Ground Grid Condition Assessment

April 2023

Outline of Presentation

- Safety in Grounding
  - Basic Problem
  - Conditions of Danger
- Accidental Ground Circuit
  - Example Shock Situations
  - Resistance of the Human Body
- Range of Tolerable Body Current
  - Effect of frequency, magnitude, and duration
- Allowable Step and Touch Voltages
  - Impacts of Surface Layer
- Design Considerations for Substation Grounding
- Evaluation of Substation Grounding System
  - Grounding Studies
  - Initial Measurements
- Substation Ground Grid Degradation
- Present Day Testing Practices for Ground Grid Condition Assessment
- Future Testing Practices for Ground Grid Condition Assessment

Safety in Grounding

Safety in Grounding

The Basic Problem

- Substation grounding is performed to achieve two primary objectives:
  - Provide a path to ground for current during normal and faulted conditions in a manner to protect substation equipment from damage.
  - Protect any person within or in the vicinity of the substation from critical electric shock.
- Typical grounding systems in a substation include buried conductors connected in such a way to control the voltages that occur when a current flows to ground either intentionally or unintentionally.
  - Since most of the grounding system may be beneath the ground, it can be difficult to know the location and integrity of the ground grid even while on site.
- Grounding system design is critical to always ensure the safety of personnel within or near a substation.
  - Each substation can have unique characteristics or challenges which gives careful grounding design a critical role in ensuring safety.

Safety in Grounding

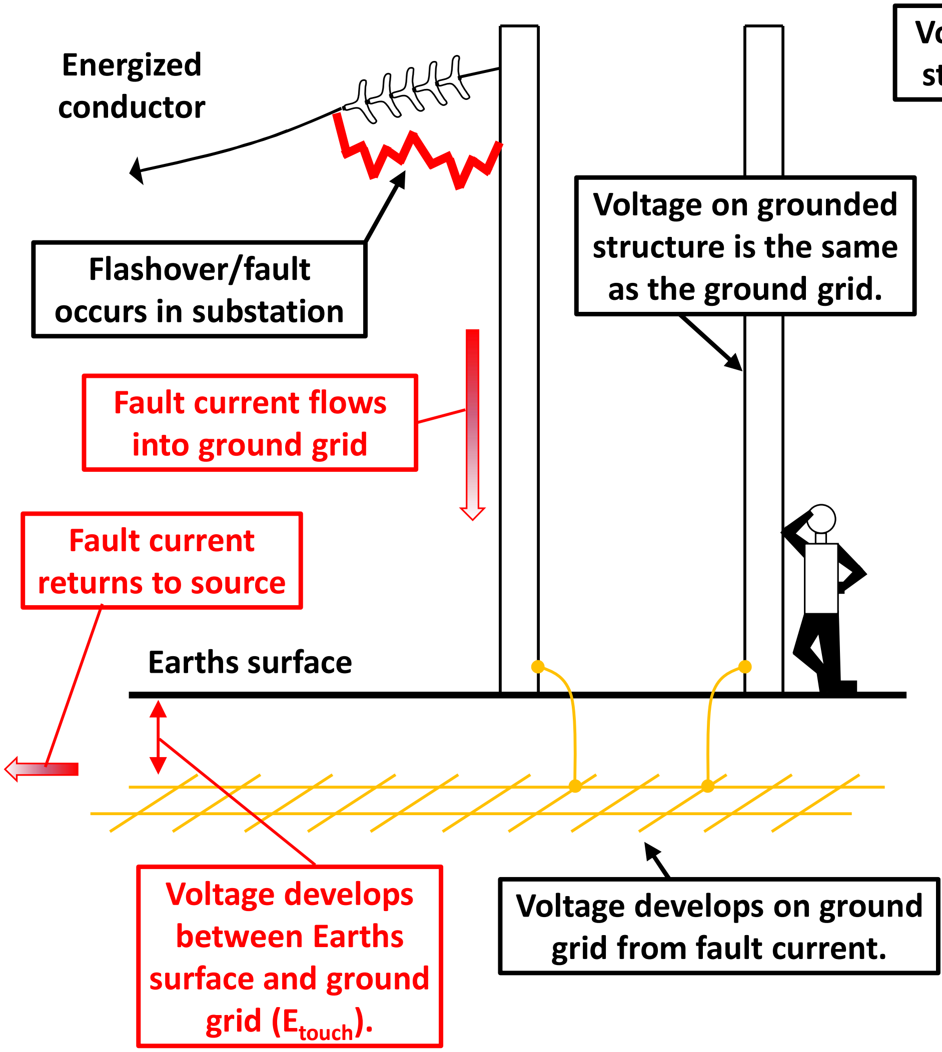
Conditions of Danger

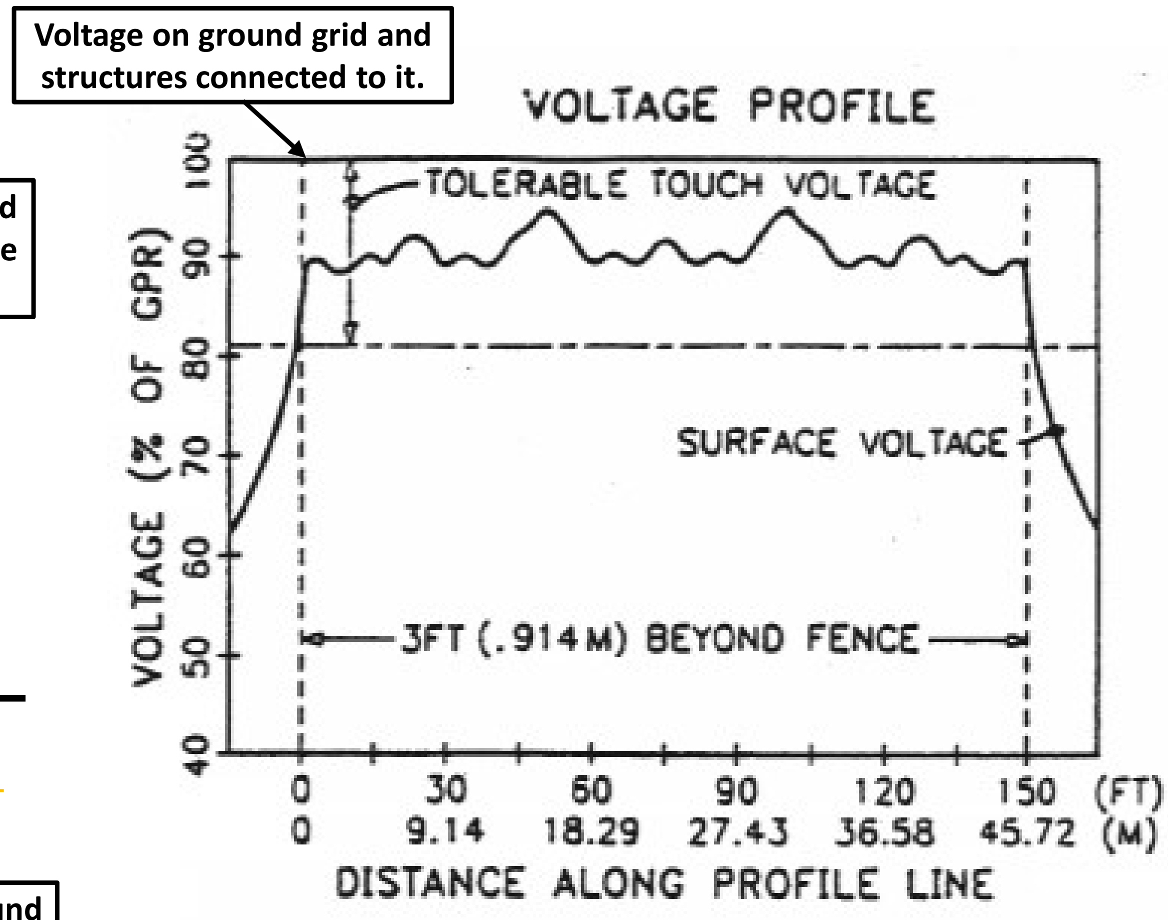
- When a fault occurs the current flowing into the ground will produce potential gradients at and near the substation. Without a proper grounding system in place these potential gradients can be high enough to result in unsafe conditions (i.e., potential shock situations).
- The level of concern for potential shock situations is dependent on each substation location and is impacted by several things such as:
  - Magnitude of the fault current and the clearing time of protective devices
  - Soil characteristics and the presence of a surface layer such as gravel
  - PPE such as gloves, boots, dielectric overshoes, etc.
  - Location of a person with respect to the grounding system at the time a fault occurs
- It is important to note that the probability of occurrence of an electrical shock from such an event (i.e. a fault in the substation while someone is inside) is low given the low probability of occurrence, however, the consequences could be severe without an adequate grounding system.

Accidental Ground Circuit

Illustration of a Fault Leading to Step & Touch Potentials

Ground Potential Rise (GPR) Caused by a Fault

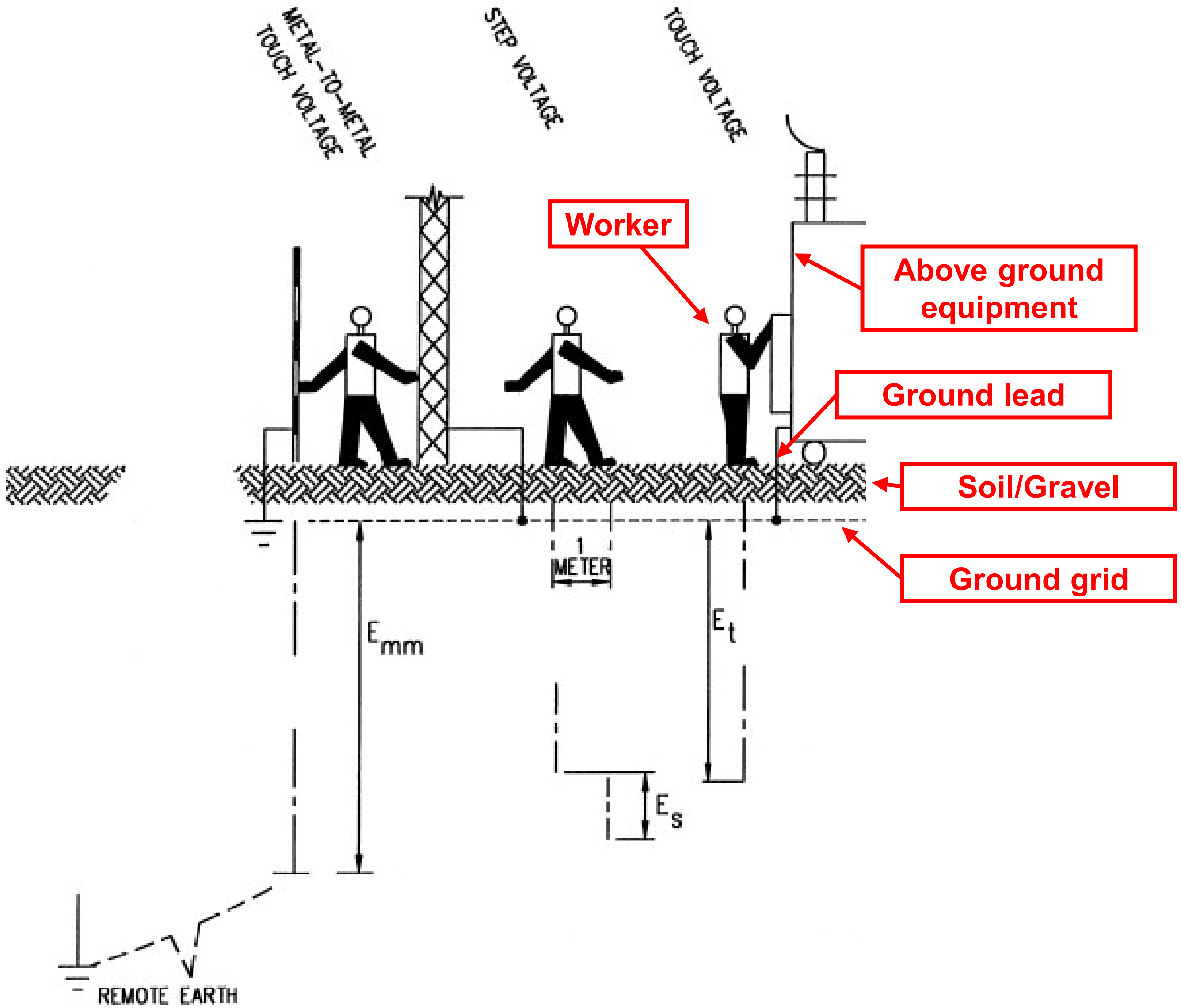




Example plot from IEEE Std 80-2000

Example Shock Situations

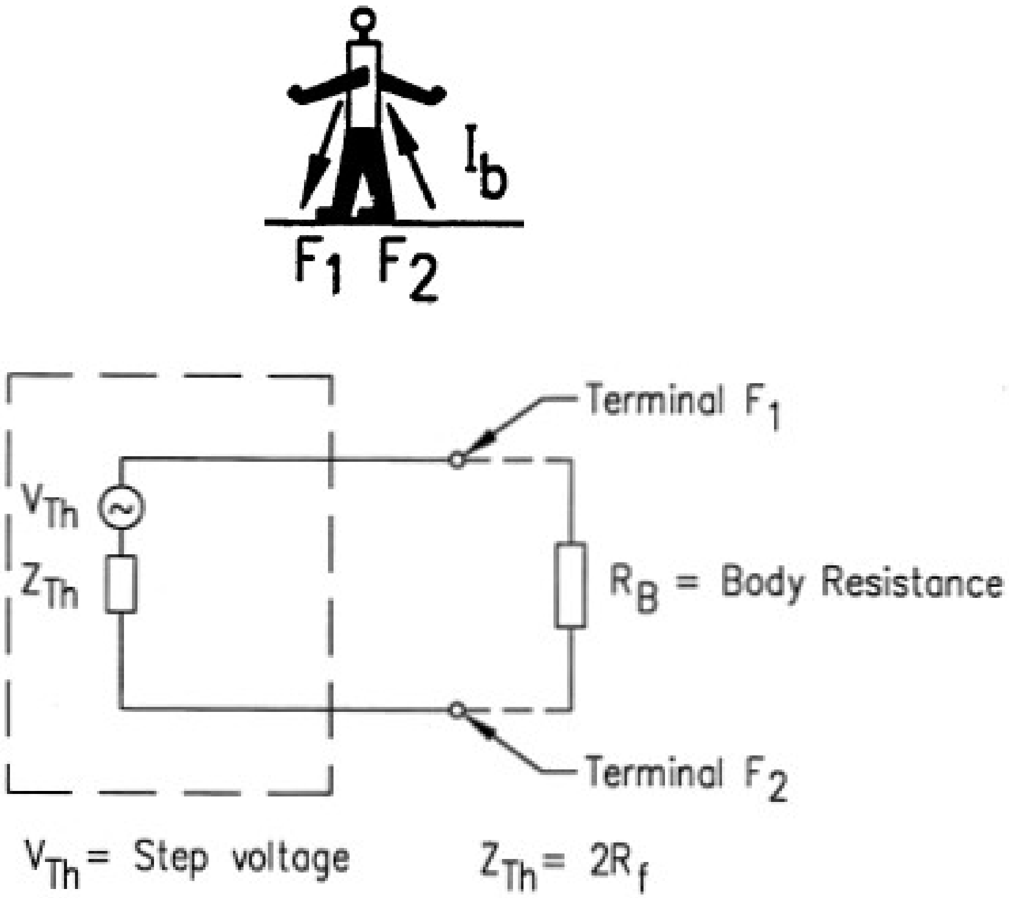
Reference: IEEE Std 80-2000 “IEEE Guide for Safety in AC Substation Grounding”



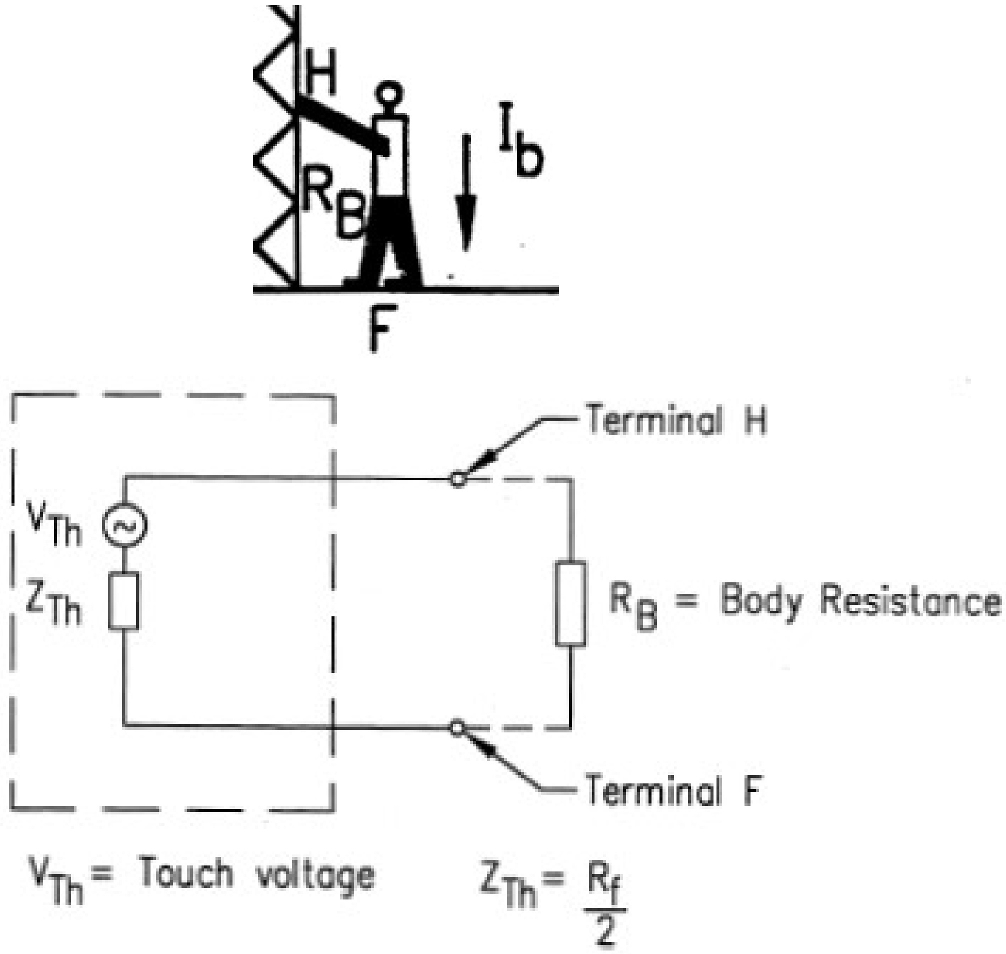
Electrical Circuit from Step & Touch Voltage

Reference: IEEE Std 80-2000 “IEEE Guide for Safety in AC Substation Grounding”

Step Voltage



Touch Voltage



Resistance of the Human Body

Reference: IEEE Std 80-2000 “IEEE Guide for Safety in AC Substation Grounding”

IEEE Std 80-2000 states the following:

“For dc and 50 Hz or 60 Hz ac currents, the human body can be approximated by a resistance. The current path typically considered is from one hand to both feet, or from one foot to the other one. The internal resistance of the body is approximately 300 Ω, whereas values of body resistance including skin range from 500 Ω to 3000 Ω….”

“It should be remembered that the choice of a 1000 Ω resistance value relates to paths such as those between the hand and one foot or both feet, where a major part of the current passes through parts of the body containing vital organs, including the heart. It is generally agreed that current flowing from one foot to the other is far less dangerous..”

It is common industry practice to assume a body resistance of 1000 Ω for calculations of tolerable step and touch voltages.

Range of Tolerable Body Current

Impact of Frequency, Magnitude, and Duration

“Humans are very vulnerable to the effects of electric current at frequencies of 50 Hz or 60 Hz. Currents of approximately 0.1 A can be lethal. Research indicates that the human body can tolerate a slightly higher 25 Hz current and approximately five times higher direct current. At frequencies of 3000–10,000 Hz, even higher currents can be tolerated…”

“The most common physiological effects of electric current on the body, stated in order of increasing current magnitude, are threshold perception, muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage, and burning….”

“Current of 1 mA is generally recognized as the threshold of perception....”

“Currents of 1–6 mA, often termed let-go currents, though unpleasant to sustain, generally do not impair the ability of a person holding an energized object to control his muscles and release it….”

“In the 9–25 mA range, currents may be painful and can make it difficult or impossible to release energized objects grasped by the hand….”

“It is not until current magnitudes in the range of 60–100 mA are reached that ventricular fibrillation, stoppage of the heart, or inhibition of respiration might occur and cause injury or death….”

Range of Tolerable Body Current

Reference: IEEE Std 80-2000 "IEEE Guide for Safety in AC Substation Grounding"

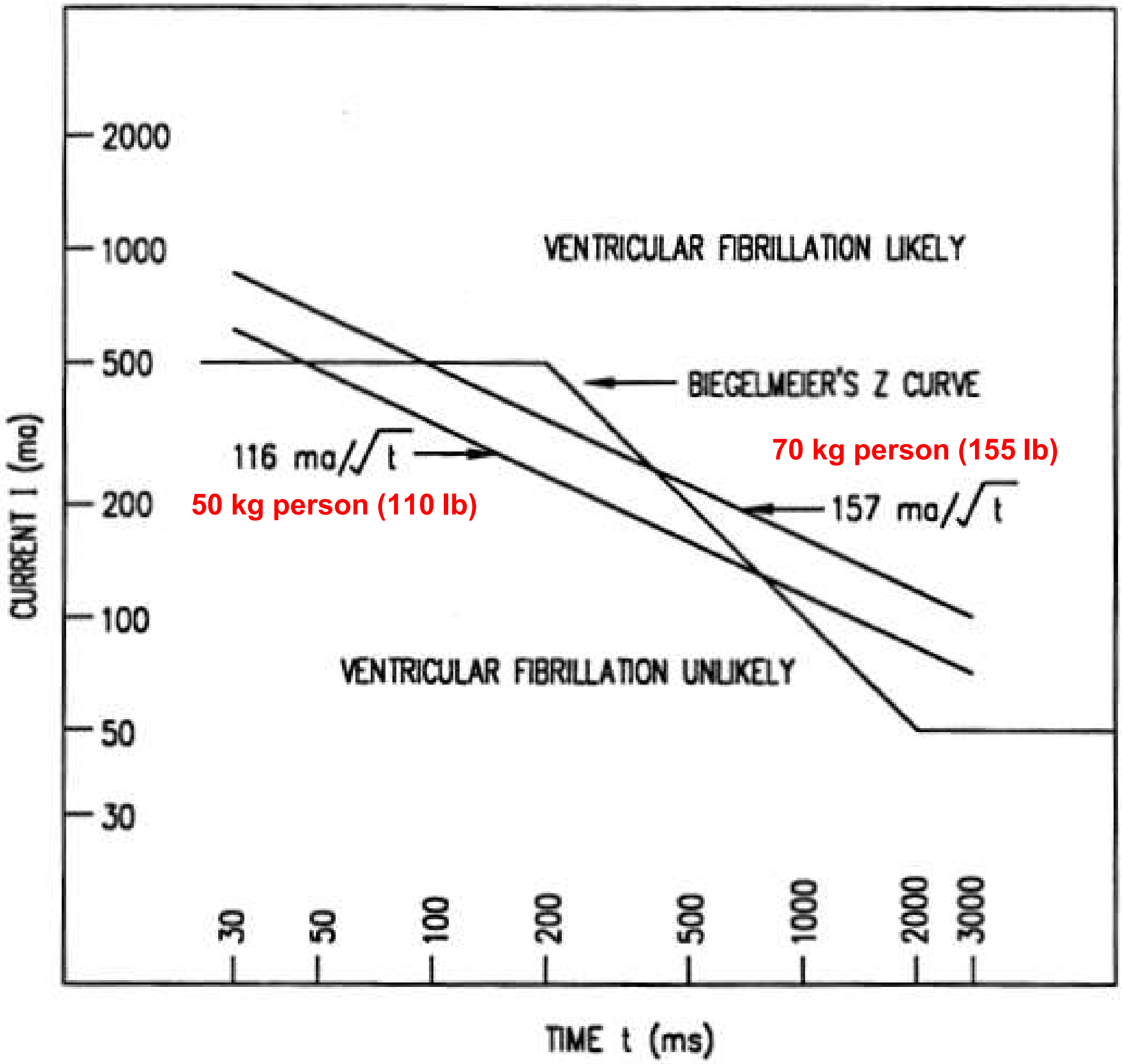


Figure 5—Body current versus time

Allowable Step and Touch Voltages

Calculation of Safe Step & Touch Voltage Limits

- Step Voltage Limit

$$E_{step} = (1000 + 6 \cdot C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}}$$

- Touch Voltage Limit

$$E_{touch} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}}$$

Where

- *t_s is the duration of the fault (s)*
- *ρ is the resistivity of the soil (Ω-m)*
- *ρ_s is the resistivity of the surface layer (Ω-m)*
- *h_s is the thickness of the surface layer (m)*
- *Note that C_s can be approximated as follows:*

$$C_s = 1 - \frac{0.09(1 - \rho/\rho_s)}{2h_s + 0.09}$$

Soil characteristics at the substation as well as duration of the fault (determined by protection settings) determine the safe levels of step and touch voltages.

Calculated Step Voltage Limit for Various Surface Layers

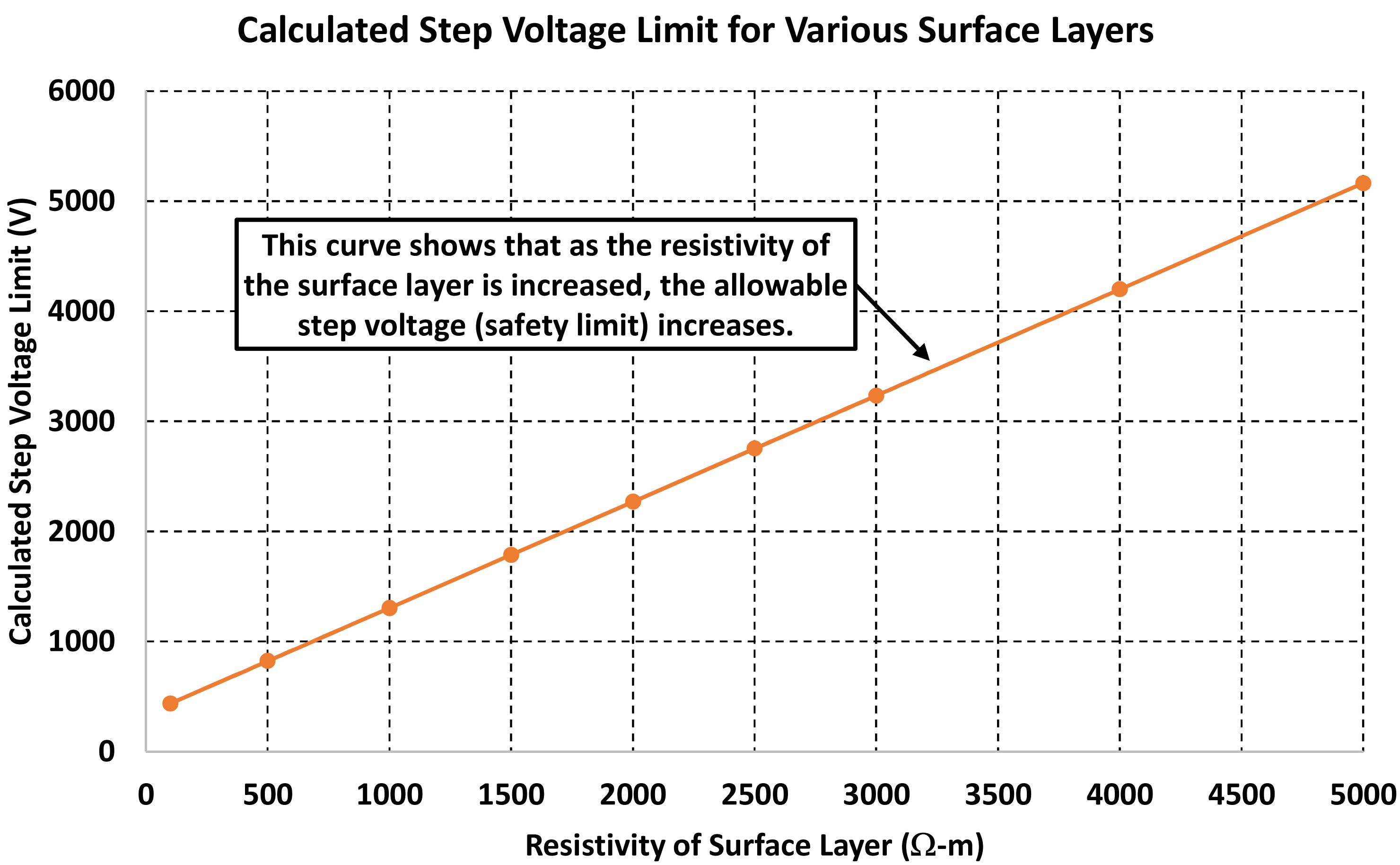


Table 7—Typical surface material resistivities

Number	Description of surface material (U.S. state where found)	Resistivity of sample Ω·m	
		Dry	Wet
1	Crusher run granite with fines (N.C.)	140×10^6	1300 (ground water, 45 Ω·m)
2	1.5 in (0.04 m) crusher run granite (Ga.) with fines	4000	1200 (rain water, 100 W)
3	0.75–1 in (0.02–0.025 m) granite (Calif.) with fines	—	6513 (10 min after 45 Ω·m water drained)
4	#4 (1 -2 in) (0.025-0.05 m) washed granite (Ga.)	1.5×10^6 to 4.5×10^6	5000 (rain water, 100 Ω·m)
5	#3 (2–4 in) (0.05-0.1 m) washed granite (Ga.)	2.6×10^6 to 3×10^6	10 000 (Rain water, 100 Ω·m)
6	Size unknown, washed limestone (Mich.)	7×10^6	2000–3000 (ground water, 45 Ω·m)
7	Washed granite, similar to 0.75 in (0.02 m) gravel	2×10^6	10 000
8	Washed granite, similar to pea gravel	40×10^6	5000
9	#57 (0.75 in) (0.02 m) washed granite (N.C.)	190×10^6	8000 (ground water, 45 Ω·m)
10	Asphalt	2×10^6 to 30×10^6	10 000 to 6×10^6
11	Concrete	1×10^6 to 1×10^9 [a]	21 to 100

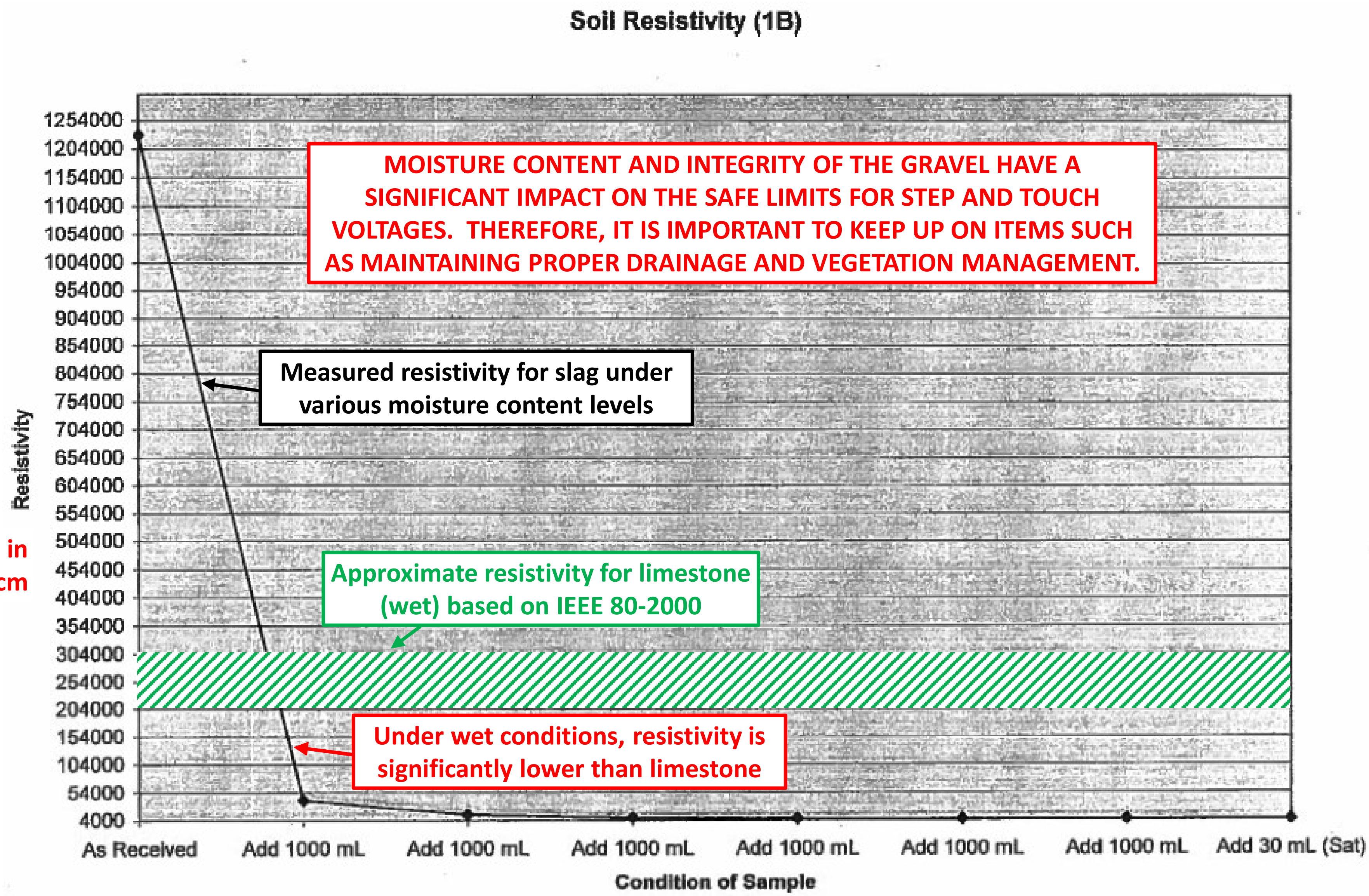
[a]Oven dried concrete (Hammond and Robson [B78]). Values for air-cured concrete can be much lower due to moisture content.

Commonly used surface material for DLC substations (present standard is to use limestone [2500 Ω-m])

In the past, slag has been used by some as a surface layer because of its absorption ability. The resistivity of slag is not listed in IEEE 80-2000. The following slide shows results for testing on slag performed by DLC.

Testing Performed for Slag

Units in Ω-cm



Design Considerations for Substation Grounding

Design Considerations for Substation Grounding

When designing a substation grounding system, the design is often developed to maintain step and touch voltages below the limit of fibrillation.

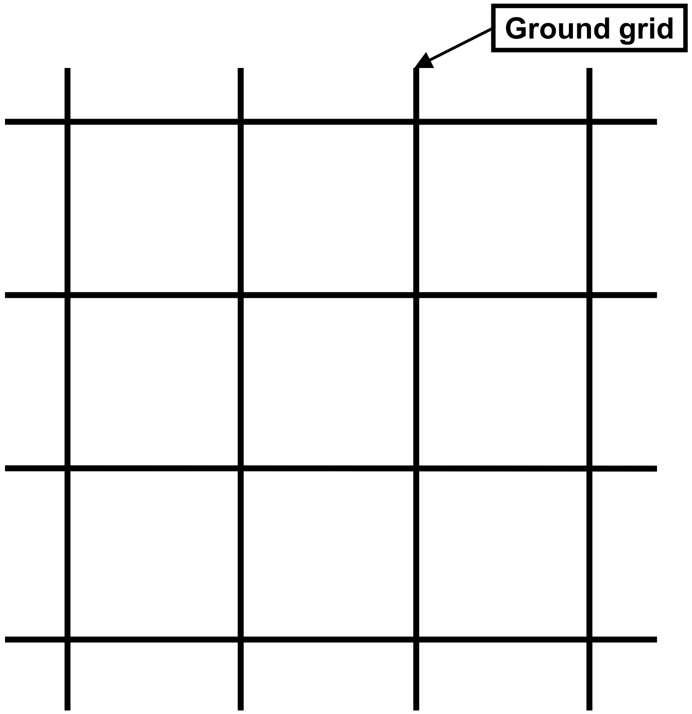
The basic construction of the substation grounding system usually includes:

- Continuous loop of conductor surrounding the perimeter of the substation
- Grid/mesh of conductors within the loop buried 12-18” below grade
- Ground rods installed around the perimeter and within the loop
- Ground leads connecting metallic structures to the ground grid
- Certain substations where high unfavorable soil conditions exist may use ground wells or other ground enhancing material

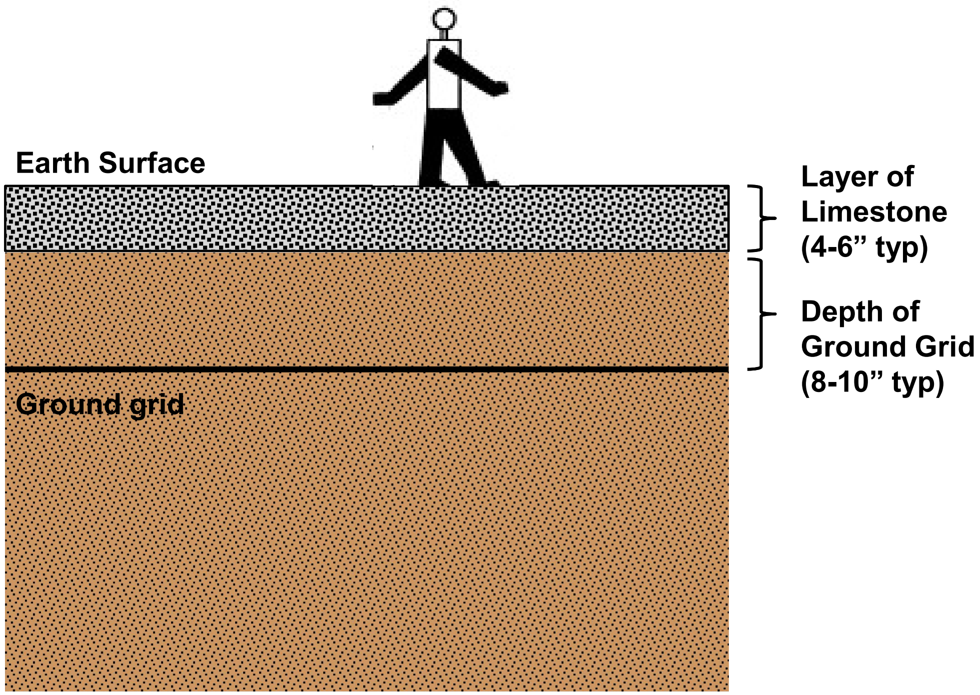
High Level Overview of Duquesne Light Practices

Preferred Method for New Substations

Top View of Substation Ground



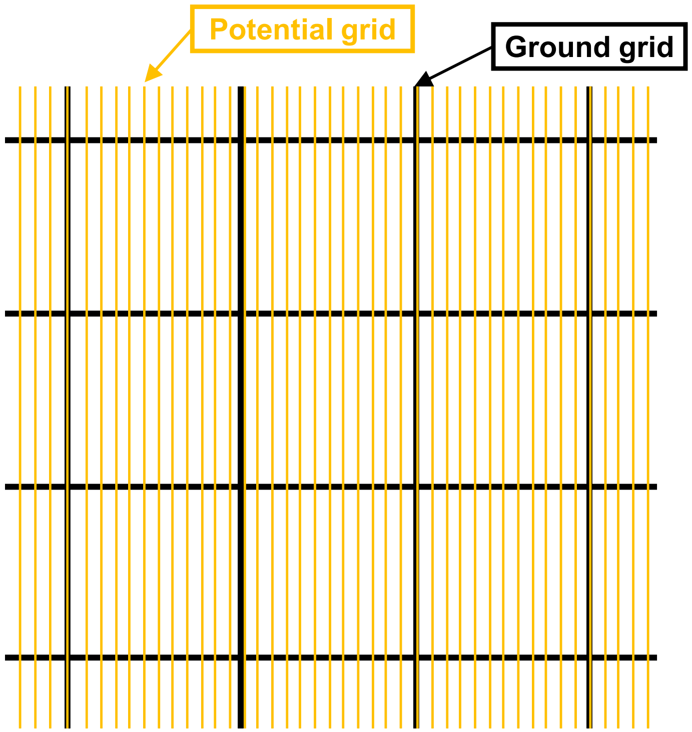
Side View of Substation Ground



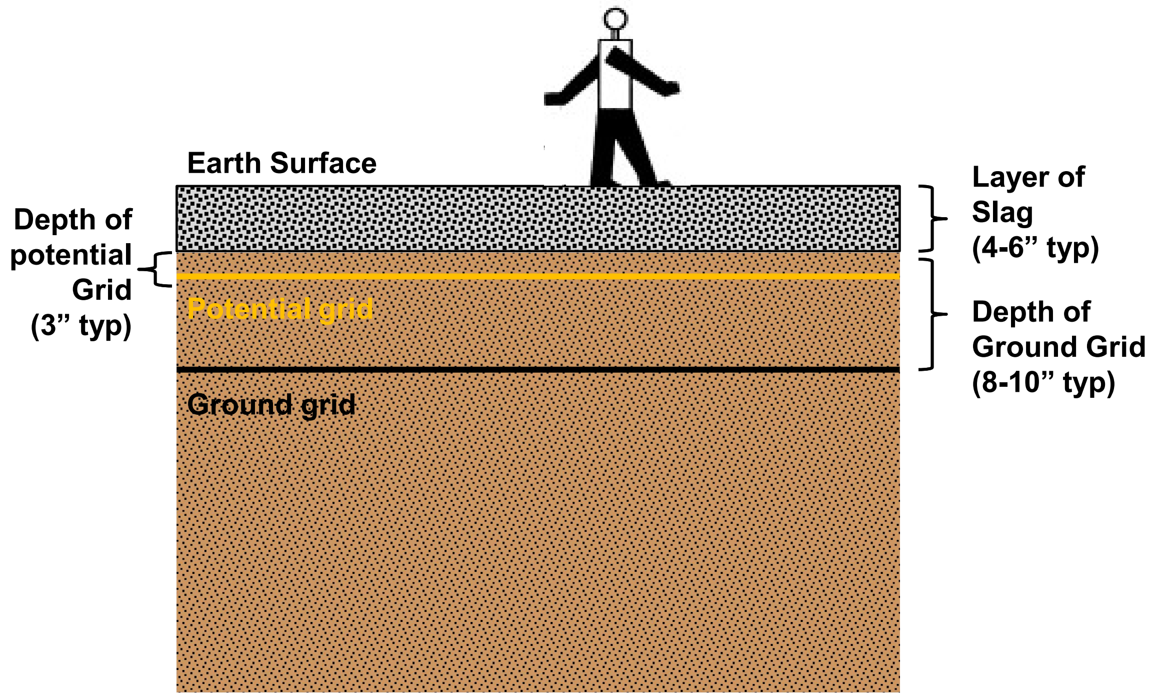
High Level Overview of Duquesne Light Practices

Existing Method for Older Substations

Top View of Substation Ground

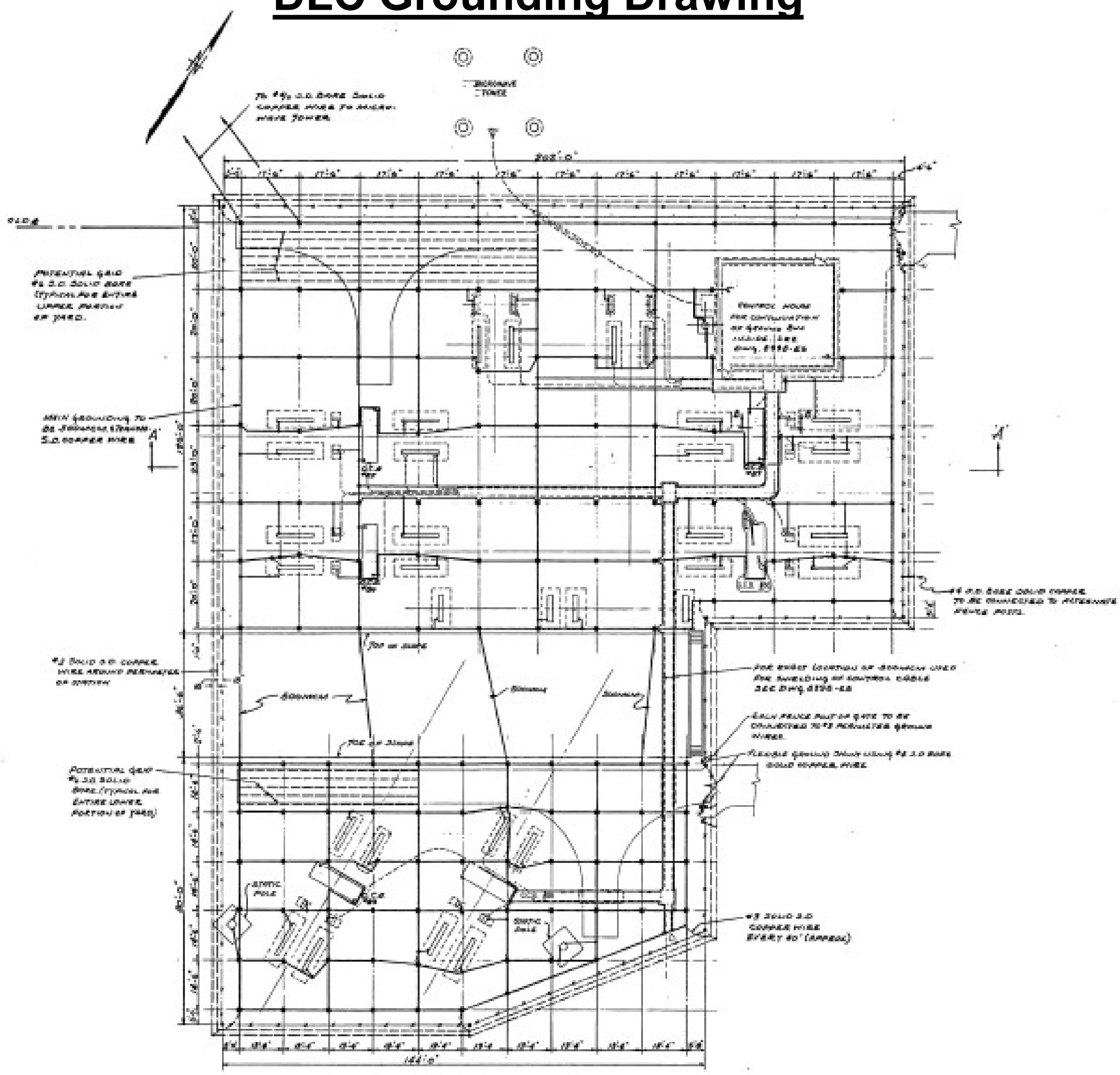


Side View of Substation Ground

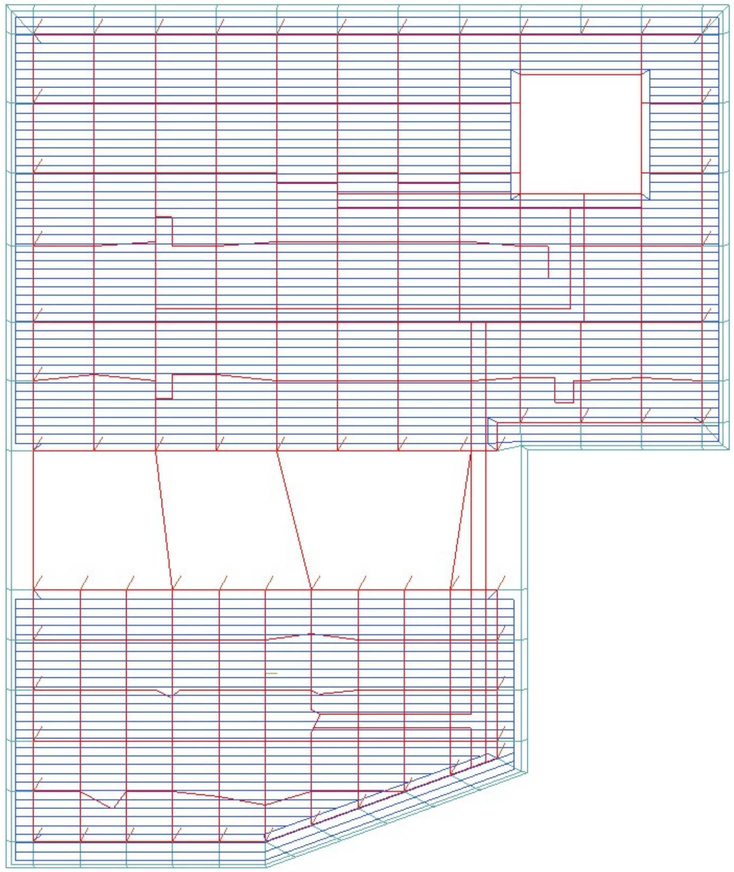


Example View of Substation Ground Grid

DLC Grounding Drawing



Drawing of Ground Grid Only



Evaluation of Substation Grounding System

“Hand” Calculations of Step & Touch Potential

$$Em = \frac{\rho\, Km\, Ki\, Ig}{L_M}$$ **Calculated Touch Voltage**

$$Km = \frac{1}{2\pi}\left[ln\left(\frac{D^2}{16hd} + \frac{(D+2h)^2}{8\,Dd} - \frac{h}{4d}\right) + \frac{Kii}{Kh}\, ln\left(\frac{8}{\pi(2n-1)}\right)\right]$$

$$Ki = 0.644 + 0.148\,n$$

Kii = 1 for grids with ground rods

$Kh = \sqrt{1 + h/ho}$ where ho = 1m (reference depth of grid)

$$L_M = L_C + L_R\left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right]$$

D = Spacing between parallel conductors (m)
d = Diameter of grid conductor (m)
h = Depth of ground grid conductor (m)
n = Number of parallel conductors in one direction, up to 25 paths
L_R = total length of all ground rods (m)
L_x = maximum length of the grid in the x direction (m)
L_y = maximum length of the grid in the y direction (m)
L_r = length of individual ground rod (m)

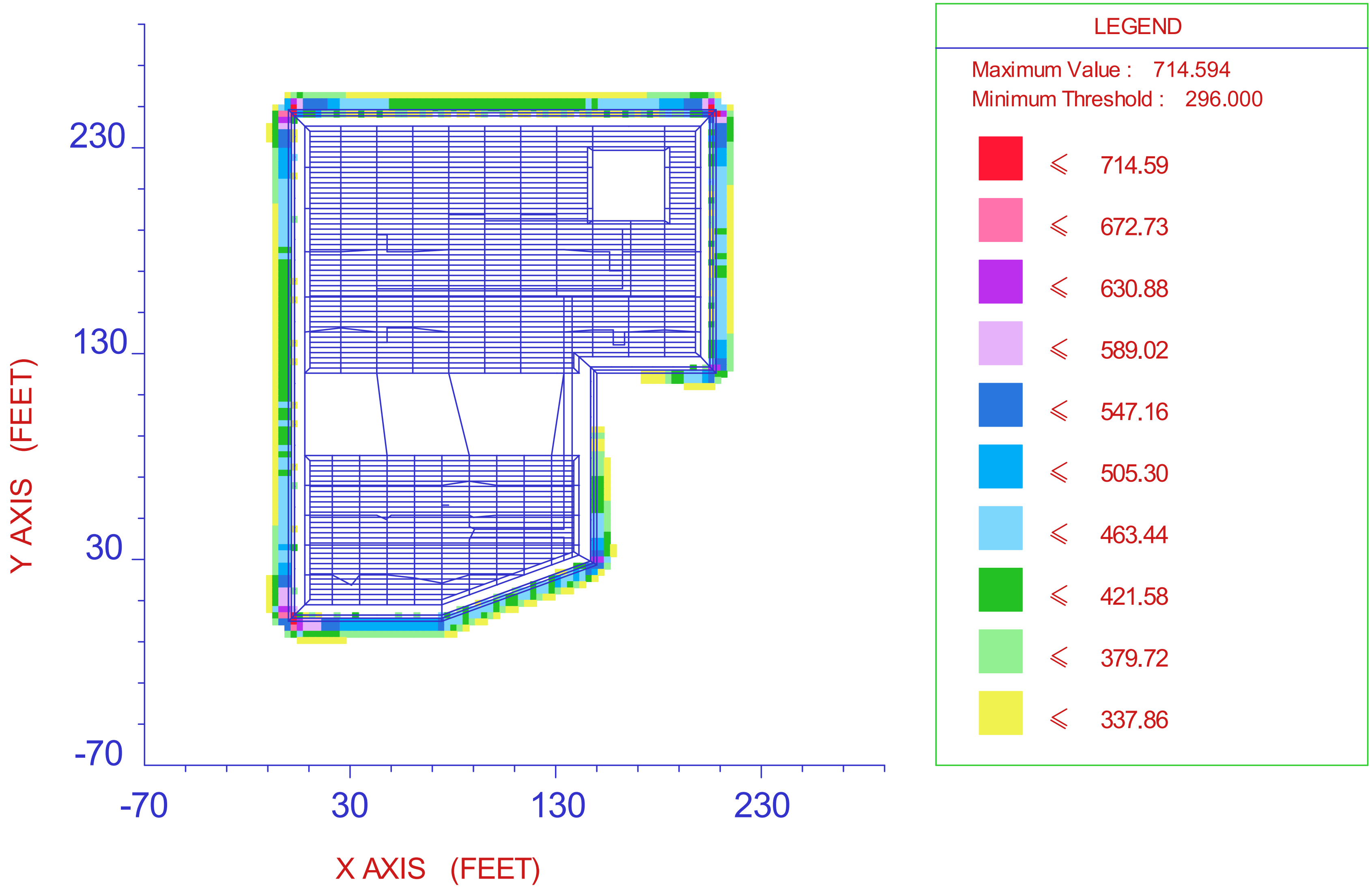
$$Es = \frac{Ks\, Ki\, Ig}{L}$$ **Calculated Step Voltage**

$$Ks = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{n-2})\right]$$

Provides an estimated maximum step & touch potential for the ground grid design, however, does not account for some of the specific details of the ground grid such as areas with less conductors or uneven spacing.

Example Step Voltage Evaluation

Detailed Analysis using a Computer Program (CDEGS)



Step Voltage-Worst Magnitude (Volts)

Initial Measurements of Substation Grounding

- Soil Resistivity Measurements
  - Performed to obtain the soil structure needed to properly design the grounding system (performed in the design stage)
  - Soil resistivity is an input into software used to perform grounding studies

- Ground Impedance Measurement
  - Measured to determine the overall impedance of the ground grid with respect to remote earth (performed after construction is complete)
  - Measured impedance should be consistent with calculations from the grounding studies

Substation Ground Grid Degradation

Substation Ground Grid Degradation

- Example reasons which may require a need for ground grid assessment:
  - Theft of ground conductors
  - Degradation from corrosive soil conditions
  - Soil erosion/improper drainage
  - Improper installation of ground grid/connections
  - Damage from excavation

Present Day Testing Practices for Ground Grid Condition Assessment

Present Day Testing Practices for Ground Grid Condition Assessment

- Duquesne Light Co. presently has the capability to perform the following tests for ground grid assessment in-house:
  - Soil resistivity measurement
  - Ground impedance measurement
  - Continuity measurements
- Other tests such as the following have been utilized by contracting with outside vendors:
  - Ground penetrating radar
  - Step & touch measurement using current injection
- The following three examples show cases in the DLC system where ground grid assessment was performed using different methods.

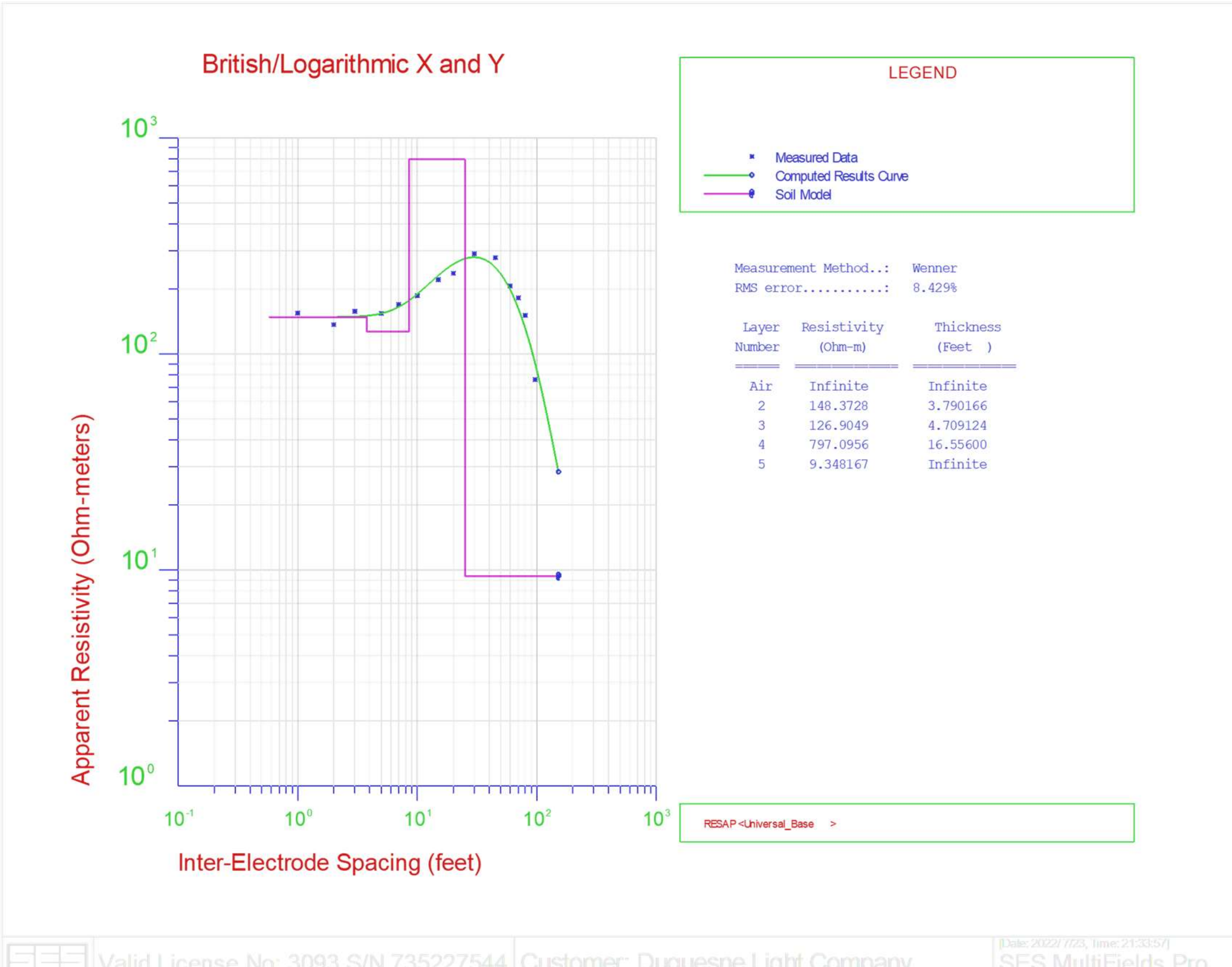
Example #1
Ground Grid Impedance Measurement and Continuity Checks

Substation with Suspect Ground Grid

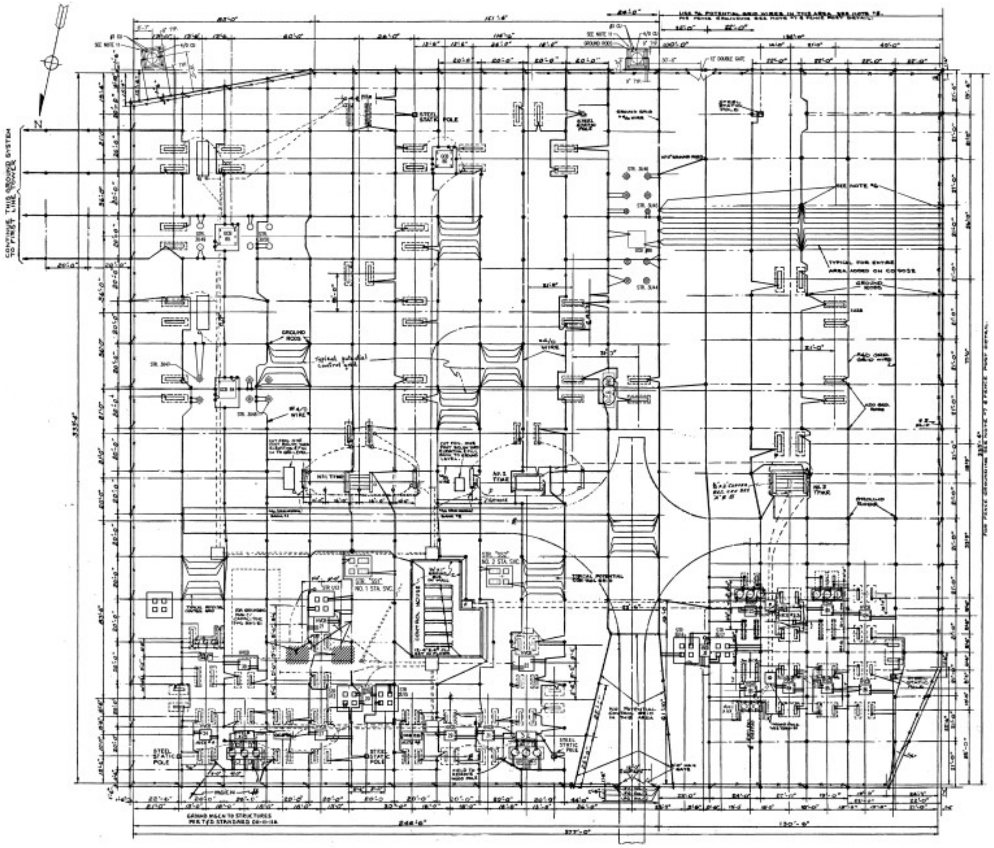
- 138/23 kV Substation with violent failures during close-in faults.
- Faults close to the station resulted in gravel displacement at some locations with evidence of gravel thrown on top of equipment after a fault.
- It was suspected that deterioration of the ground grid had impacted the effectiveness of some equipment ground connections.
- Typical DLC practice for situations such as this involve existing equipment/practices such as:
  - Perform soil resistivity measurements to perform a ground grid analysis.
  - Perform ground grid impedance measurement to determine overall grid impedance.
  - Perform continuity checks throughout the substation.


North
Gate
Google Ea

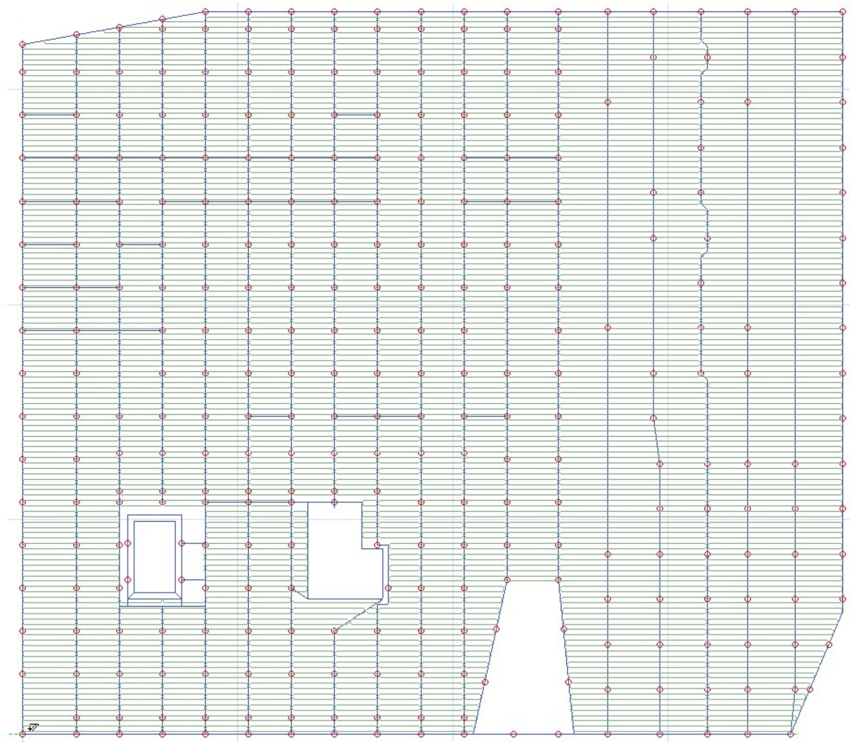
Soil Resistivity Measurements



DLC Drawing 4234-E8 (Rev.49)



CDEGS Model



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CONFIGURATION OF MAIN ELECTRODE
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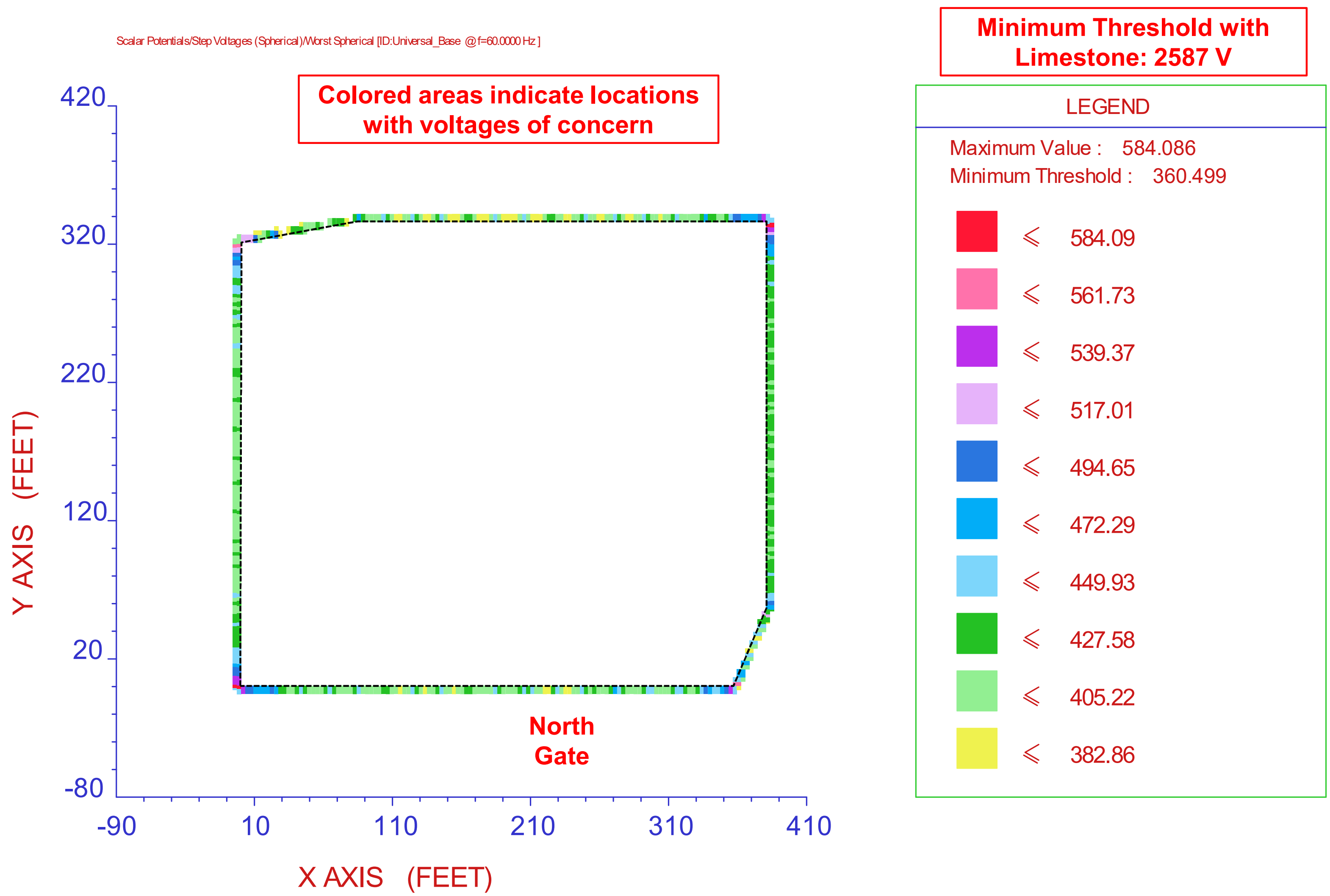
Original Electrical Current Flowing In Electrode..:   1000.0     amperes
Current Scaling Factor (SPLITS/FCDIST/specified)..:   12.373
Adjusted Electrical Current Flowing In Electrode..:   12373.     amperes
Number of Conductors in Electrode.................:  5768
Resistance of Electrode System....................:  0.31363     ohms
```

High slope coefficient indicates measurements (X) were not taken far enough from the ground grid. Because of property boundaries and the terrain surrounding the substation, measurements at a greater distance were not possible using the test set available (Megger DET2/2). For reference, the measured resistance was 0.114 Ω.

Step Voltage

Surface Layer: None/Slag

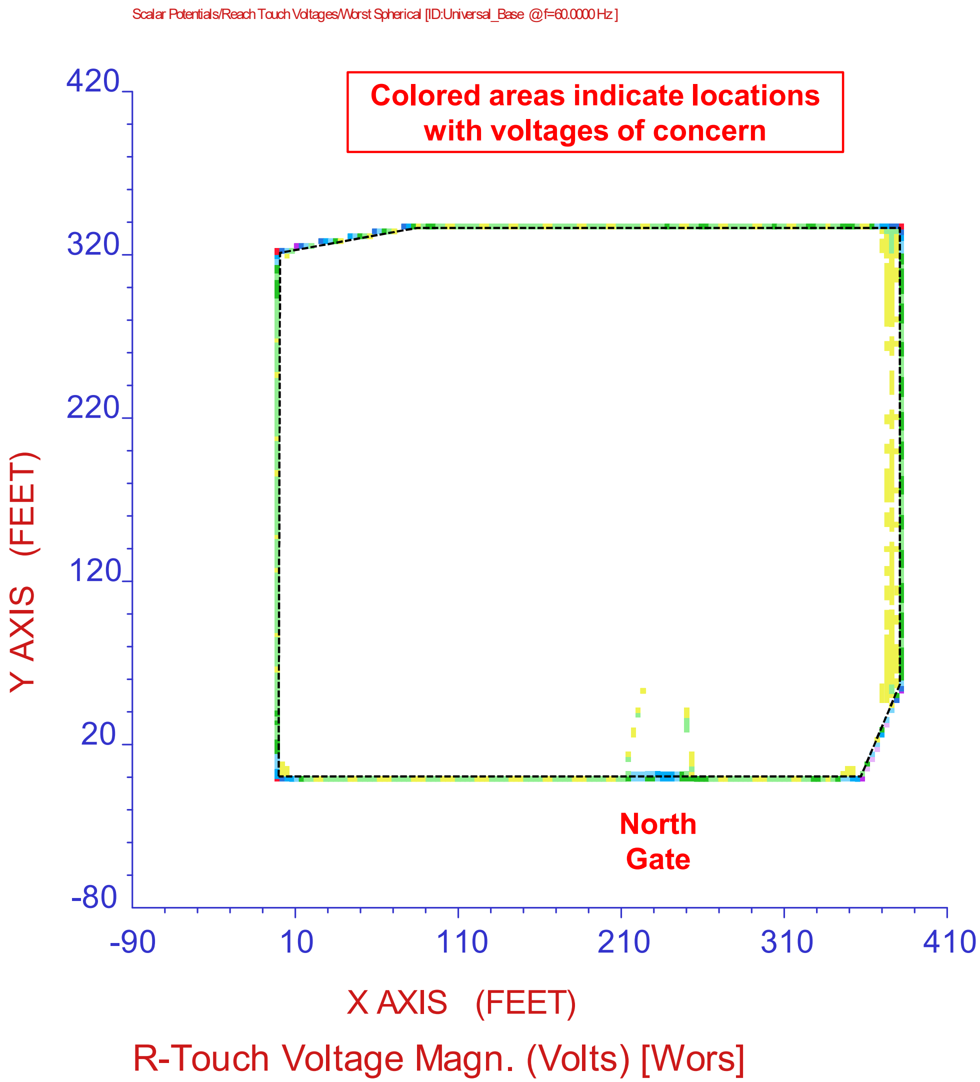


Step Voltage-Worst Magnitude (Volts)

DUQUESNE LIGHT CO.

Reach Touch Voltage (3 ft)

Surface Layer: None/Slag



Minimum Threshold with Limestone: 807 V

LEGEND
Maximum Value : 870.202
Minimum Threshold : 250.279
⩽ 870.20
⩽ 808.21
⩽ 746.22
⩽ 684.23
⩽ 622.23
⩽ 560.24
⩽ 498.25
⩽ 436.26
⩽ 374.26
⩽ 312.27

Action Items Resulting from Analysis

- Required repairs were identified through the continuity testing.
- Addition of limestone to key areas.

Example #2
Use of Ground Penetrating Radar

Substation with Evidence of Copper Theft

- 23/4 kV Substation in an urban area with signs of copper theft.
- DLC workers, using proper PPE for an unapproved ground grid, investigated the substation and could not find buried conductors where it was anticipated a ground grid should exist.
- To determine the integrity of the existing ground grid, an outside contractor was used to perform a ground penetrating radar analysis to determine location of any existing buried conductors.
- The following diagram shows the results of the analysis performed with locations of buried utilities such as ground grid, conduit, storm drains, etc.

Ground Penetrating Radar

Action Items Resulting from Analysis

- Ground grid analysis was performed using the information gathered from the ground penetrating radar analysis to determine potential concerns for step and touch potentials based on the existing conditions.
- Required repairs and modifications were identified by the ground grid analysis to ensure step and touch potentials are mitigated to with guidelines defined by IEEE Std. 80.
- Example for the actions taken were:
  - Addition of ground grid conductor
  - Bringing in a neutral conductor from a nearby circuit
  - Anti-theft measures

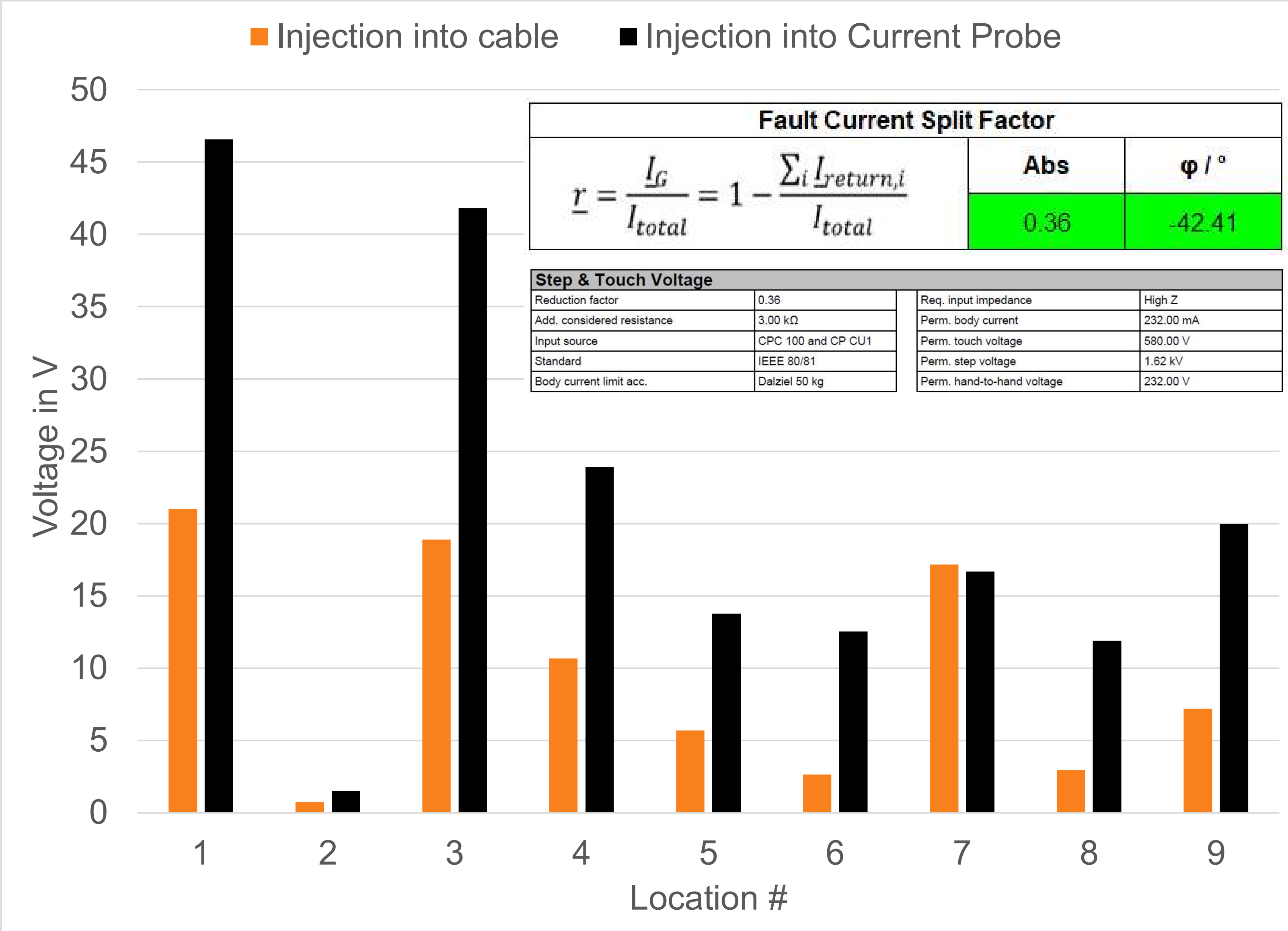
Example #3
Step and Touch Potential Measurement Using Current Injection Method

Substation with Unapproved Ground Grid

- 23/4 kV Substation in an urban area with an unapproved ground grid (requires the use of dielectric footwear to enter).
- Old substation with some uncertainty on the condition of the ground grid.
- To determine the effectiveness of the ground grid at maintaining safe step and touch voltages, testing was performed using a current injection method.

High-Level Setup

Example Step & Touch Voltage Results



Action Items Resulting from Analysis

- Initial testing showed adequate ground grid performance
- Further testing is required to consider this station as having an approved ground grid

Future Testing Practices for Ground Grid Condition Assessment

Future Testing Practices for Ground Grid Condition Assessment

- Purchased the following testing equipment to perform ground grid testing using the current injection method:
  - Omicron CPC 100 Line Impedance Test System
  - Omicron Ground Impedance and Step & Touch Voltage Set (HGT1)
  - Omicron PTM Advanced for HGT1 (software)
- Allows for ground grid testing with substation online and shield wires/cable sheaths connected.
  - Test set can be used to calculate fault current split factor
  - Overall ground grid impedance can be measured with the substation online
  - Step and touch voltages can be measured and compared with simulation results

Future Testing Practices for Ground Grid Condition Assessment

CPC 100 + CP CU1 + HGT1

CPC 100 provides a lightweight and modular solution for obtaining accurate ground impedance measurements in medium and high voltage systems. Our support of power line injection and current probes offers users a flexible way of adapting to on-site testing conditions. With CPC 100, users can choose between on-device operation or testing via the Primary Test Manager™ (PTM). With CPC 100, direct voltage measurements on the device are possible, whereas with PTM, the voltage pickup is performed with our mobile handheld meter HGT1.

CPC 100

Universal primary injection test set for substation assets

READ MORE

+

CP CU1

Coupling unit for injection into powerlines and HV cables

READ MORE

+

HGT1

Handheld grounding tester

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