Fundamentals of Grounding

Next Generation Network

For power system expertise

Grid of the Future

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Introductions

- Mark McVey, Dominion Energy
- Robert Allison, Dominion Energy
- Camp Parker, Dominion Energy
- Randy Horton, EPRI

Safety Moment

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Safety Moment – Hazards Associated with Copper Theft

- Many incidents over the years involving copper theft from substations and lines
- Missing equipment and fencing grounds can cause serious or fatal injuries and equipment failure
- Inspect for missing equipment of fencing grounds
- Be aware of suspicious activities in and around company facilities – review perimeter fencing to make sure there are no openings or cut fabric
- Do not enter facilities if there are signs of forced entry and/or suspicious behavior or activity

Copper Theft

Check grounds before touching equipment

Copper Theft

Check grounds before touching equipment

Copper Theft

Check grounds before touching equipment

Agenda

1. Principles
2. Application
3. Mitigation

Principles of Grounding

- Shielding (Lines and Substations)
- Switching Over-Voltages
- Lightning Flash
- Shielding (Lines and Substations)
- Surge Impedance
- Backflash (Impulse Resistance of Ground Electrodes)
- Skin Effect
- Highlights/Takeaways
- Questions

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Applications of Grounding

- Ground Grid vs. Ground Mat
- Ground Grid Design and Materials
- Equipment Grounding (Lead Length)
- Safety Grounding (Step and Touch, Switch Grates, etc.)
- Transmission/Distribution Lines Grounding
- Grounding Cages/Counterpoise
- EMP
- Highlights/Takeaways
- Questions

Mitigation of Grounding Concerns

- Testing
- Maintenance
- Commissioning
- Soil Testing and Modeling
- Highlights/Takeaways
- Questions

Principles

Basic Principles

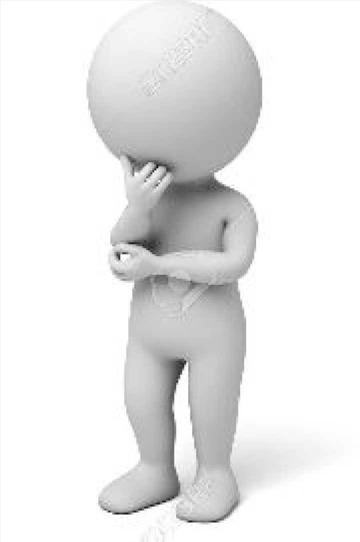
AC current and its relation to effective grounding

Impedance and Inductance

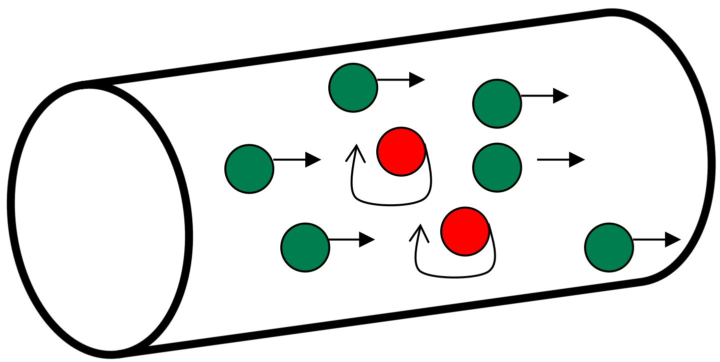
- Conductors have resistance and inductance
- Inductance is not a major factor in short lengths at 60 hertz but is a significant issue at higher frequencies – such as lightning
- Inductance has two components:
  - Self inductance: “skin effect” - at high frequencies, electrons flow on surface of conductor
  - Mutual inductance: impacted by close proximity to other circuits or due to coils (90-degree bends) in wire

Inductance

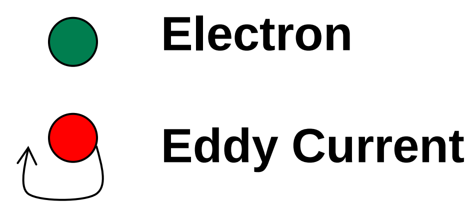
- Lightning is a high-frequency event and must have grounding that reduces inductance impacts.
- Surges on transmission lines or substations are high-frequency events and must have designs that reduce inductance impacts.
- ***Remember – frequency is directly related to inductance!***



Eddy Currents

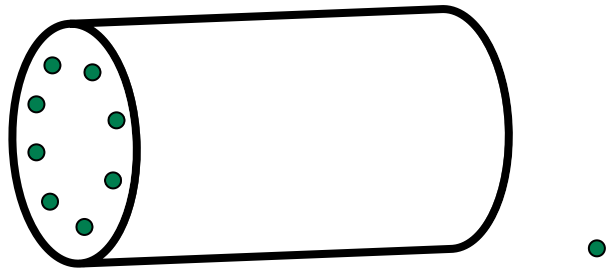


In AC circuits, small voltages are created in the wire, forming “eddy currents.” These currents create a greater resistance in the wire when compared to a DC circuit voltage with similar wire.



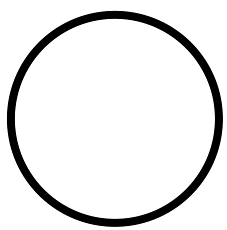
An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the change in original magnetic flux.

Skin Effect

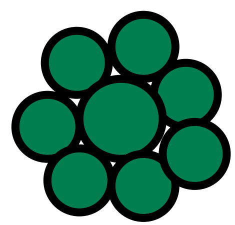


electrons

In AC circuits, the electrons tend to flow near the surface of the conductor due to the voltages set up in the conductor. This reduces the conductor effective surface area and creates more resistance.



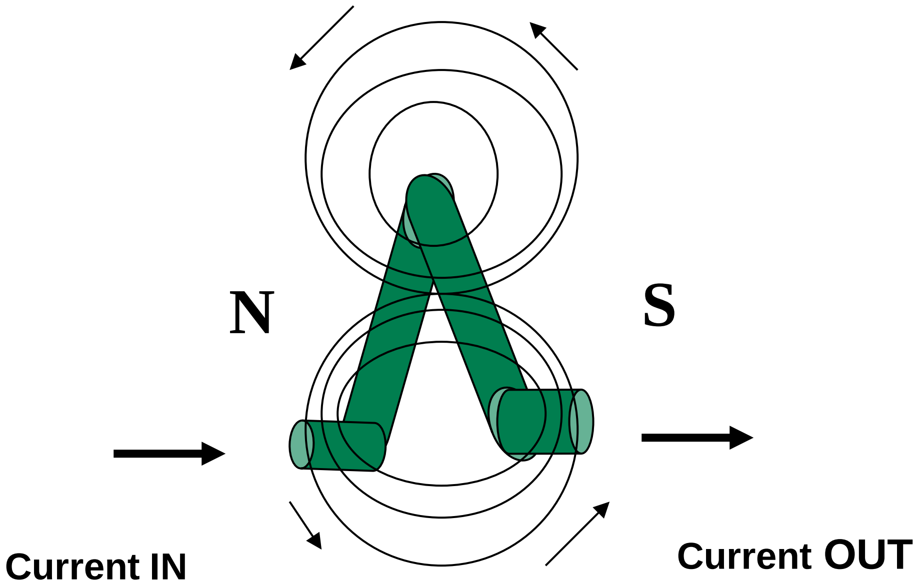
Solid wire



Stranded wire

Stranded wire provide more surface areas and less resistance than equivalent sized solid wire due to “skin effect” of AC current.

Electromagnetism in a Loop



The flux lines are compressed in the center of the loop to create a strong field. The north pole is created on the side that the flux lines come out.

Shape and geometry matter!

Resistance – AC Circuits

- Eddy currents and skin effect are directly proportional to the frequency of the current flowing in the conductor.

$$Z = R_{dc} + \text{eddy current} + \text{skin effect}$$

or

$$Z = R_{dc} + X\text{, where } X \text{ is the inductance of the wire!}$$

Inductance

- Present in a straight wire
- Increases with loops due to strength of magnetic fields produced
- Inductance affected by number of loops (more loops = more inductance) and distance (closer loops = stronger magnet = more inductance)

Inductance

- Inductance opposes a change in current by creating a “back” voltage
- Back voltage is a function of the change in current in a given interval of time

$$V = -L\frac{dI}{dt}$$

Inductance

Inductance = L

For grounding of electric lines to quickly bleed lightning current, remember:

L = <u>L</u>oops or <u>L</u>ong leads

L is <u>bad</u> and will resist taking energy off of the electrical system.

Inductance

- Important rule for high-frequency protection:
  - L for an arrester lead ***must*** be as small as possible to the hot and grounded side of arrester.
  - Current from lightning can approach 200,000 Amperes from 0 Amperes in as little as .000001 seconds.

Inductance

For a lightning stroke:

The “back” voltage or (DROP) to the arrester from a lead could be:

(-L) 200,000 / .000001 or

(-L) 200,000 x 1,000,000

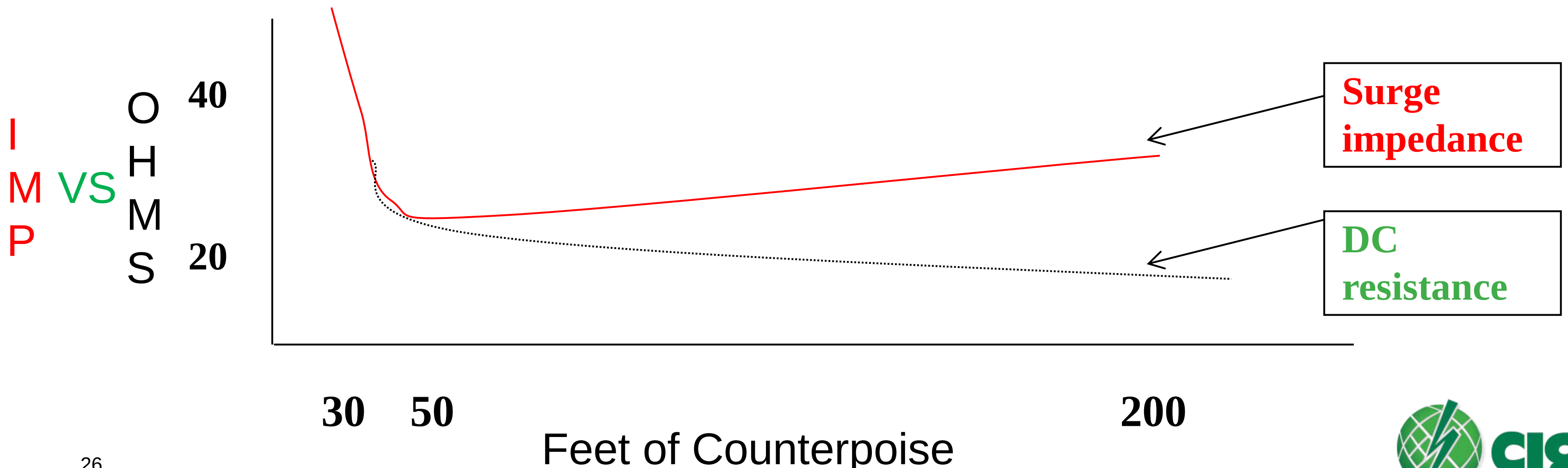
In other words, the inductance factor can create a HUGE voltage across the leads preventing the arrester from ever operating!

Inductance

Sometimes for straight conductors, we refer to inductance as "surge impedance." To help eliminate or reduce surge impedance, you should have multiple paths to increase surface area (minimize skin effect).

Just like having multiple downspouts from a roof gutter!

Tests show Ohmic value should not exceed 40 ohms to be effective in absorbing surges.



Inductance Takeaways

REMEMBER:

1. Loops, 90-degree bends and long leads are bad for lightning protection due to inductance created.

2. Inductance cannot be measured with DC current as it does not exist!

3. Surface area is more important than thickness!

Can You Spot the Good and the Bad?

Applications

Lightning and Static Protection

Lightning Strikes

- Can generate millions of volts across line insulators sometimes leading to:
  - Tracking
  - Punctures
  - Shed damage
- Can cause an insulation failure that faults a transmission line (Back-flash)
- Generate arcs that are a major source of melting, burning, and pitting of wires, corona shields and supporting hardware
- Inject high-voltage waves in the phase conductors that can travel long distances back to the substations and present severe challenges for transformers, circuit breakers and other components

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Insulator Tracking

Shed Damage

Punctured Insulator

Transmission Structure Lightning Damage

Transmission Structure Lightning Damage

Lightning Definitions

- **Back Flashover**
  - Stroke to tower or shield wire
  - Discharge: tower to phase
- **Shielding Failure**
  - Stroke to phase conductor
  - Discharge: phase to tower
- **Induced Flashover**
  - Stroke to another object or ground
  - Discharge: phase to tower

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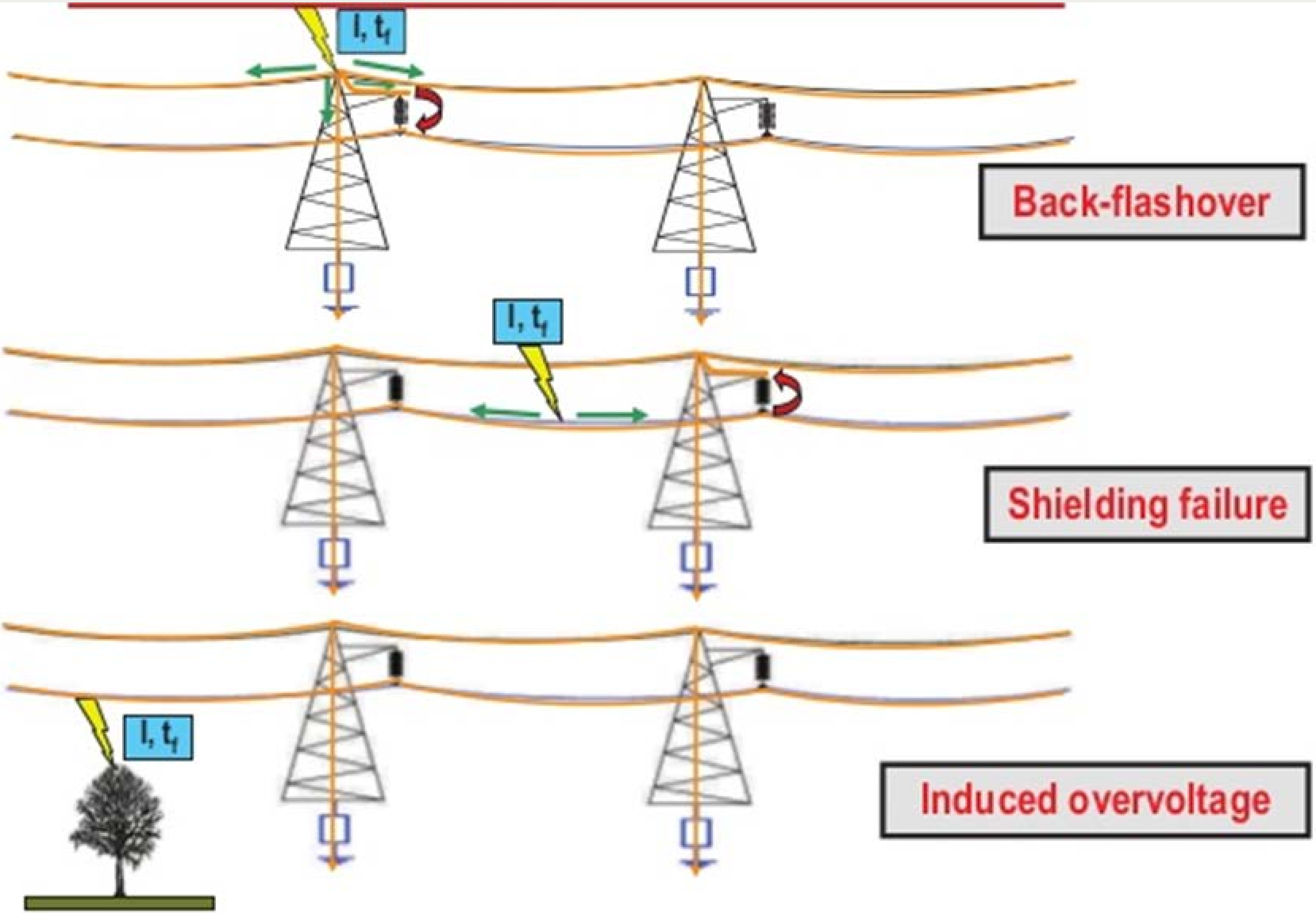
Lightning Definitions



Tree on Line

Line is locked out?

Fixing the Problem

- **Back Flashover**
  - Reduce footing resistances
  - Increase insulator lengths
  - Install arresters
- **Shielding Failure**
  - Relocate/add static wires
  - Relocate phases
  - Increase insulator length
  - Add line arrester
- **Induced Flashover**
  - Add static wires
  - Increase line insulator BILs
  - Install line arresters

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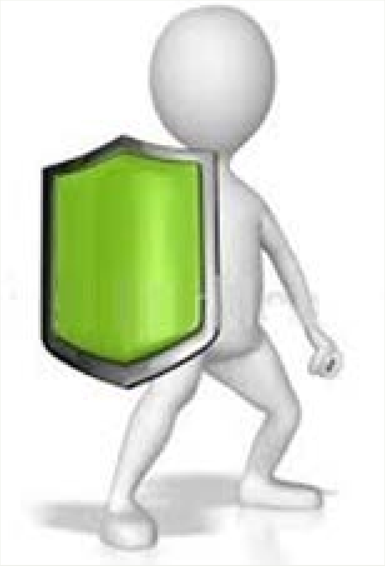
Performance Parameters

- **Routing**
  - Lightning frequency: Ground Flash-Density (GFD) Maps
  - Exposure of line to lightning (mountains vs. valleys)
  - Variation of soil resistivity with alternate routes
- **Structure Height**
- **Insulation**
  - Ratings (CFO & BIL)
  - Levels (number of sheds or bells)
- **Shielding**
  - Angle
  - Size and Type (mechanical strength, fault current, fiber optic)
- **Grounding**

Shielding Protection



Lightning Shield Protection

- Static Wire for Line and Substation Protection
- Static Masts for Substations
- Static Wire Shield Angle
- Rolling Sphere

Lightning Shield Protection

The Design Problem?

- The unpredictable, probabilistic nature of lightning
- The lack of data due to the infrequency of lightning strokes in substations
- The complexity and economics involved in analyzing a system in detail

Shield Wire

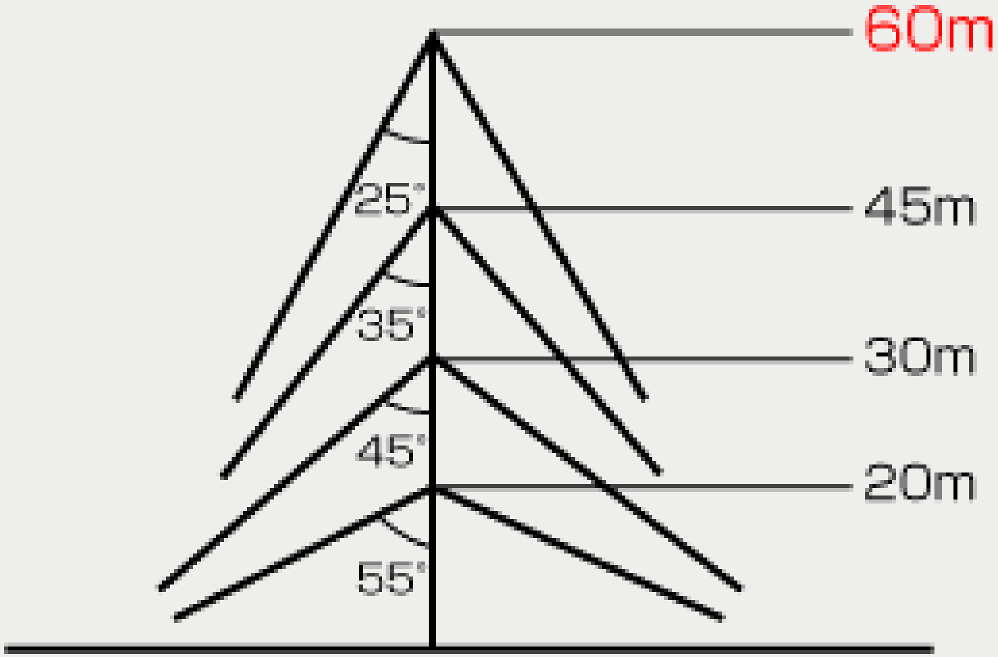
- Grounding wire(s) placed above phase conductors
- Protects phase conductors from direct lightning strokes as a secondary measure
- Intercepts the stroke and shunts the current to the ground through a properly grounded system
- Reduces induced voltages from external magnetic fields

Table 4-1 —Calculated frequency of shielding failures as a function of the height and the protective angle

Height of earth wire in m	Shielding failure/100 km per year with protective angle:						
	15°	20°	25°	30°	35°	40°	45°
10	0	0	1.1E-4	0.0087	0.0383	0.1032	0.2286
15	0	6.4E-5	0.0068	0.0351	0.0 982	0.2182	0.4483
20	8.3E-6	0.0026	0.0214	0.0711	0.1695	0.3466	0.6903
25	0.0011	0.0087	0.0404	0.1123	0.2468	0.4819	0.9429
30	0.0035	0.0170	0.0620	0.1565	0.3275	0.6208	1.2008
35	0.0069	0.0269	0.0853	0.2024	0.4100	0.7616	1.4608
40	0.0109	0.0378	0.1096	0.2494	0.4936	0.9035	1.7214
45	0.0155	0.0493	0.1345	0.2969	0.5776	1.0462	1.9820
50	0.0204	0.0612	0.1598	0.3447	0.6619	1.1892	2.2423

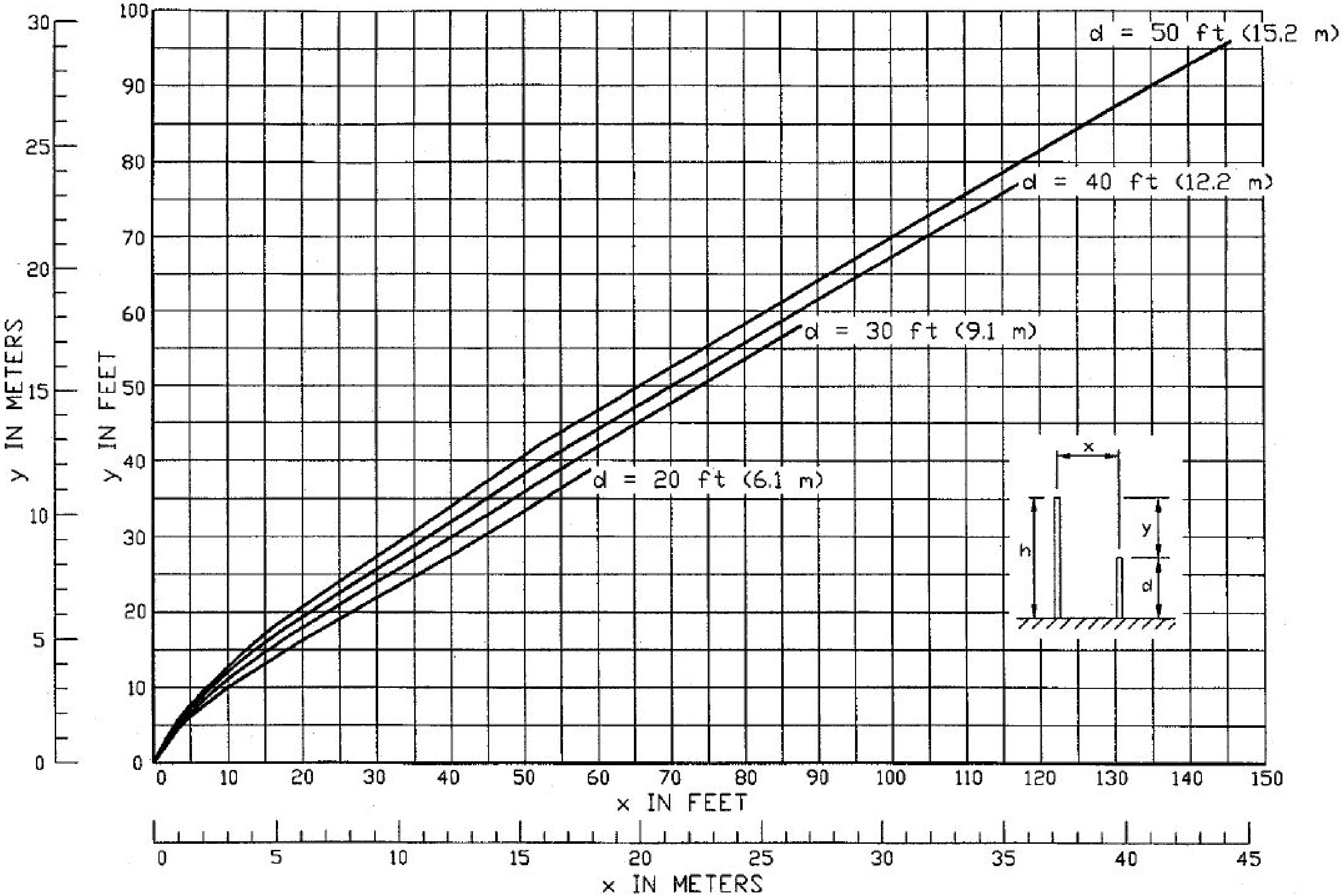
Source: [B42]. Reprinted with permission of Research Studies Press Ltd.

Shield Angle

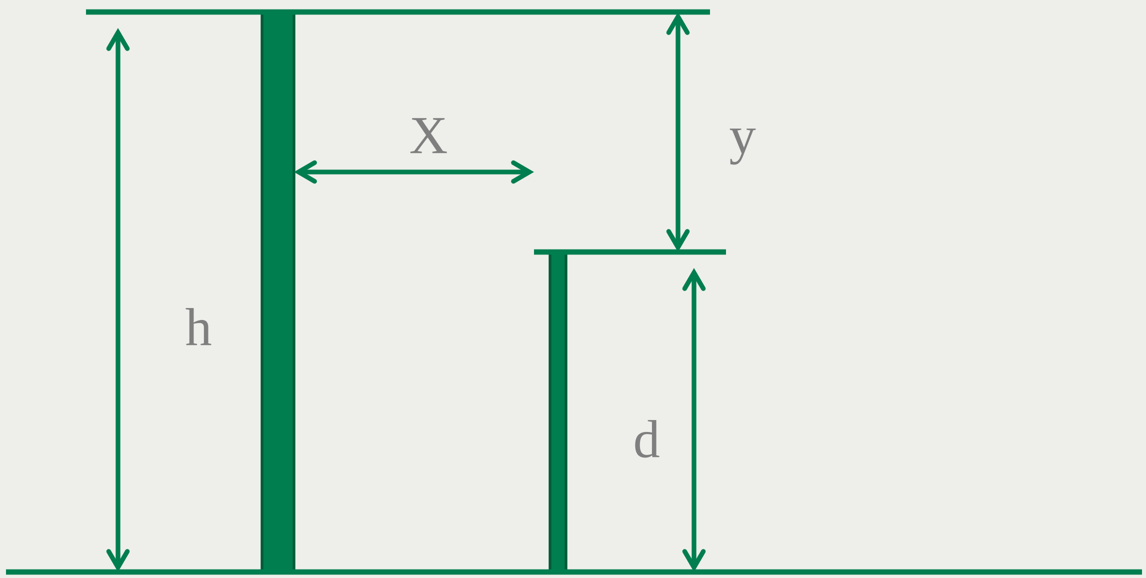


The probability of a strike increases with height and shield angle.

Single Lightning Mast Protecting Single Object—0.1% Exposure



Example: Static Shield Protection



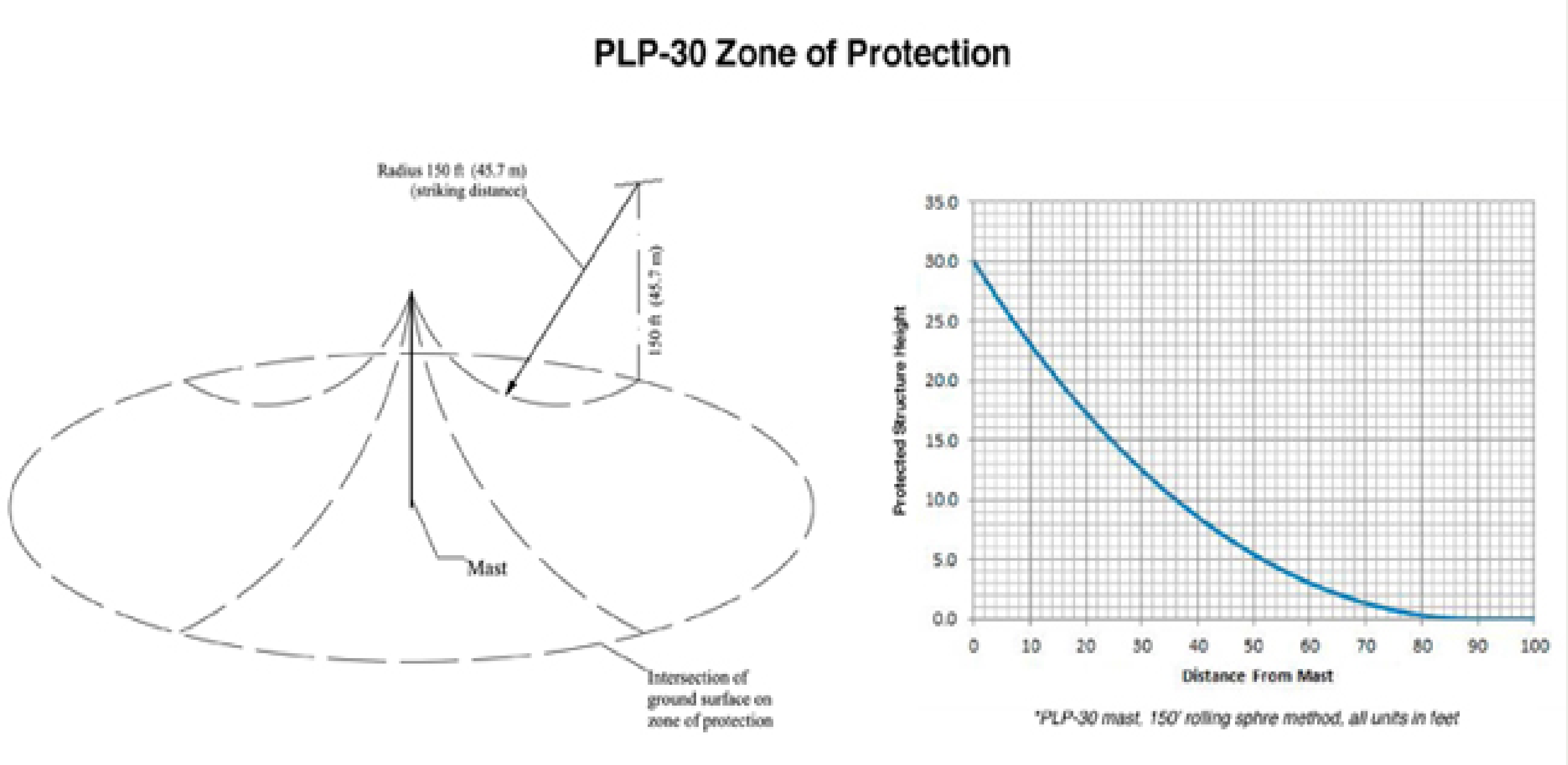
For *d = 20 ft.:*

h = 20/0.46 = 43.48 ft. min.
x = 0.6 ´ 43.48 = 26.09 ft. max.
y = 43.48 - 20 = 23.48 ft. max.

Rolling Sphere

- Calculate bus surge impedance Z_s from the geometry. For two heights, use the higher level
- Determine the value of CFO (or BIL). For higher altitude, use correction factor for BIL
- Calculate the value of I_s
- Calculate the value of the striking distance (or radius of the rolling sphere)
- Use two or more striking distance values based on BIL voltage levels in a substation with two different voltage levels

Example



PLP-30 Zone of Protection
Radius 150 ft (45.7 m)
(striking distance)
150 ft (45.7 m)
Mast
Intersection of
ground surface on
zone of protection
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Protected Structure Height
0
10
20
30
40
50
60
70
80
90
100
Distance From Mast
'PLP-30 mast, 150' rolling sphre method, all units in feet

Allowable Stroke Current

I_s = Allowable stroke current in kA

BIL = Basic lightning impulse level in kV

CFO = Negative polarity critical flashover voltage of the insulation in kV

Z_s = Surge impedance of the bus system in Ohms

$$I_s = BIL * \frac{1.1}{Z_s/2} = \frac{2.2 \; * BIL}{Z_s}$$

$$I_s = 0.94\, CFO * \frac{1.1}{Z_s/2} = \frac{2.068 * CFO}{Z_s}$$

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Calculating “S” Radius from IEEE 998

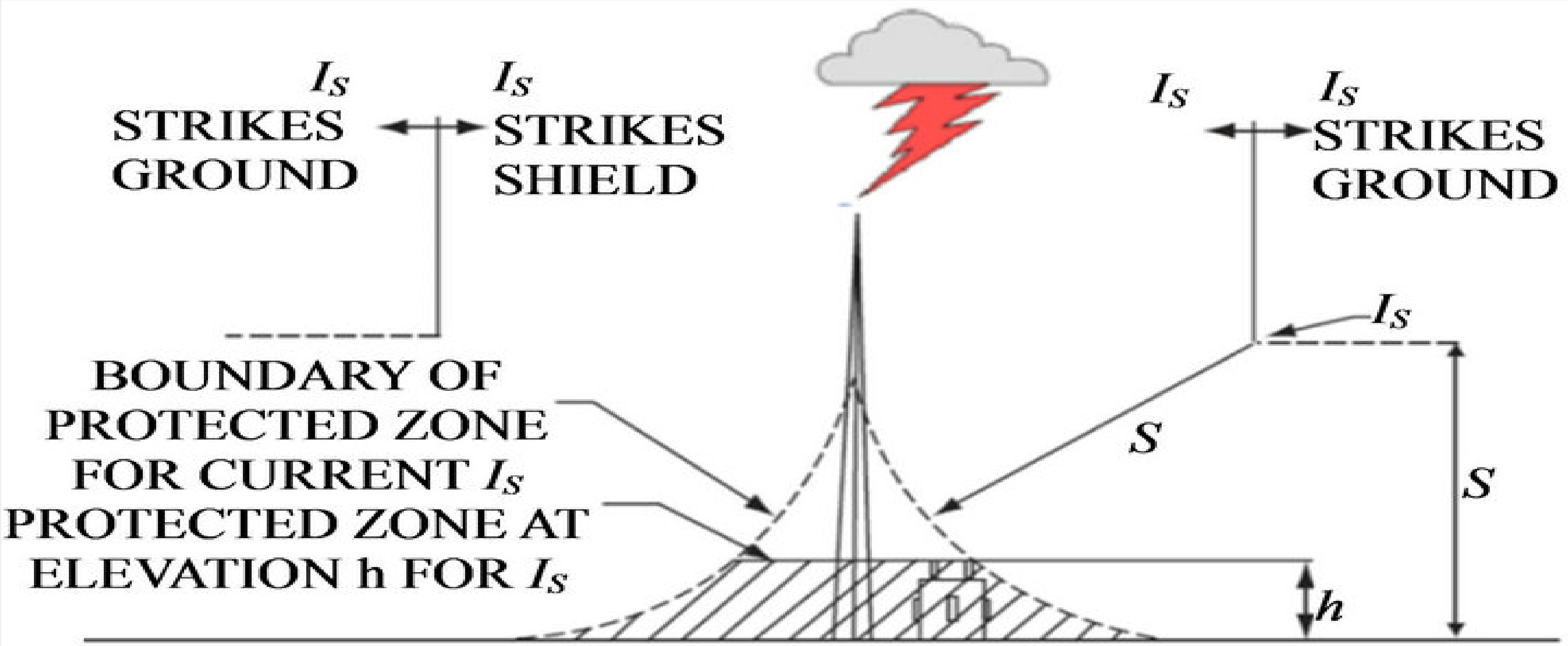
$S = 8 * I_s * 0.65$ IEEE 998 *[B46] (4)*

$I_s = 0.041 * S^{1.54}$ *(6)*

S = Radius of Rolling Sphere

I_s = Allowable Stroke Current in kA

Rolling Sphere



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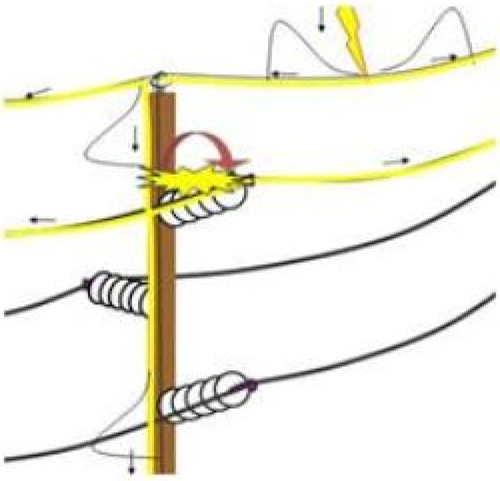
Lightning Backflash

Backflash

An insulator flashover originating from the pole or tower ground across the insulator onto the phase conductor. This can occur during a lightning strike to the overhead shield wire and where the ground impedance is high. It is referred to as a back flashover since it is in the opposite direction of flashovers produced in laboratory tests. The backflash is usually followed by a standard flashover of the insulator with power frequency current that requires a breaker operation to terminate.



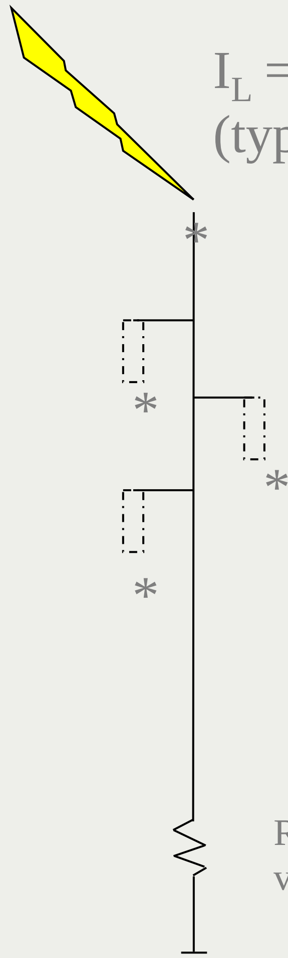
Lightning Strikes and Limits

Year	Count
2007	2,858,531
2008	2,848,780
2009	2,235,275
2010	2,239,980
2011	2,886,935
2012	2,401,009
2013	1,485,064
2014	1,841,646
2015	969,403

Lightning Subcause Coding

Line Voltage (KV)	Strike Intensity	Lightning >Limits?
69	≥ 35kA	Yes
115	≥ 35kA	Yes
138	≥ 35kA	Yes
230	≥ 60kA	Yes
500	≥ 120kA	Yes

Stroke Interception by Shield Wire



I_L = 20 kA
(typical value)

Basic Impulse Level (BIL) = 670 kV (7 bells)

R_{str} = 25 Ω (targeted value)

Nominal Conditions

V_{tower} = 20 kA * 25 Ω

= 500 kV

NO BACKFLASH

Poor Grounding

V_{tower} = 20 kA * 100 Ω

= 2000 kV

BACKFLASH

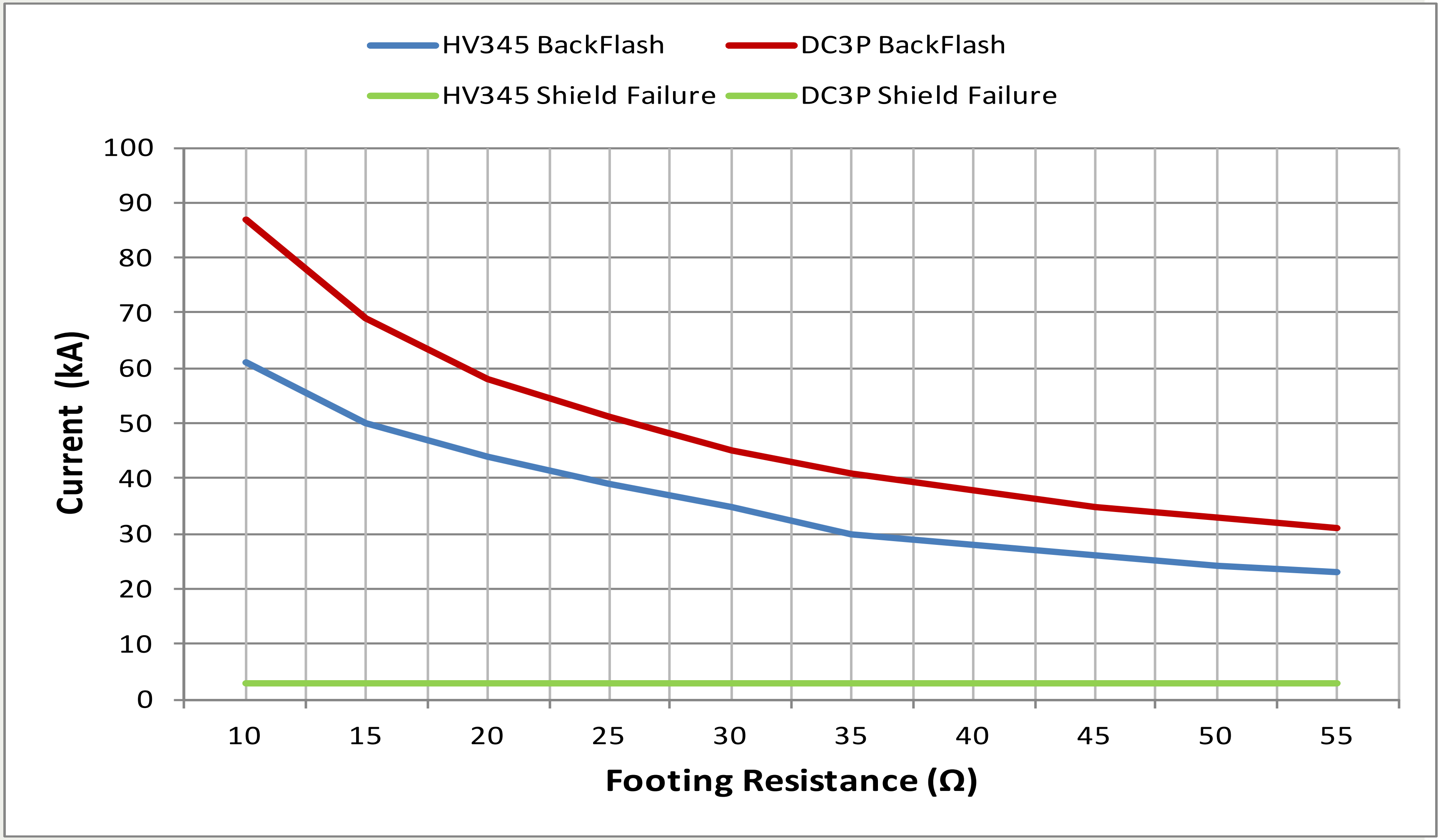
High Magnitude Strike

V_{tower} = 100kA * 25 Ω

= 2500 kV

BACKFLASH

115 kV Lightning Limits



Lightning Shield Protection

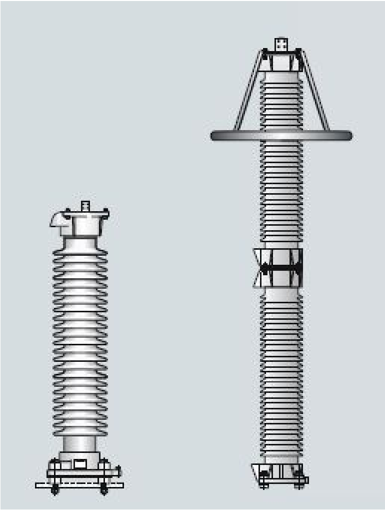
Ground Design Standard is modeled from IEEE 998.

Anderson, J.G. (1982). “Lightning Performance of Transmission Lines,” Chapter 12 (53 pp.) of Second Edition of Transmission Line Reference Book 345 kV and Above, EPRI, Palo Alto, California.

Wagner C.F., McCann, G. D., Lear, C. M., “Shielding of Substations *AIEE Transactions*,” vol. 61, pp. *96Ð100,*313,448, February 1942

Andrew R. Hileman, “Insulation Coordination for Power Systems”

Arrester Protection



Insulation Coordination and Protective Margins

Three Protective Margins (PMs) are normally calculated.

$PR(L1) = [(CWW/FOW) \,.\, 1)] \times 100\%$ (20% or >)

$PR(L2) = [(BIL/LPL) \,.\, 1)] \times 100\%$ (20% or >)

$PM(S) = [(BSL/SPL) \,.\, 1)] \times 100\%$ (20% or >)

CWW: Chopped Wave Withstand

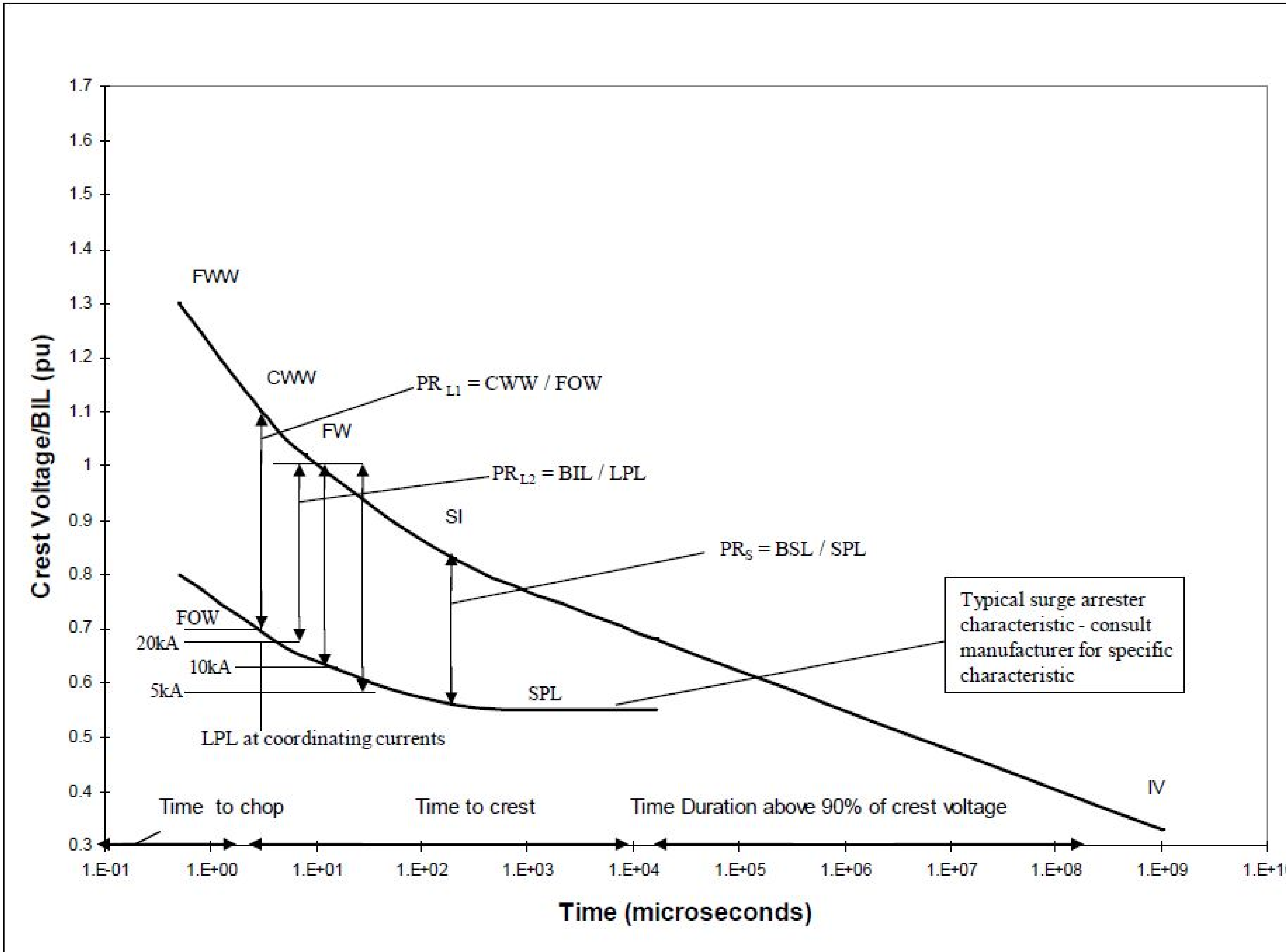
FOW: Front-of-Wave

BIL: Basic Lightning Impulse Insulation Level

LPL: Lightning Impulse Classifying Current (also called IR: Lightning Discharge Voltage)

BSL: Basic Switching Impulse Insulation Level

SPL: Switching Impulse Protective Level


Crest Voltage/BIL (pu)
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
FWW
CWW
FW
SI
PR_{L1} = CWW / FOW
PR_{L2} = BIL / LPL
PR_S = BSL / SPL
Typical surge arrester characteristic - consult manufacturer for specific characteristic
FOW
20kA
10kA
5kA
SPL
LPL at coordinating currents
IV
Time to chop
Time to crest
Time Duration above 90% of crest voltage
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
1.E+10
Time (microseconds)

Importance of Lead Length

Both High Voltage and Ground Connection

Lead Length Voltage:

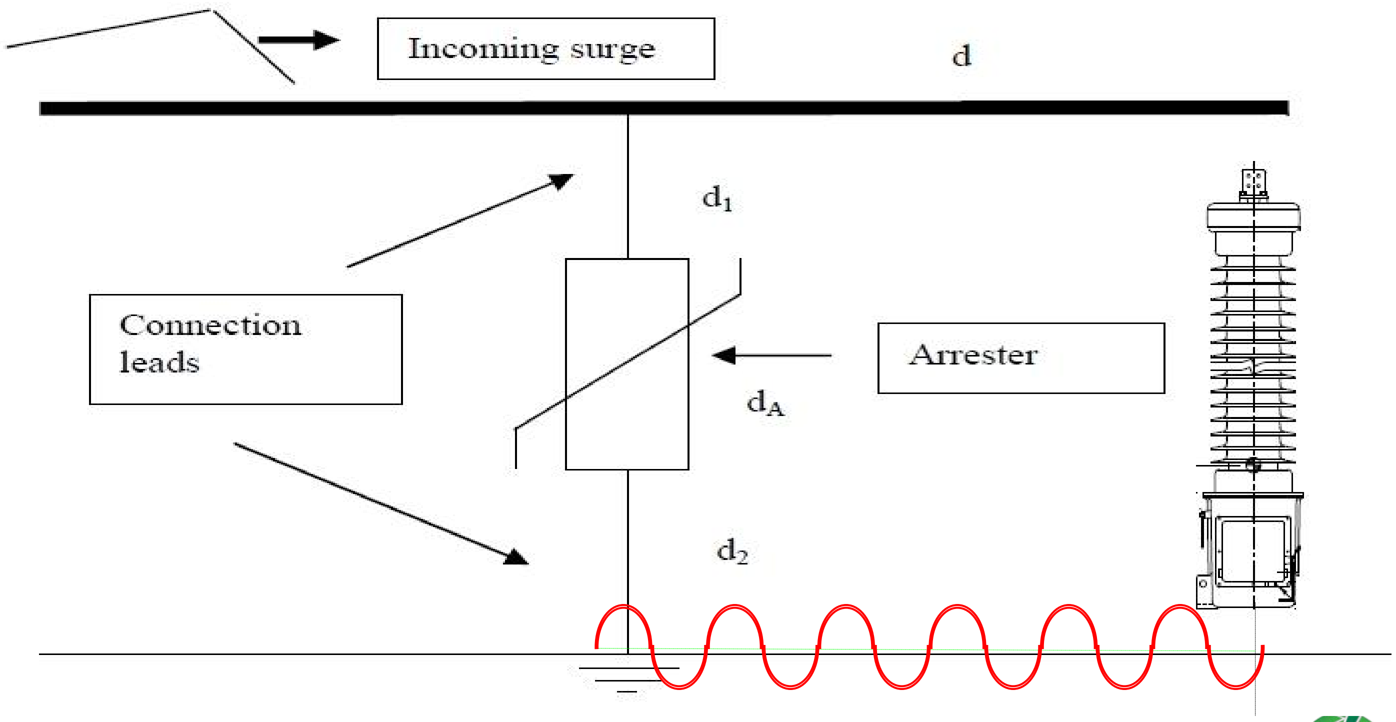
- **For standard lightning surge current test waves (8 x 20 µs), the value is approximately 1.6 kV/ft.**
- **For actual lightning current, this value is between 6-10 kV/ft.**

$$v(t) = L * \frac{di(t)}{dt}$$

$$L = \sim 0.4\, uH/ft$$

Lead Length

- Wire acts as a large inductance (impedance) to surges
- All lead lengths are crucial to proper operation of arresters and needs to be as SHORT as possible



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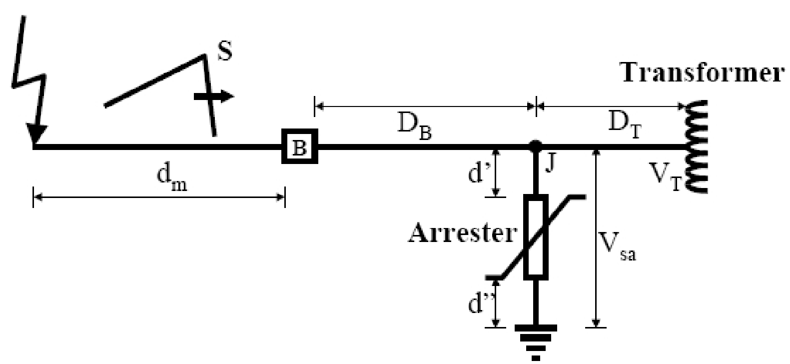
Calculation of Lead Length

c=		300	(m/us)	Velocity of Light 300 m/us
Vsa=	Va+L(di/dt)	1248	(kV)	Calculated
S=	Kc/dm	500	(kV/us)	
Vt=	1.1(xfmr BIL/1.15)= .957xfmr BIL	1243	(kV)	Calculated
Va=		1140	(kV)	Surge arrester data page 10 (FOW)
L=	(d'+d").313=	5.024	(uH/m)	Calculated (Value of .313 uH per meter) Actual reactance value 4/0CU
di/dt=	2S/Z	21.53	(kA/uH)	Calculated
Z=		325	Ohms	IEEE C62.11-2005 Table 11
d'=		2	Meters	Measured
d"=		14	Meters	Measured
xfmr BIL=		1300	kV	Transformer Name Plate
Kc=		1000	kV-km/us	IEEE C62.22 Table C.1
dm=	1/n(MTBF)(FOR/100)	2		
MTBF=		100	Years	IEEE C62.22 page 99 ref.
FOR		2	flashovers/100 km-year	Assigned value Substation Engineering Manual
n=		1	line	One Line #of Lines (1 line is worst case)

Arrester Ground Lead Length
Too Long To Protect

$$Dt = \frac{(.385)cVsa}{S} \; \frac{(0.957\ \text{xfmr BIL}) - Vsa}{(2.92\ Vsa) - (0.957\ \text{xfmr BIL})} = -0.49\ \text{Meters}$$

Ref IEEE Std C62.22-2009 Annex C

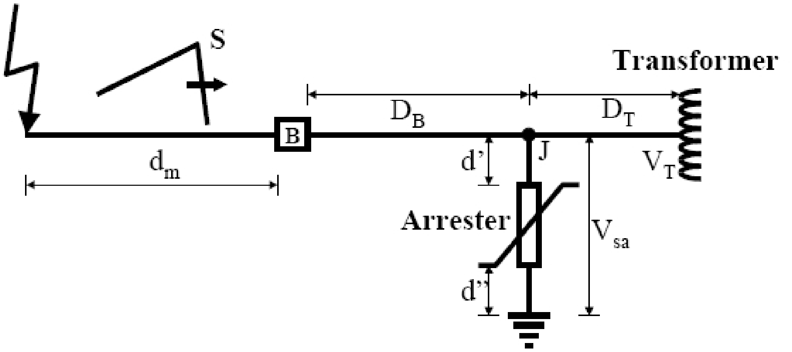


Calculation of Lead Length

c =			300	(m/us)	Velocity of Light 300 m/us
Vsa =	Va+L(di/dt)		1187	(kV)	Calculated
S =	Kc/dm		500	(kV/us)	
Vt =	1.1(xfmr BIL/1.15)=	.957xfmr BIL	1243	(kV)	Calculated
Va =			1140	(kV)	Surge arrester data page 10 (FOW)
L =	(d'+d").313=		2.198	(uH/m)	Calculated (Value of .313 uH per meter) Actual reactance value 4/0CU
di/dt =	2S/Z		21.53	(kA/uH)	Calculated
Z =			325	Ohms	IEEE C62.11-2005 Table 11
d' =			2	Meters	Measured
d" =			5	Meters	Measured
xfmr BIL =			1300	kV	Transformer Name Plate
Kc =			1000	kV-km/us	IEEE C62.22 Table C.1
Dm =	1/n(MTBF)(FOR/100)		2		
MTBF =			100	Years	IEEE C62.22 page 99 ref.
FOR			2	flashovers/100 km-year	Assigned value Substation Engineering Manual
n=			1	line	One Line #of Lines (1 line is worst case)

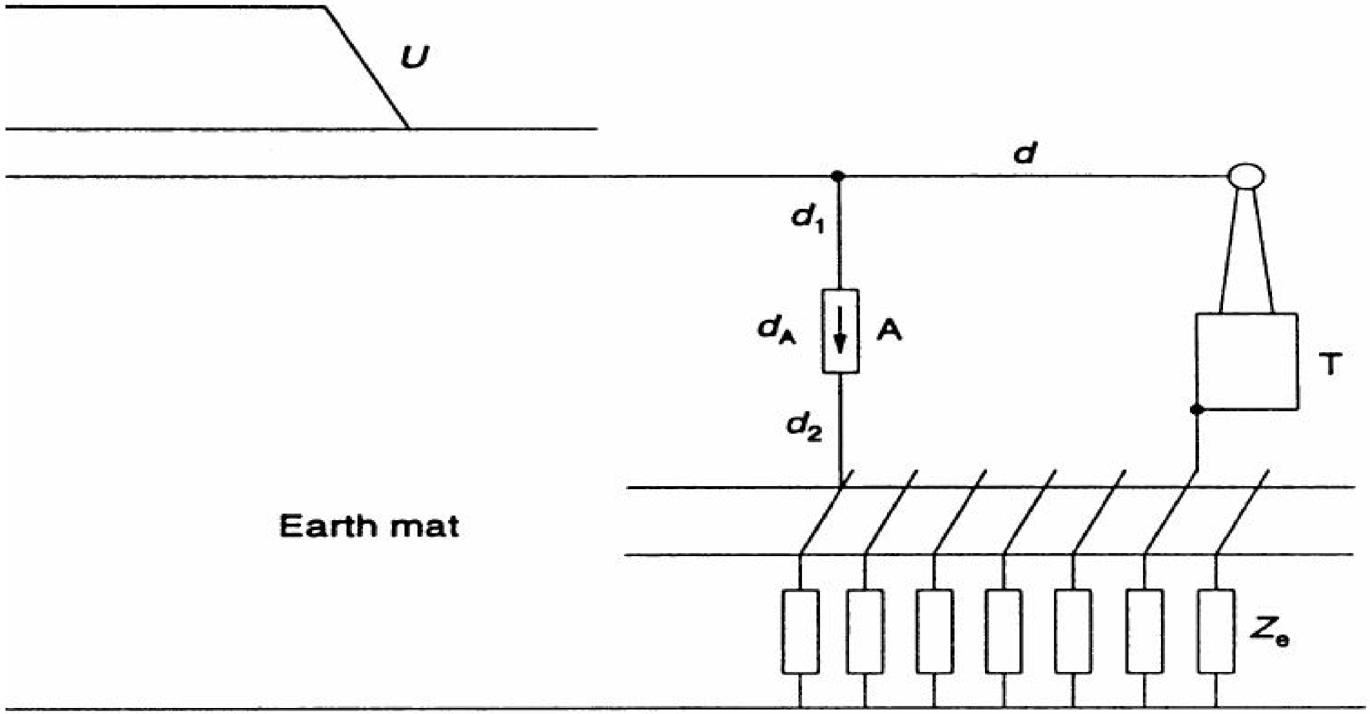
$$Dt = \frac{(.385)cVsa}{S} \quad \frac{(0.957\ xfmr\ BIL) - Vsa}{(2.92\ Vsa) - (0.957\ xfmr\ BIL)} = 7.003\ \text{Meters}$$

Ref IEEE Std C62.22-2009 Annex C



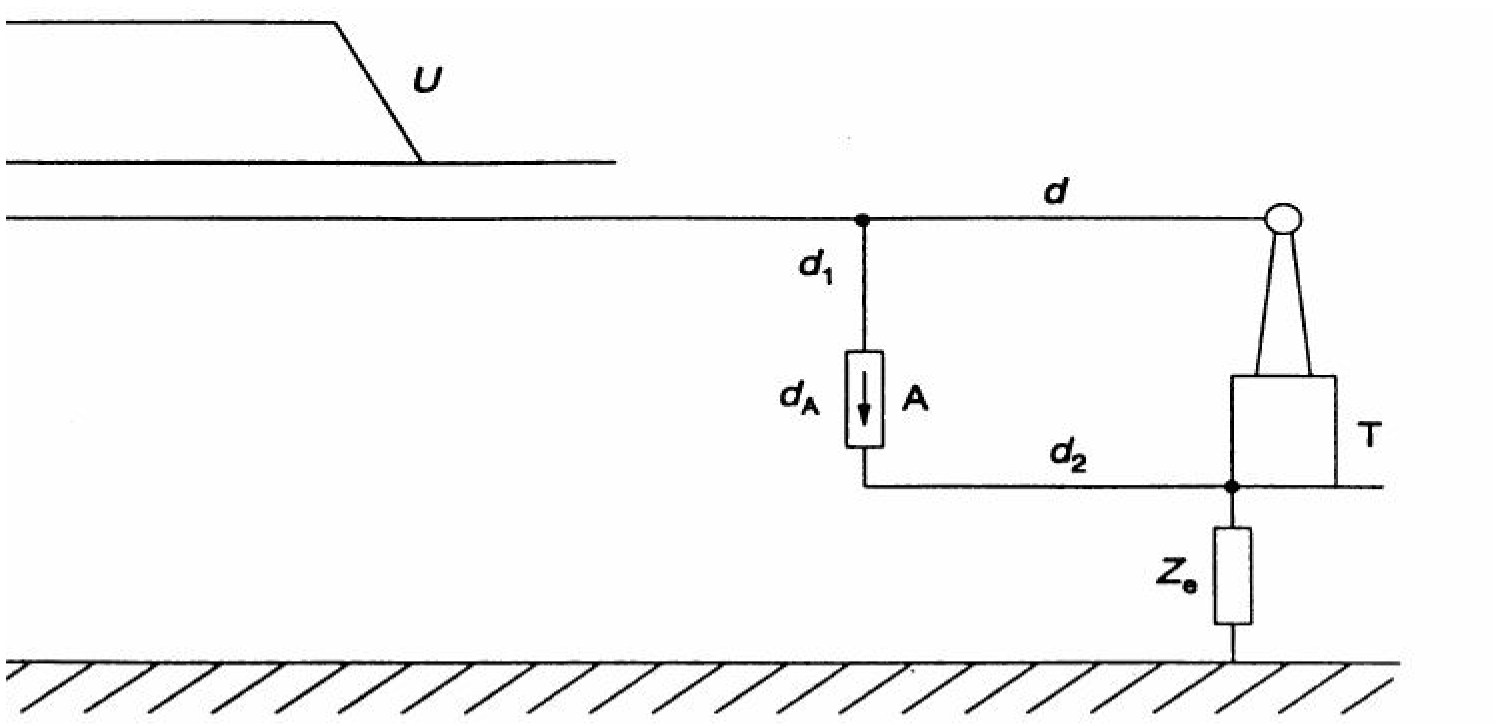
Lead Length

- All lead lengths are crucial. For proper operation of arresters and needs to be as SHORT as possible



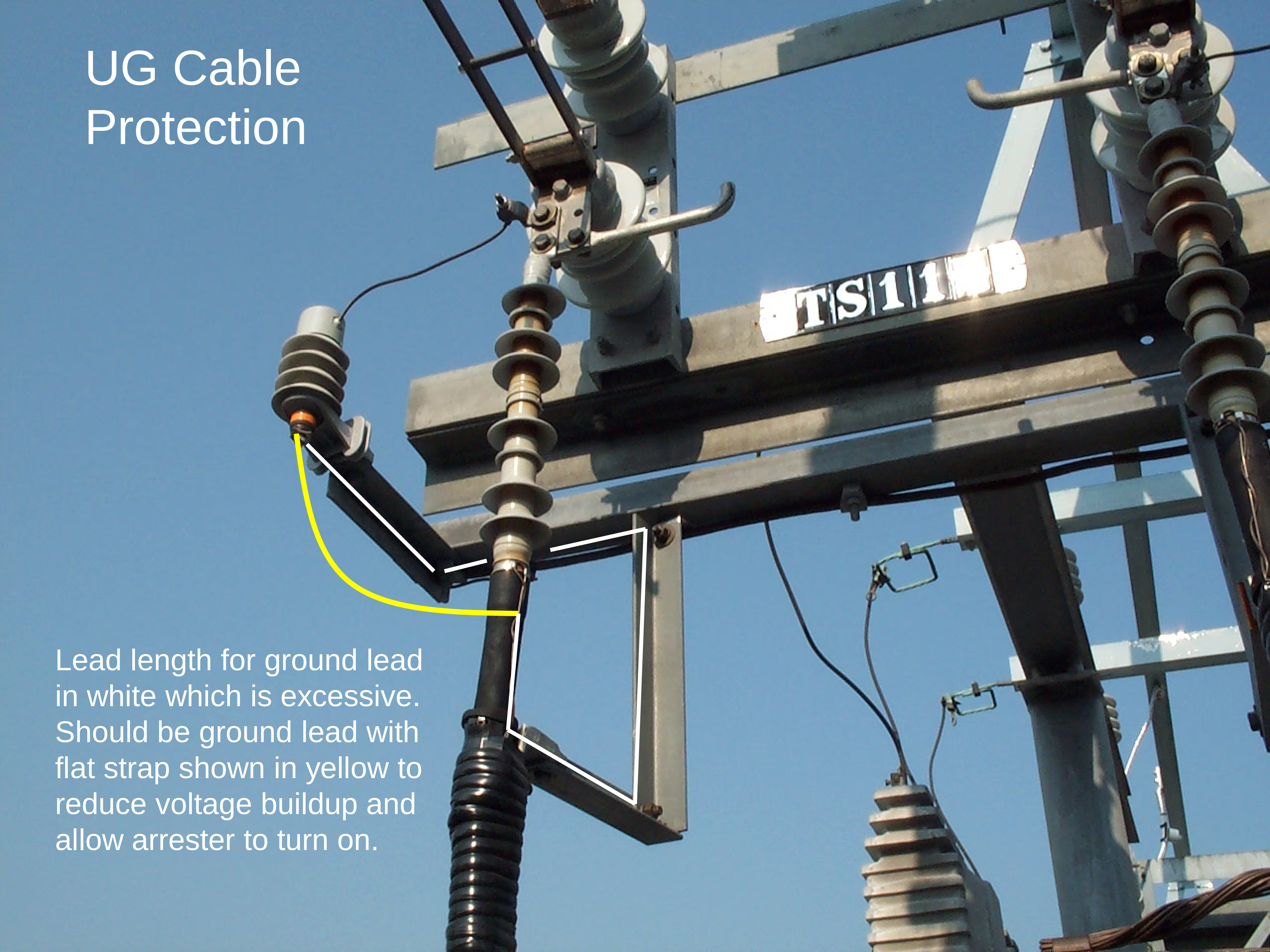
Lead Length

- For both d1 and d2, add inductance and increase the discharge level of the arrester




Braided Strap

UG Cable Protection



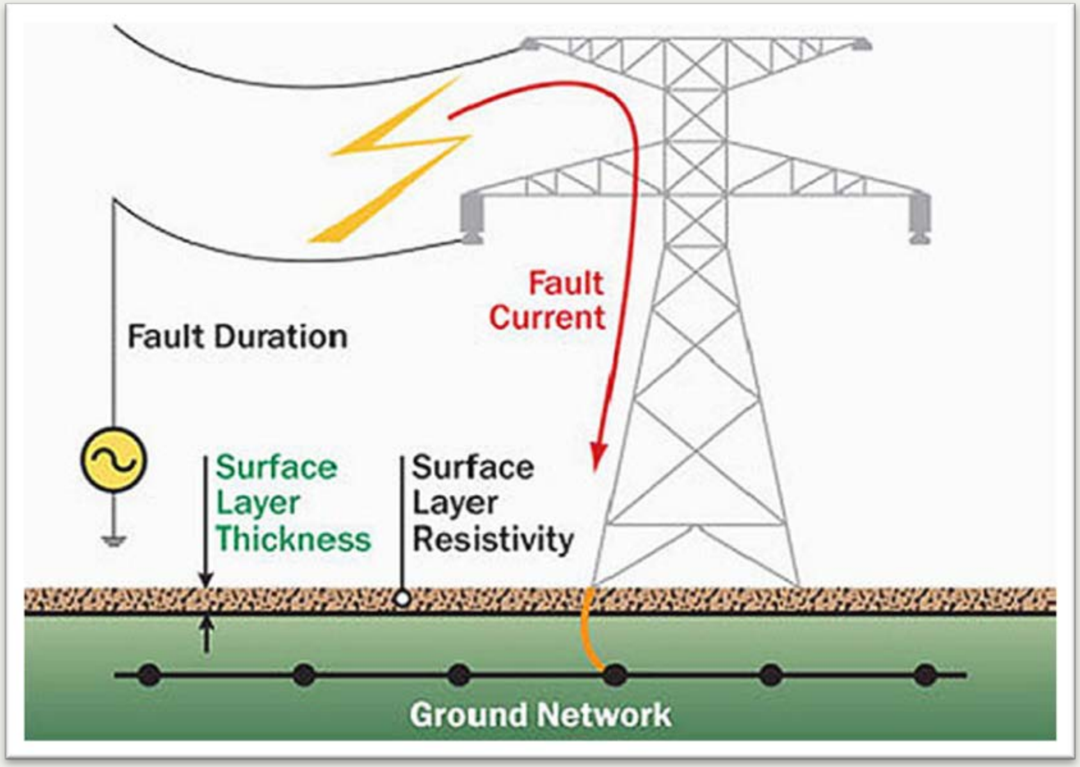
Lead length for ground lead in white which is excessive. Should be ground lead with flat strap shown in yellow to reduce voltage buildup and allow arrester to turn on.

Transmission and Distribution Structure Grounding

Transmission and Distribution Grounding

Reliability of the transmission and distribution system depends upon properly grounded structures.

When installing, replacing or enhancing transmission and distribution structures, it is critical to ensure that the grounding system adequately supports the resistance requirements.



Structure Grounds

Poorly grounded structures:

- Can cause protective devices and equipment to fail:
  - Increasing preventable outages such as damage to transformers and associated equipment
  - Waste repair time, effort and money
- Provide an unreliable personal protective source

Properly grounded structures protect against:

- External surges caused by storms, debris, trees, animals, etc.
- Internal surges such as switching, hardware and equipment failures

Line Pole Fire

Earth Resistivity Testing

What is earth resistivity?

- Earth's resistance to current flow from a ground electrode
- Largest factor influencing ground system effectiveness

What factors affect earth resistivity?

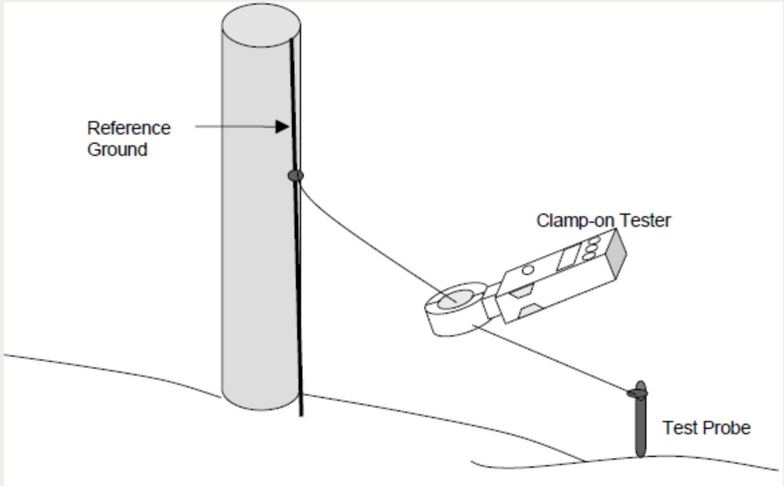
- Type of soil
- Amount of moisture/presence of salts
- Temperature

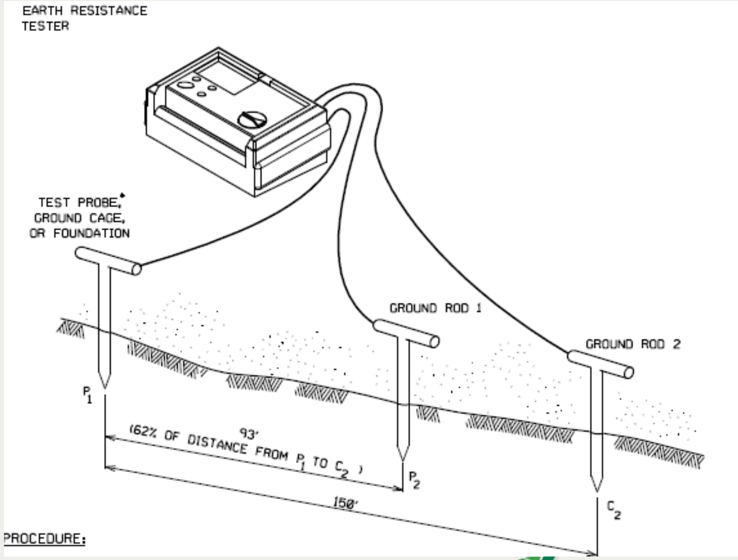
Table 1—Geological period and formation [B57]

Earth resistivity ohm-meters	Quarternary	Cretaceous tertiary quarternary	Carboniferous triassic	Cambrian Ordovician Devonian	Precambrian and combination with Cambrian
1 Sea water					
10 Unusually low		Loam Clay			
30 Very low		Chalk	Chalk		
100 Low			Trap Diabase Shale		
300 Medium			Limestone Sandstone	Shale	
1000 High				Limestone Sandstone	
3000 Very high	Coarse sand and gravel in surface layers			Dolomite	Sandstone Quartzite
10 000 Unusually high					Slate Granite Gneisses

Resistivity Testing

- Soil resistivity can vary greatly, both vertically and horizontally
- Clamp-on Method
- “Three Point” Method
- Identify the area with the lowest possible resistivity prior to burying grounding components
- Properly grounded R ≤ 25Ω



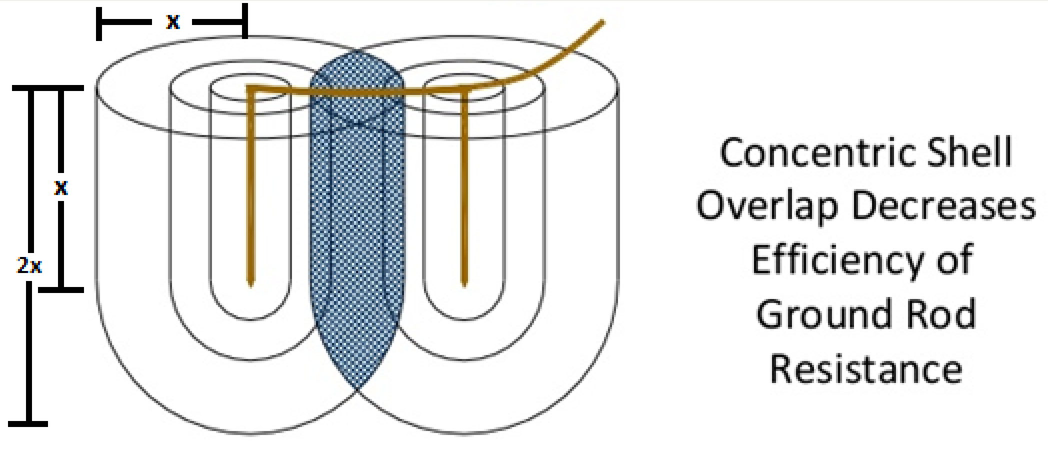


Foundation Construction

- Engineered poles or lattice towers
- Reinforced concrete foundations that continue the conductive path from structure to Earth, allowing the foundations to act as grounding electrodes.
- Anchor bolt cluster and reinforced cages are bonded together inside the foundation

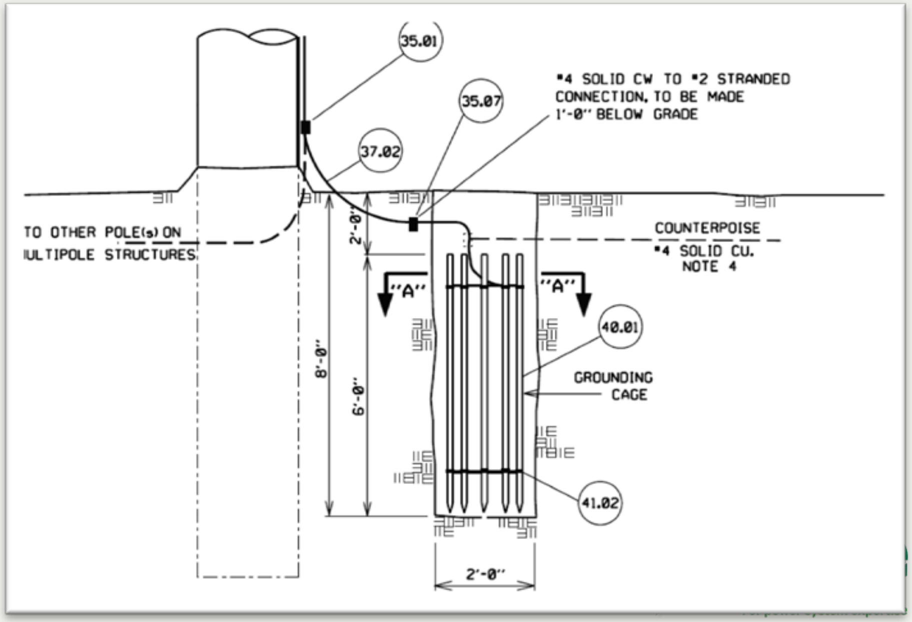
Structure Grounding

- Ground rods are influenced by soil surrounding rods and proximity to adjacent rods
- Soil resistance influences impedance seen when tested due to air and type of soil around grounding conductor / rod
- Parallel conductors or rods provide lower high-frequency designs



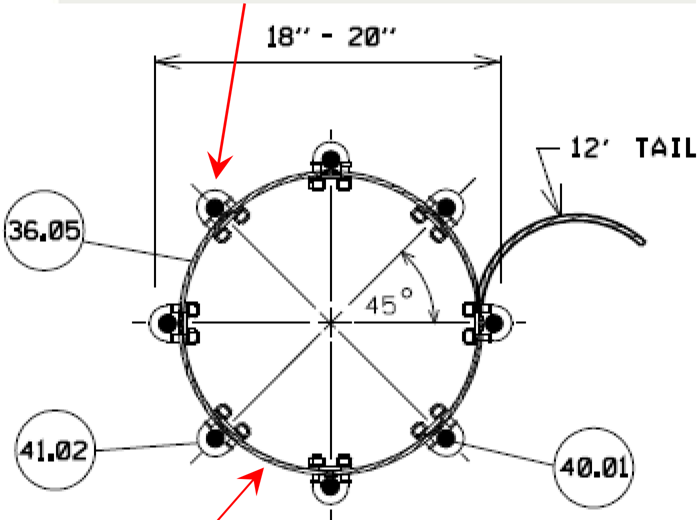
Monopoles / Steel Poles / Wood Poles

- Ground cage assembly
- Ground rods joined together in a cylindrical shape by No. 2 stranded copper wire
- Grounding cages provide significantly better ground contact and lower surge impedance for grounding systems

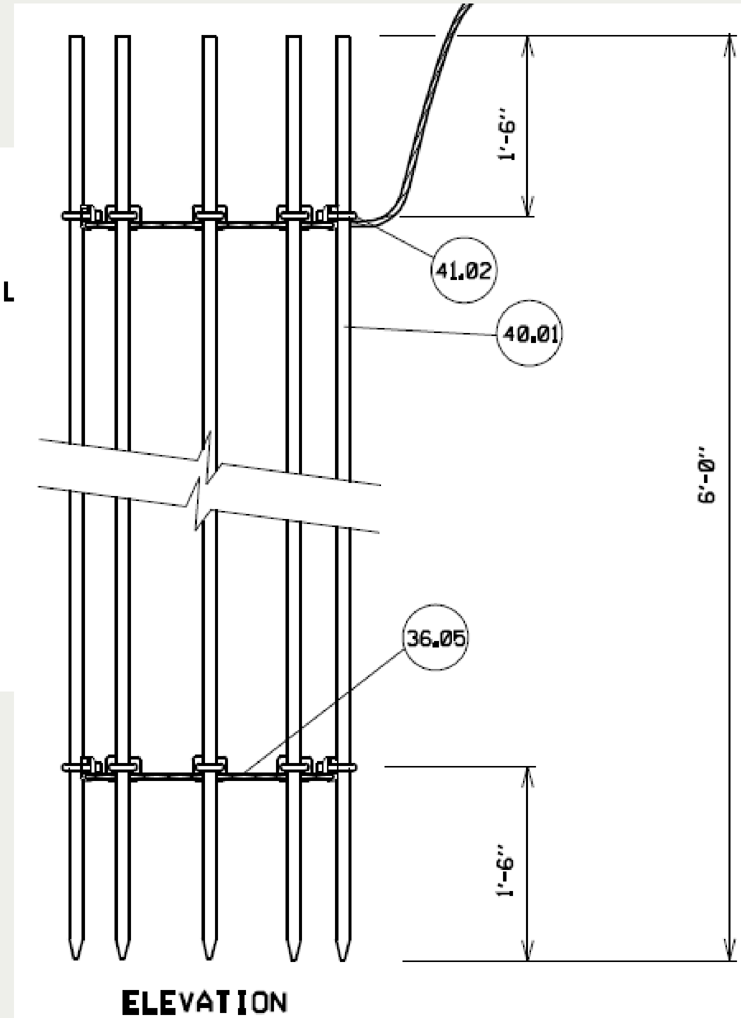


Grounding Cage

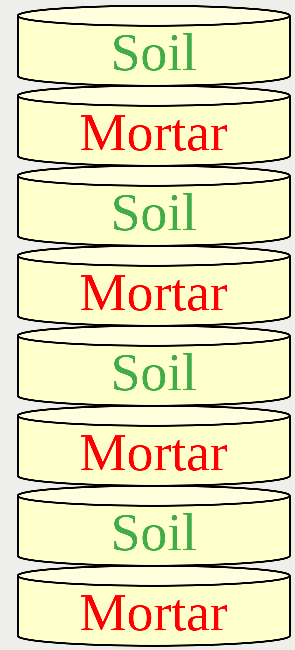
6-Foot Ground Rod



No. 2 Stranded Cu Wire



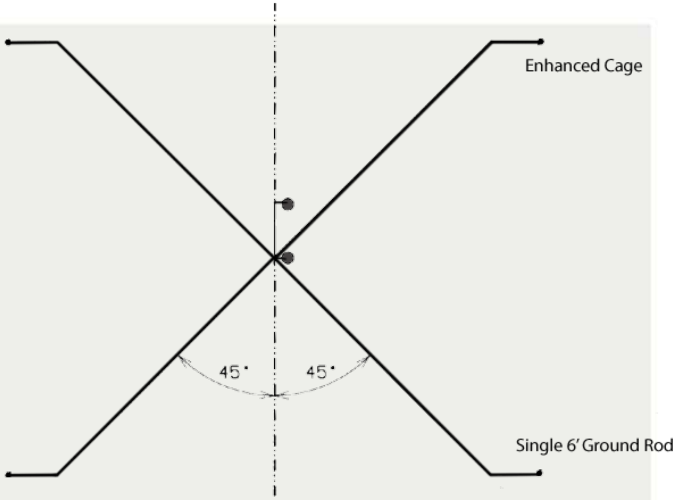
Backfilling of Cage Hole



Note: *Enhancing material consists of six 70-lb. bags of Type-N mortar mix.*

Counterpoise

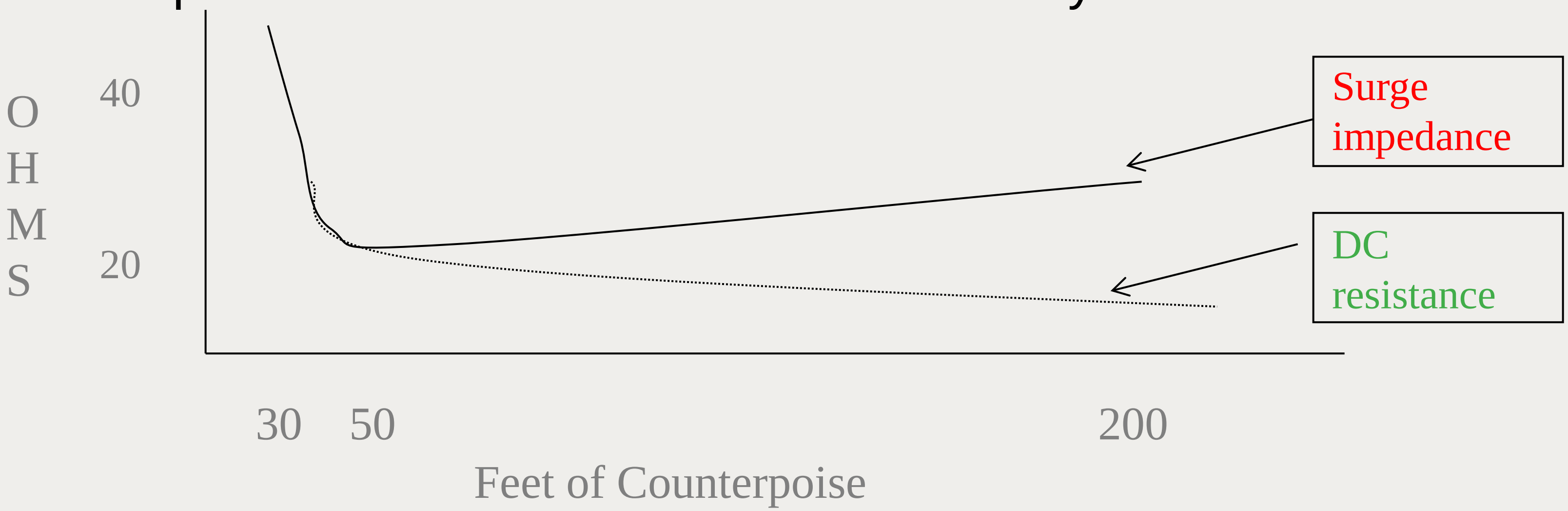
A system of trenched No. 4 solid wire buried at a minimum of 2 feet that consists of several legs originating at the base of the structure and spreading out in a radial pattern.



- Increases the total surface area of Earth that comes in contact with the grounding system and thus provides greater grounding coverage
- The design is based on soil resistivity test results
- Minimum of three and a maximum of four legs installed per structure
- Each leg of counterpoise should be at least 30 feet long but no longer than 50 feet
- A ground rod or grounding cage is connected and buried at the end of each leg

Counterpoise

- Counterpoise is used to provide a lower resistance ground but should not exceed 200 feet as surge impedance of wire will make it ineffective (~100 feet and multiple legs)
- Counterpoise must have ground rods on ends of wire to get to deeper soil to maintain resistance under dry soil conditions

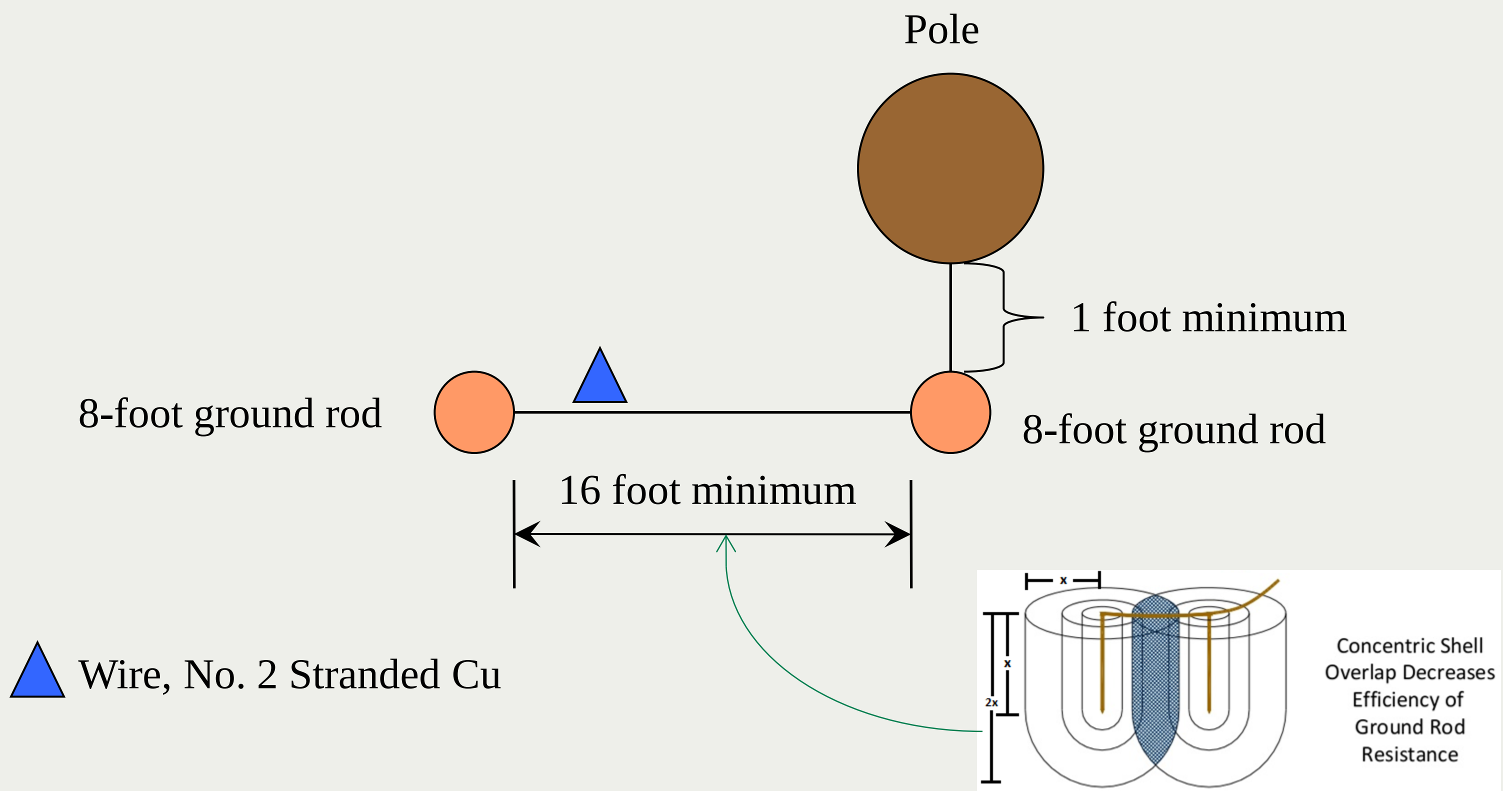


Test shows ohmic value should not exceed 40 ohms to be effective in absorbing surges.

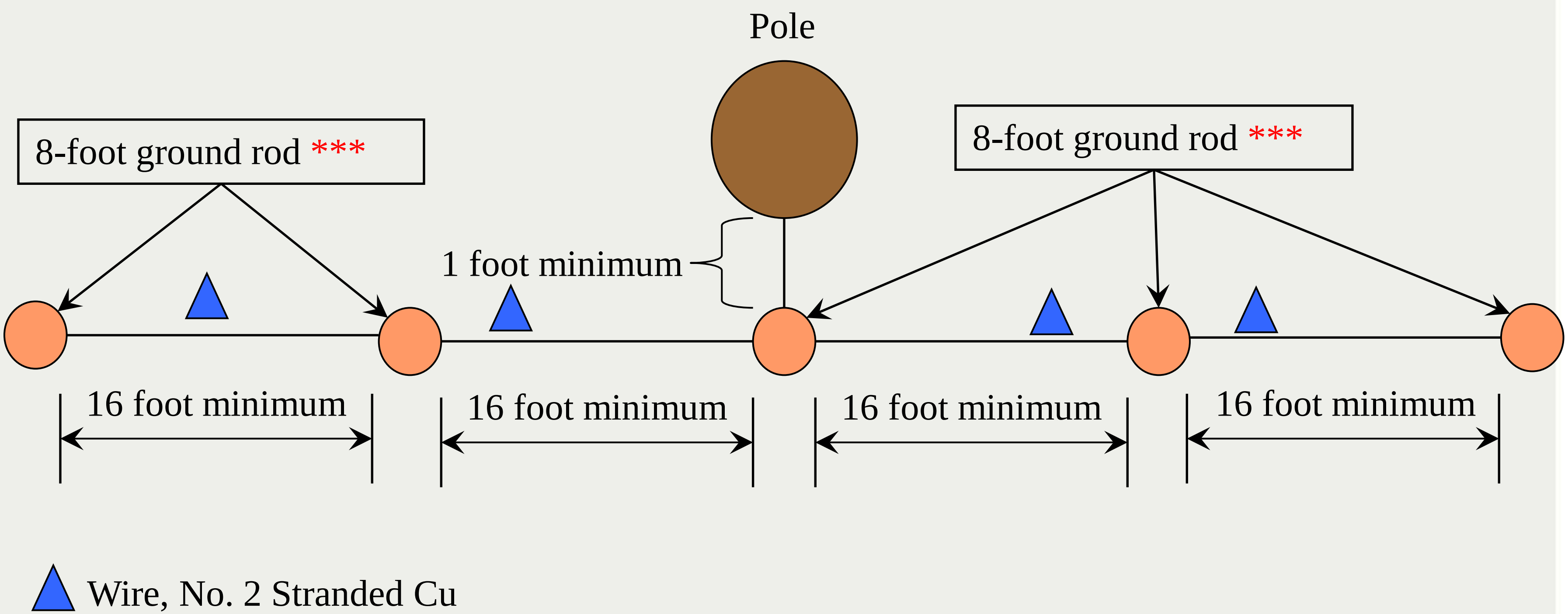
Example Counterpoise Configurations

Test Results		Case 1	Case 2	Case 3
Test Rod Resistance Range (ohms)	Eight Foot Rod Resistance Value (ohms)	Base Case + 1 Additional Eight Foot Rod	Base Case + 2 stacked 8 foot rods (or two 16 foot rods)	Base Case + 3 Enhanced Grounding Cages
0 – 400	0 – 85	X		
400 – 1000	85 – 230		X	
1000 & up	230 & up			X

Case 1: Installing a second 8-foot ground rod at a minimum of 16 feet from the initial test rod.

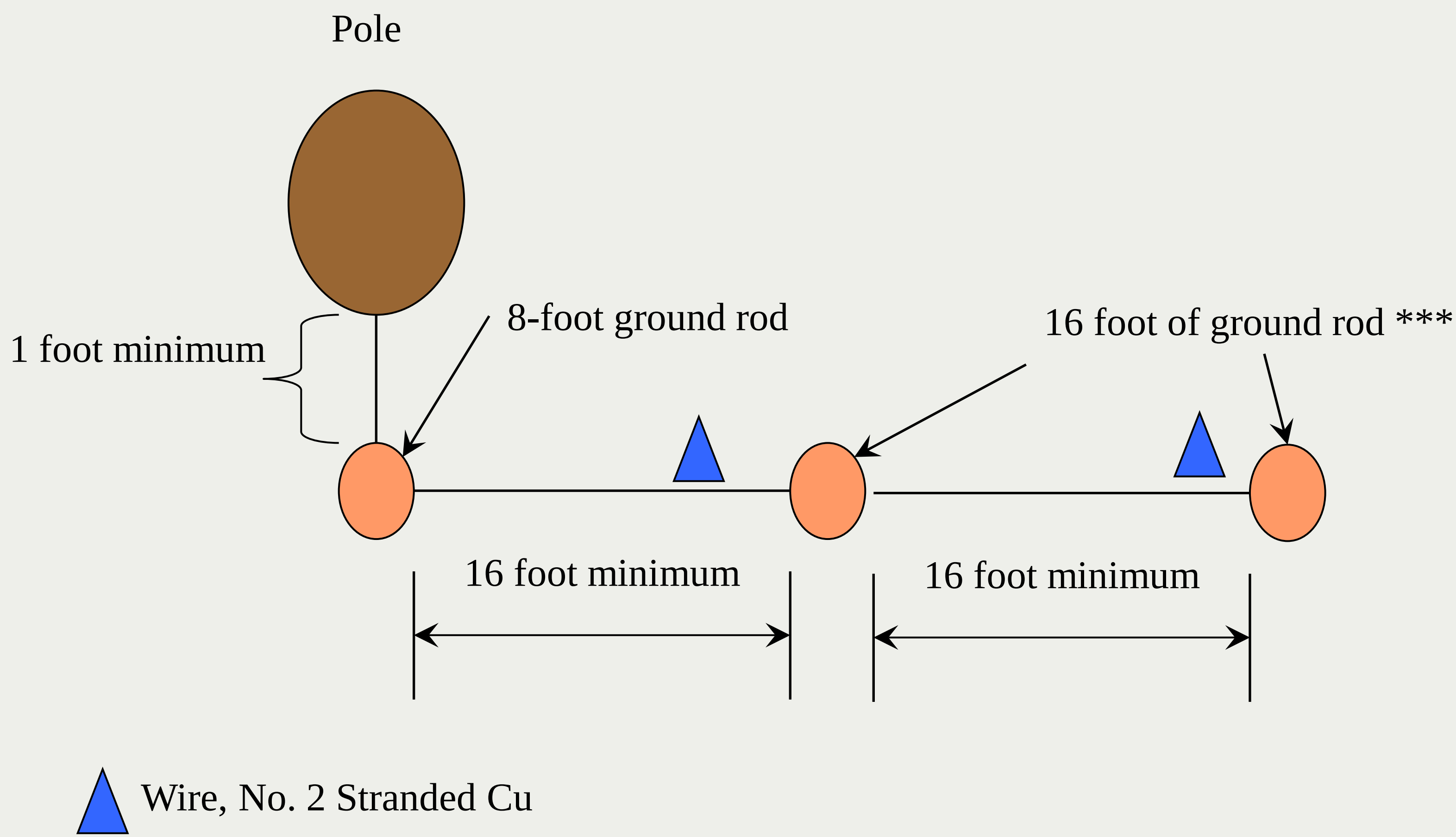


Case 2: Installing four 16-foot counterpoise with 8-foot rods.



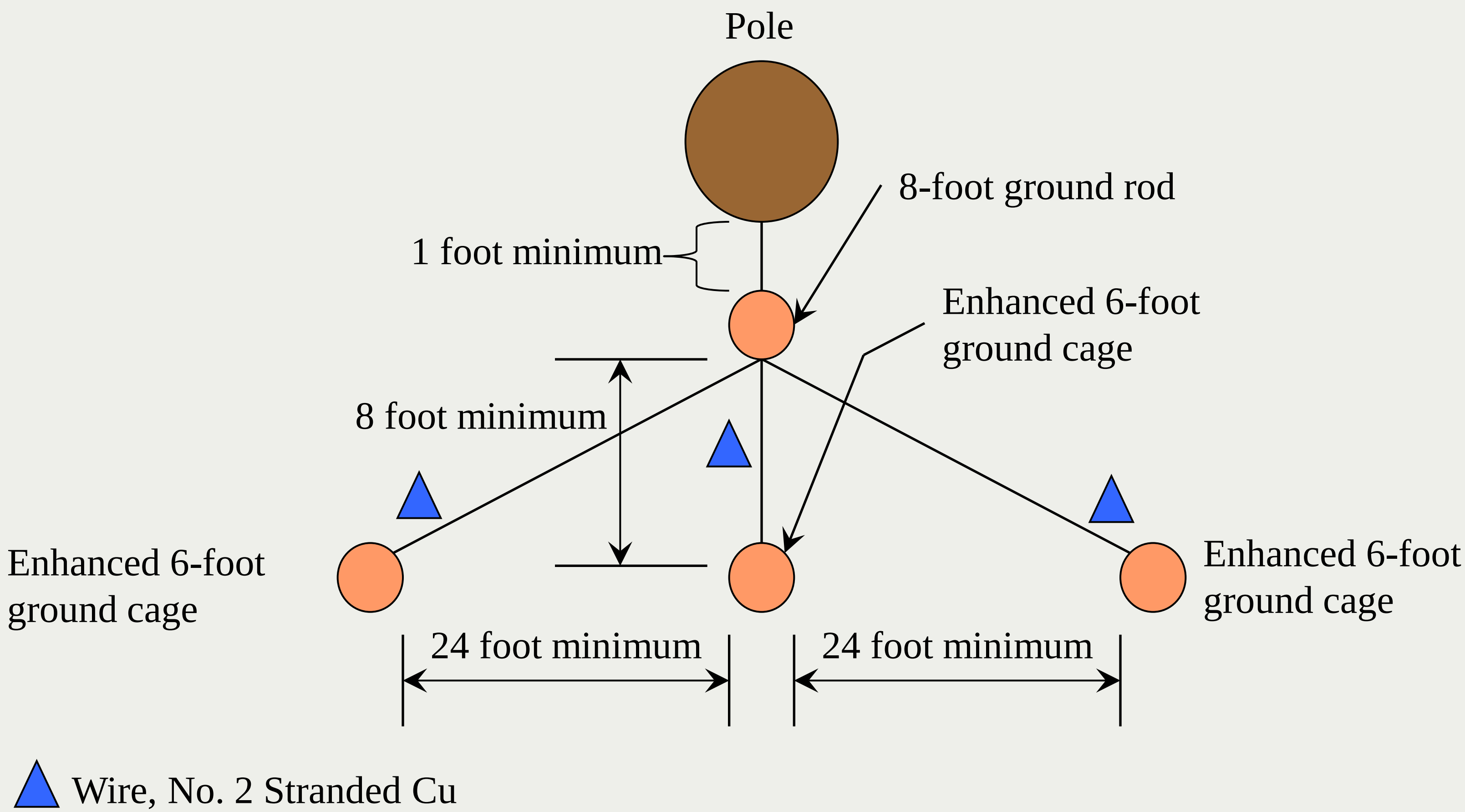
****** *Drive one 8-foot rod in each location, attach counterpoise, read. If necessary, replace one end rod with a cage.***

Case 2 (Alt.): Installing two 16-foot counterpoise with two stacked 8-foot rods.



****** Drive one 8-foot rod in each location, attach counterpoise, read. If necessary, add second rod.***

Case 3: Installing three 6-foot enhanced cages and one 8-foot rod.

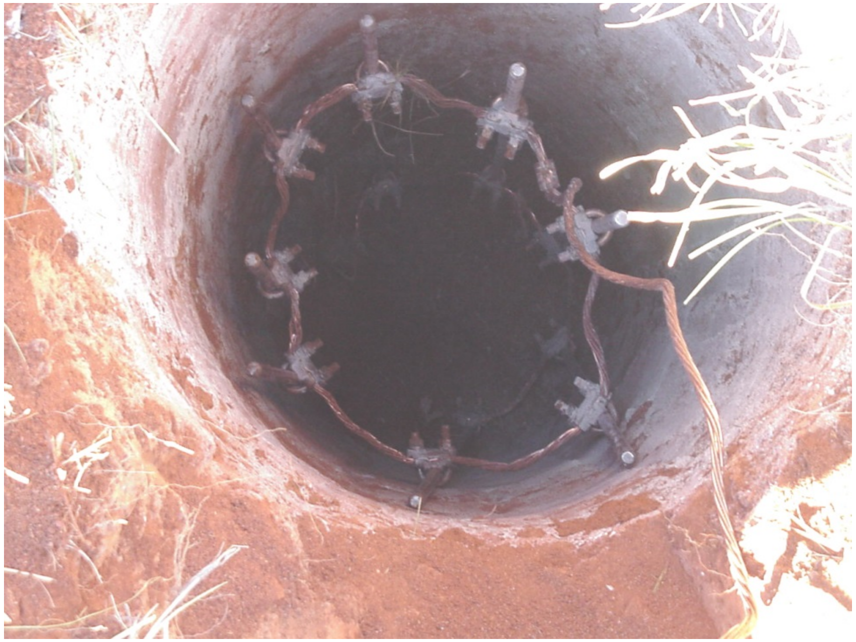


Note: *Enhancing material consists of Type-N mortar mix. It is required when the test rod ohms exceed 1100 ohms or OL on the meter.*

Ground Cage Installation

Ground Cage Installation

Ground Cage Installation



Structure Grounding Takeaways

- Install ground components in lowest resistance area
- Combine grounding rods and cages in counterpoise to increase effectiveness
- Use Type-N mortar mix to improve soil conductivity
- Strive for ~25 Ohms to achieve adequate ground

Substation Grounding Design

Grounding Systems in a Substation

Purpose

- Provides a surface under and around a substation that is:
  - ✓ At a uniform voltage
  - ✓ As close to zero as is economically feasible (0.75 volts or lower)

Definition: Ground Grid or Ground Mat

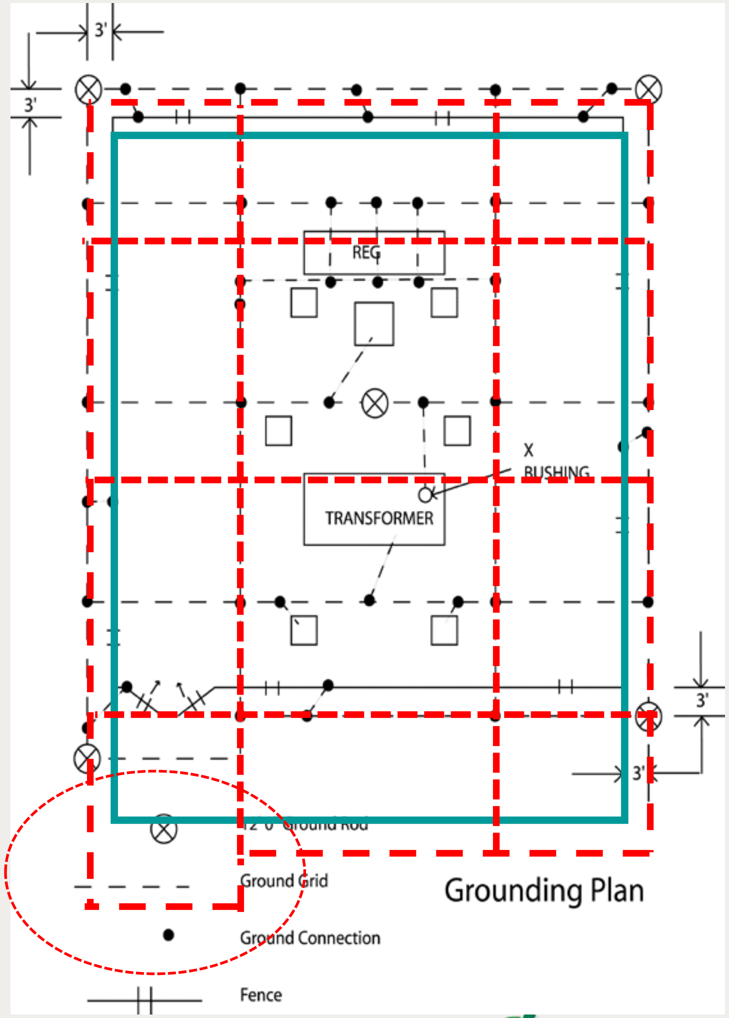
- Grounded system of wires and rods interconnected beneath substations
  - ✓ Designed to Reduce Potential (Voltage) Hazards
    - ➢ Step and Touch Potential
    - ➢ Provide Equipment Grounding

Grounding System Design

Goal:

Provide a surface under and around the substation that is at *uniform ground potential*

(as close to zero as is economically feasible: 0.75 volts or lower)



Grounding accomplished by:

- ✓ Formation of a ***ground mat or ground grid***
  - Includes the fence
  - Bury 4/0 cable in ground
  - Perimeter conductor 3 foot outside fence
  - Perimeter conductor 6 foot beyond gates
- ✓ All structures/equipment connected
- ✓ All neutrals of the power system are connected

Substation Ground Grid Design Standards

Ground grid design standards are generally based on conservative, worst-case assumptions:

- Worst case, single contingency phase-to-ground fault currents
- Worst case, single-contingency fault clearing times
- Most conservative soil model

Step 1 – Soil Analysis and Modeling

Sources of Error

- Background AC noise
- Bare buried metallic structures
- Instrument error
- Ground loops
- Poor connections
- Failure to plot data in the field

Step 2 – Fault Current Model and Earth Current Split Calculation

- Determine all transmission and distribution lines entering/leaving the substation
- Static wire
    - Type
    - Configuration
    - Continuity
- Determine available line-to-ground fault current
- Build current model

Step 3 – Ground Grid Spacing, Layout and Safety Analysis

- Use soil model and current model to determine safe step and touch potentials
- Evaluate the ground grid design based on calculation results
- Iterate the grounding design to improve safety
- Import grounding design into grounding plan

References

- ANSI/IEEE Std 80, IEEE Guide for Safety in AC Substation Grounding, 2000
- ANSI/IEEE Std 81, IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System
- IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems
- IEEE Std 665-1995, IEEE Standard for Generating Station Grounding.
- IEEE Std 487, Recommended Practice for the Protection of Wire-Line Communication Facilities Serving Electric Supply Locations.
- IEEE 776-1992 (R1998) IEEE Recommended Practice for Inductive Coordination of Electric Supply and Communication Lines. (Reaffirmed-2003).
- IEEE 1137-1991 (R1998) IEEE Guide for the Implementation of Inductive Coordination Mitigation Techniques and Applications. (Reaffirmed-2003).
- P1590 Draft Recommended Practice for the Electrical Protection of Optical Fiber Communication Facilities Serving or Connected to Electrical Supply Locations.
- Send e-mail to Larry Young/Percy Pool to get copy
- IEEE Std 837-1989, IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding (New Edition: 2002)
- IEEE Std 1246-1997, IEEE Guide for Temporary Protective Grounding Systems Used in Substations.
- IEEE Std 1048-1990, IEEE Guide for Protective Grounding of Power Lines
- IEEE Std 525-1992, IEEE Guide for the Design and Installation of Cable Systems in Substations.
- IEEE Std C37.122-1993, IEEE Guide for Gas-Insulated Substations.
- National Electrical Code
- National Electrical Safety Code

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Selection of Ground Grid Components and Connections

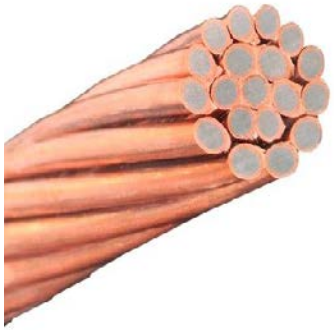
- Resist fusing and deterioration under the most adverse combination of fault current magnitude and duration
- Mechanically reliable and rugged to a high degree
- Sufficient conductivity, as to not contribute to local voltage differences
- Be able to function when exposed to corrosion or physical abuse

Components of a Ground Grid

Standard Ground Conductors:

- 4/0 CU
- 19#9 CCS
- #4 CCS SOL
- #4 AL SOL (Fence Fabric)

Soft Drawn Copper (CU)



Copper Clad Steel (CCS)

Components of a Ground Grid

Ground Rods

- Copper weld or equivalent
- 5/8 inch in diameter
- Free from grease and paint
- Minimum of one 6-foot section at each location

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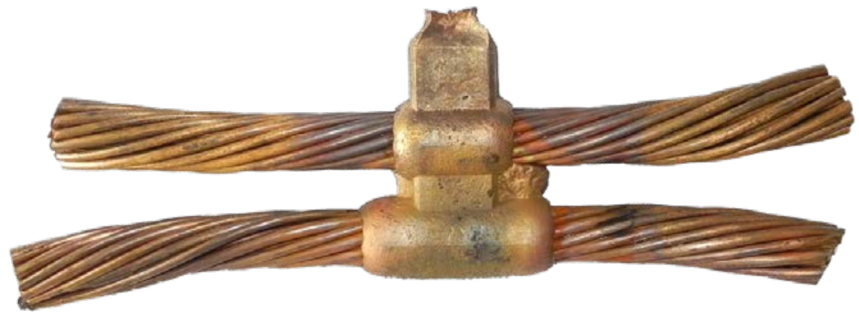
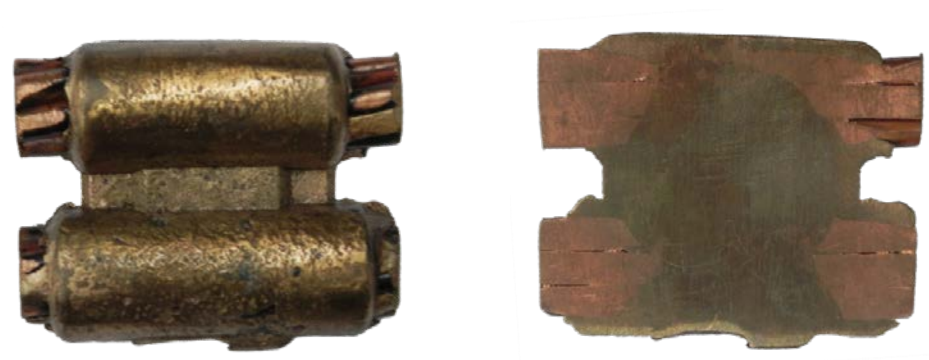
Ground Grid Connections – Below Grade

Standard: Exothermic welds for ALL below-grade connections





Cross-section of parallel connection

Ground Grid Connections – Above Grade

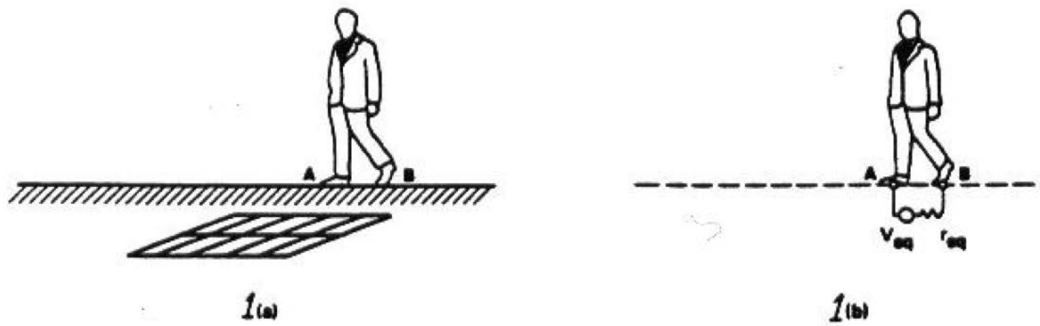
Standard Ground Connections:
- 1H or 2H compression connector
- Exothermic welds (fence post)

Personnel Safety Grounding

Important Concepts

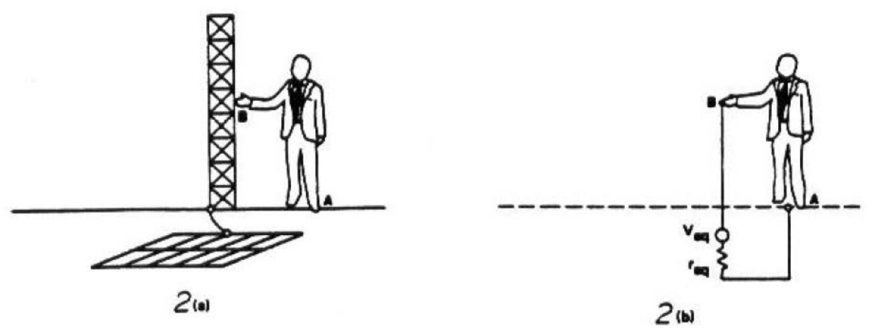
- Step Potential

Figure 1 - Equivalent circuit for computation of body currents due to step voltage

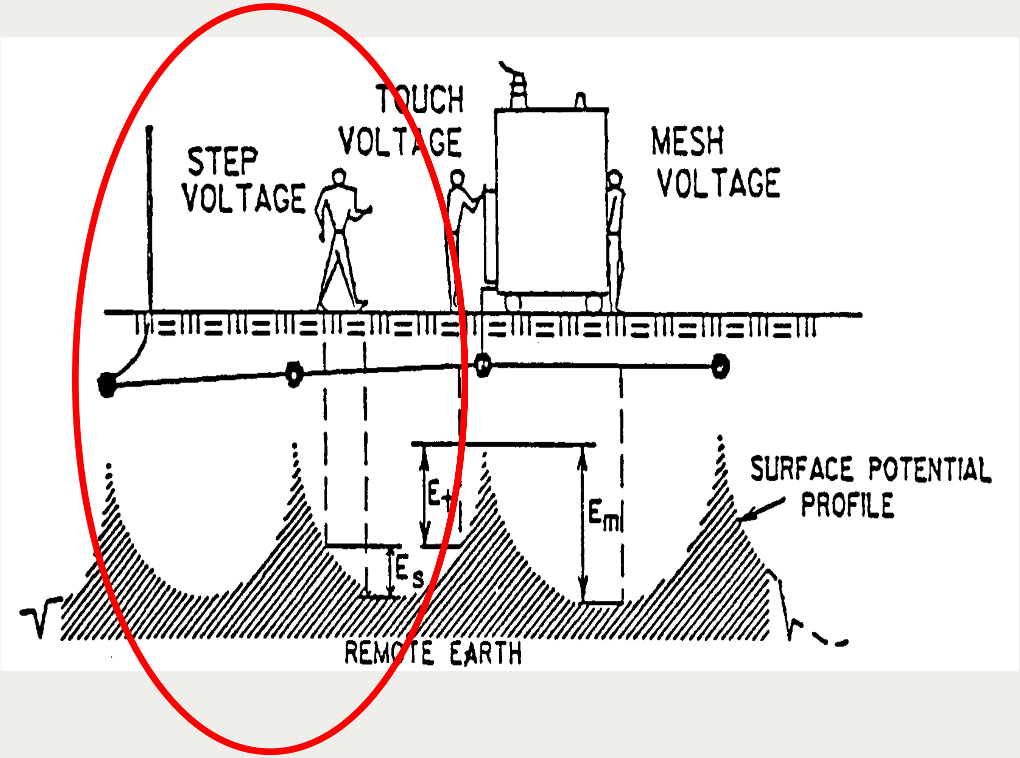


- Touch Potential

Figure 2 - Equivalent circuit for computation of body currents due to touch voltage



Personnel Potential Hazards



Step Voltage

http://electrical-engineering-portal.com/6-voltages-a-person-can-be-exposed-to-in-a-substation

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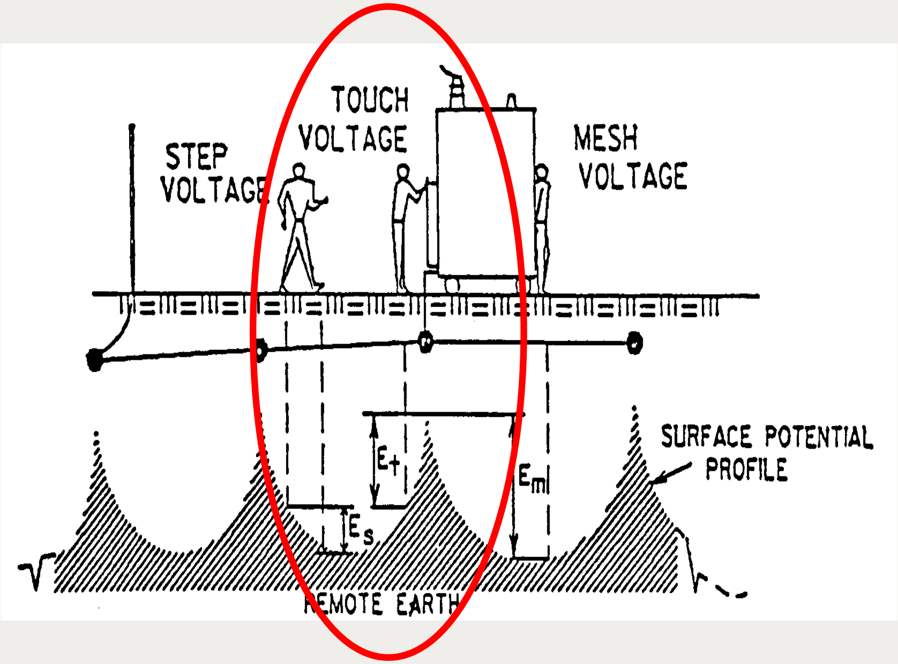
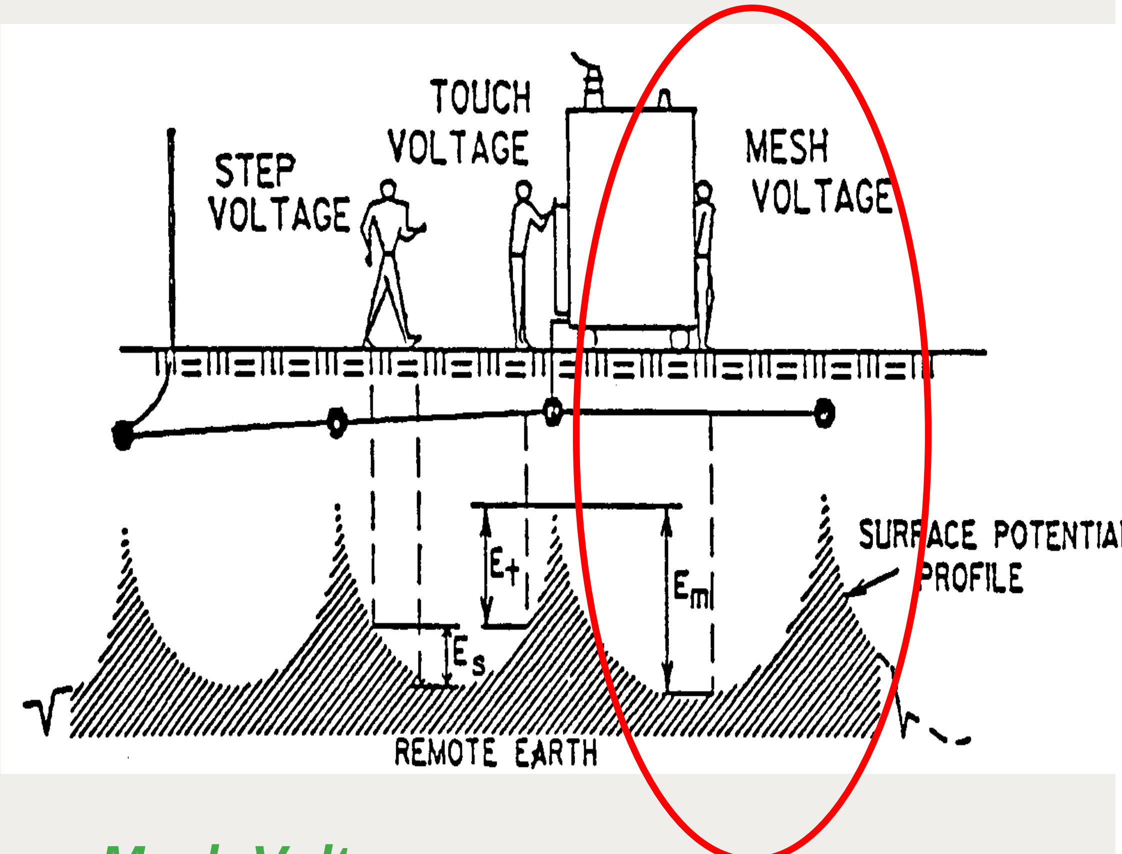
Personnel Potential Hazards



Touch Voltage

Personnel Potential Hazards



Mesh Voltage =
Maximum Touch Voltage

Substation Equipment Grounding

Grounding Substation Equipment

Goal: Provide a surface under and around the substation that is at *uniform ground potential*.

(as close to zero as is economically feasible: 0.75 volts or lower)

- ✓ All equipment is grounded to the station ground grid
- ✓ Has same potential

Substation Equipment

Circuit Breakers

- Tanks connected with two separate ground connections
- Each to a different section of the grid

Transformers

- Grounded with two separate connections
- Connections to two different sections of the ground grid
- When transformer neutral to be grounded directly, neutral and at least one case ground should be visibly connected together

Substation Equipment

Capacitor Banks

- Metal supporting structures are grounded regardless of whether capacitor neutral is grounded or ungrounded
- Supporting structure is grounded on diagonal corners with the ground lead being the same size conductor as the ground grid

Voltage Regulators

Tank or cases grounded with two separate ground connections, each from a different section of the grid:

- One connects to stand and then to tank
- One connects to tank and to SL bushing

Substation Equipment Grounding

- Switch Operating Mechanisms
  - Flexible braid
    - Connected to operating rod
    - Bonded to mounting steel
    - Steel structure grounded at base

- Switch Grates
  - Ground tails placed at alternate corners
  - Tails bonded above grade to switch stand leg
  - Same ground point as the operator handle (ensures that operator is same potential as equipment)

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Steel Structures

- Structure is grounded at the base plate
- Two ground conductors bonded to different X-Y crossings of ground grid
- Single-legged structures
  - Redundant conductors placed on adjacent corners of base plate
- Multi-legged structures
  - Single conductors on opposite legs
- Structures comprised of multiple steel members
  - Pieces are mechanical bonded by fasteners and no additional grounding is required.

Security Fence Grounding

- Perimeter ground ring
  - Internal loop
  - External loop
  - 3 feet off of fence line

- All post bonded to internal loop

- Individual panels jumpered at top and bottom of fence
  - Tied to grid every six line posts (max)

Control Enclosure Grounding

Effectively grounding the control enclosure will shield sensitive electronic components from high-voltage transients and high-altitude electromagnetic pulse (EMP) events. Important design features include:

- Metal enclosed top-of-building entry point for yard cables
- Perimeter ground grid ring installed at 3-foot offset around building footprint and tied to multiple ground grid crossings to allow for multiple bonding points for dedicated building ground conductors
- Building steel is externally grounded to the grid via predetermined ground pad locations. The conductors that ground the building externally are also bonded to the interior ground conductors at the base/corner ground bars with dedicated chases through walls.
- Internal ground bars are mounted in key locations inside the building and tied together with dedicated 4/0 CU conductors. Internal ground bars include:
    - Base/corner ground bars that are bonded to external building grounds (noted by G on plan view) with dedicated 4/0 CU conductors
    - Cable entrance points for a dedicated messenger bonding point to ground
    - Above the relay panels for a dedicated shield bonding point to ground

Takeaways

Selection of ground grid components meet four main requirements:

- Electrically conductive
- Corrosion resistant
- Adequate current carrying capacity
- Mechanically strong

A robust ground grid protects people AND equipment!

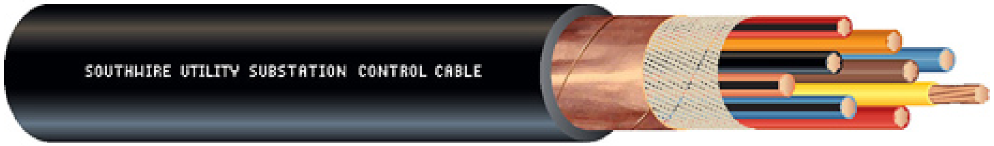
Shielded Control Cable and Messenger

Definitions

Electro Magnetic Interference (EMI)

EMI in high-voltage substations is a result of:

- Power frequency (60 Hz) faults
- Lightning
- Switching
  - Air break switches
  - Capacitor bank switching



Shielded Cable

Multi-conductor cables where the group is wrapped by a non-ferrous (non-magnetic) conductor that will provide immunity between magnetic coupled voltages.

Messenger (Parallel Ground Conductor)

A dedicated conductor (generally the same size or diameter as a ground grid conductor) that is placed in parallel with the control cable and connected at the two shield ground points.

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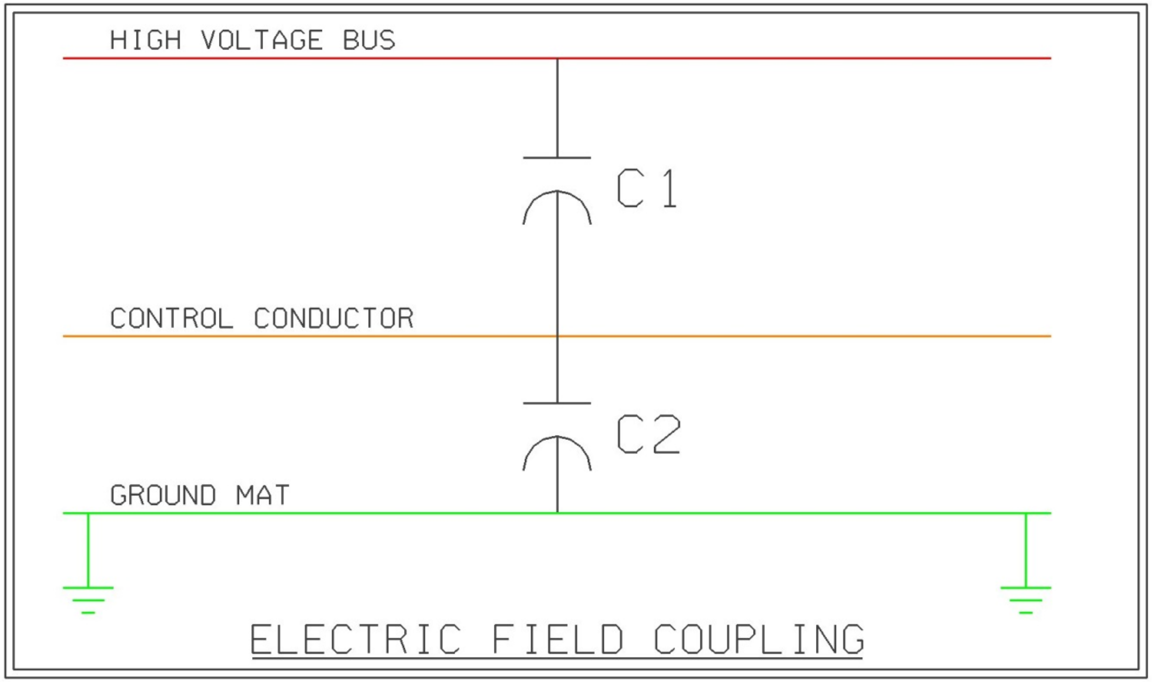
Unshielded Cable

<u>Electric Field Coupling</u>

- These capacitances act like a voltage divider connected to the control cable
- This results in some intermediate transient potential on the control cable



Unshielded Cable

<u>Magnetic Field Coupling</u>

- The rate of change of the magnetic field is rapid due to the high frequency of a surge current
- This makes it possible to induce a rather large transient voltage in a modest size loop, far away from the bus

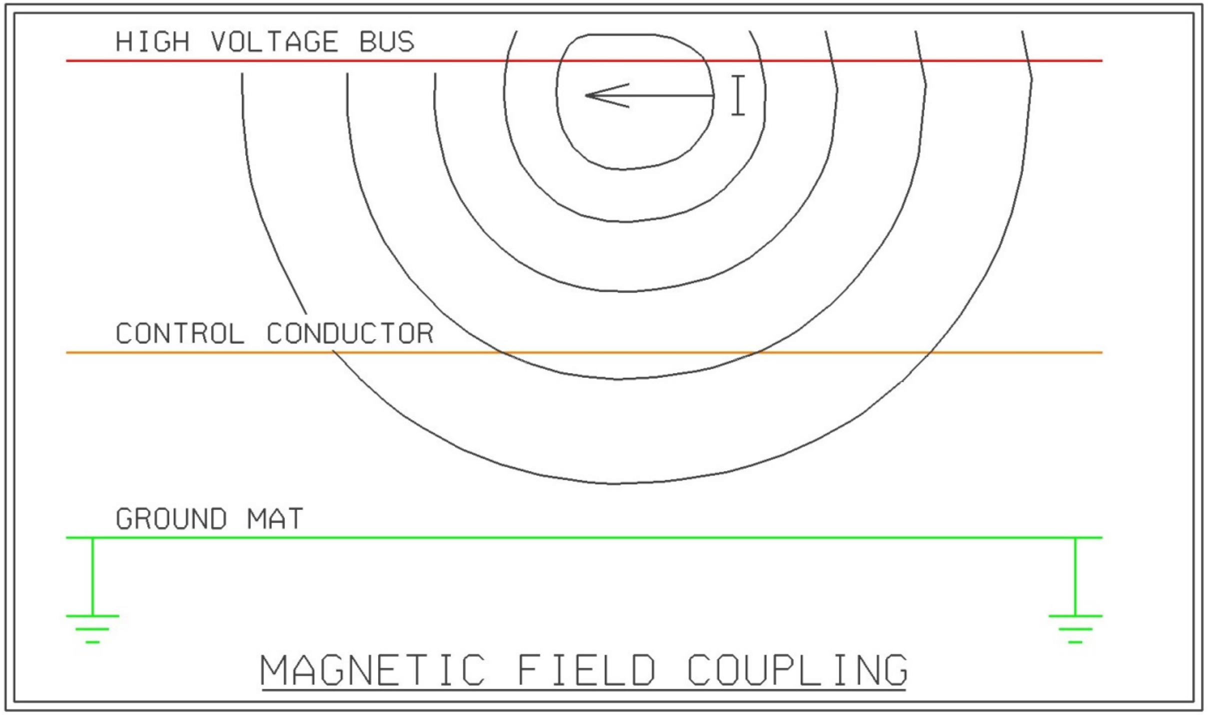
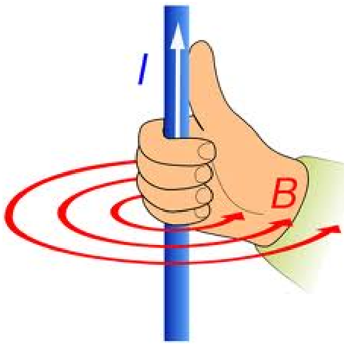


Figure 3



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Unshielded Cable

When does electric and magnetic coupling of transients to control cable become an issue?

- In high-voltage substations, generally rated 230 kV and above
- In high-voltage substations with low-profile bus/capacitor banks/CCVTs, generally 115 kV and above
- In high-voltage substations with a poor ground reference
- When parallel to high-voltage bus

EMI incidences are generally divided equally among three sources:

1. Lightning, which is primarily an issue at 115 kV or lower
2. Switching/arcing, which is primarily an issue at 230 kV or higher
3. Power frequency (60 Hz) faults

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Shielded Cable

<u>Shield Grounding:</u>

- In order for a conductive shield to provide protection it should be grounded
- Practices exist for grounding the shield in three ways:
    1. At the equipment or sending end
    2. At the control enclosure or receiving end
    3. At both ends

At the equipment (sending end) only

- Coupling of an electric field to the control cable is eliminated
- The magnetic field would still be coupled to the cable

At the control house (receiving end) only

- Coupling of an electric field to the control cable is eliminated
- The magnetic field would still be coupled to the cable

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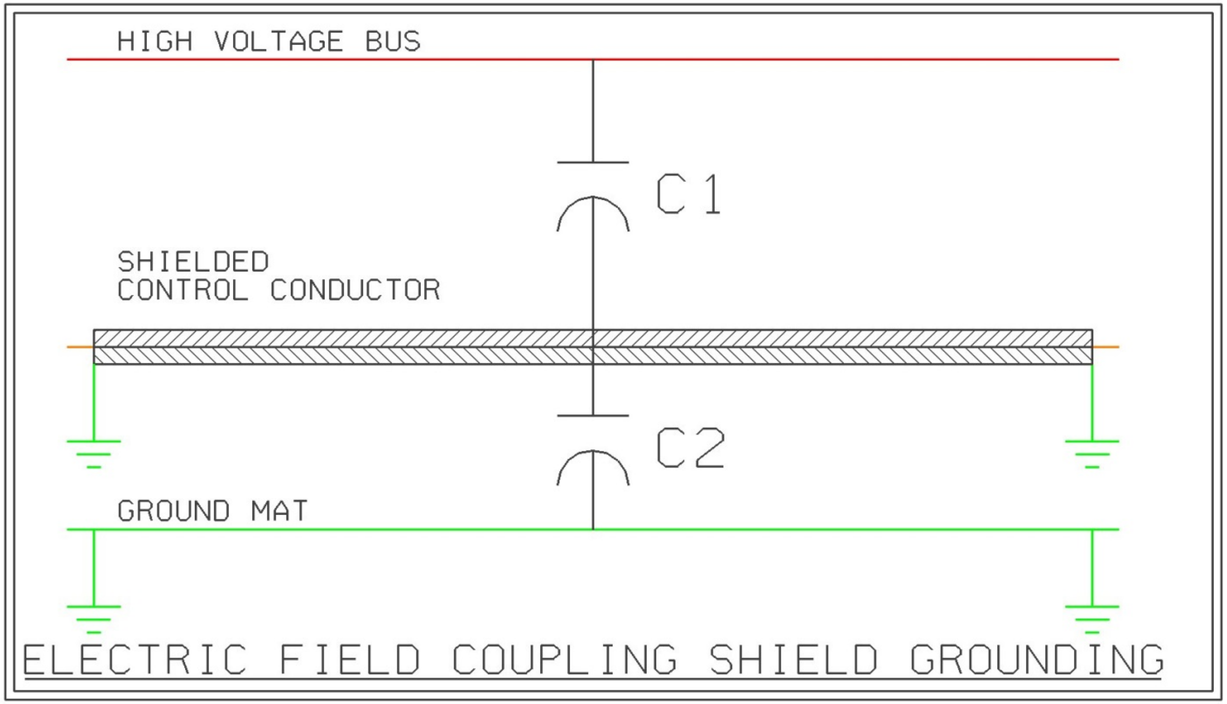
Shielded Cable

Shield Grounding (continued)

At both ends

- In the case of electric-field-induction, the displacement currents from the high-voltage bus are diverted to ground so that no transient voltage appears on the cable

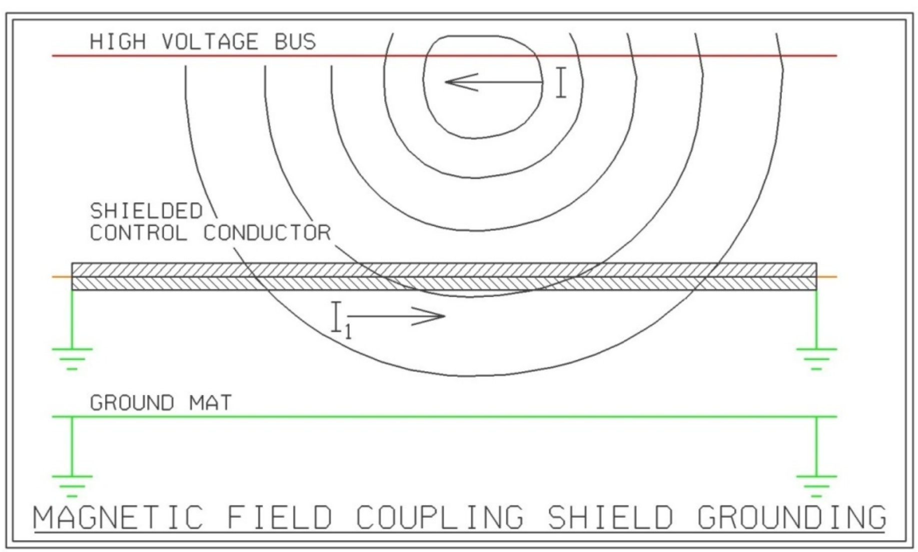


Shielded Cable

Shield Grounding (continued)

At both ends

- In the case of magnetic-field-induction, the transient magnetic field that links the loop created between the shield and the ground grid produces a secondary current that opposes the primary field so that the net field is only equal to the reactive impedance and potential drop around the loop.
- The remaining transient on the shield is proportional to the IR drop along the shield, usually only a few volts.



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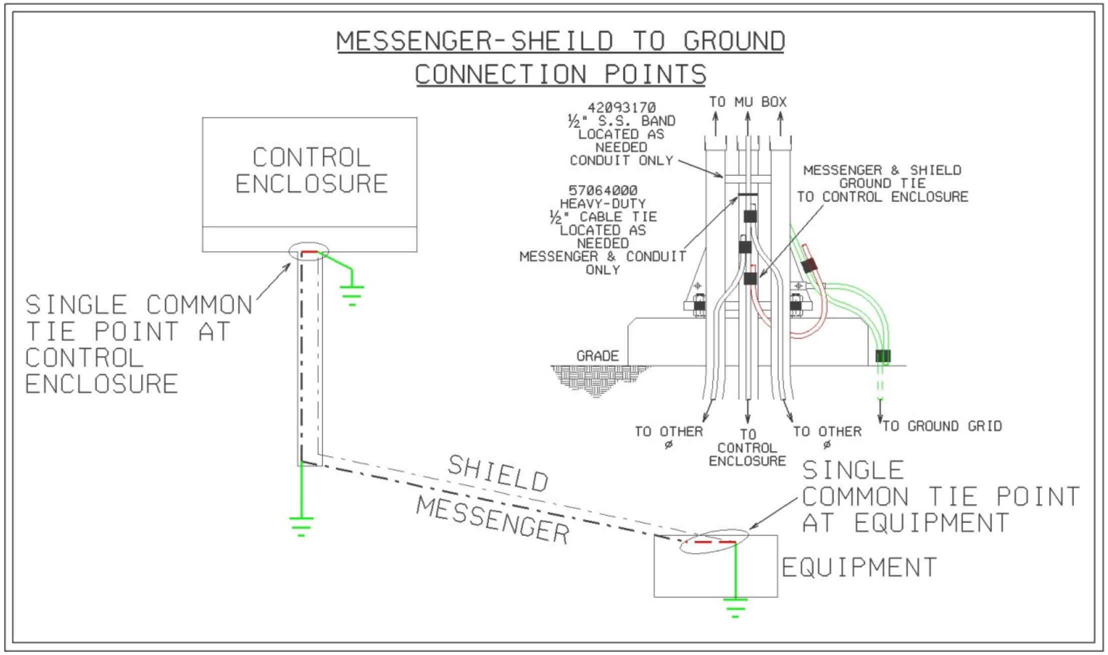
Messenger

<u>To carry fault current</u>

- Grounding the shield at both ends puts the shield in parallel with the ground grid.
- As fault currents return to the substation through the ground grid, they will flow in the shield.



Shielded Cable and Messenger Takeaways

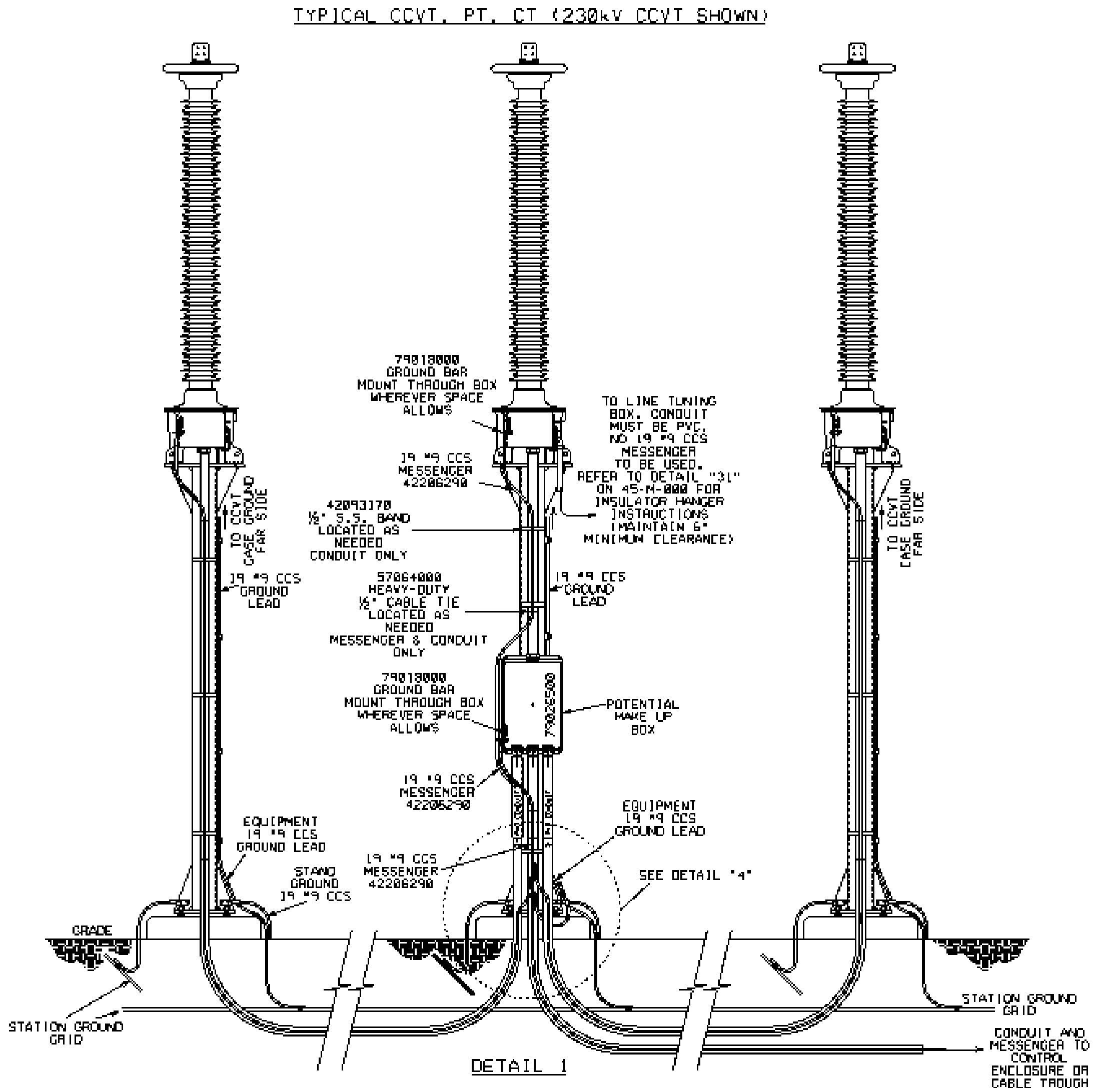
Shielded Cable:

- Shielded control cable is specified for all substations regardless of voltage level. This ensures that defenses are in place against high-voltage transients, and helps to reduce fast pulse transients (like a high-altitude electromagnetic pulse) to a level that is safe for electronic equipment
- Shielded control cable shall always be grounded at both ends

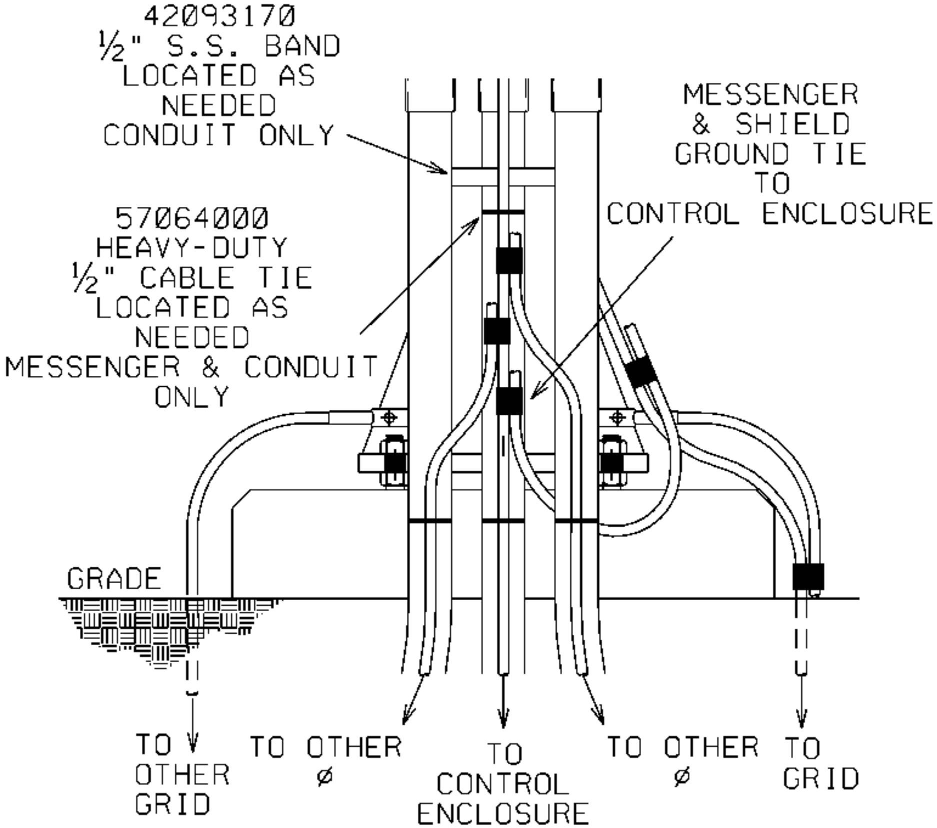
Messenger:

- Messenger must be connected to ground on both ends to ensure it is in parallel with shielded control cable
- Messenger must be installed in close proximity to the conduit containing the shielded cable
- Messenger wires inside the cable trough should be tied together at the ends, and connected to ground grid at the ends and every 100-150 feet
- When required, two risers from both messenger wires in yard cable tray should enter the control enclosure via the cable hood and attach to the cable entrance bus bar

Messenger Typical



Messenger Typical



TYPICAL CONDUIT/MESSENGER
FROM CABINET/MAKE-UP BOX

DETAIL 4

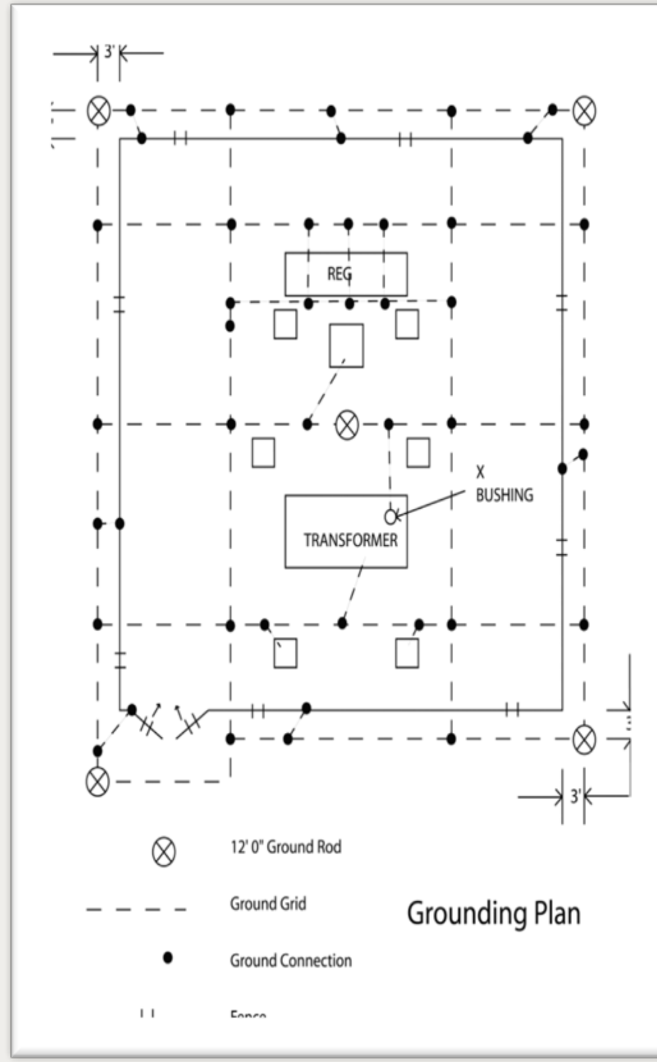
References and Resources

- NEETRAC Study 02-214, "*Protection of Instrumentation, Control and Data Circuits in Substations*," 2004.
- IEEE Std. 525-2007, "*Guide for the Design and Installation of Cable Systems in Substations.*"

Mitigation

Substation Ground Grid Testing

Ground Grid Testing



Ground grid testing is used to detect ***faulty ground connections***.

Remember…
The ground grid provides:

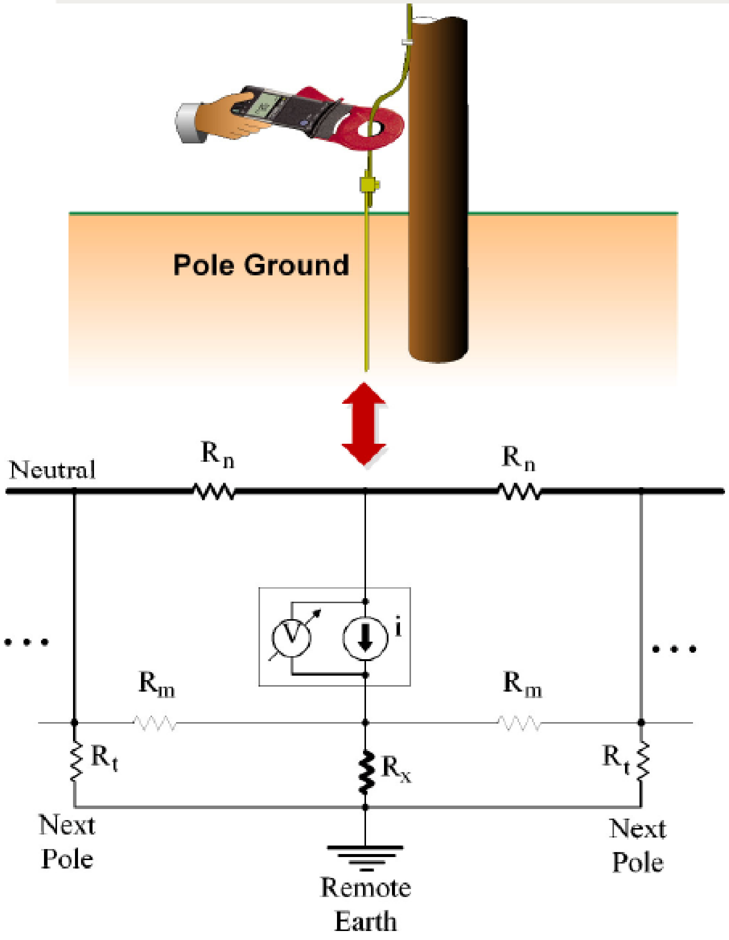
- Personnel safety
- Equipment safety
- Reliable operation of electrical devices

Types of Safety Hazards

The following *safety hazards* may occur when ground grid testing:

- **Touch Potential**
  - Fault occurs while carrying/pulling the test lead
- **Fault Potential**
  - Ground fault occurs during connection or disconnection of leads
  - Fault current has the capability of flowing through the test leads and set

Handheld Clamp-on Testing



- Tester measures a small amount of high-frequency current through the amp meter. This verifies a connection, but not how strong the connection is.

High Current Test Method

Purpose

- Tests integrity of substation ground grids

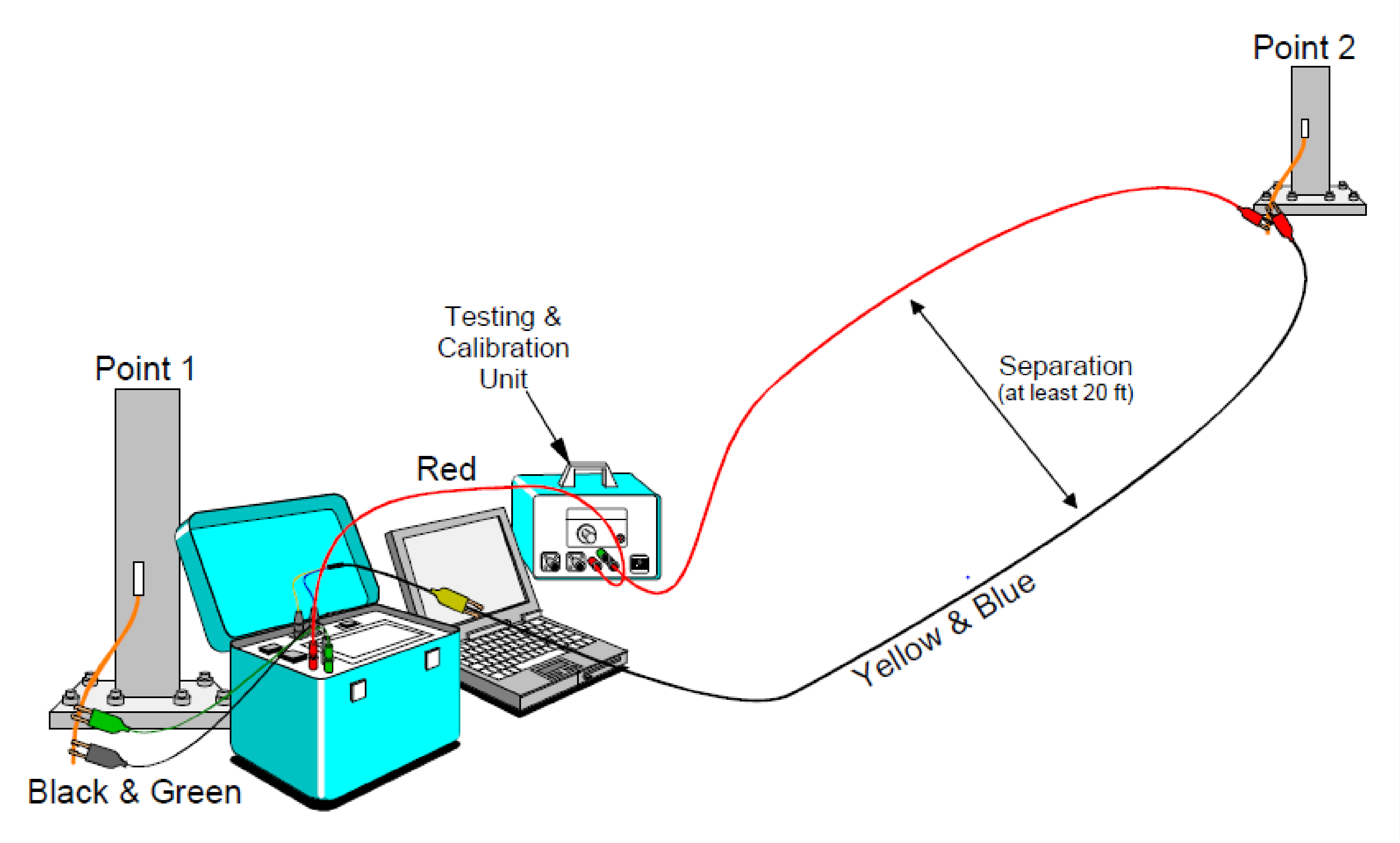
Methodology

- Pass high current (300 Amperes DC) through ground grid between *reference point* and *test ground*

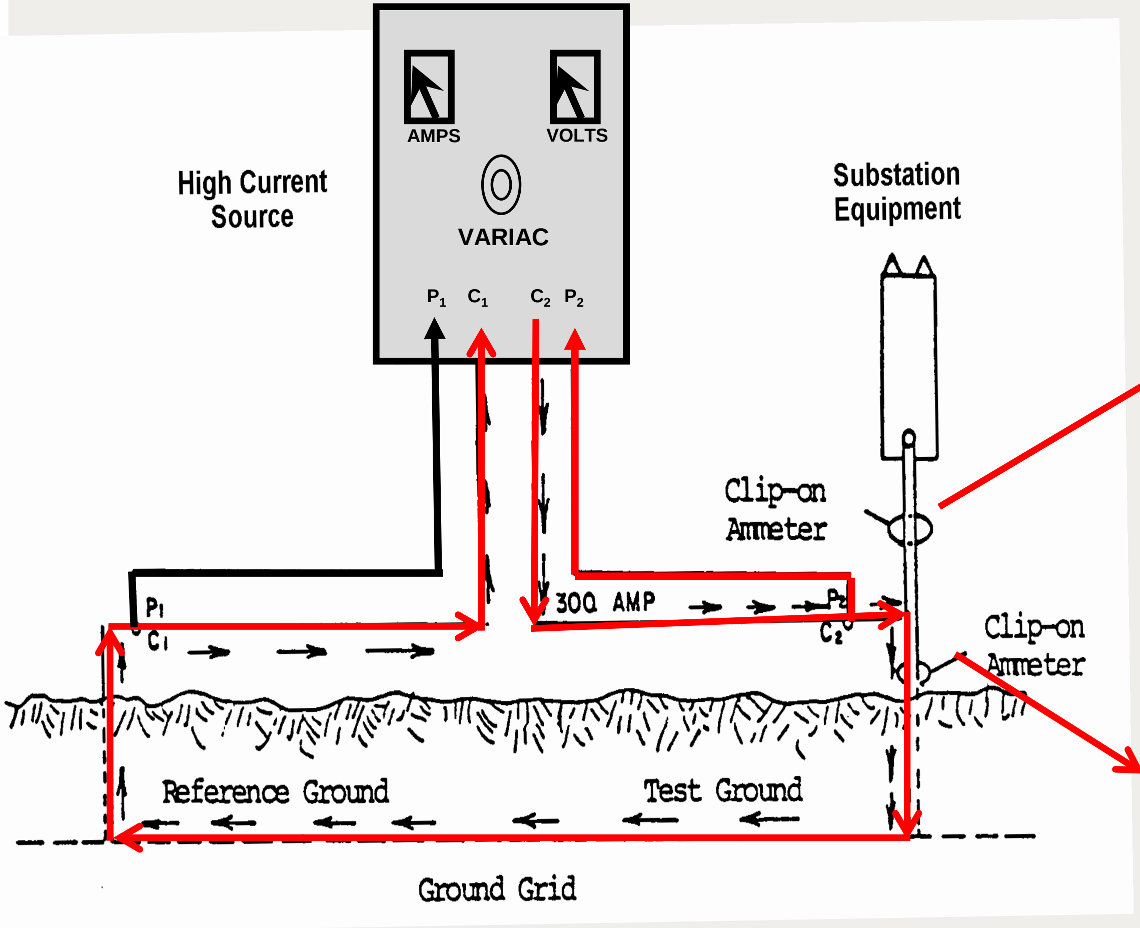
Record Keeping

- Record voltage drop across grid
- Path of current flow

High Current Injection Testing



Test Equipment Setup



Current Up

Current Down

Terms for Testing

Test Lead
Current Source In

Current UP

Current DOWN

- **Current up –** current flowing from the test lead toward the steel
- **Current down –** current flowing from the test lead toward the ground grid
- **Current split –** the total of the current up and the current down

Terms for Testing

Riser

- Ground connection to a piece of equipment

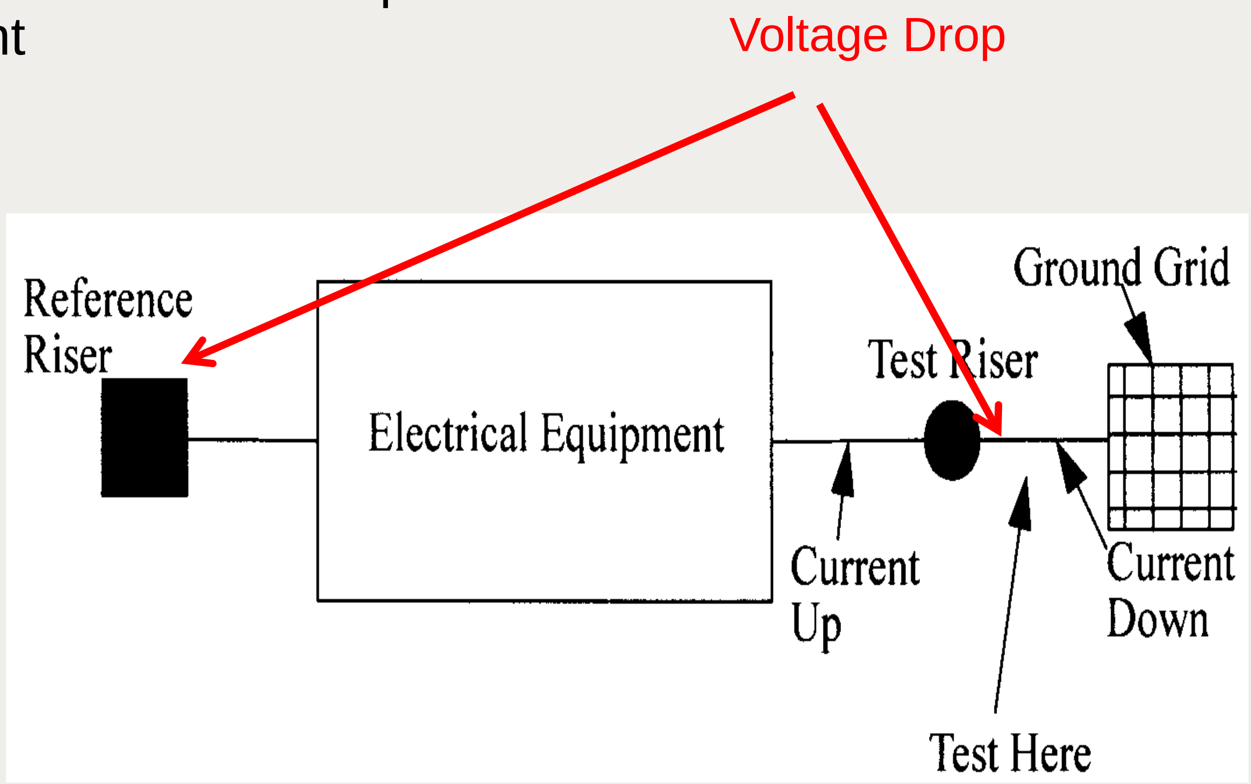
Test current

- Value of current applied during a test

Terms for Testing

Voltage drop

- Value of voltage between the test point and the reference point



Roles During Testing Procedure

Test Set Operator	Connection Electrician
• Marks reference points and test points on grounding plan • Sets up test set • Operates the test set • Records voltage drop, current flow readings • Shuts down test set	• Labels each test riser location with number • Connects and disconnects leads to reference and test risers • Positions ammeter on test riser • Takes ammeter and multimeter readings

Testing the Test Set (Lead-to-Lead Test)

- Prior to testing, it is necessary to establish the test set and leads.
- Clamp the two test leads together
- Energize the leads to 300 Amperes DC
- Read the voltage drop. The voltage drop must be below .05 VDC. If not, de-energize the test set and clean lead connections until this reading is acquired

- A higher than 0.05 VDC reading on the lead-to-lead will make the results look like the grid is degrading. *<u>This must be rectified before testing.</u>*

Selecting Test Reference Riser

Before performing a ground grid test:

- Assess the station layout and select a good reference riser

Examples of *good references:*

- “A-frame” structure
- Multi-pad switch frames
- Multi-grounded equipment
- Need piece of equipment with at least two ground connections (four or more preferred)
- Structure near center of ground grid

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Selecting Test Reference Riser

Examples of “BAD” references:

- Distribution bay
- Transformer neutral
- Capacitor banks
- Any single riser

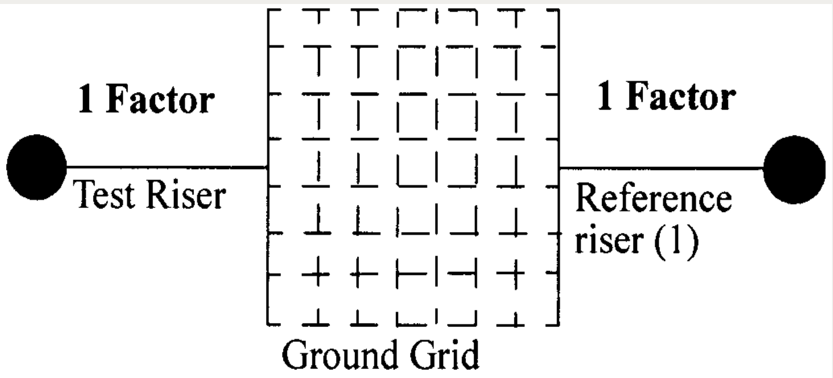
Reference Riser Difference

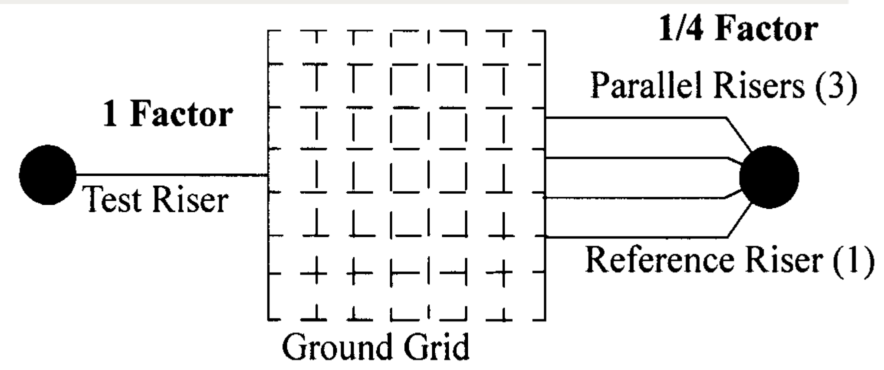
Single Reference Riser

- The reference riser and the test riser have equal effect on the reading.
- The room for error is great.

Multi-Riser Reference

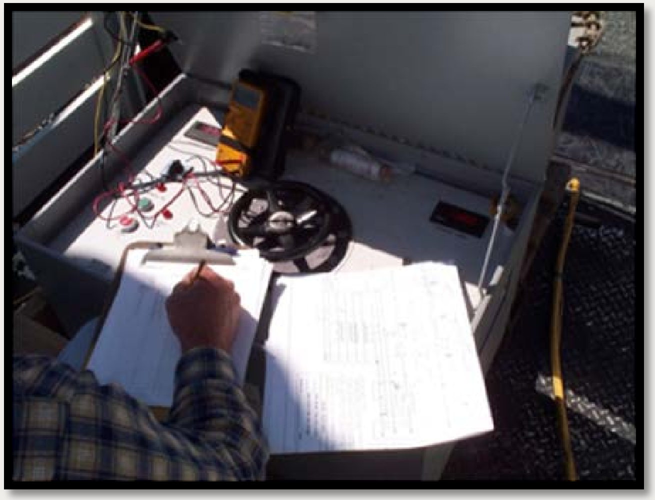
- The reference riser has ¼ the effect on the overall reading.
- The room for error is lessened.





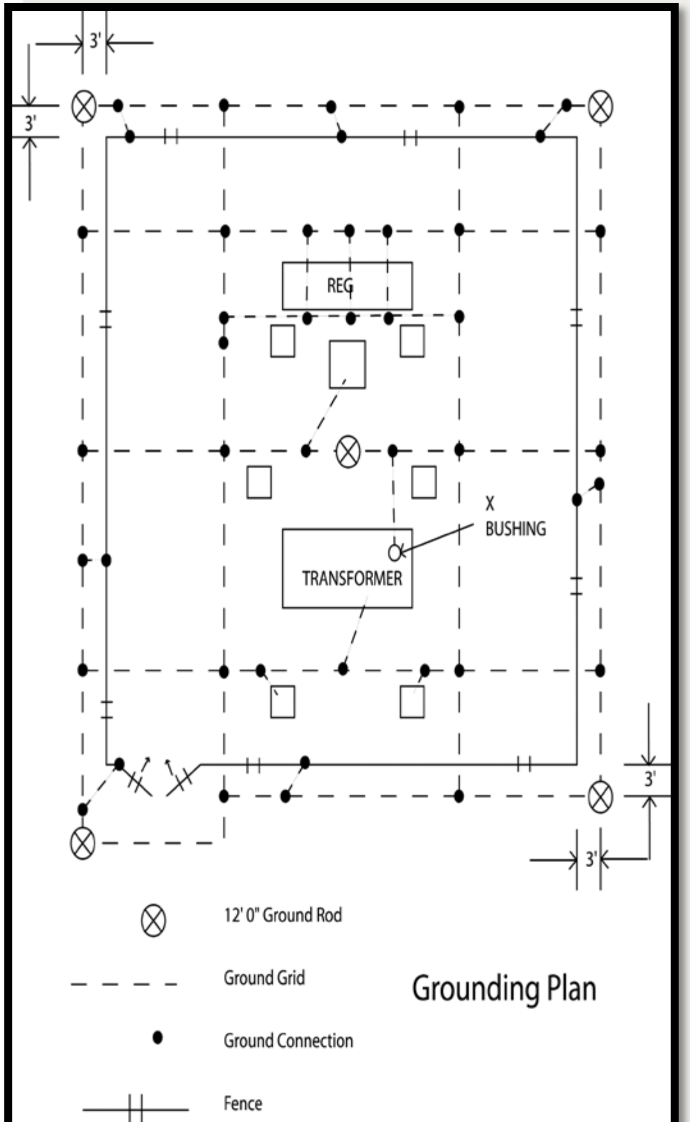
Preparing to Test

1. Position test equipment in central area near planned reference point.



2. Operator should wear Class 2 rubber gloves or be on an insulated mat.

Preparing to Test



3. Mark up grounding plan with test points and reference point. Also indicate any equipment removed or added to station.

4. Consecutively number all risers to be tested with a paint pencil.

   Note: Be sure to include the fence as a test point.

5. Perform the lead to lead.

   Note: Make sure to record the voltage drop for the lead to lead.

Taking Readings

1. After connections are made:
   - **Test Set Operator** energizes the test set
   - Advises that the test set is "*coming hot*"

   ***Test specimen is considered armed and dangerous.**

2. **Test Set Operator** increases output of 300 amps through riser

3. **Connection Electrician** measures the current down.
   - **Test Set Operator** records the reading in the "Current Down" column on the Ground Grid Test Sheet.

4. **Connection Electrician** measures the current up.
   - **Test Set Operator** records the reading in the "Current Up" column on the Ground Grid Test Sheet.

5. Use multi-meter to measure voltage drop.
   - **Test Set Operator** records in the "Voltage Drop" column on the Ground Grid Test Sheet.

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Total Voltage Drop

Goal of the test is to measure voltage drop of individual test riser only

Reference Riser Voltage

Test Riser Voltage

Total Voltage Drop

Voltage Drop is the electrical effort necessary to force the test current through the ground grid and back to the reference.

Voltage Drop Results

4/0 Copper Riser

Total Voltage Drop	Interpretation
Less than 0.75 volts	Good grid
0.75 volts to 1.50 volts	Safe grid but weakened
1.50 volts +	Bad grid

Voltage Drop Results

Copper Clad Steel (CCS)

Total Voltage Drop	Interpretation
Less than 1.40 volts	Good grid
1.41 volts to 2.79 volts	Safe grid but weakened
2.80 volts +	Bad grid

Current Split

When testing, the 300 amps applied splits into two paths:

current flowing **DOWN** toward the grid

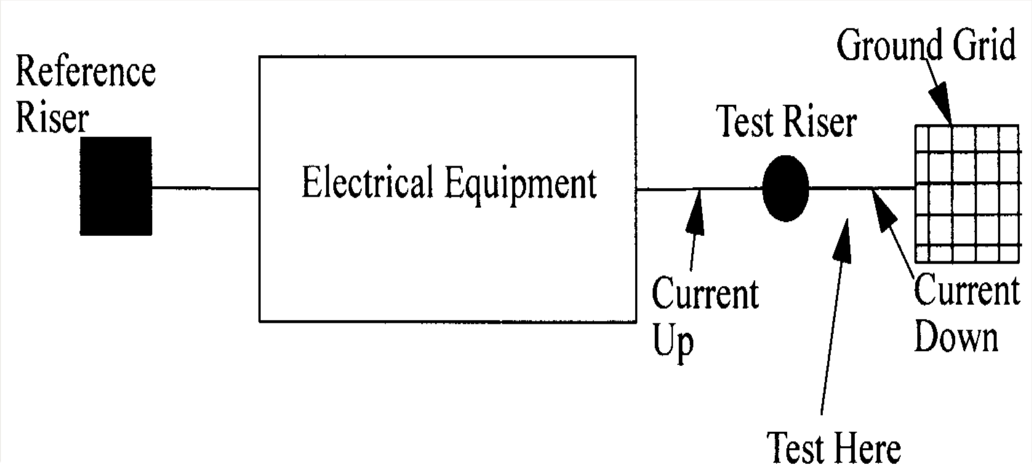
\+

UP toward the equipment

Example:

Apply 300 amps to the Test Point = Current Up + Current Down

260 amps **UP** + 40 amps **DOWN** = 300 amps



Record Keeping

Ground Grid Test Sheet

Station	Date
Region	Electrians
Reason for Test	Equipment Used

Reference Number	Riser Number	Voltage Drop	Amps. Up	Amps. Down	Notes
Lead to Lead					volt drop < 0.05

Troubleshooting

Situation	Possible Cause
Current does not flow	Possible open test connection
High voltage	Possible bad connection or bad specimen
Low voltage (below 0.2 volts)	Possible connection problem Possible equipment failure
Unusual current split	Possible break in the ground or loose connection to structure