driving Point Impedance

Simplified Network



$$GPR = R_g \times I_g = Z_{n1} \times I_{fC\ (S1)} = Z_{n2} \times I_{fC\ (S2)} = (R_g || Z_{n1} || Z_{n2}) \times I_{fC\ (T)}$$

Transformer Circulating Current



$I_{fC\ (T)} = I_{f\ (T)} - I_{f(S2)\ (inductive)} - I_{f(S1)\ (inductive)} - I_{TX}$

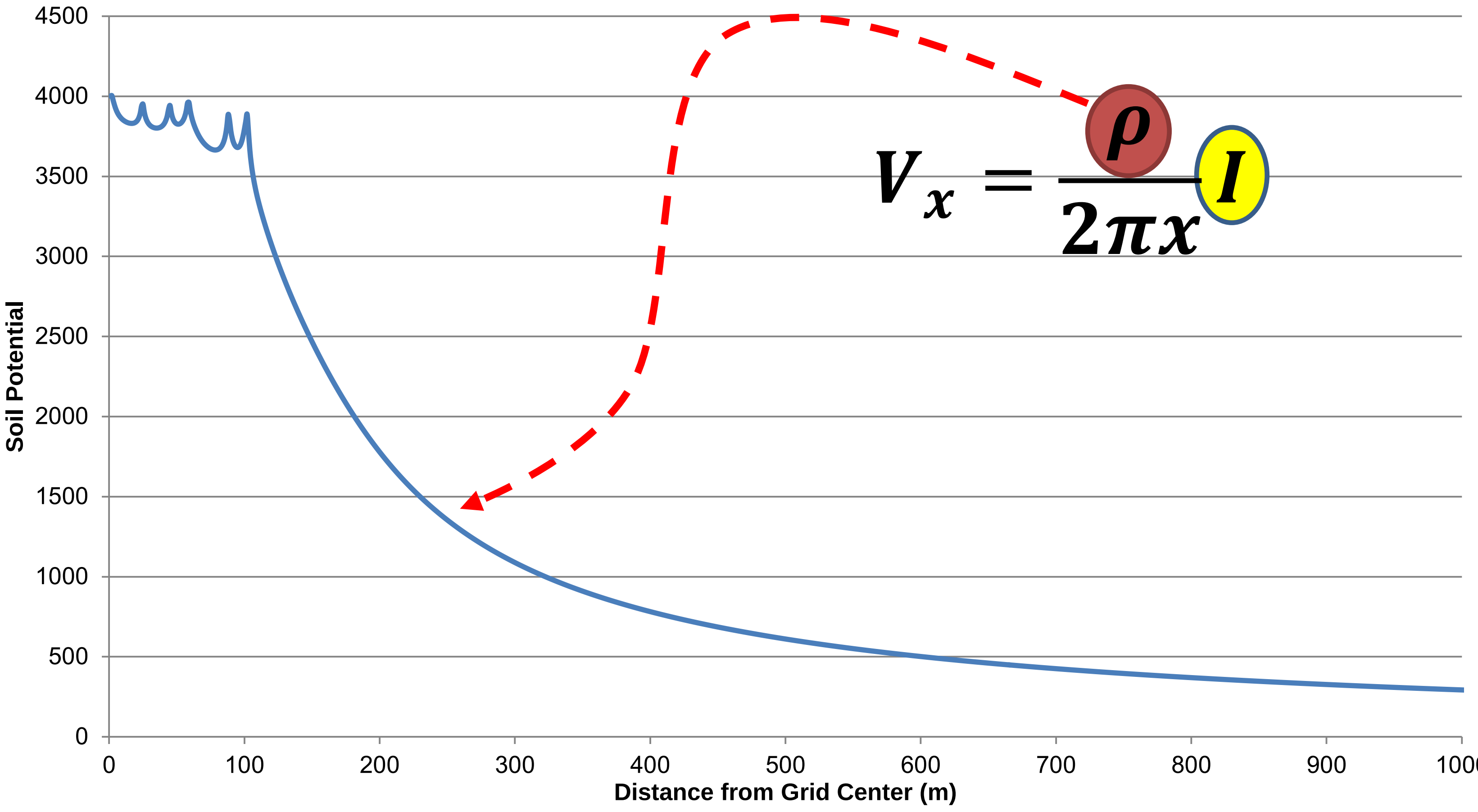
I_{TX} = Transformer Circulating Current

Zone of Influence

- IEEE Std. 367
- 300 V peak contour
- Affected telephone communication pedestals
  - Twisted pairs – Pedestal ground is ok…

IEEE 367 - Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault

Zone of Influence



Evaluating the Grounding System Performance

- Two Aspects:

When a fault happens, what is the potential rise of the grounding system (GPR) and will it be safe to touch grounded equipment (touch potential) or walk within the yard (step potential)? ➡ **Current Injection Tests (Fall of Potential)**

Are all equipment/structures properly tied to the grid with fault rated ground conductors? ➡ **Integrity Tests**

Ground Grid Performance

- Current injection Test
  - Soil Resistivity Testing
  - Ground Grid Resistance
  - Current Injection Testing
  - Step and Touch Potentials
- Integrity Tests

Ground Grid Performance

- Current Injection Test
  - **<u>Soil Resistivity Testing</u>**
  - Ground Grid Resistance
  - Current Injection Testing
  - Step and Touch Potentials
- Integrity Tests

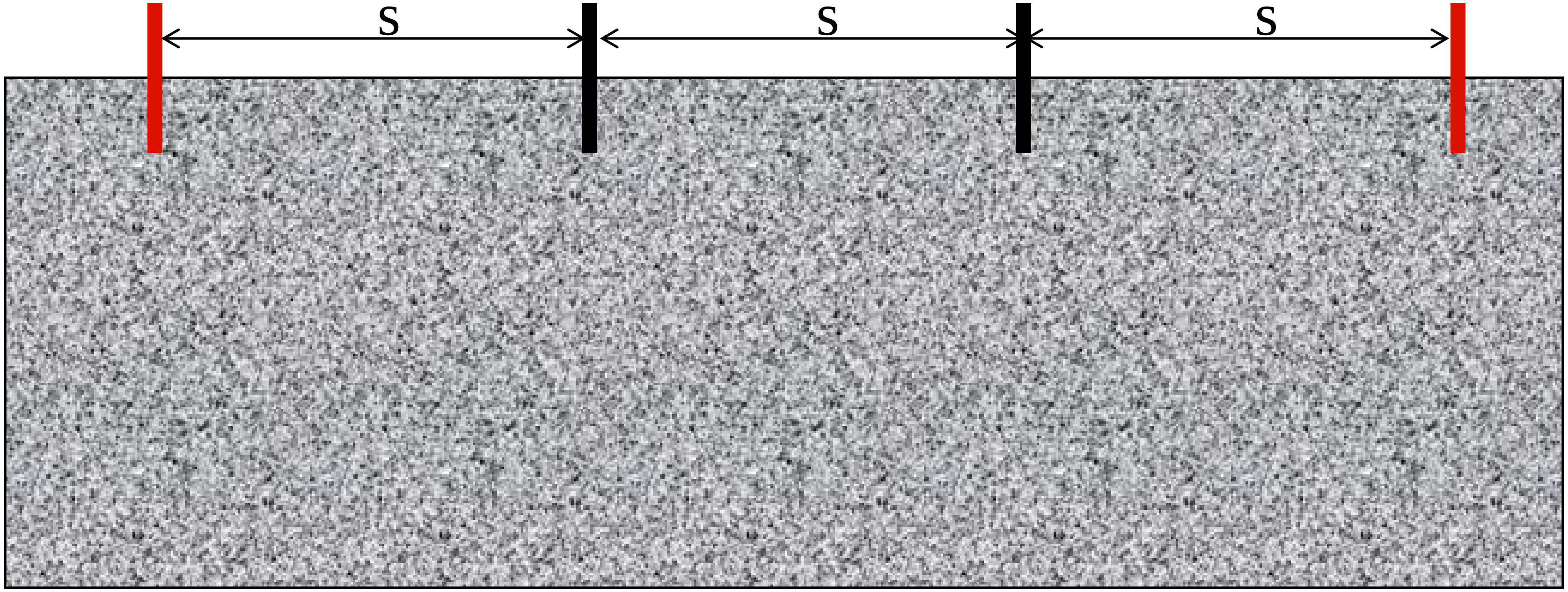
Typical Resistivity for Different Soils

Type of Earth	Average Resistivity (Ohm-m)
Wet organic soil	10
Moist soil	100
Dry soil	1,000
Bedrock	10,000

Measurement Techniques

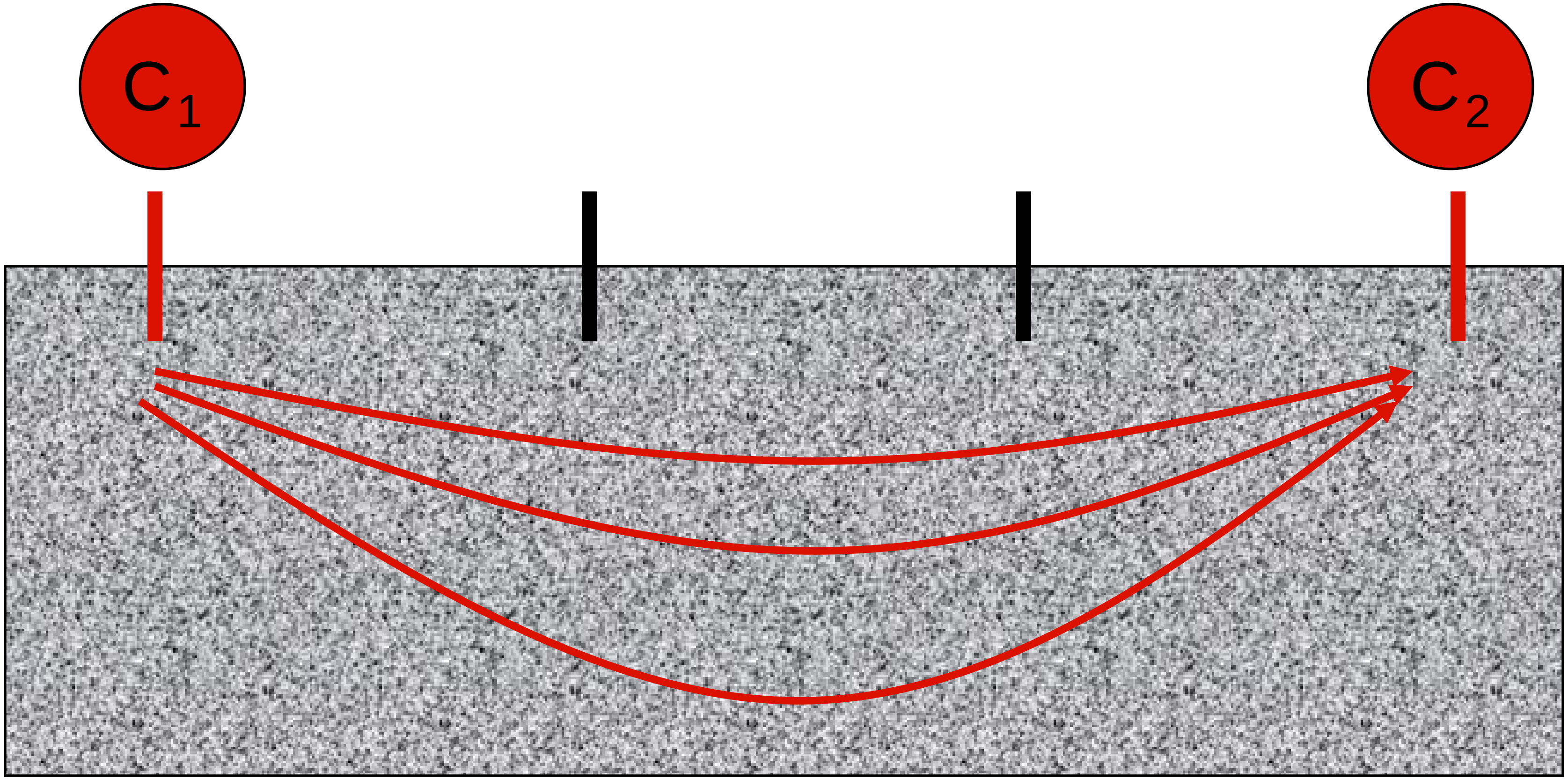
Wenner Survey Techniques

Four equally spaced probes are driven into the soil.



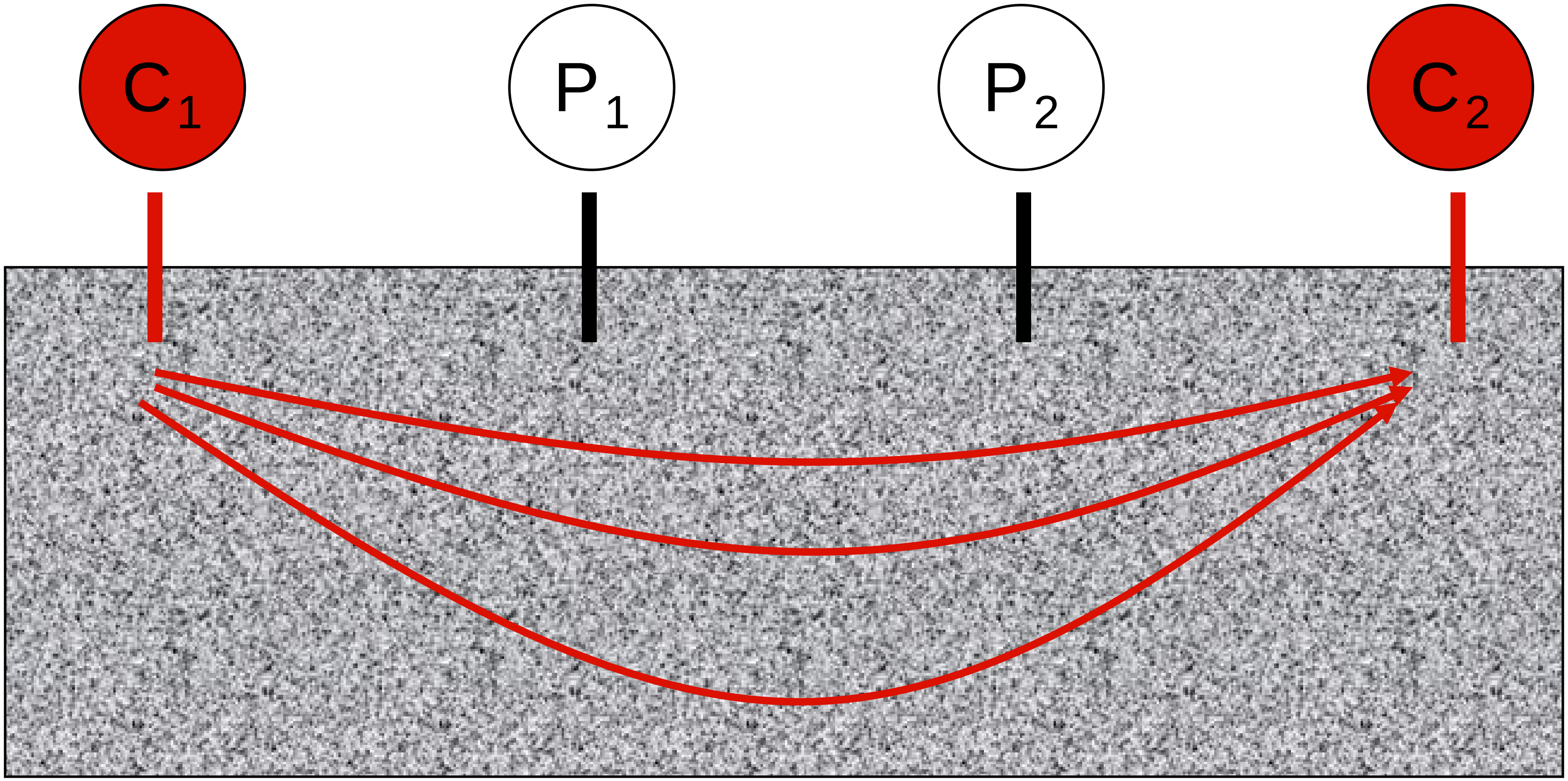
Wenner Survey Techniques

A current is injected into the outer probes.



Wenner Survey Techniques

A voltage is measured at the inner probes.



Wenner Survey Techniques

- The apparent resistivity is calculated:

$$\rho_a = \frac{\Delta V}{I} \frac{4\pi s}{1 + \frac{2s}{\sqrt{s^2 + 4{l_w}^2}} - \frac{s}{\sqrt{s^2 + {l_w}^2}}} R_m(s)$$

- l_w is the probe depth
- s is the Wenner probe spacing

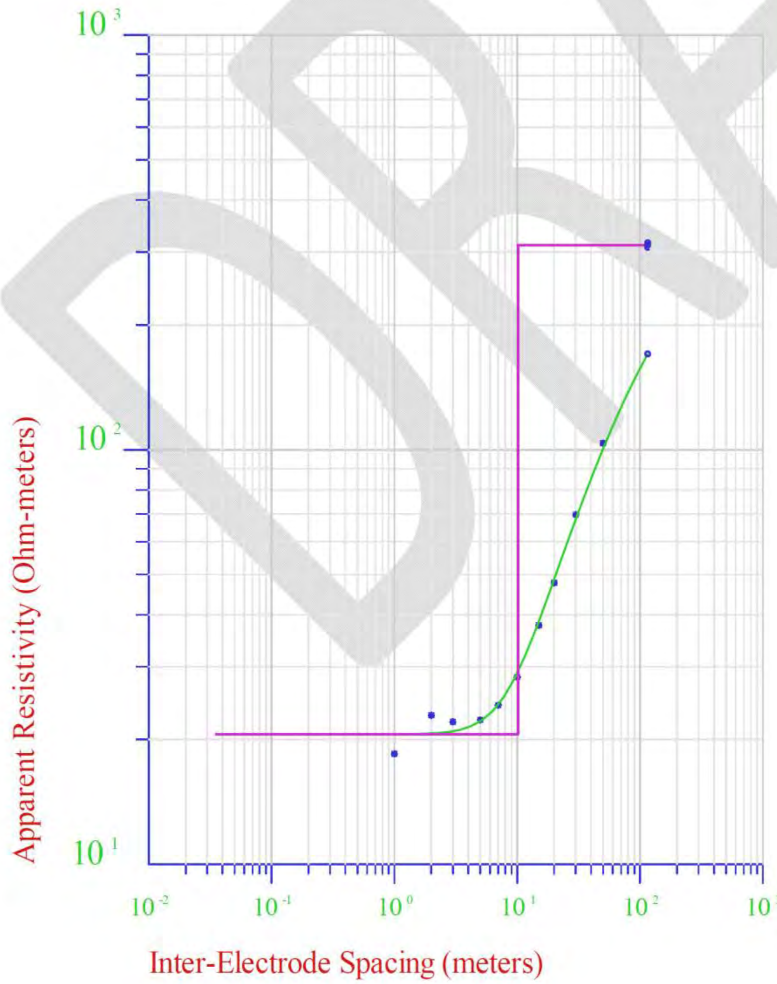
for $l_w << s$

$$\rho_a(s) = 2 \cdot \pi \cdot s \cdot R_m(s)$$

Soil Resistivity Testing

Soil Resistivity Surveys

Soil Model Interpretation – 2L



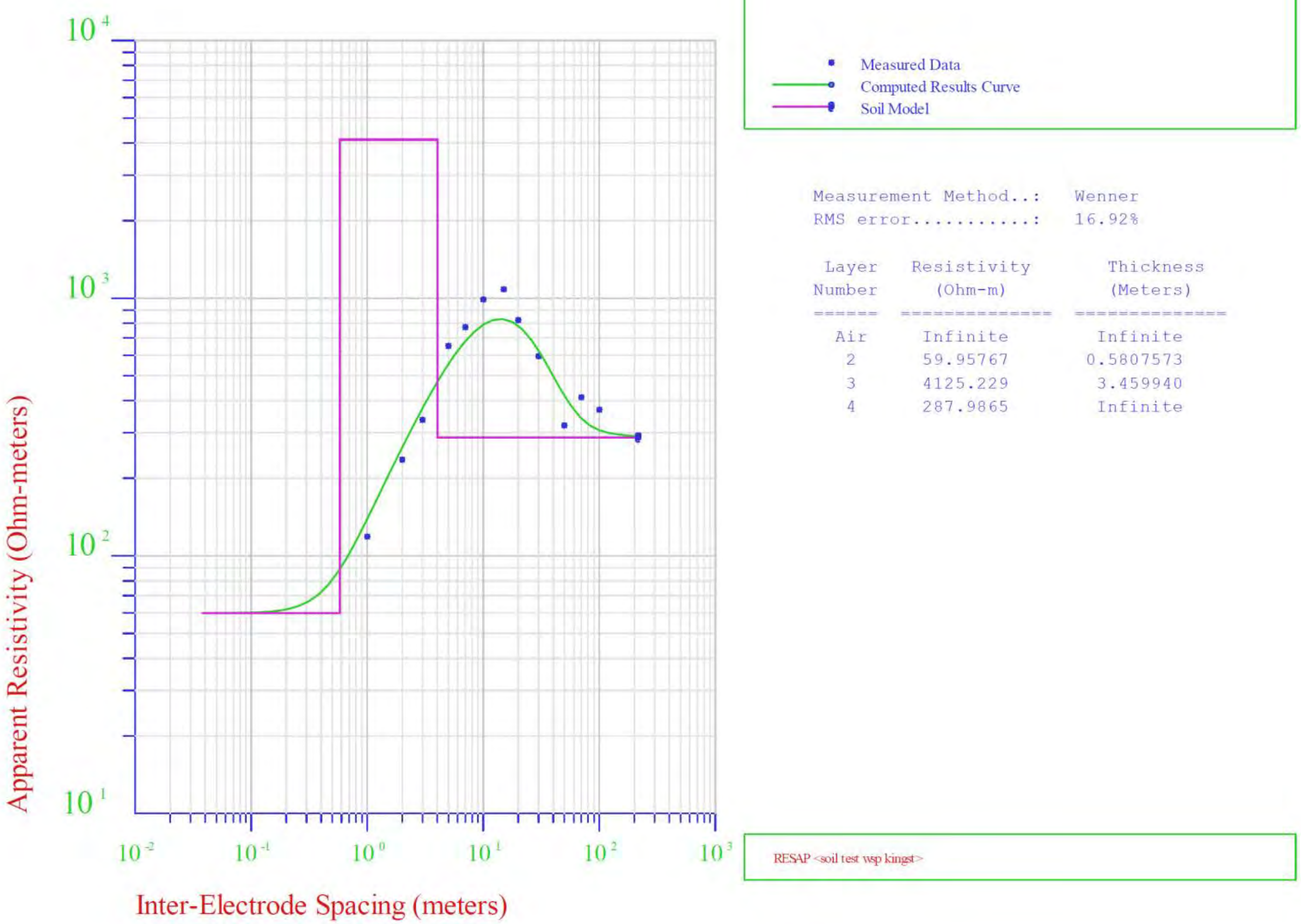
Measured Data
Computed Results Curve
Soil Model

Measurement Method..: Wenner
RMS error...........: 5.271%

Layer Number	Resistivity (Ohm-m)	Thickness (Meters)
Air	Infinite	Infinite
2	20.57695	10.13981
3	311.5842	Infinite

RESAP <Soil Bridge 11 - T1 >

Soil Model Interpretation – 3L



Measurement Method..: Wenner
RMS error...........: 16.92%

Layer Number	Resistivity (Ohm-m)	Thickness (Meters)
Air	Infinite	Infinite
2	59.95767	0.5807573
3	4125.229	3.459940
4	287.9865	Infinite

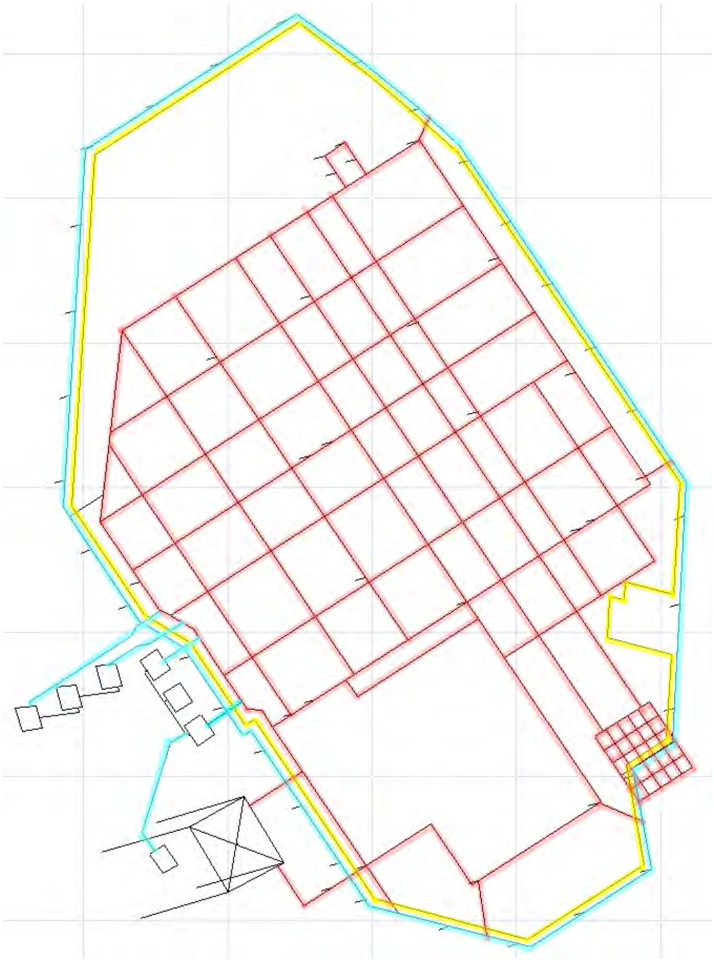
RESAP <soil test wsp kingst>

Ground Grid Performance

- Current injection Test
  - Soil Resistivity Testing
  - **Ground Grid Resistance**
  - Current Injection Testing
  - Step and Touch Potentials
- Integrity Tests

Isolated Electrodes

- No external connections
- Any injected current should return through the soil



Fall of Potential (FOP) or 3 Pin Method

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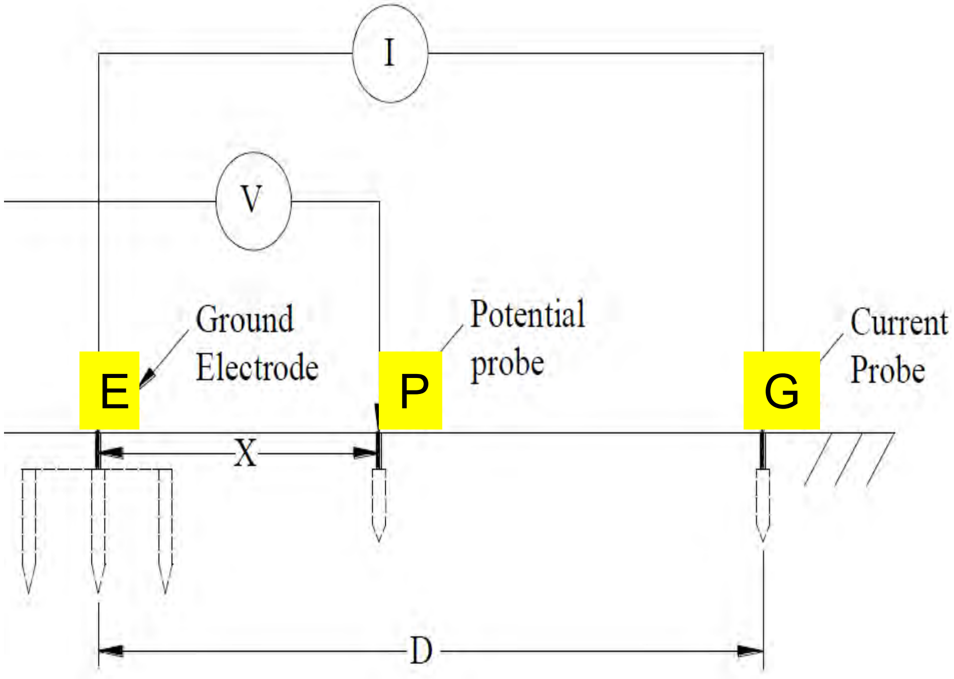
- Widely accepted method
- Isolated grid only
- Test current - 50 Hz to 3400 Hz
- Reference electrodes E and G
- P usually in the same direction as EG
- How far should EG be?



IEEE Std 81-2012

Deriving the 62% formula

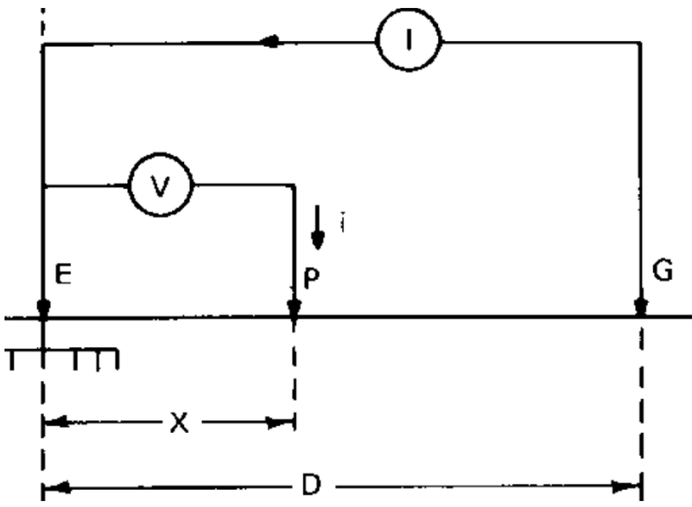
$$V_P = V_P^E \cdot (I') + V_P^G \cdot (-I')$$

$$V_E = V_E^E \cdot (I') + V_E^G \cdot (-I')$$

$$V = V_E - V_P$$

$$V = I'(V_E^E - V_E^G - V_P^E + V_P^G)$$

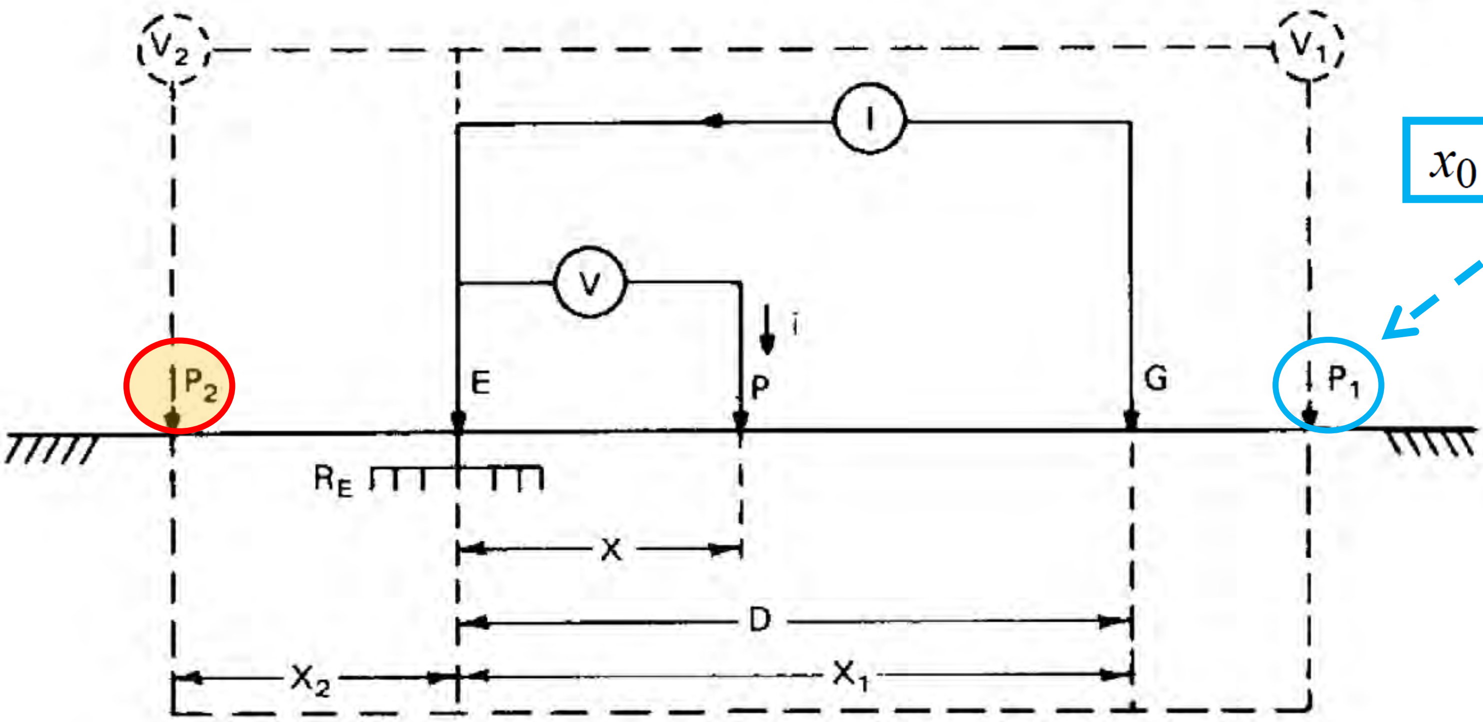
$$R = \frac{V}{I} = R_E + (V_P^G - V_E^G - V_P^E)/1\,A$$



$$1/(D - x) - 1/D - 1/x = 0$$

$$\boxed{x_0 = 0.618\,D}$$

Variations of 3-Pin FOP

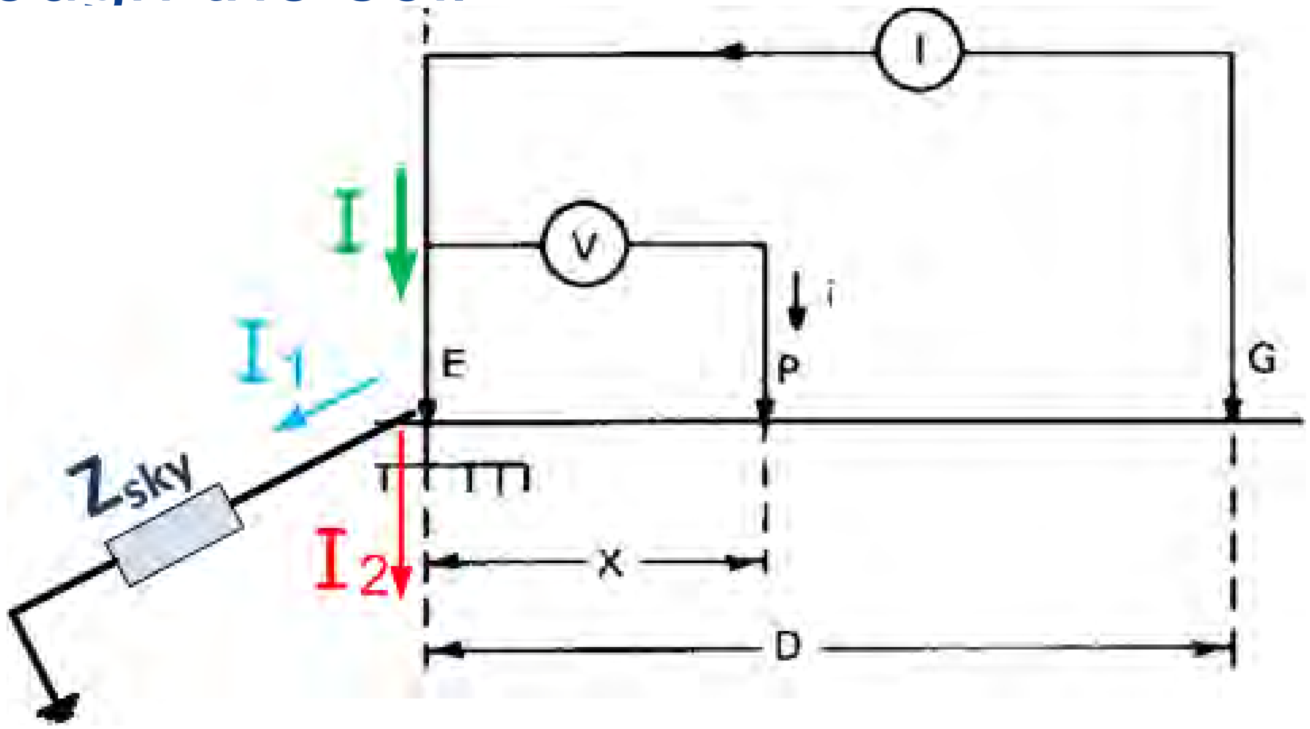


$x_0 = 1.618\ D$

Figure C.1—Fall-of-potential method

Main Assumption for the 3-Pin Test

- Entire injected current to the ground electrode returns to the injection point through the soil



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Drawbacks with the 3- Pin Test

- Not intended for grids with interconnections
- Can't measure Step and Touch voltages
- Can't measure Current Splits into external connection
- Phase angle information not recorded

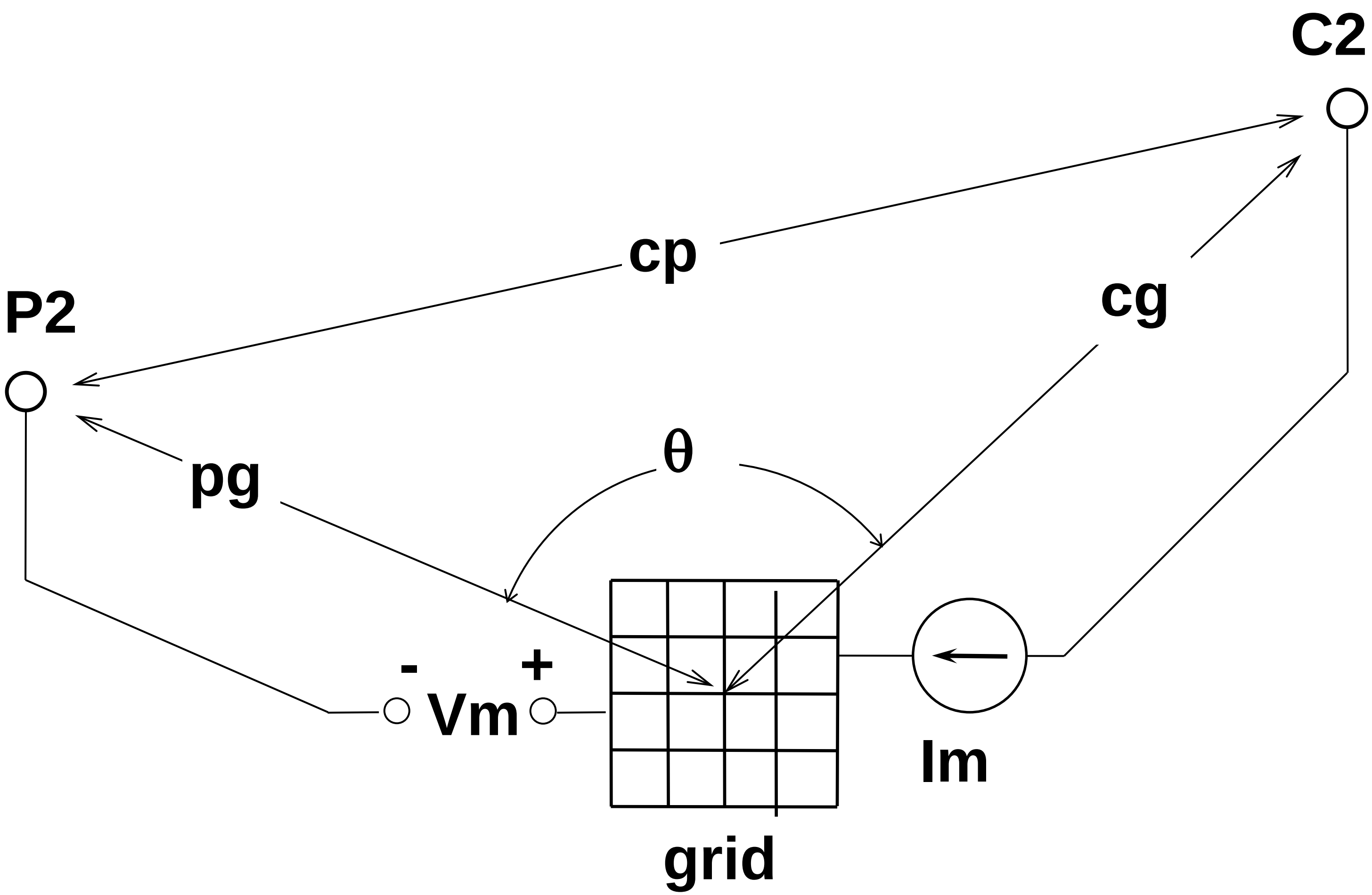
Solution?

- Current Injection Testing
- Customized off-frequency current injection
- Recording soil potential profiles (complex)
- Measuring Current Splits
- Measuring Step and Touch

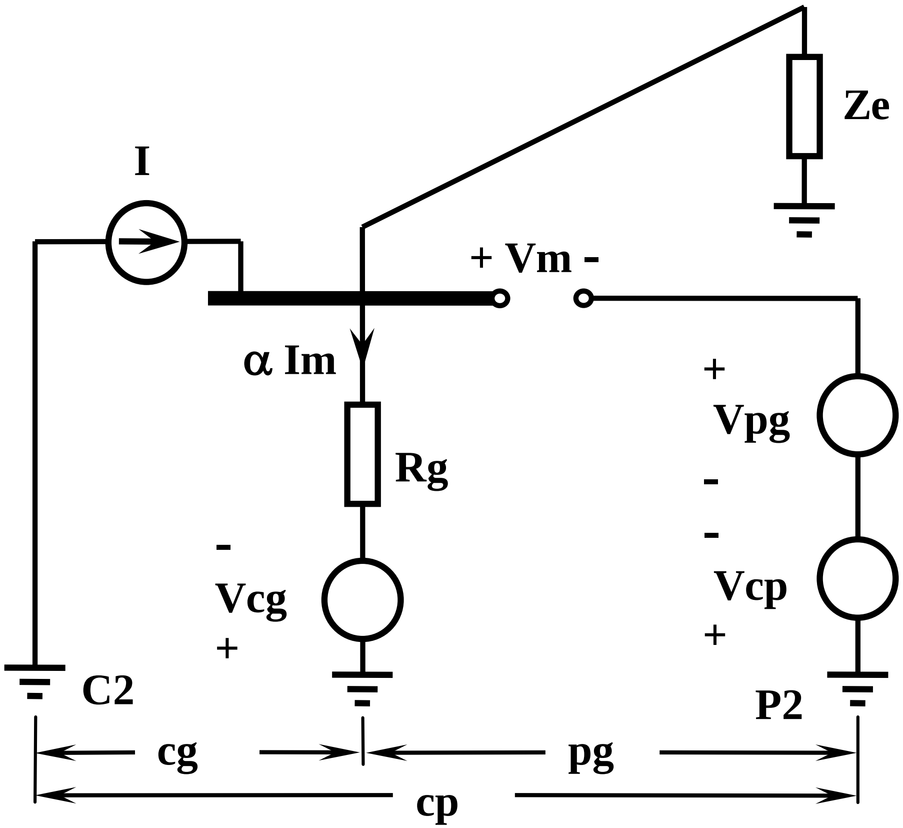
Ground Grid Performance

- Current injection Test
  - Soil Resistivity Testing
  - Ground Grid Resistance
  - **Current Injection Testing**
  - Step and Touch Potentials
- Integrity Tests

Overland Current Injection Testing



Proximity Correction

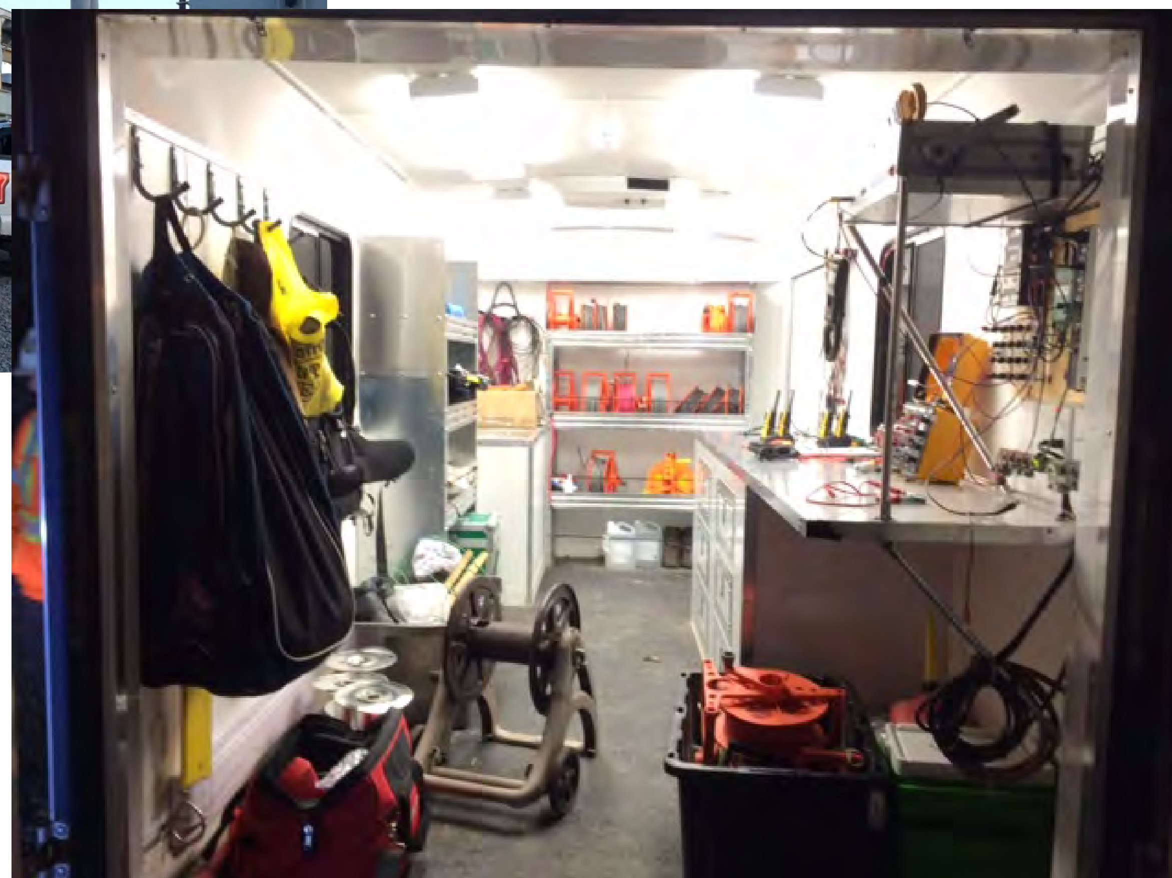


Solving for Zg needs soil resistivity info, current split test and modelling of Rg

$$Zg = Zt + Rm(cg)\frac{Ze}{Ze + Rg} + \alpha Rm(pg) - Rm(cp)$$

Test Set up…


KINECTRICS
Advanced Substation Grounding
& Transformer Testing
kinectrics.com
Liberty



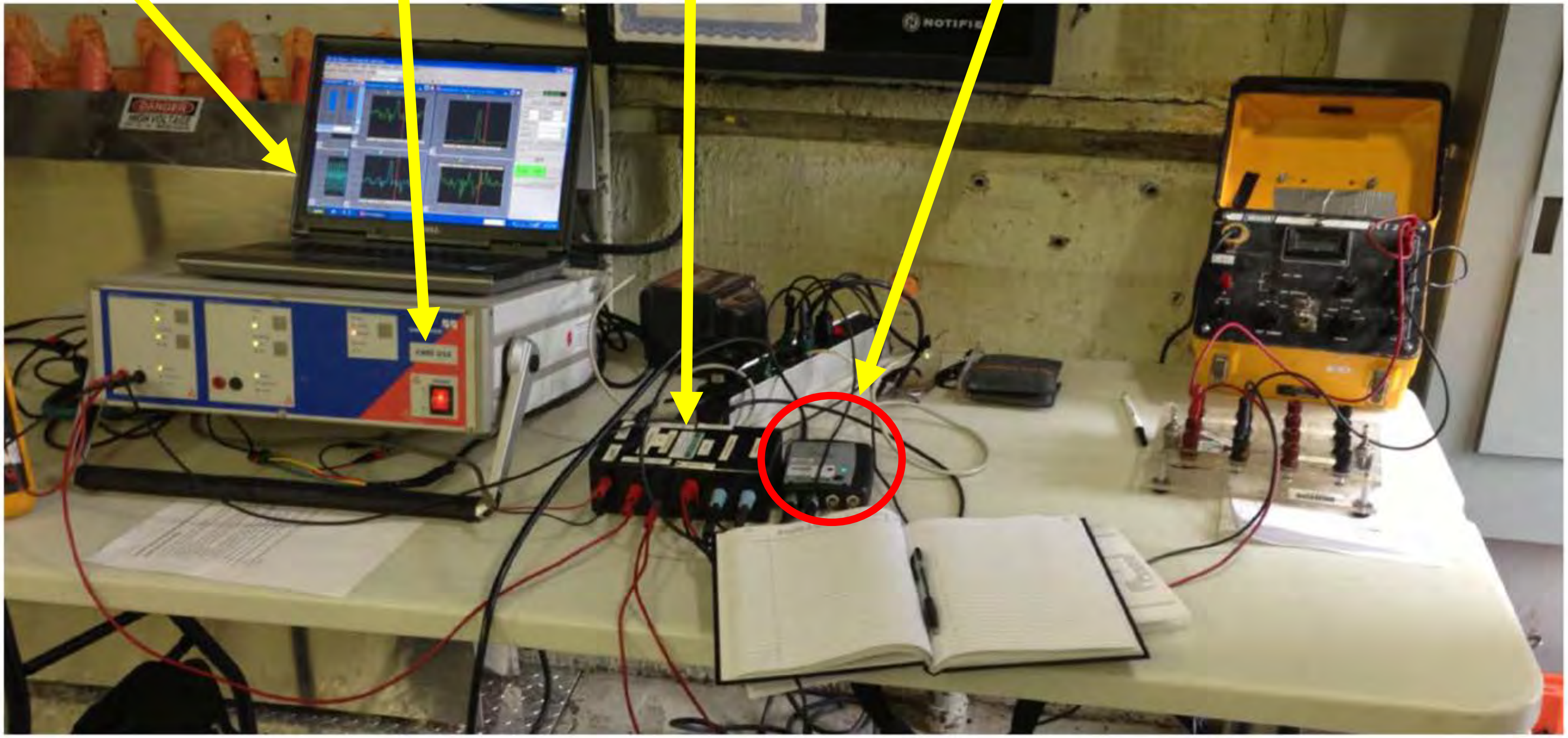
Current Injection Test Set up

Post Processing

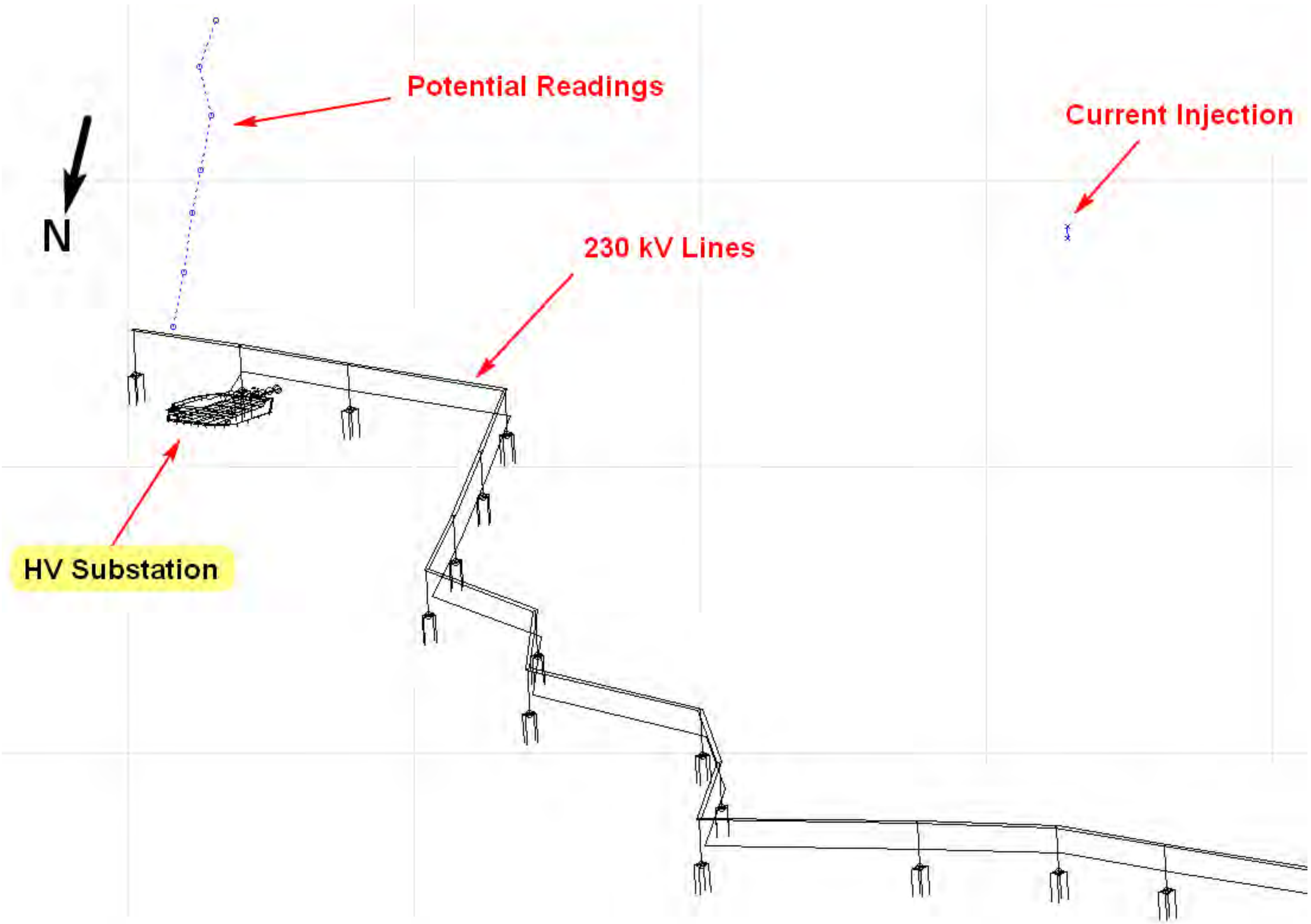
Amplifier

Protection Box

- Off-frequency Signal Generator
- 4 channel signal analyser
- Signal post-processing



How to correct for proximity?



Proximity Correction

#	Distance From P to G	Measured Impedance Readings			Modelled Impedance Readings		
		Abs	**Ph**	**Complex**	**Abs**	**Ph**	**Complex**
1	330 (m)	0.0619	53.9	0.0365+0.0500i	0.0769	35.9	0.0623+0.0451i
2	530 (m)	0.0783	43.6	0.0567+0.0540i	0.0862	36.2	0.0696+0.0509i
3	735 (m)	0.0825	42.1	0.0612+0.0553i	0.0884	37.9	0.0698+0.0543i
4	885 (m)	0.0842	40.5	0.0640+0.0547i	0.0883	39.5	0.0683+0.0561i
5	1,085 (m)	0.0855	38.1	0.0673+0.0528i	0.0875	41.6	0.0656+0.0580i
6	1,260 (m)	0.0857	39.6	0.0660+0.0546i	0.0865	43.6	0.0627+0.0596i
7	1,430 (m)	0.0861	35.0	0.0705+0.0494i	0.0859	45.0	0.0609+0.0607i
RMSE (Magnitudes) – Model vs. Measured					8.2%		

Source: Kinectrics Inc.

Ground Grid Performance

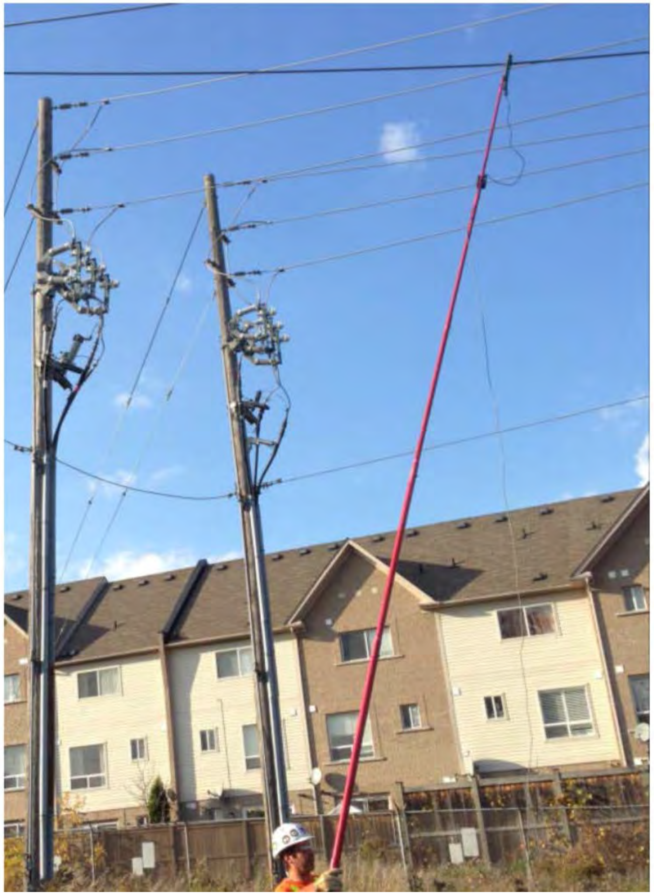
- Current injection Test
  - Soil Resistivity Testing
  - Ground Grid Resistance
  - Current Injection Testing
  - **<u>Step and Touch Potentials</u>**
- Integrity Tests

Step and Touch Potentials

Frequency
Selective
Voltmeter

Stone Tests

Current Splits



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Grounding Tests at a Generating Station

Hydroelectric Station – FOP Test Layout

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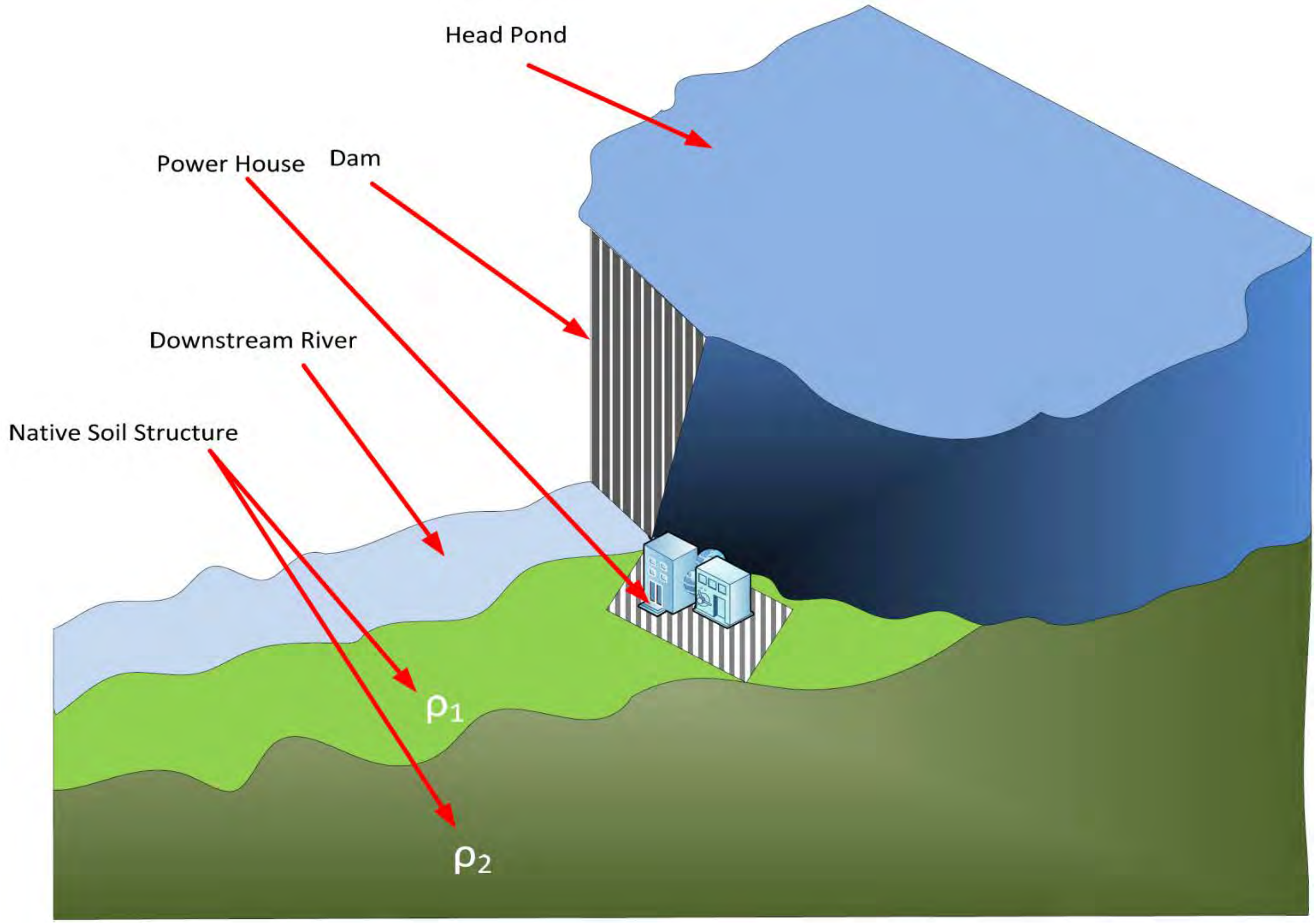
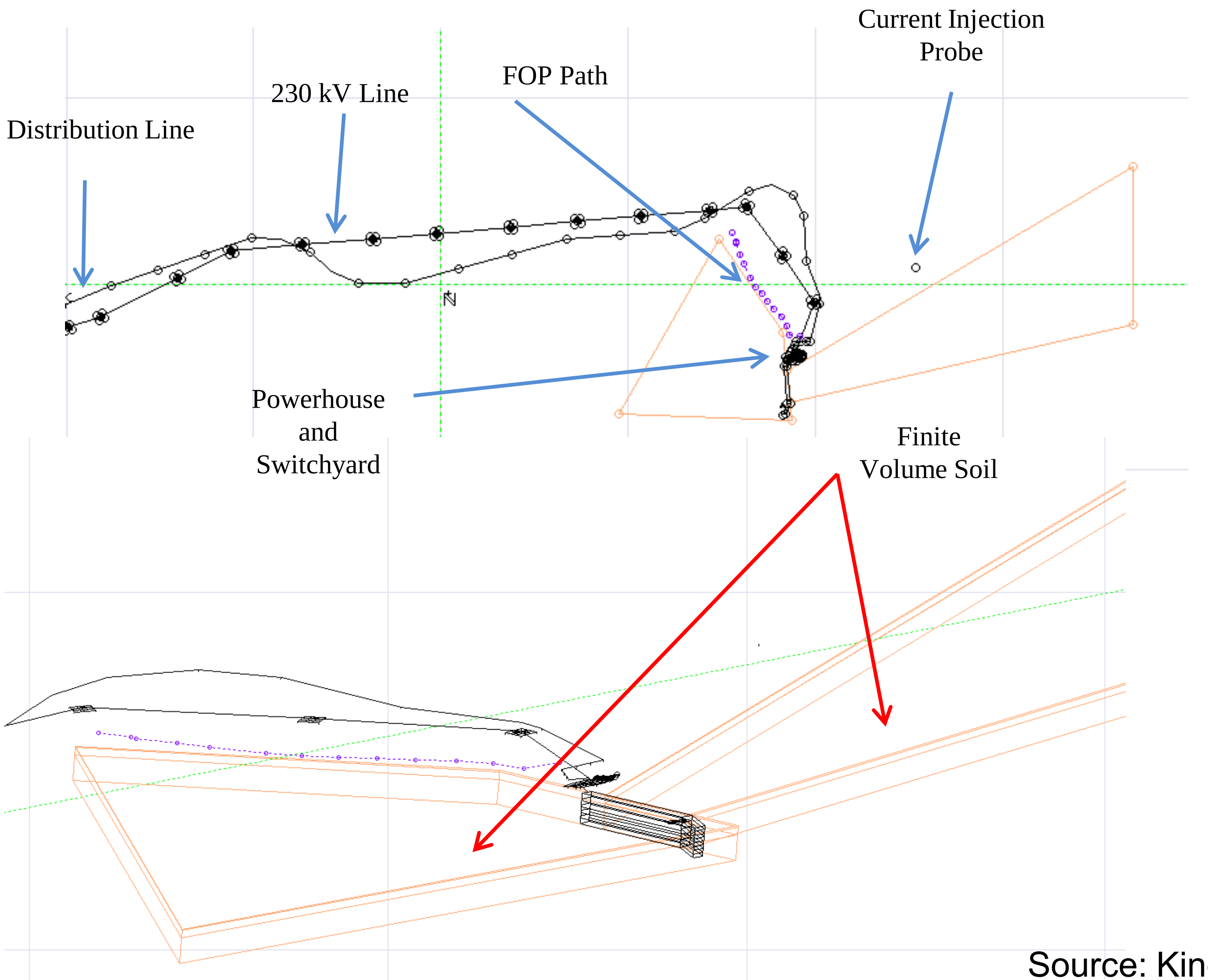
Soil Anolmolies



Building the Model – Complex Soil

KINECTRICS



Source: Kinectrics Inc.

Ground Grid Performance

- Current injection Test
  - Soil Resistivity Testing
  - Ground Grid Resistance
  - Current Injection Testing
  - Step and Touch Potentials
- **Integrity Tests**

Grid Integrity Tests - Why ?

- Check for dig ins after construction
- Test for fused conductors after heavy faults
- Measure fence interconnection / isolation
- Look for corrosion on connectors
- Confirm gradient control at gates
- Locate grid conductors

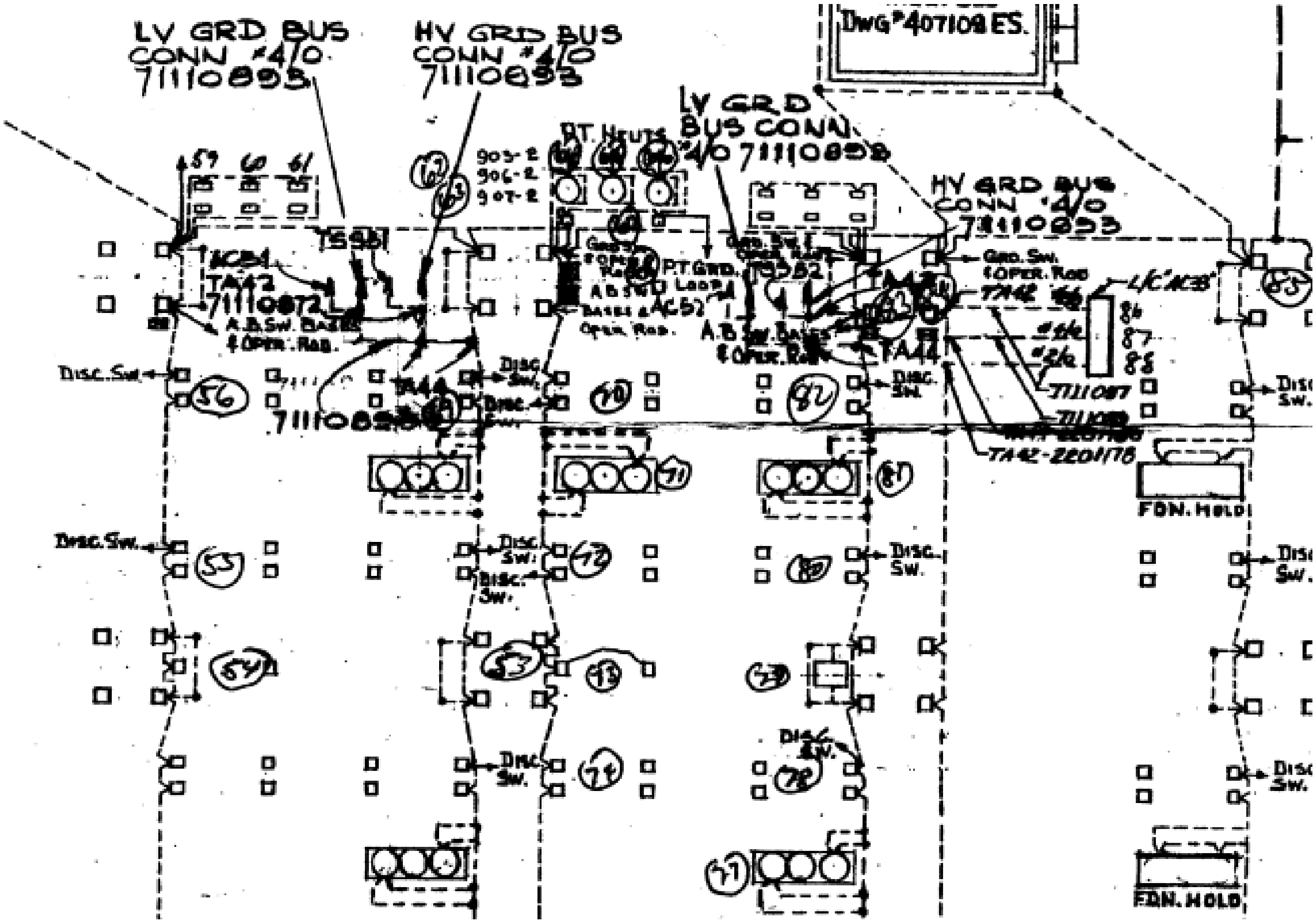
Custom Micro Ohmmeter & Leads

Battery powered (10 A) micro ohmmeter

Grid Integrity Test - How ?

- Measure R between nearby accessible loops
- Pace out distance, add vertical loop length
- Estimate P as number of parallel conductors
- Check routing of grid conductors

Grounding Print with Integrity Nodes



Record GPS coordinates of nodes

KINECTRICS

Reporting the measurements

From	To	Description	Measured Resistance (mΩ)
20	26	87-M80B GROUND MAT	1.77
20	26	87-M80B STRUCTURE	1.62
20	27	87M80BCVT B PHASE LEG	1.88
20	28	87M80BCVT W PHASE LEG	2.15
20	29	87M80BCVT R PHASE LEG	2.27
20	30	87-M7E GROUND MAT	2.28
31	30	87-M7E GROUND MAT	0.55
31	30	87-M7E GROUND MAT	0.62
31	30	87-M7E STR	0.55
31	32	M7E CVT B PHASE	1.36

Higher than Estimated Values

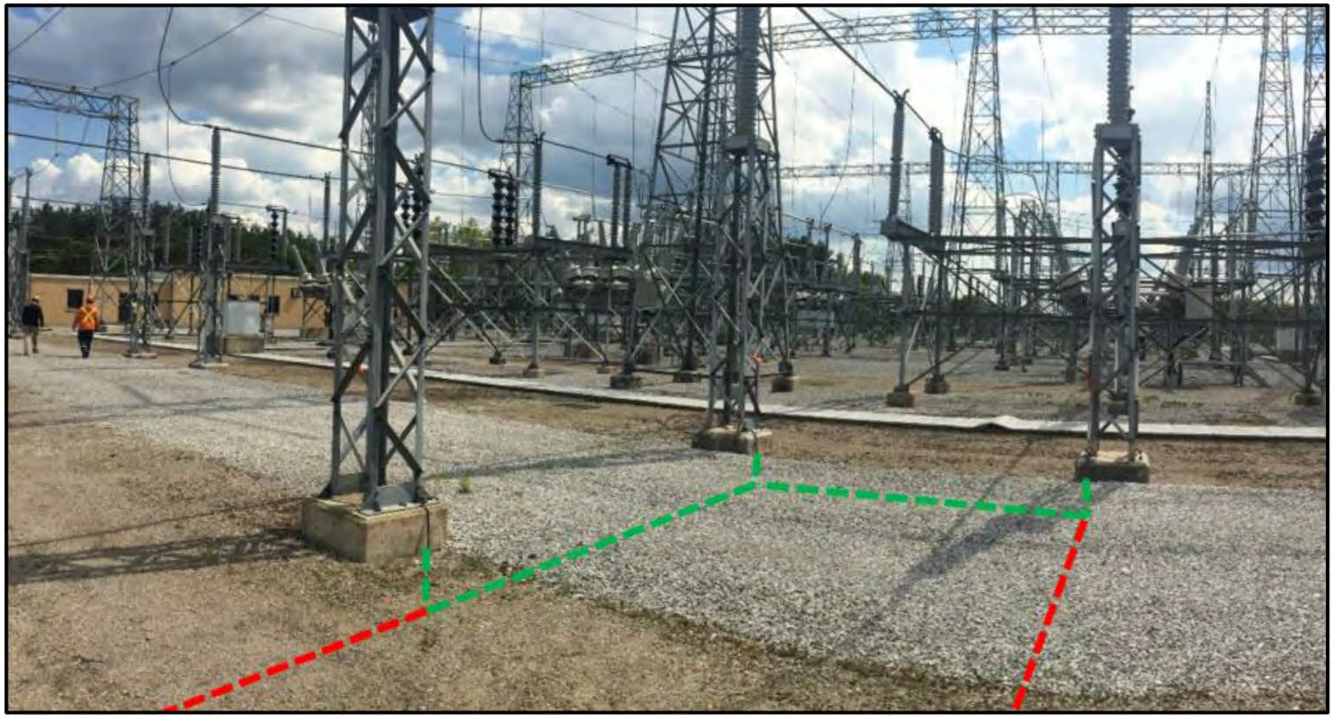


Figure 5-10: Bus Support Structures (Measured Weak Connections shown in red)

Testing Longitudinal Fence Conductor

Short Time Current Limits (kA rms)

		Fault Duration	
AWG	**mm²**	**0.5 s**	**1.2 s**
2	34	9.6	
1/0	53	15.0	
2/0	67	19.3	13.0
4/0	107	30.7	20.7
350kcm	177	50.9	34.2
500kcm	253	72.7	48.9

Tests Benefits

Integrity Tests Can Identify:	Current Injection Tests Can Identify
Bonds not rated for faults	Excessive GPR
Structures completely floating	Excessive Step Potentials inside the yard and outside on native soil
Major equipment with a single bond (no contingency)	Excessive Touch Potentials on all major equipment inside the yard and station fence
Missing bonds to equipment	Excessive transfer potential to nearby residential houses
High resistance between equipment and the ground grid, and across gates	Current Splits into external connections (such as skywires/cable concentric neutral)
Part of yard completely isolated	Coordination issues with other utilities (pipeline/gas/water)

Current Injection Using De-energized Phase Conductors

- When the grid footprint is large
- Downtown/busy residential areas with multi-grounded neutral

Solution?

- – Use grounded phase conductors as the current lead (outage required)
- – Needs more powerful equipment
- – Test fault gets injected from the actual phase conductor
- – Higher test fault → Better step and touch measurement

Current Injection Using De-energized Phase Conductors – Test Setup

900 MW combined Cycle Gas/Steam

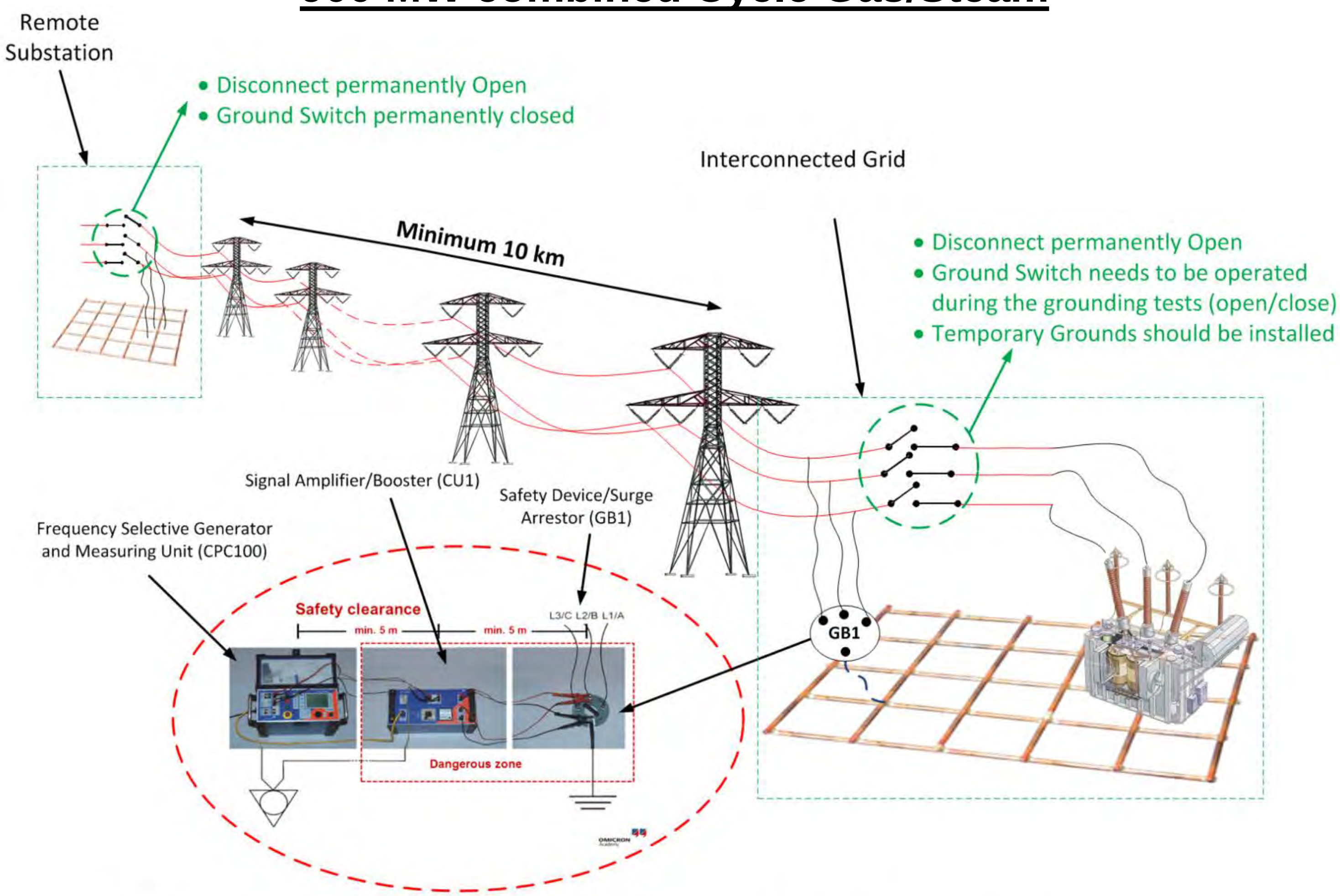


Figure 1 – Test Arrangement for Current Injection Tests Using De-energized Phase Conductors

Questions?