Overview of Grounding for Industrial and Commercial Power Systems

Presented By
Robert Schuerger, P.E.

HP Critical Facility Services delivered by EYP MCF

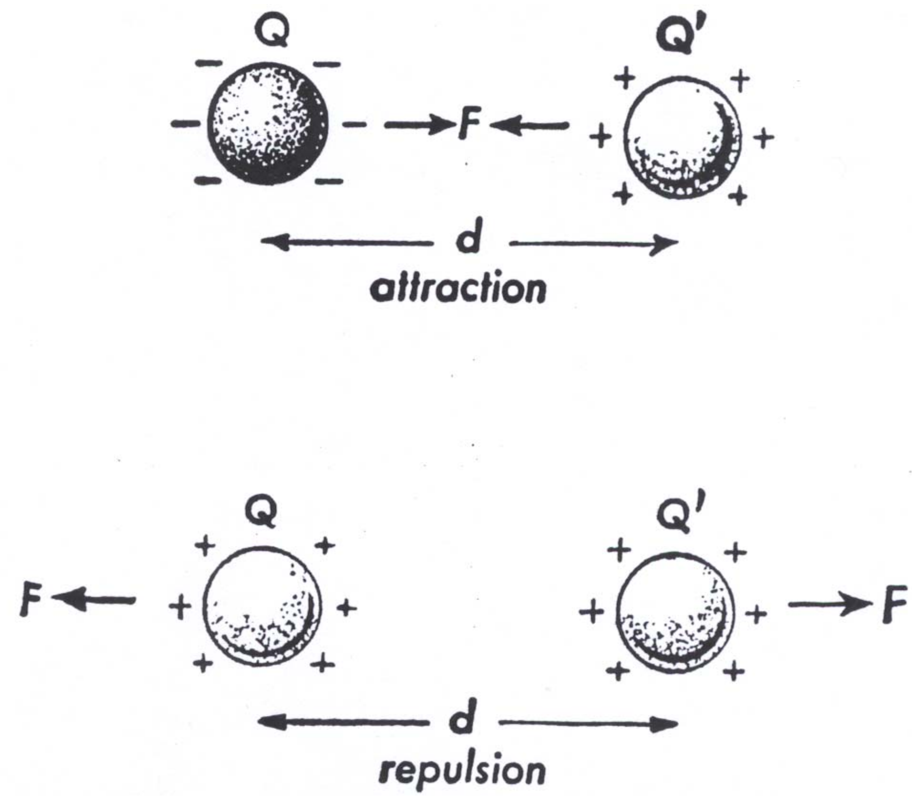
What is VOLTAGE?

- Difference of Electric Potential
- Electromotive Force (EMF)

Electromotive Force (EMF)

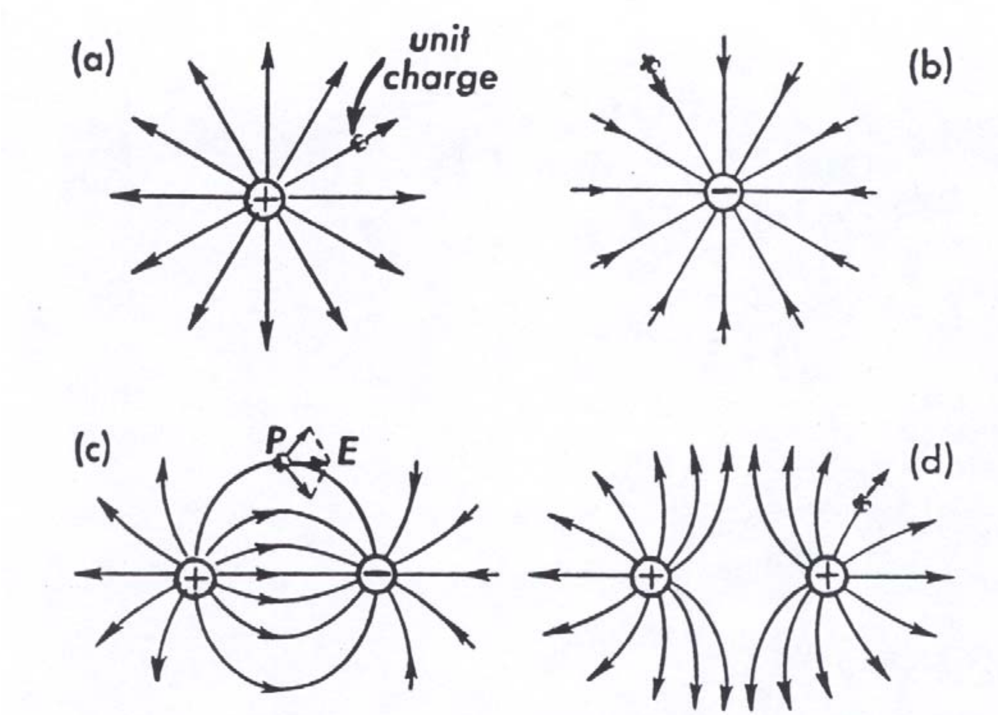
Opposite charges attract

Like charges repel



Electric Fields

- Exist whenever there is an electrically charged particle
  - Exist whenever there is a voltage



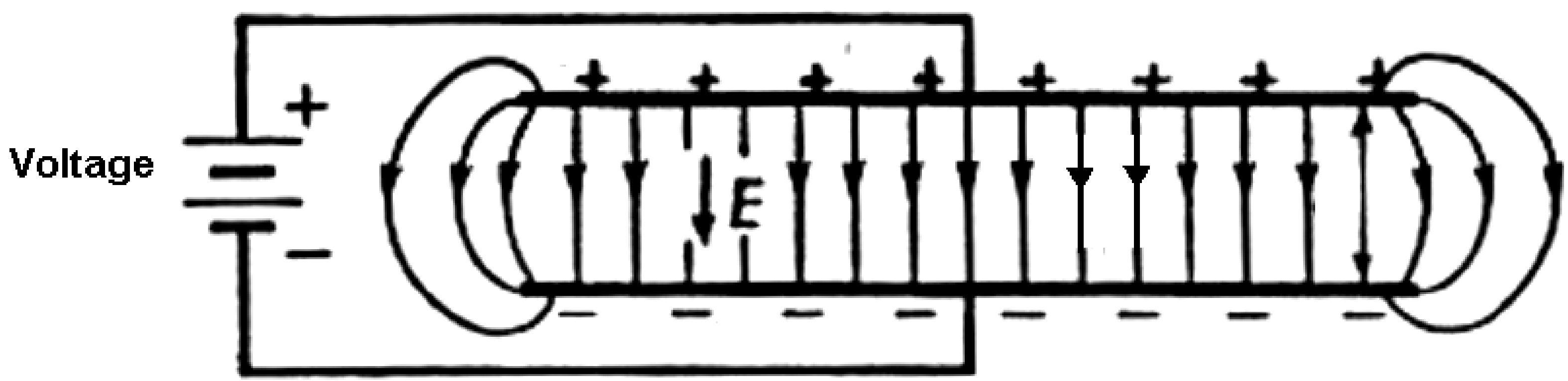
CAPACITANCE is the ratio of the total charge on two surfaces to the potential difference between them.

$$C = Q / V$$

C = capacitance, in Farads

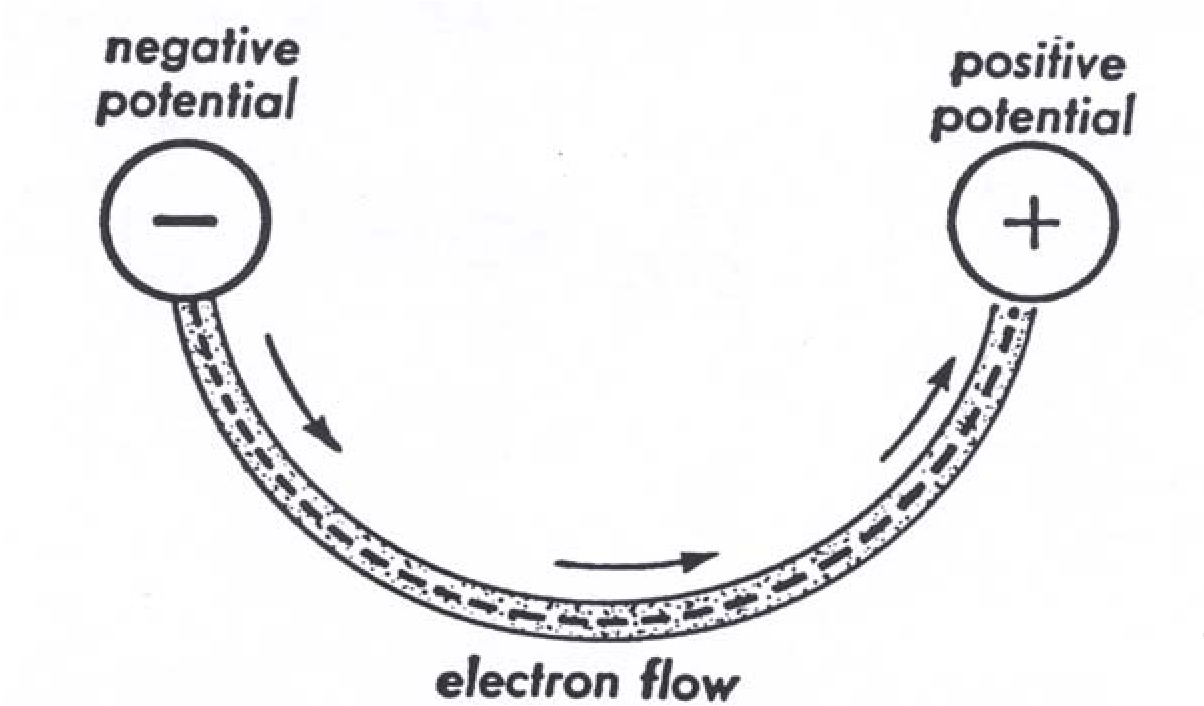
Q = charge, in Coulombs

V = voltage, in Volts



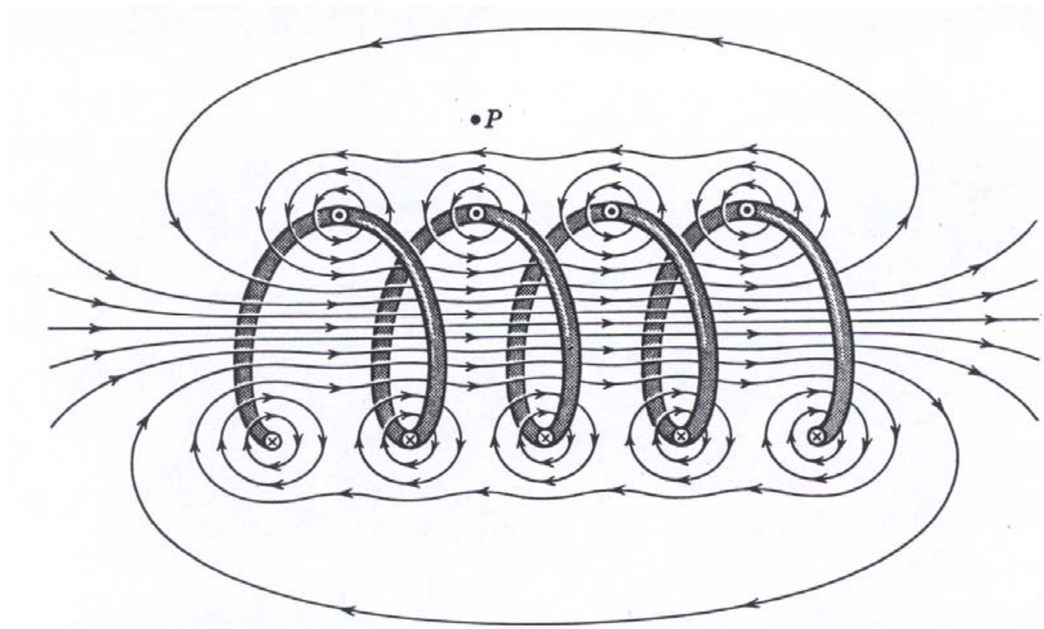
What is CURRENT?

- The flow of electrons.



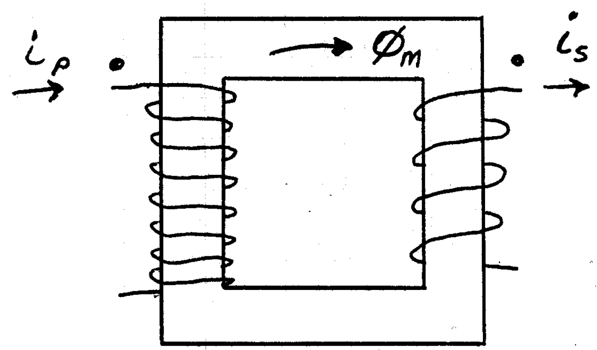
Magnetic Fields

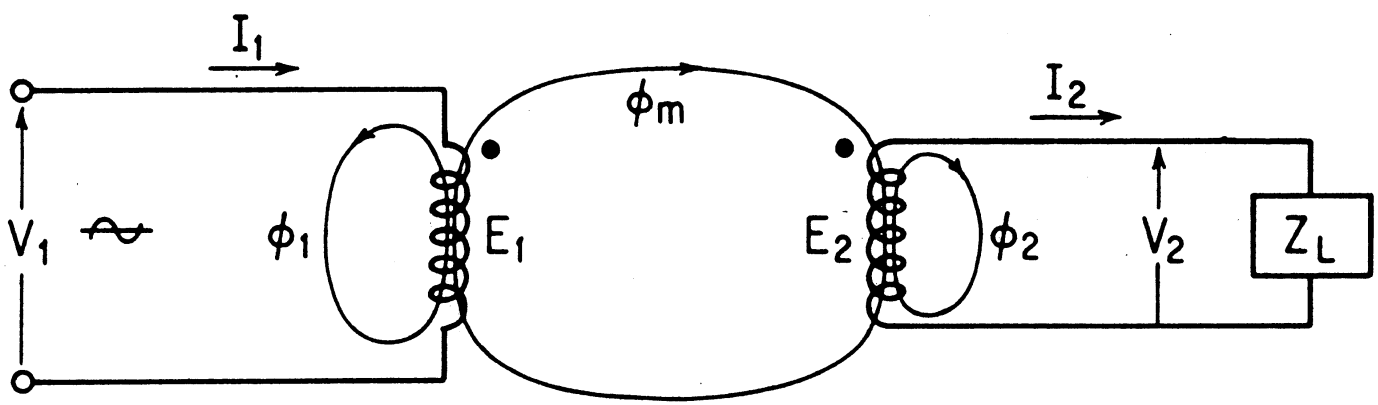
- Exist naturally in the earth's core
  (North and South Poles)
- Exist naturally due to permanent magnets
- Exist around the wire when a current flows (Electromagnetism)



Transformers

- Energy is transferred from the primary winding to the secondary winding by the magnetic flux $Ø_m$.





What does any of this have to do with grounding?

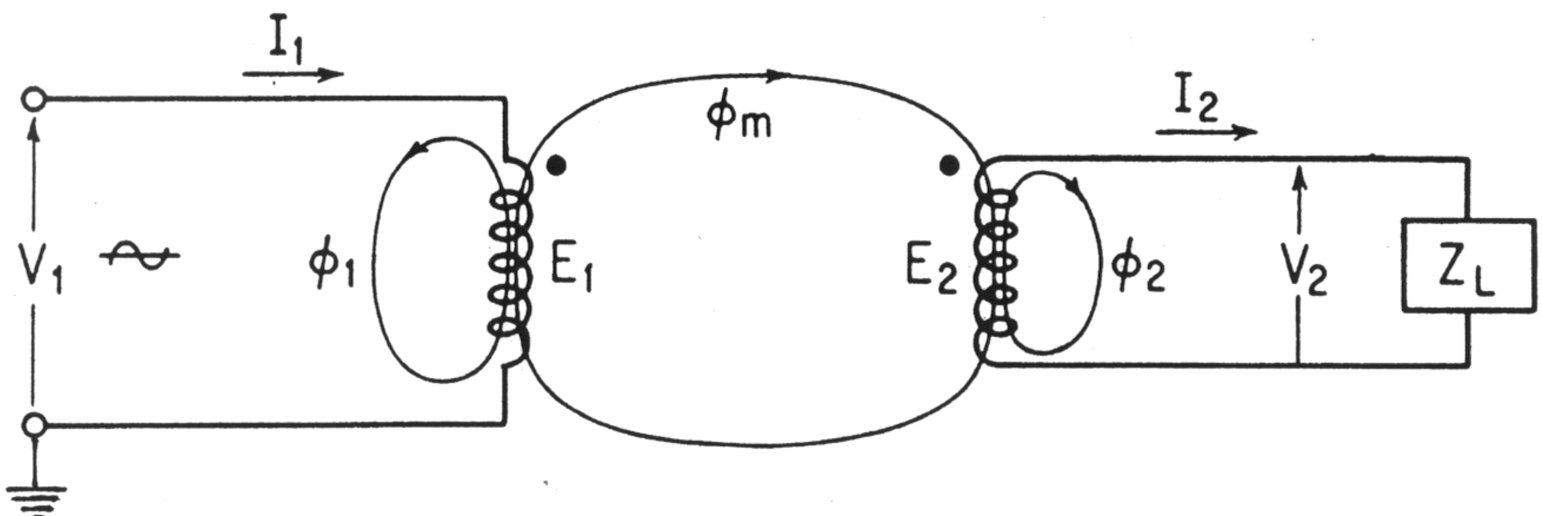
- There are two distinctly different functions the "ground" can perform:
  - The first is the safety/protection function of connecting a specific part of the electrical generation, transmission or distribution system, or the utilization equipment to the earth.
  - The second function is to provide a "common" or "reference" or "point of zero volts," which is usually thought of as a system operation requirement.

Understanding Grounding

- Voltage is a *difference* of potential, requiring a minimum of two points
  - Ground is often one of the two (or more) points
  - Ground is used as a "reference" or "point of zero potential"
  - **People stand on it, which makes it part of electrical safety**
- The secondary of a transformer is *electrically isolated* from the primary, since it moves the energy magnetically
  - Regardless of how the primary is connected relative to ground, the secondary is isolated from ground until connected externally
  - "You cannot *transform* ground." Professor Grumbach

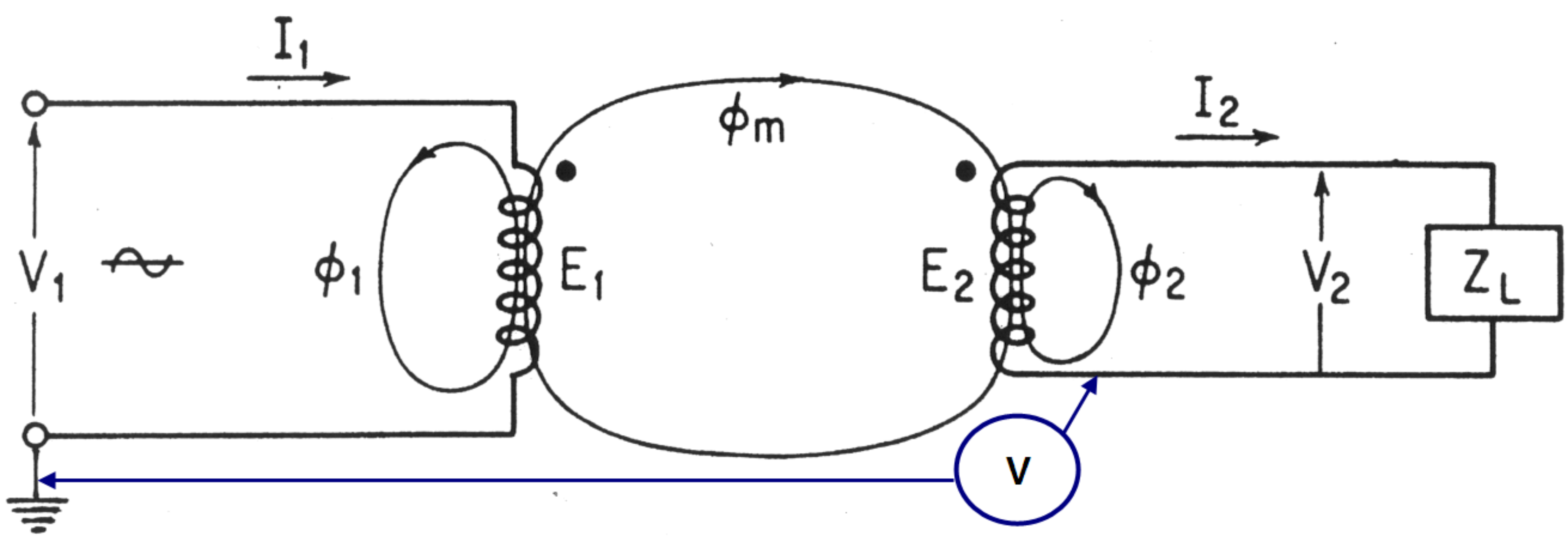
Solidly Grounded Primary

- With AC voltage, one terminal is often intentionally grounded; ground is used as “zero volts”



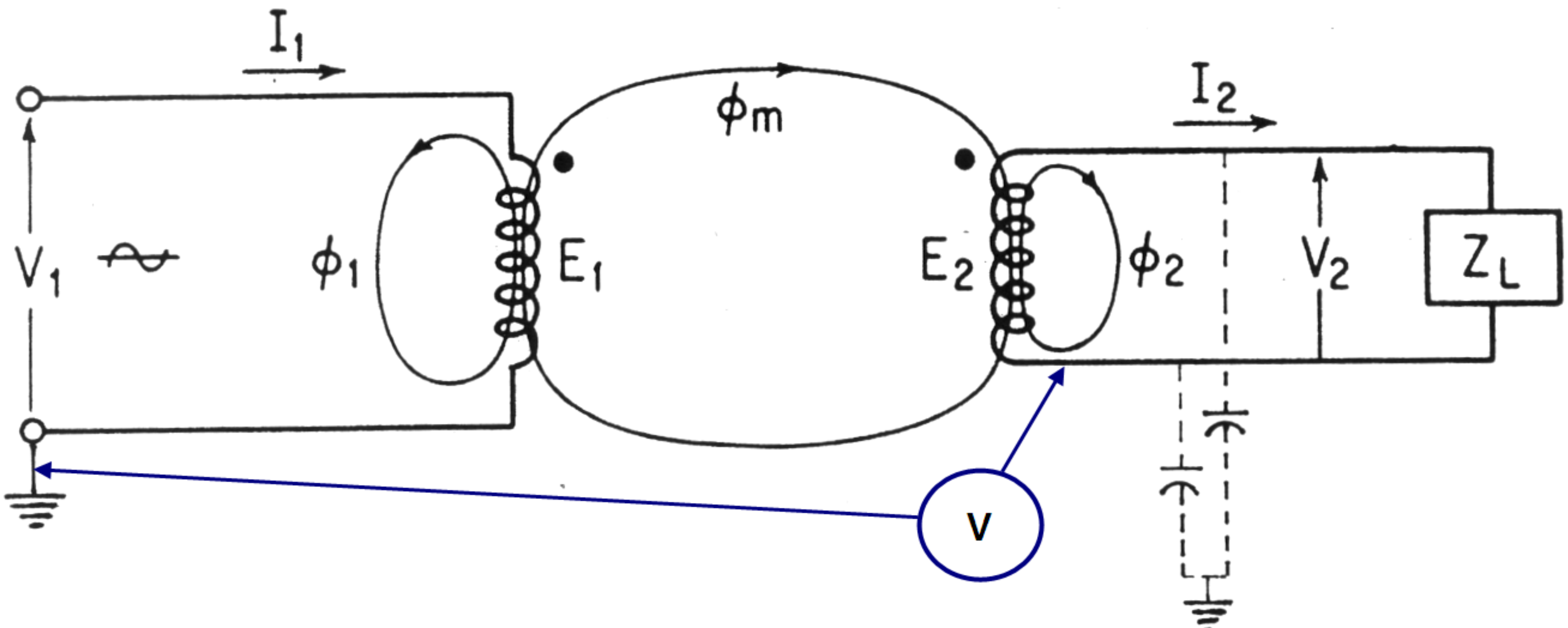
Solidly Grounded Primary

- If V_1 = 480 V and V_2 = 120 V, what will a voltmeter (V) most likely read and why?



Solidly Grounded Primary – Capacitively Grounded Secondary

- The voltmeter (V) will read approximately 60 V, assuming the capacitive coupling between each set of wires and ground is about the same



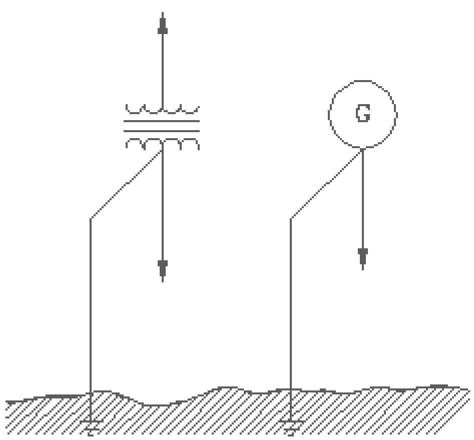
What are the keys to understanding Grounding?

- Understanding basic electricity
  - What is voltage
  - What is capacitance
  - What is inductance
  - How does a transformer work (magnetic coupling of windings)
- Understanding when “ground” is in the circuit, directly or indirectly
- The earth is not an “electrical sewer” that magically eliminates interference!

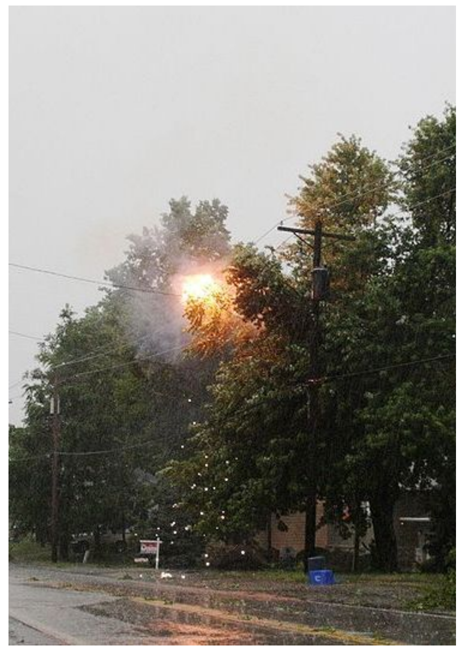
Picture from Wikipedia

When is ground in the circuit?

When supply transformer or generator are solidly grounded



Electrical Faults



Picture from Wikipedia

Lightning

Picture from www.insidesocal.com

Minimizing Shock Hazard – a primary reason for grounding

OSHA ODE-1070 sign

The requirements for equipment grounding are expressly specified in NFPA 70:

1. Conductive materials enclosing electrical conductors or equipment, or forming part of such equipment, shall be connected to earth so as to limit the voltage to ground on these materials. Where the electrical system is required to be grounded, these materials shall be connected together and to the supply system grounded conductor.
2. Where the electrical system is not solidly grounded, these materials shall be connected together in a manner that establishes an effective path for fault current.

The requirements for equipment grounding are expressly specified in NFPA 70:

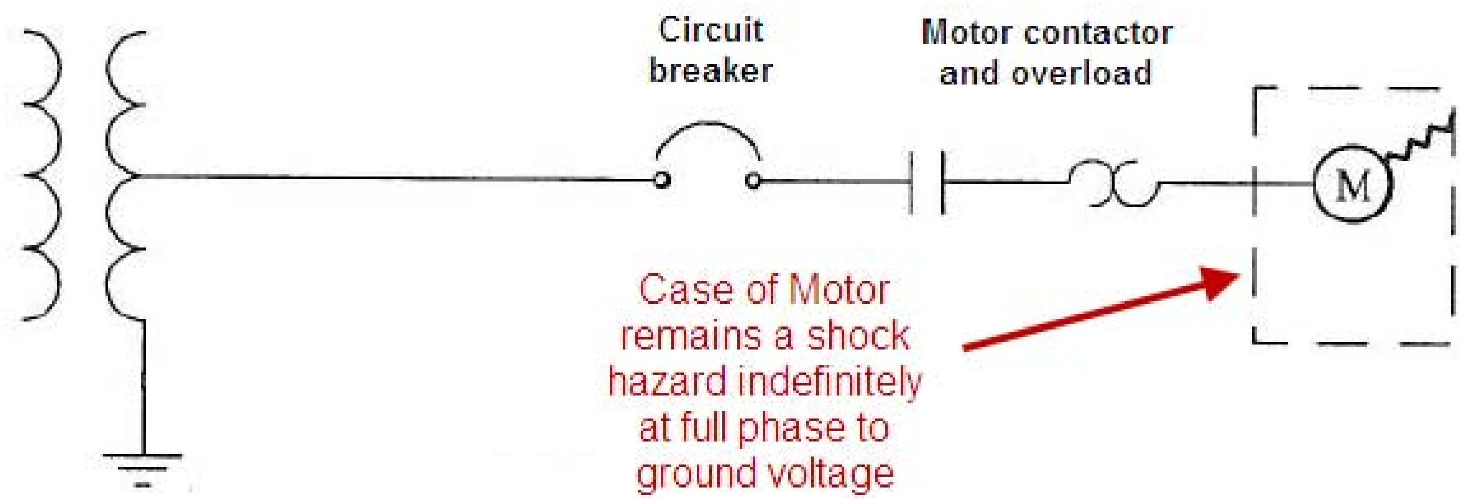
3. Electrically conductive materials that are likely to become energized shall be bonded to the supply system grounded conductor or, in the case of an ungrounded electrical system, to the electrical system grounded equipment, in a manner that establishes an effective path for fault current.
4. The earth **shall not** be used as the **sole** equipment grounding conductor or fault current path.

Basic objectives of an equipment grounding system:

1. To reduce electric shock hazard to personnel.
2. To provide adequate current carrying capability, both in magnitude and duration, to accept the ground-fault current permitted by the overcurrent protection system without creating a fire or explosive hazard to building or contents.
3. To provide a low impedance return path for ground-fault current necessary for the timely operation of the overcurrent protection system.

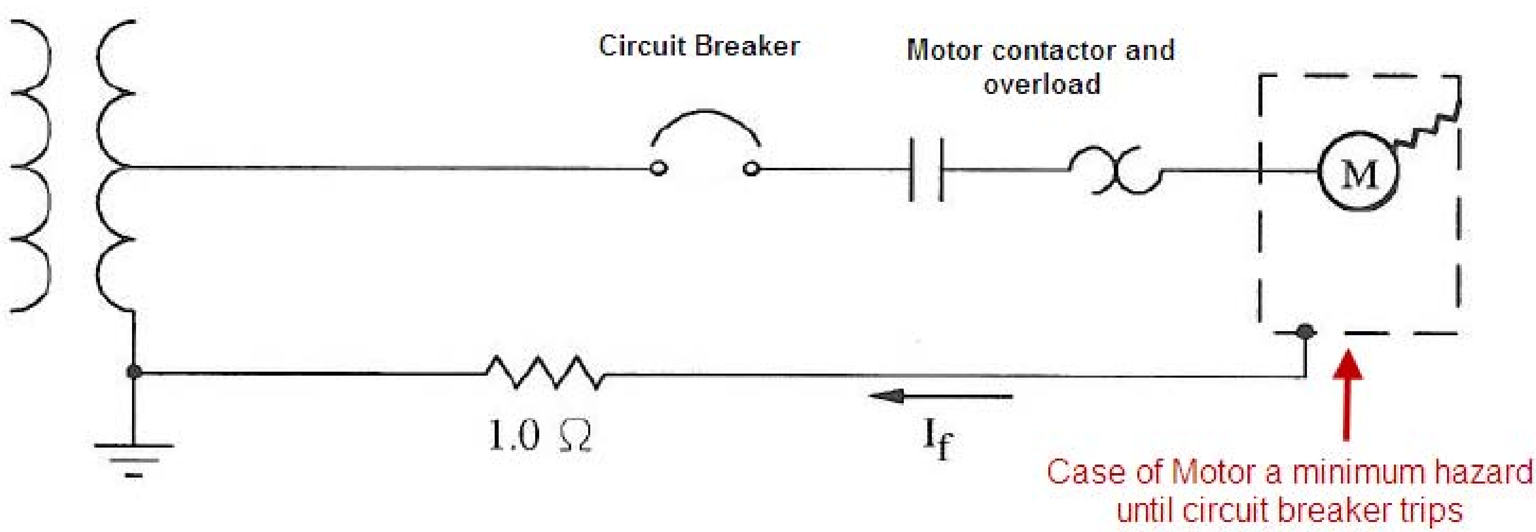
Three phase Motor - Shock hazard

- If the insulation fails in a three phase motor, the case becomes energized at phase to ground voltage
- With no ground on the case, it would remain energized indefinitely exposing anyone who passed by to a shock hazard



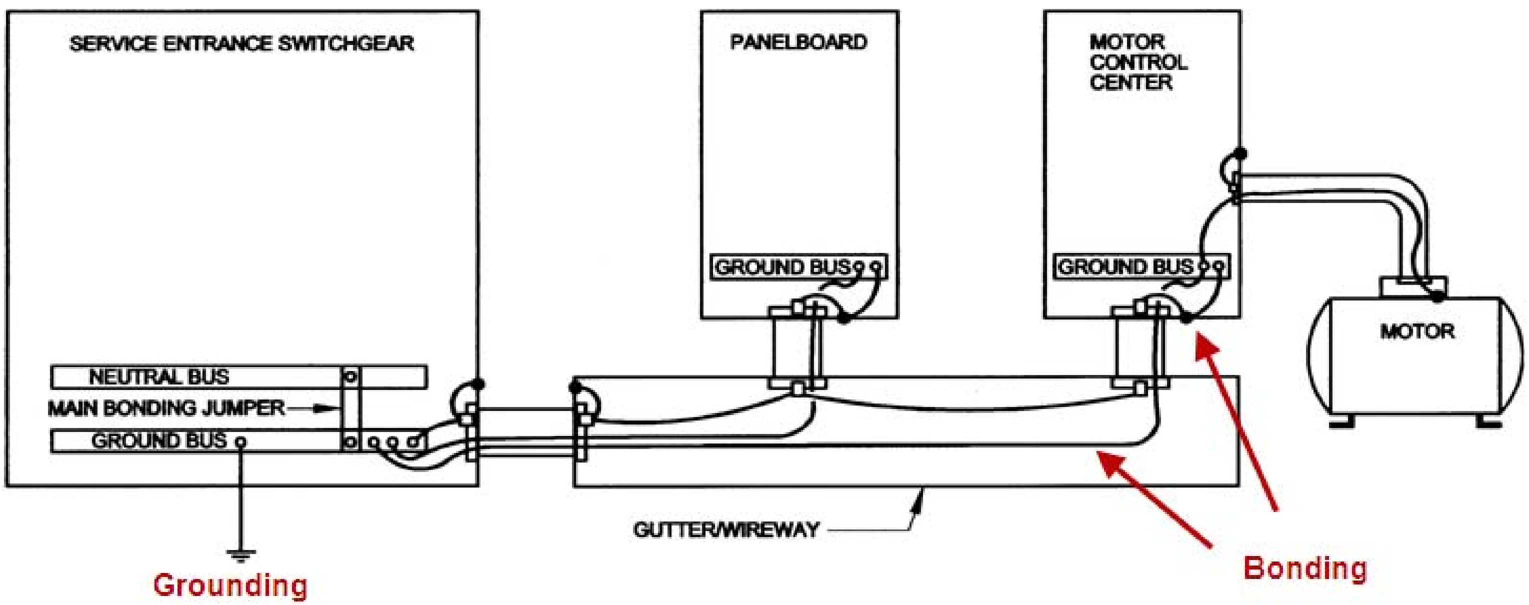
Three phase Motor – Effectively Grounded

- By having an **equipment grounding conductor** connected to the case, the shock hazard is quickly eliminated – the circuit breaker trips, often by the instantaneous unit



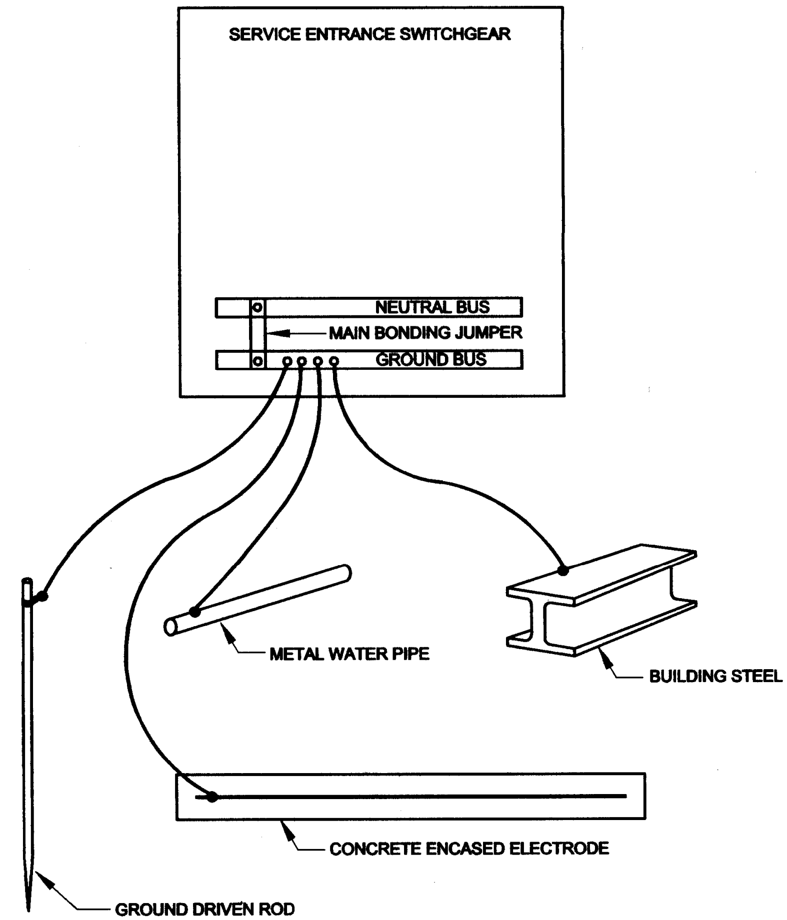
NEC "Grounding" Terminology

- "Grounding" has to do with connecting to the earth (outside the US this is often referred to as "earthing")
- "Bonding" is providing a low impedance path to clear faults



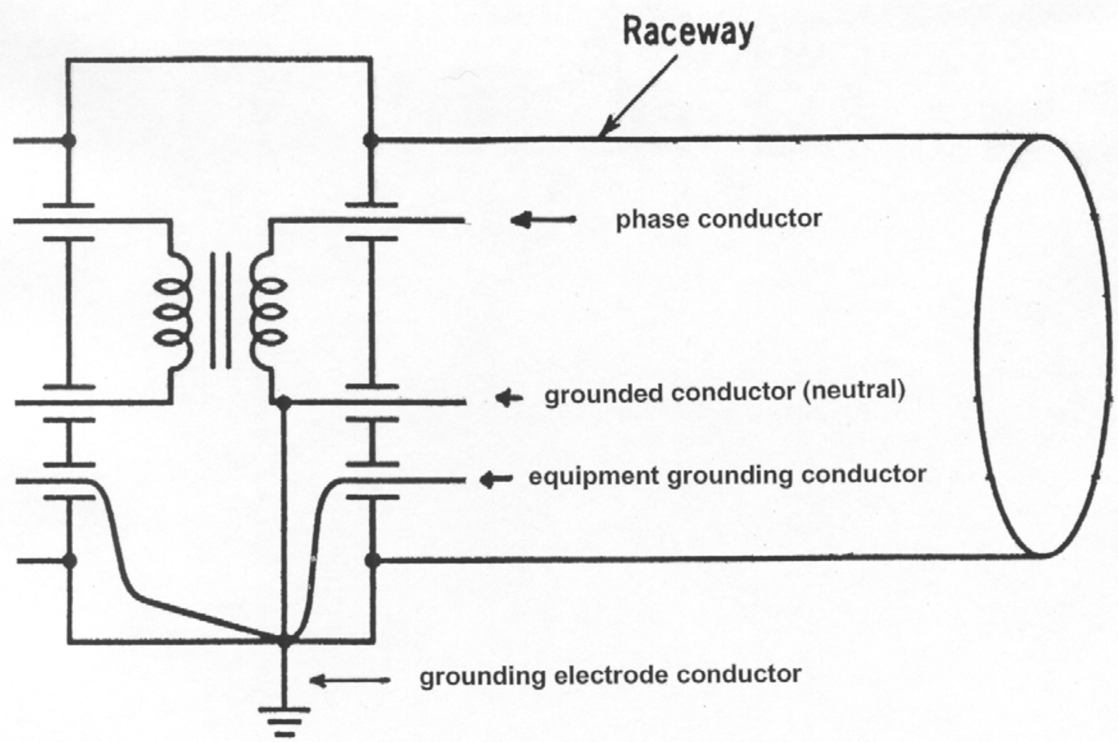
NEC "Grounding" Terminology

- **Grounded -** Connected to earth or to an extended conducting body that serves instead of the earth, whether the connection is intentional or accidental.
- Examples of **grounding electrodes** →



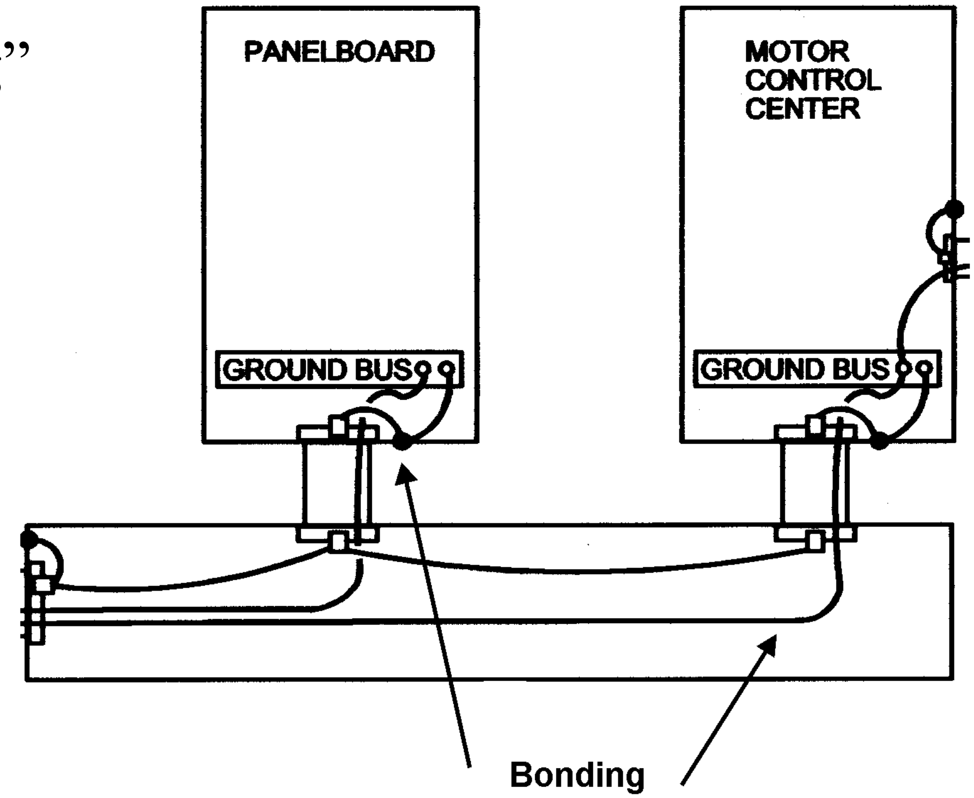
NEC "Grounding" Terminology

- **Grounded conductor** (neutral).
- **Equipment grounding conductor (**green or bare wire)
- **Grounding electrode conductor (**ground wire to ground rod, usually bare**)**



NEC "Grounding" Terminology

- Most of the "grounding" in a facility is actually **bonding** per the NEC
- The **equipment grounding conductor** (green or bare wire) is part of the **bonding** system

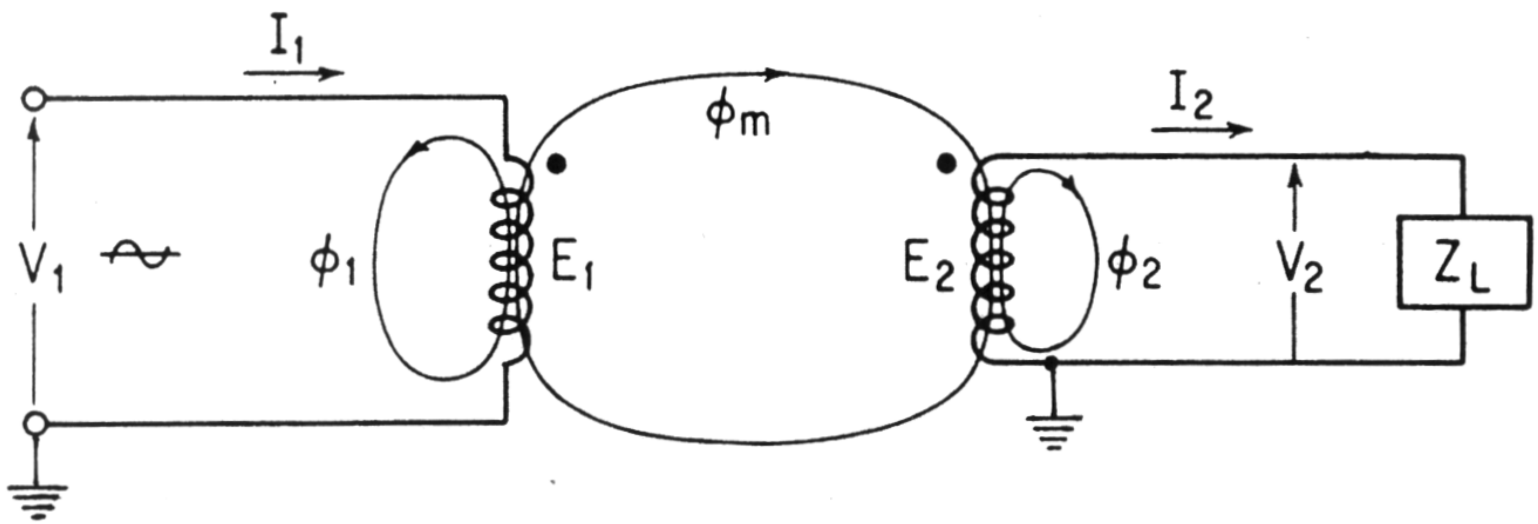


Grounding of separately derived system

- **separately derived system -** A wiring system whose power is derived from a generator, transformer, or converter windings and has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system.

Solidly grounded transformer secondary

- For AC systems over 50 V, the NEC requires a “separately derived system” to be grounded [250.20(D)] in accordance with 250.30(A)

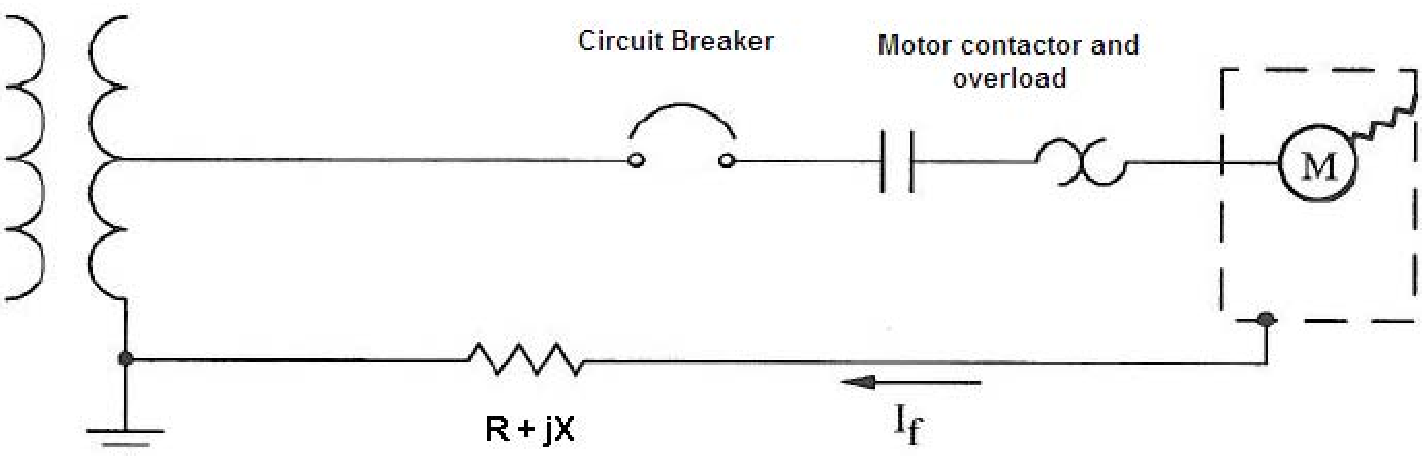


What about the electronic equipment – is "ground" in the circuit?

- Most electronic equipment uses the frame as "reference"
- The frame is usually grounded, either intentionally to the raised floor or by means of the equipment grounding conductor
- Even though the equipment grounding conductor will ultimately connect to ground, the operation of the equipment does not depend on a low impedance to ground (earth)

Overcurrent Protection Operation

- The equipment-ground system is an essential part of the overcurrent protection system. The overcurrent protection system requires a low-impedance ground return path in order to operate promptly and properly.



Total impedance (R + jX) of conductive path

- In 60 Hz circuits rated 40 A or less, the circuit reactance (jX) is an insignificant part of the circuit impedance.
- Because reactance increases significantly with conductor separation, reactance is the predominant element of impedance for open wire and tray systems for circuits rated above 200 A.
- The reactance of an ac circuit is determined mainly by the spacing between outgoing and return conductors and is only slightly affected by conductor size.

Variation of R and X with Conductor Size and Spacing

CONDUCTOR SIZE	1 in (25.4 mm) CONDUCTOR SPACING				8 ft (2.44 m) CONDUCTOR SPACING			
	R	X	Z	Z/R	R	X	Z	Z/R
750 kcmil	0.0168	0.0219	0.0276	1.64	0.0168	0.1268	0.1279	7.61
500 kcmil	0.0246	0.0268	0.0364	1.48	0.0246	0.1312	0.1339	5.44
250 kcmil	0.0487	0.0351	0.060	1.23	0.0487	0.1400	0.1482	3.04
00	0.0911	0.0439	0.1011	1.11	0.0911	0.1488	0.1745	1.92
2	0.181	0.0509	0.1881	1.04	0.181	0.1558	0.2389	1.32
4	0.288	0.0559	0.2934	1.02	0.288	0.1608	0.3298	1.15
6	0.453	0.0639	0.4575	1.01	0.453	0.1688	0.4834	1.07

R = Resistance, in Ω/1000 ft (300 m), at 50°C, 60 Hz
X = Inductive reactance, in Ω/1000 ft (300 m), at 60 HZ
Z = Impedance, R + jX
From IEEE Std 141–1986 (ANSI) [3], Chapter 6, Tables N1.3, N1.5, and N1.6.

Fig 2-2 -- Single Wire as Grounding Conductor

- Imagine the circuit to be of 350 ampere capacity, employing 500 KCMil phase conductors and a # 4/0 grounding conductor (copper).
- It is assumed that the line-to-ground fault current at the outer terminal is 5500 A.

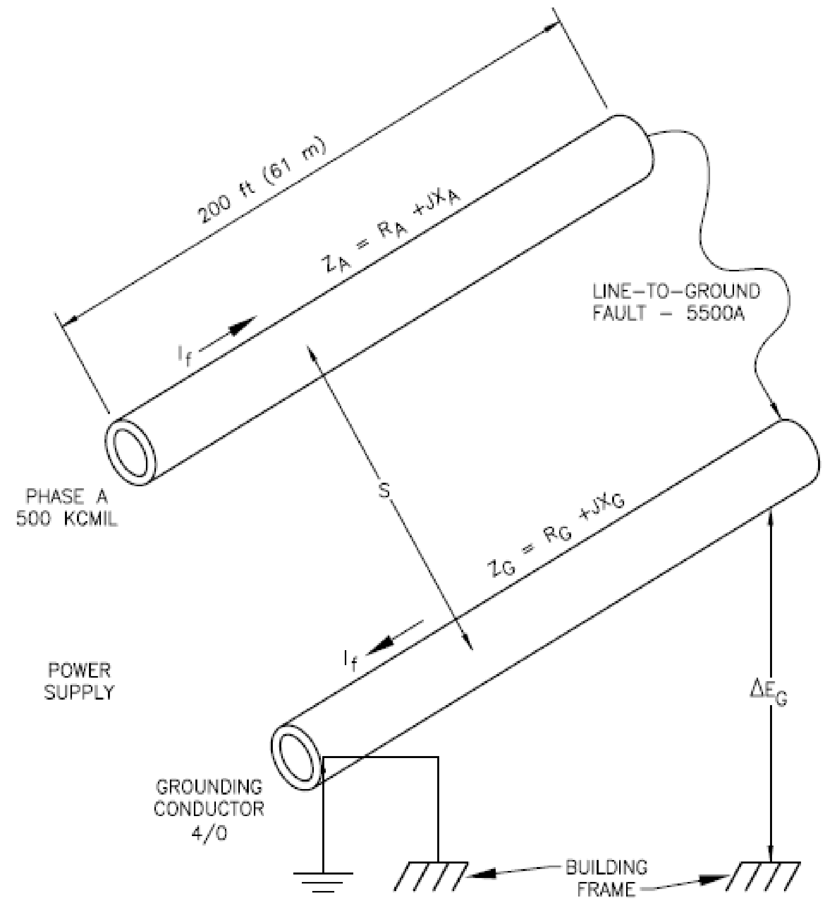


Table 2-1
Impedance as a Function of Conductor Spacing

	Spacing		R	X	Z
	(mm)	(in)	Ω	Ω	Ω
Phase Conductor A	51	2	0.0049	0.0085	0.0098
	203	8	0.0049	0.0149	0.0157
	762	30	0.0049	0.021	0.0216
Grounding Conductor G	51	2	0.0115	0.0108	0.0158
	203	8	0.0115	0.0172	0.0207
	762	30	0.0115	0.0233	0.026

Shock Voltage as a Function of Conductor Spacing

Spacing		EG
(in)	(mm)	(V)
2	51	86.9
8	203	113.9
30	762	143

Fig 2-3 -- Magnetic Field of Wire as Grounding Conductor

- Throughout the space between the two conductors [8 in wide and 200 ft long] exists a powerful 60 Hz magnetic field with a driving magnetomotive force of 5500 A turns.

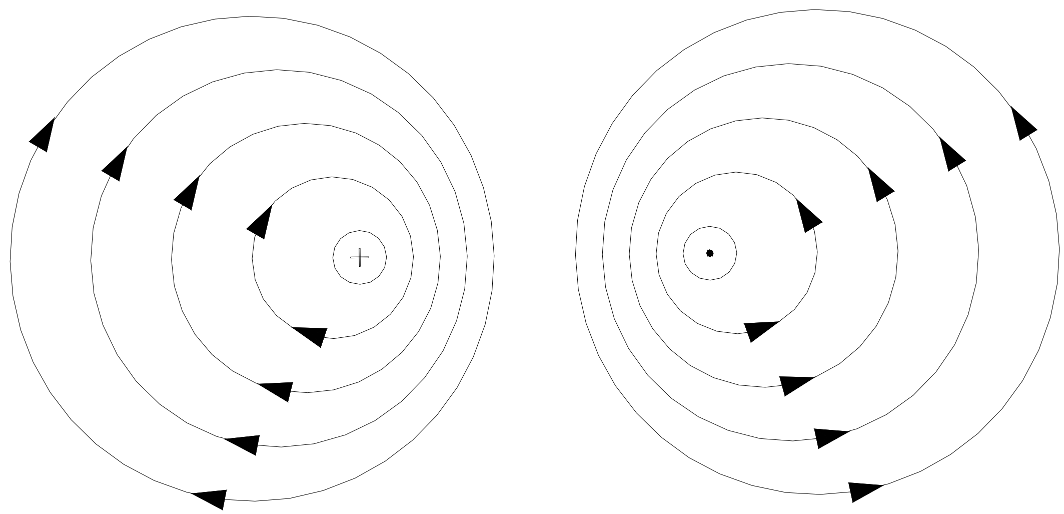
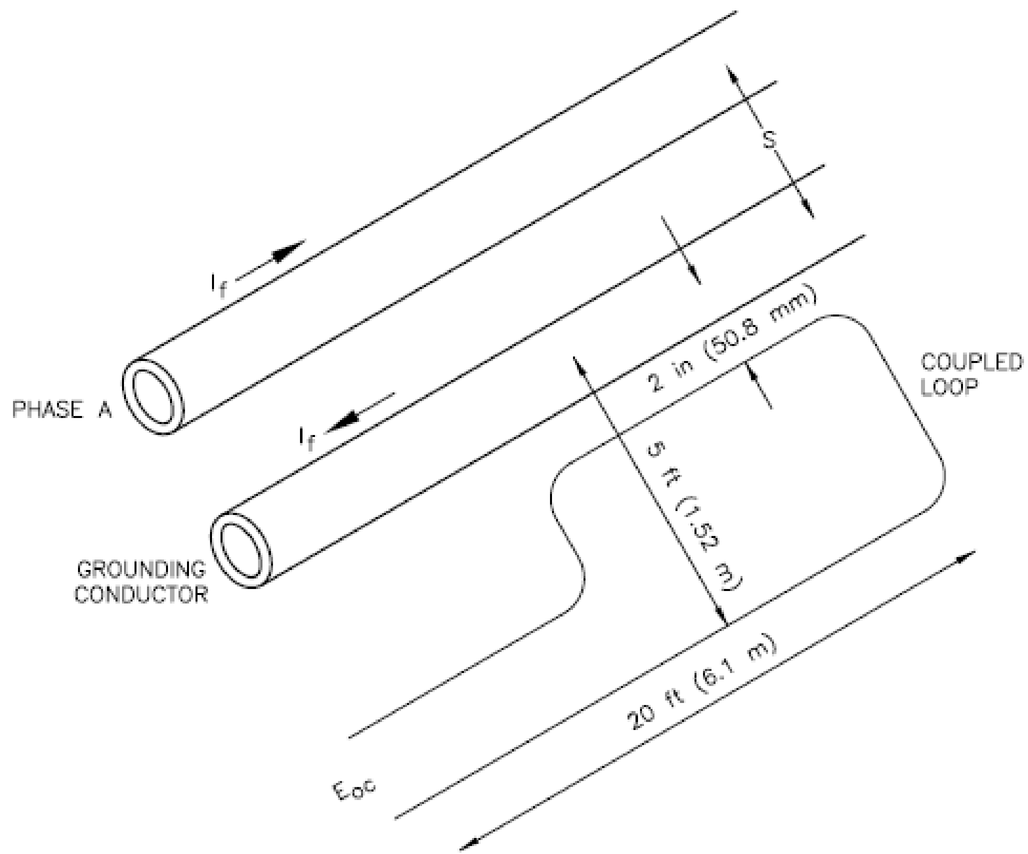


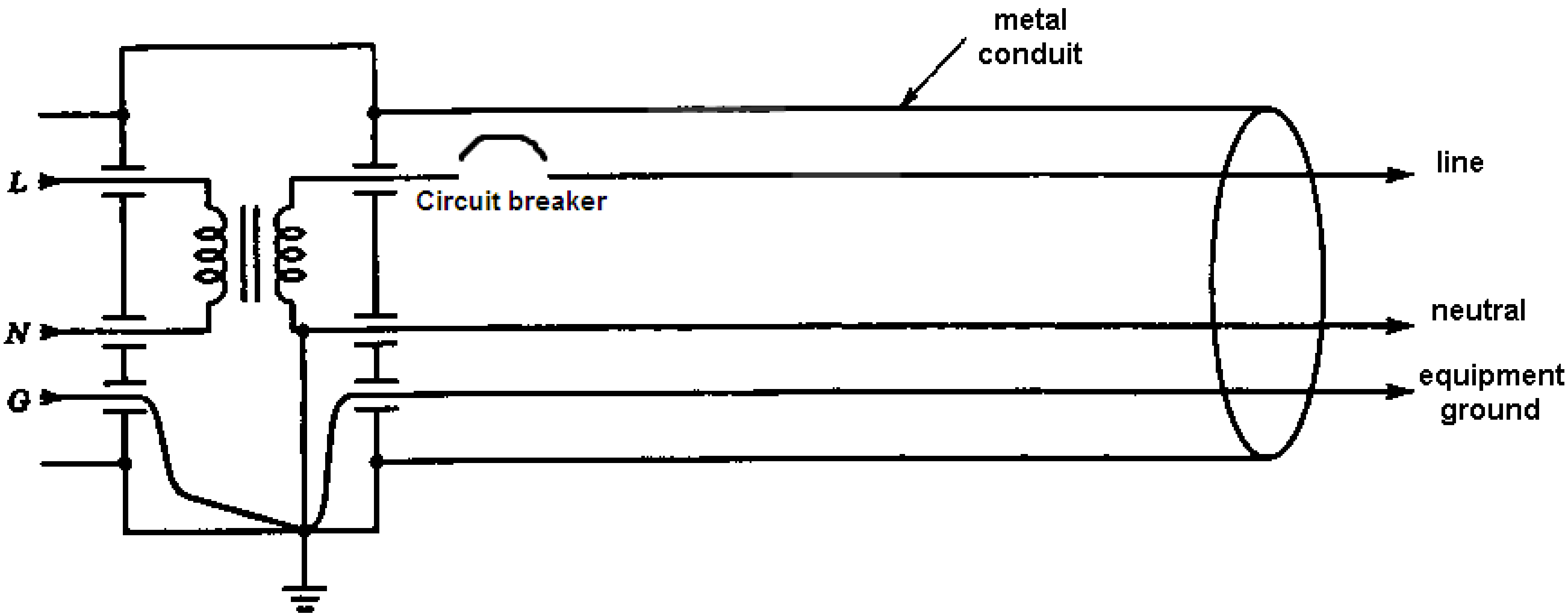
Fig 2.4 -- Electromagnetic Induction of Wire as Grounding Conductor

- Any loop of conducting material (wire, pipe, messenger cable, steel structure, etc.) through which some portion of this magnetic field passes will have induced in it a corresponding 60 Hz voltage.
- If the loop in which the voltage is mutually coupled is closed, then instead of a voltage, a circulating current will exist.



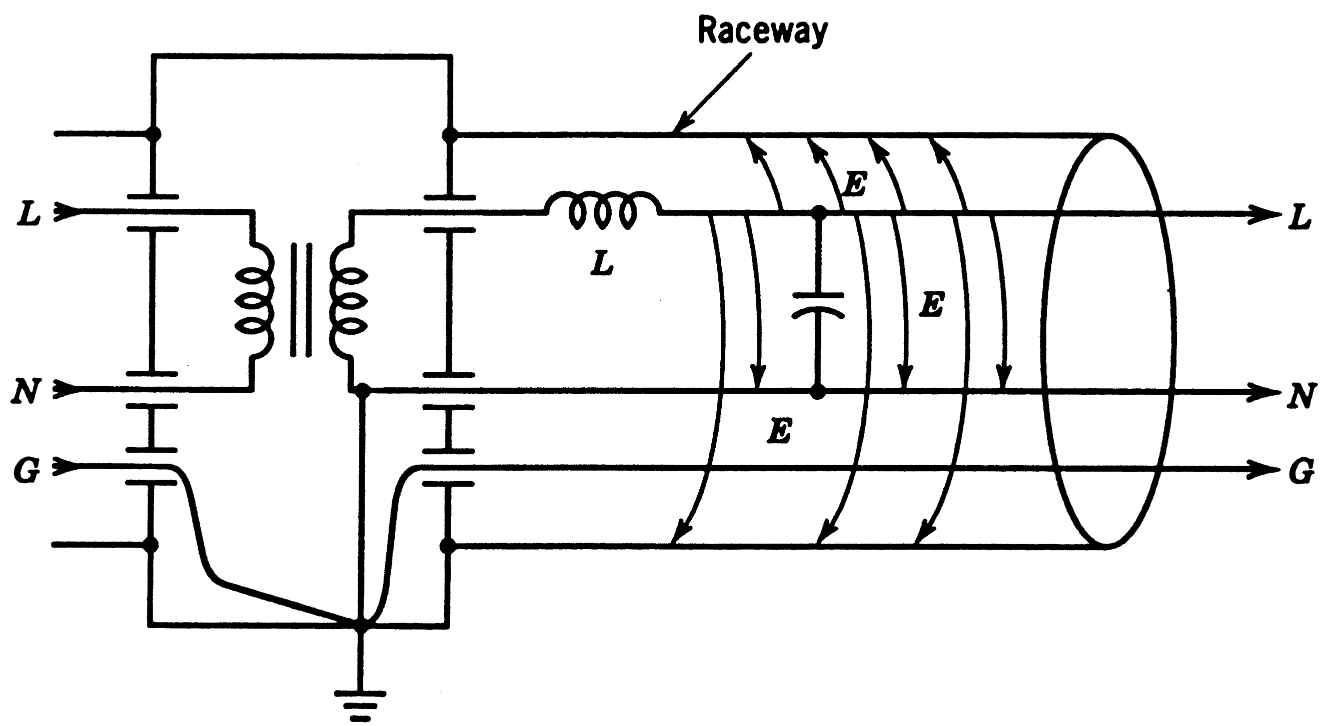
What is the correct circuit?

- For electrical distribution, we tend to think in terms of the circuit as shown below



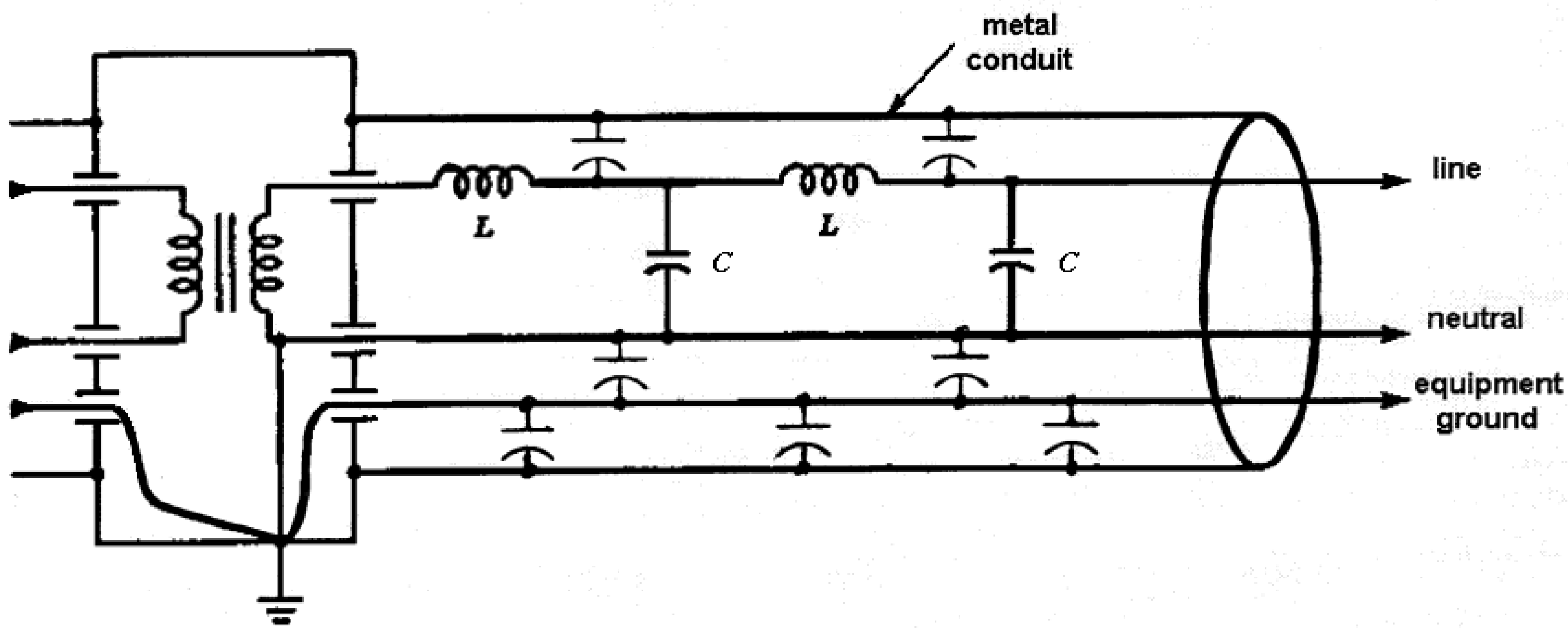
What is the correct circuit?

In terms of the Electric Field, the circuit looks more like this



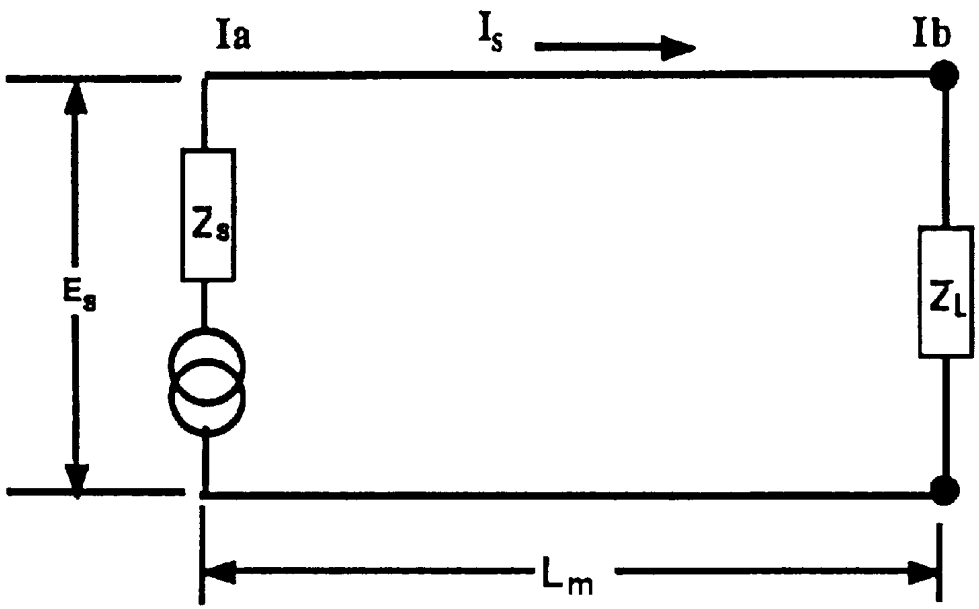
What is the correct circuit?

- In terms of impedance, particularly for high frequency issues like interference, the actual circuit looks more like this
- When do we need to consider the distributed aspect of the capacitance and inductance?



Electrically "small" circuits

- E_S drives current I_a in closed loop to the load Z_L, along path length L_m, all current and voltage around the loop will be considered as occurring instantaneously and continuously



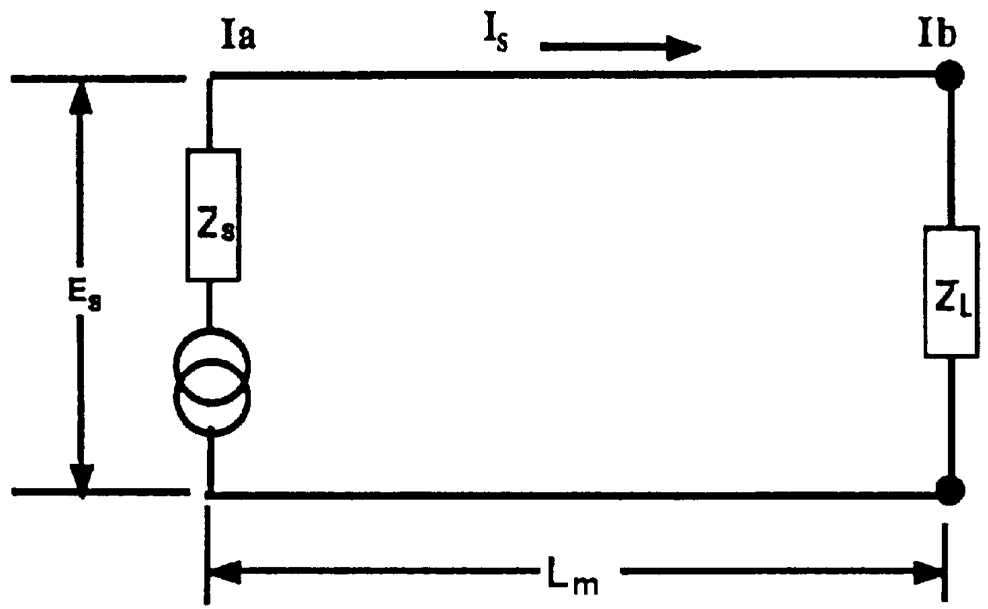
Electrically "large" circuits

- *When* length $\boldsymbol{L}_{\mathbf{m}}$ is large relative to the frequency of E_S circuit analysis with lumped parameter no longer applies and transmission line theory addressing wave propagation is necessary

$$L_m \geq (1/20)\lambda$$

$$v = \lambda f$$

v propagation velocity
λ wavelength
f frequency in Hertz



Large Circuits - Examples of wavelength (λ) vs frequency (*f*)

- For copper, the velocity of propagation (***v***) is 983,576,337 feet per second
  1. f = 60 Hz, λ = 3,104.7 miles, (1/20)λ = 155.2 miles
  2. f = 1 kHz, λ = 186.3 miles, (1/20)λ = 9.3 miles
  3. f = 1 MHz, λ = 983.6 feet, (1/20)λ = 49.2 feet
  4. f = 60 MHz, λ = 16.4 feet, (1/20)λ = 9.84 inches
- Power transmission lines were the first "large circuits" to be addressed, hence the name "transmission line theory"

What grounding issues require "transmission line theory"?

- Lightning has both high and low frequency aspects to address:
  - The leading edge has high frequency aspects
  - The major energy of the discharge has low frequency aspects
- Communications/Interference:
  - IT equipment operate in the MegaHertz range, where the wavelength of the signal can measure in feet
  - Interference can occur across a relatively large frequency band
- Most data transfer is now done with "differential voltage" in which neither the "1" nor "0" is actually zero volts

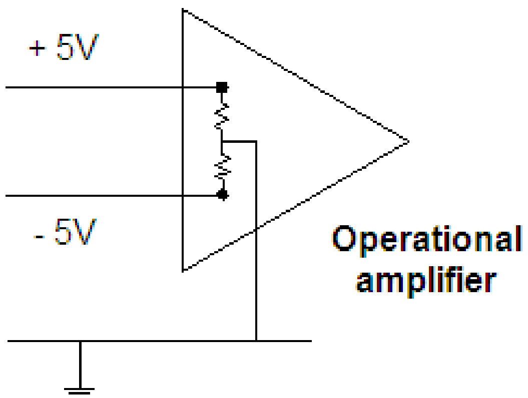


Fig 3-8 Cumulative Frequency Distribution of Maximum Rates of Rise of Lightning Currents 1. Negative First Strokes 2. Negative Subsequent Strokes

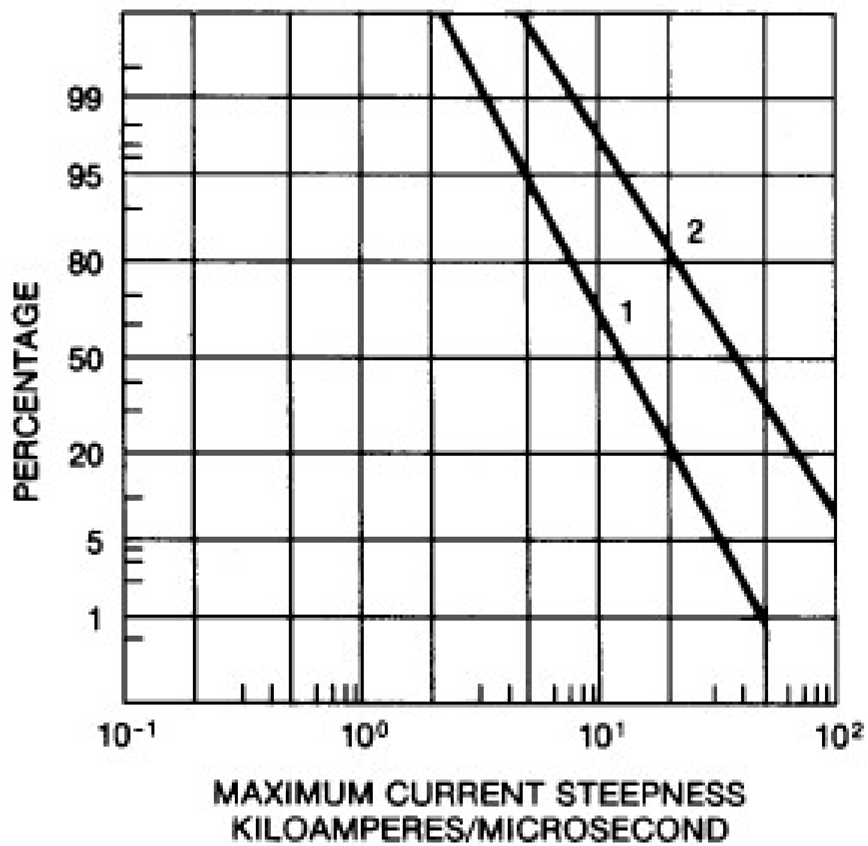


Fig 3-11--Contour Map of Mean Annual Lightning Strike Density

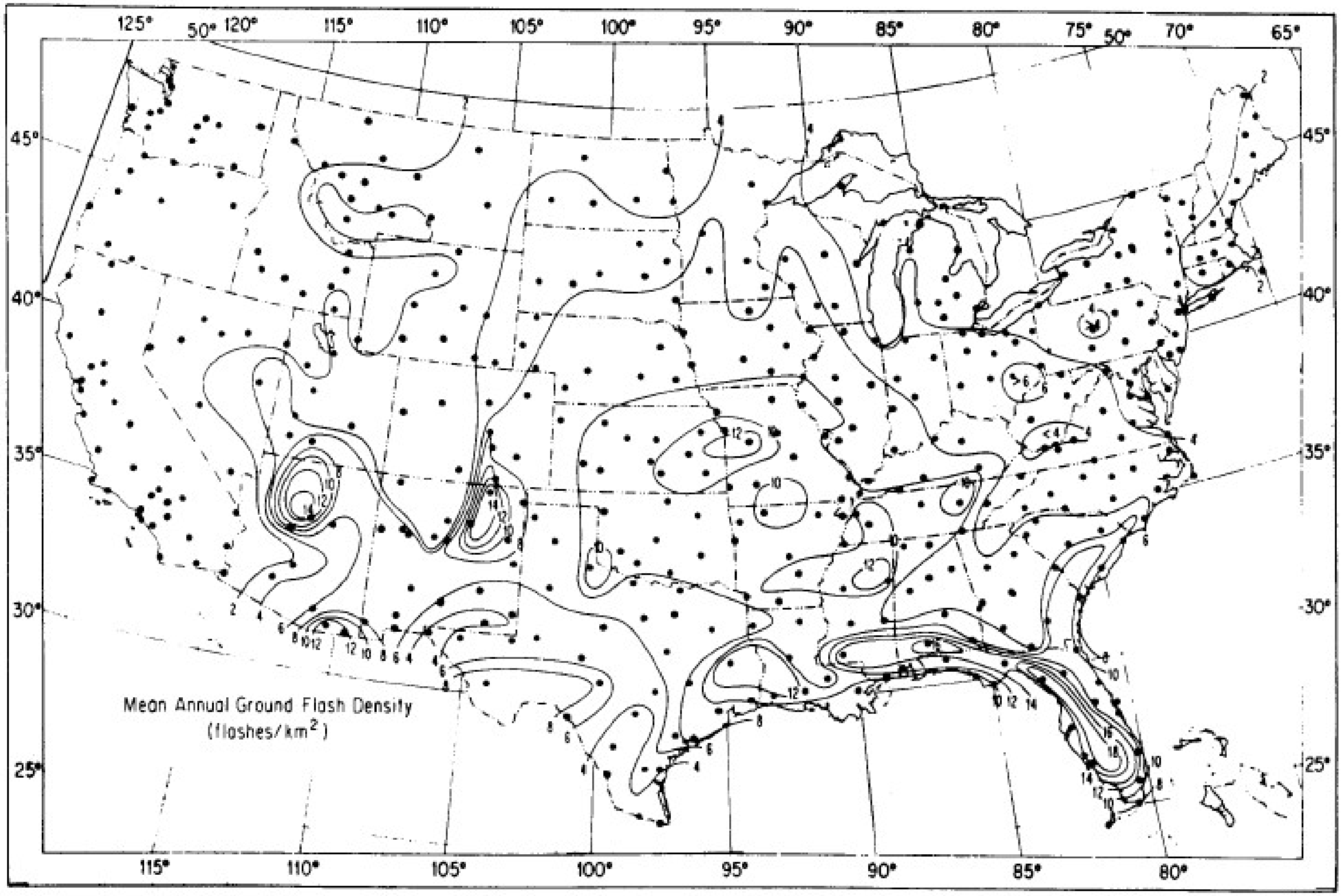
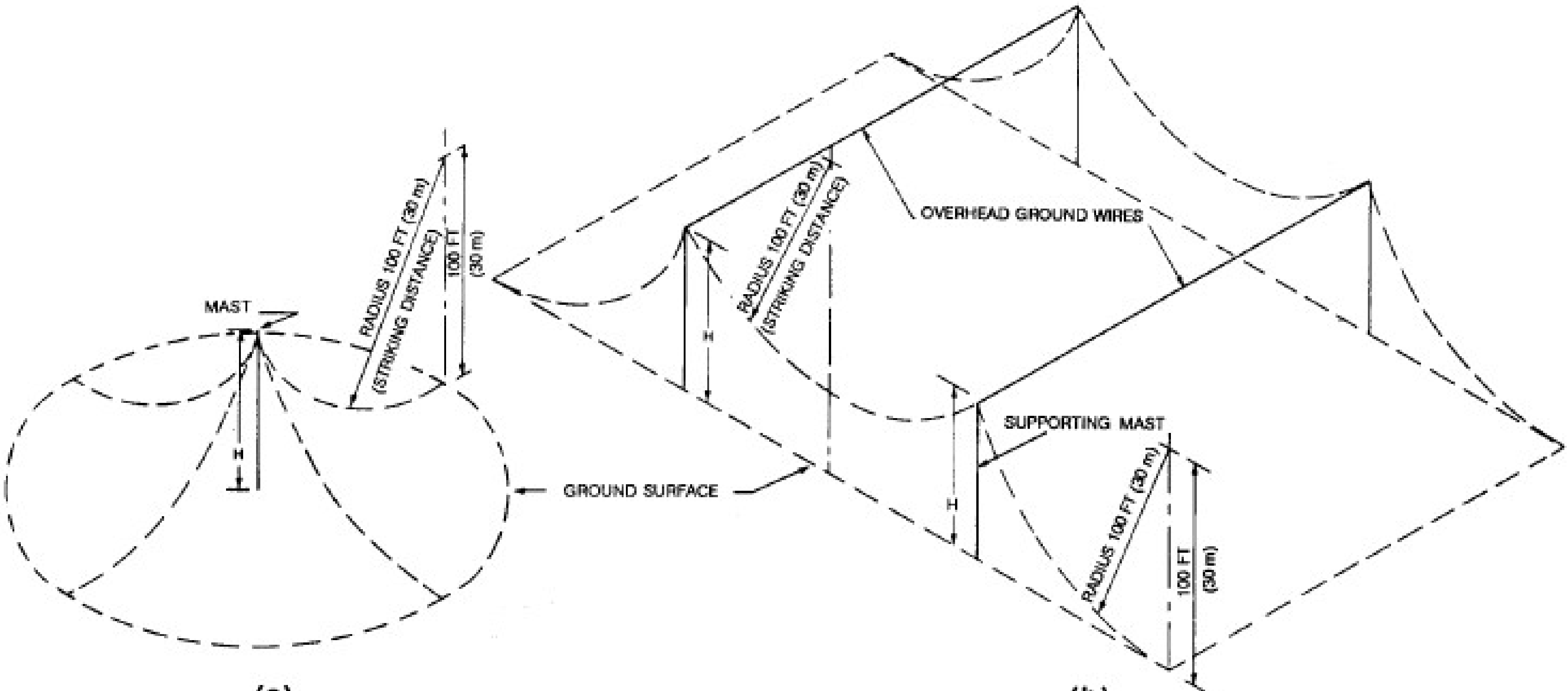


Fig 3-12 Lightning Protection for Structures



(a)
SINGLE MAST
ZONE OF PROTECTION DEFINED BY DASHED LINES

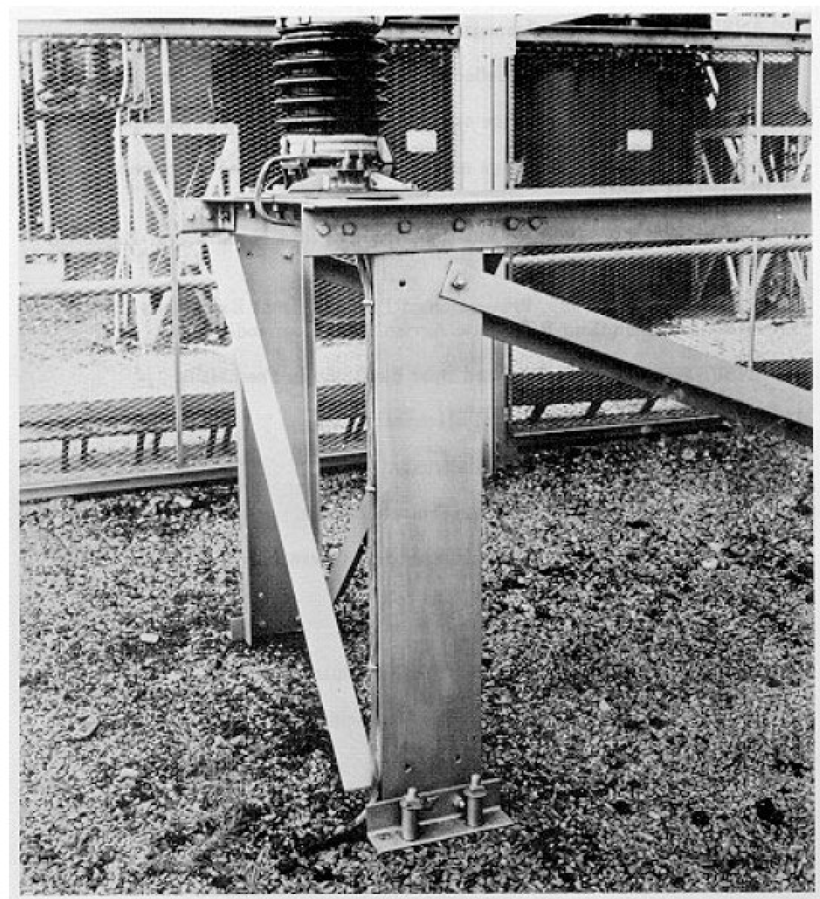
(b)
OVERHEAD GROUND WIRES
ZONE OF PROTECTION DEFINED BY GROUND WIRE(S)
AND DASHED LINES

Lightning Protection

- NFPA 780 provides specific direction on how to protect a building from lightning
- When the building has structural steel, the steel is an important part of the "lightning protection system"

Grounding Connections Associated with Steep Wave Front Voltage Protection Equipment

- The function of the grounding conductor is to provide a conducting path over which the surge current can be diverted around the apparatus being protected, without developing a dangerous voltage magnitude.



Steep Wave Front Voltage

- Actual values of di/dt range over wide limits, but a value of 10 kA/μs is representative. With such a rate of rise of current, even 1 μH of inductance can be significant.

$$E = L \cdot di/dt$$

$$= 10^{-6} \cdot 10{,}000 \cdot 10^{6}$$

$$= 10{,}000 \text{ V}$$

- It would take only a 3 ft length of No. 4/0 AWG conductor spaced 5 ft away from the transformer in Fig 2-7 to add 10,000 V to the arrester voltage.

Fig 2-7--Surge Arrester Location on Transformer

- To take full advantage of the protective properties of the surge arrester in Fig 2-7, the arrester should be mounted so as to be in direct shunt relationship to the terminal bushings.

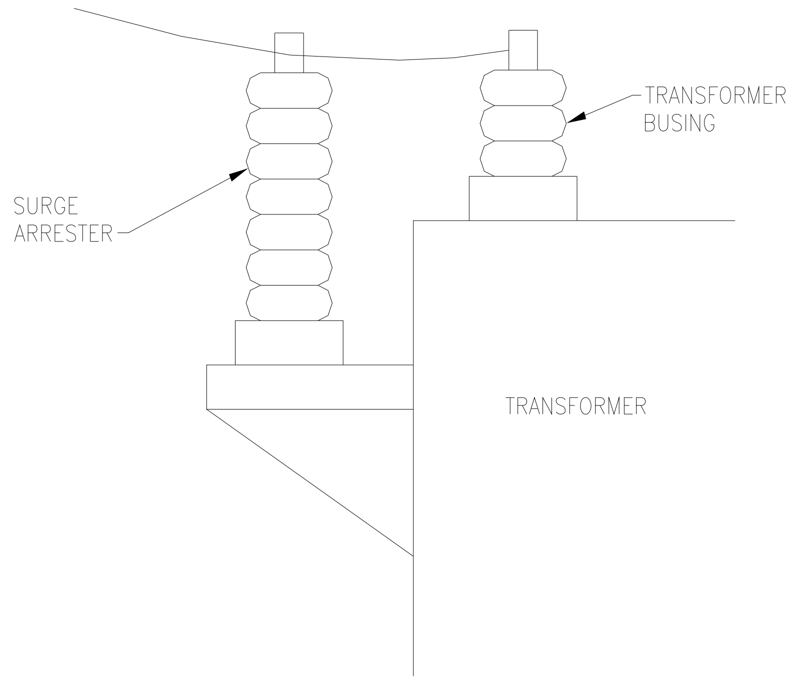
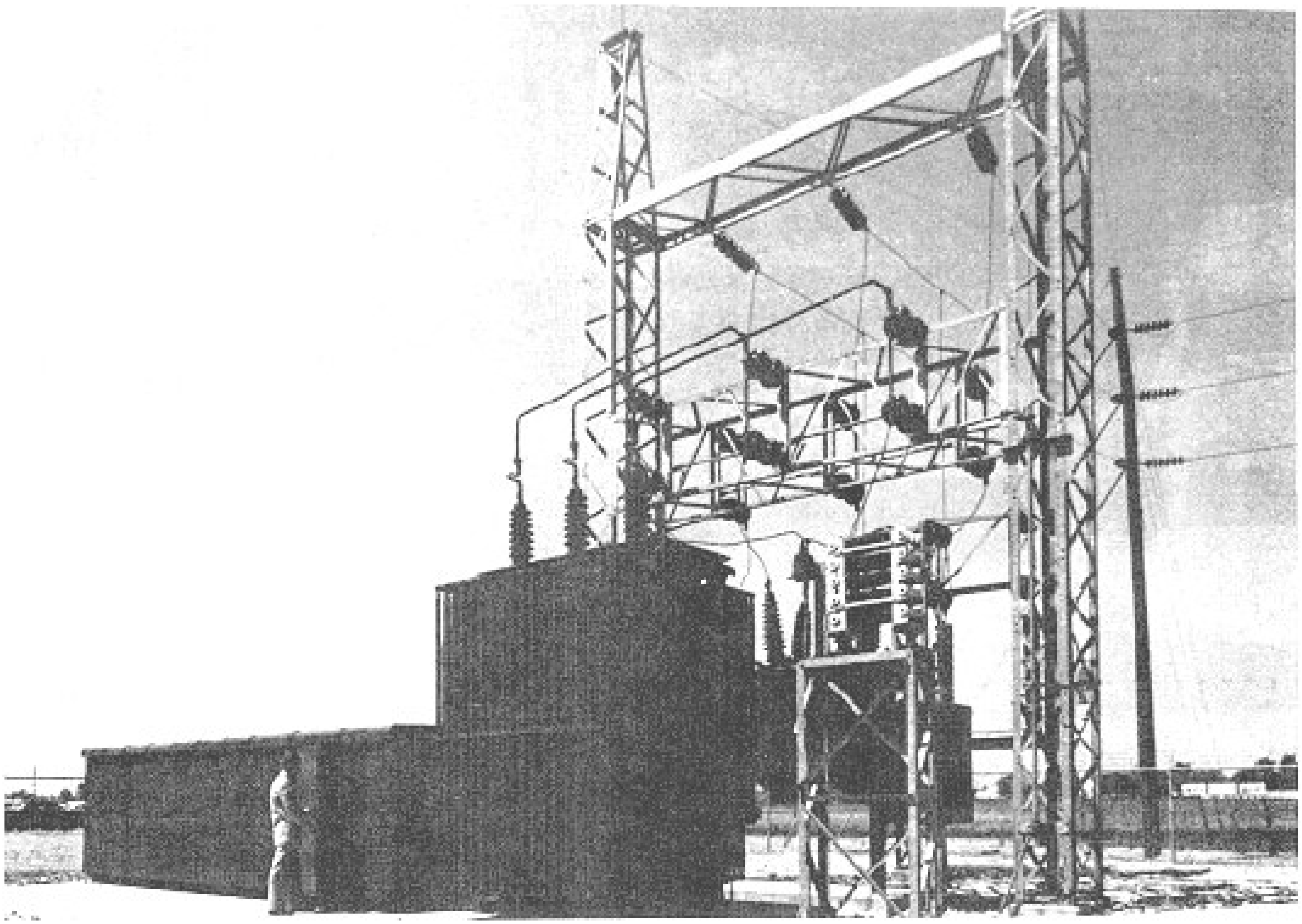


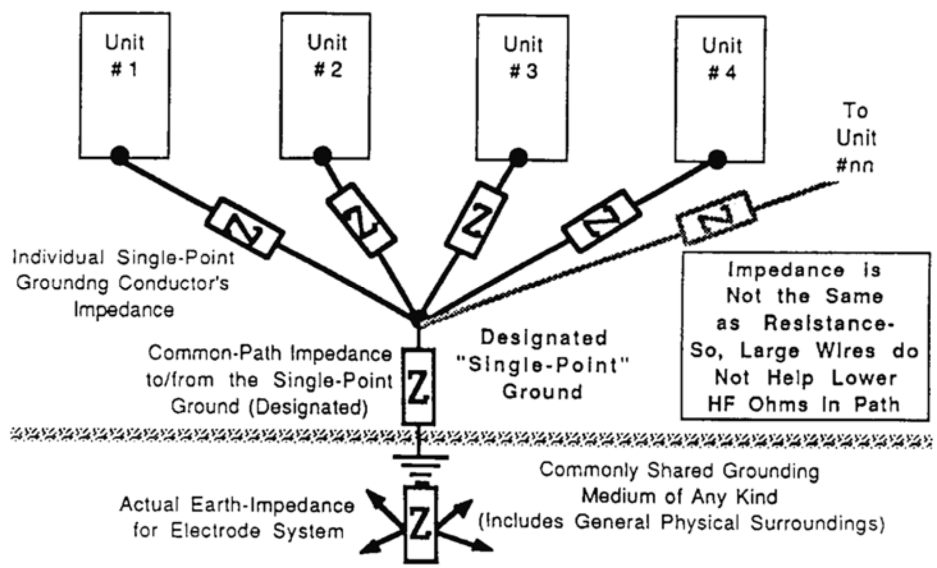
Fig 2-12: Outdoor Unit Substation



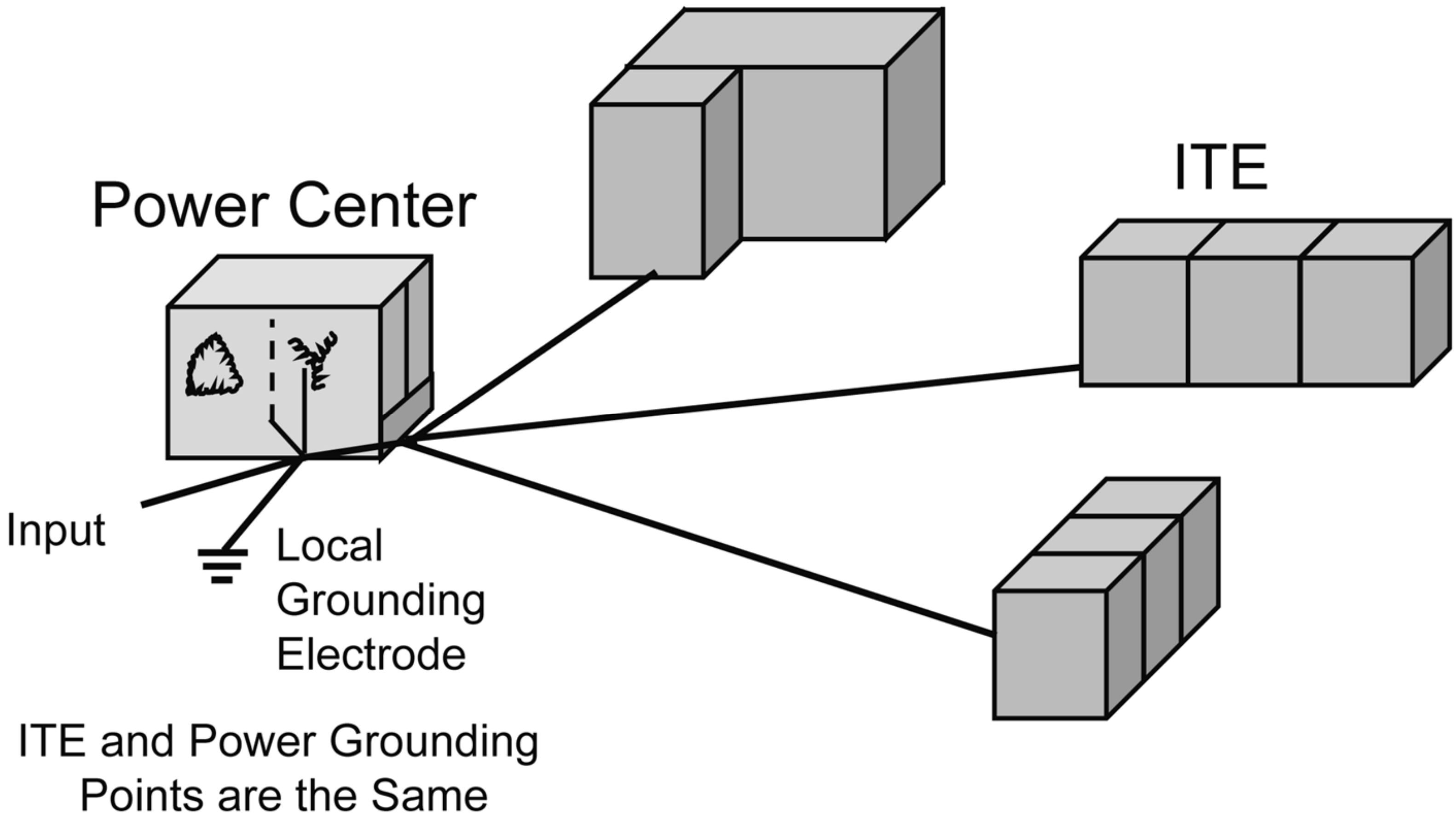
Grounding techniques to minimize interference problems

- There are two major strategies that have been used with grounding to minimize interference issues:
  - Single point grounding
  - Signal reference grid

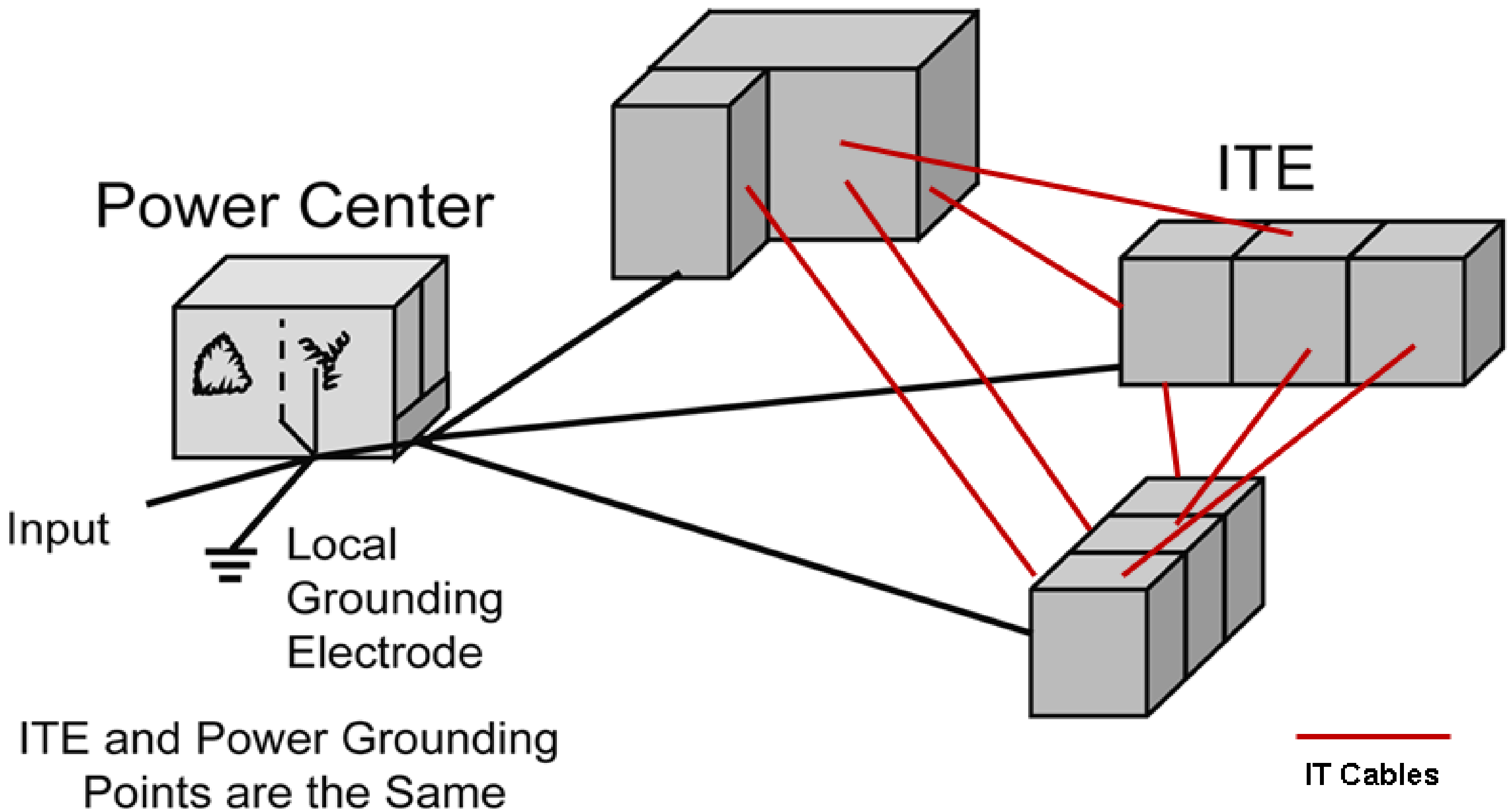
- Single point grounding uses a radial approach in which all the pieces connect to a single place with no “ground loops”



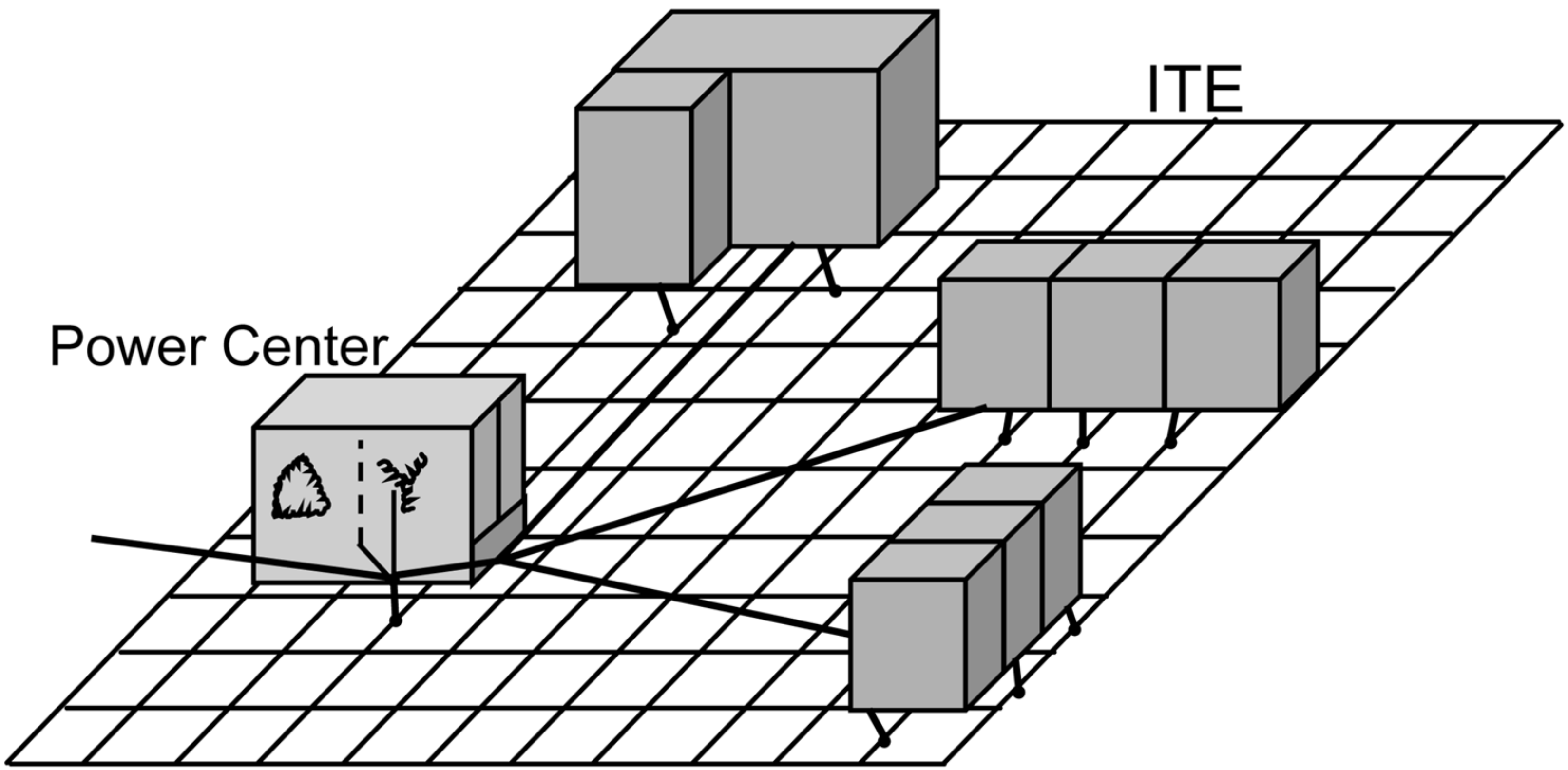
Single point grounding - theory



Single point grounding - practice



Multi-point grounding using a signal reference grid



Signal Reference Grid

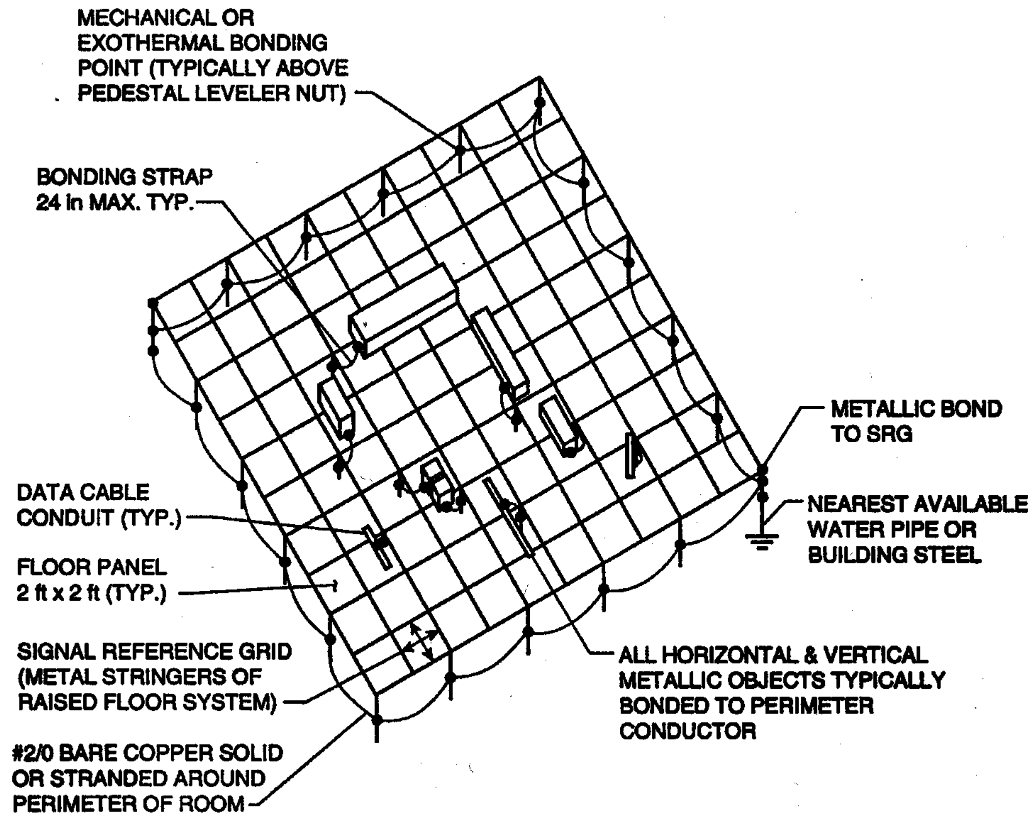
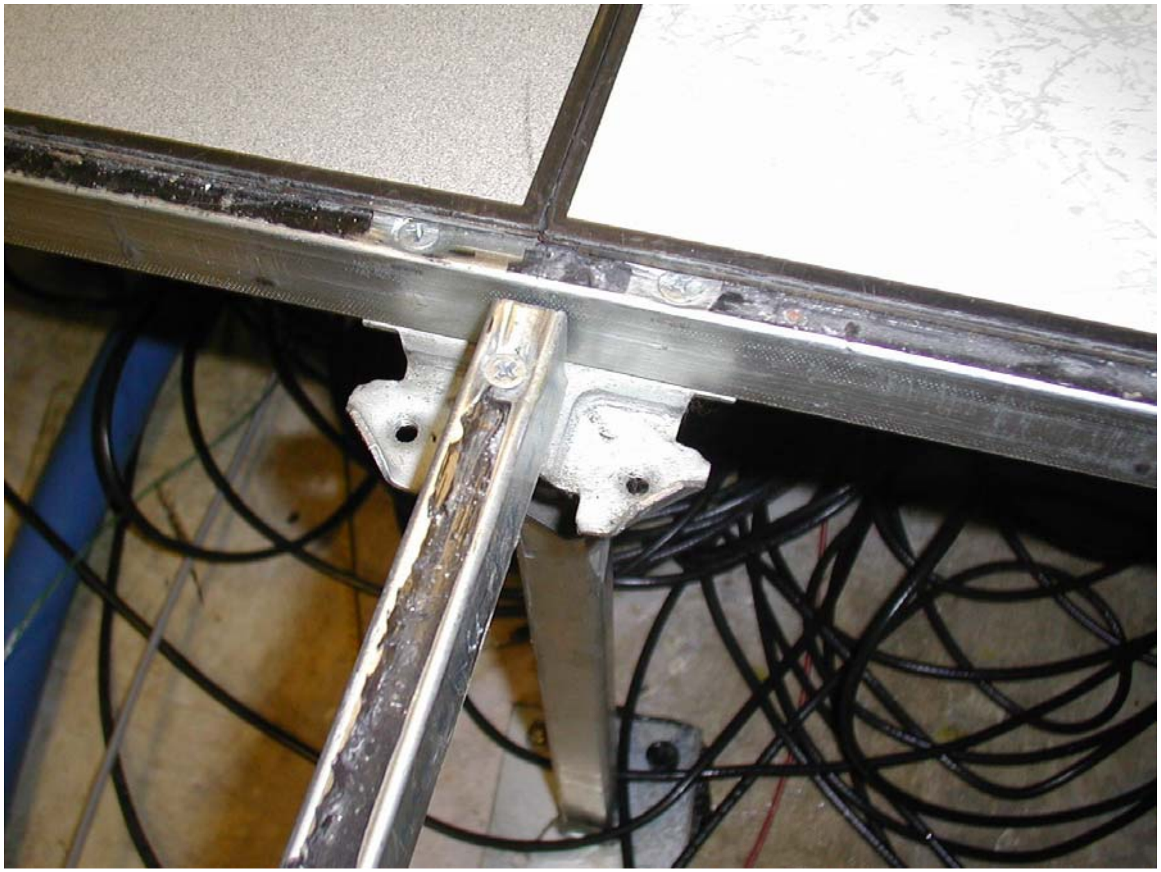
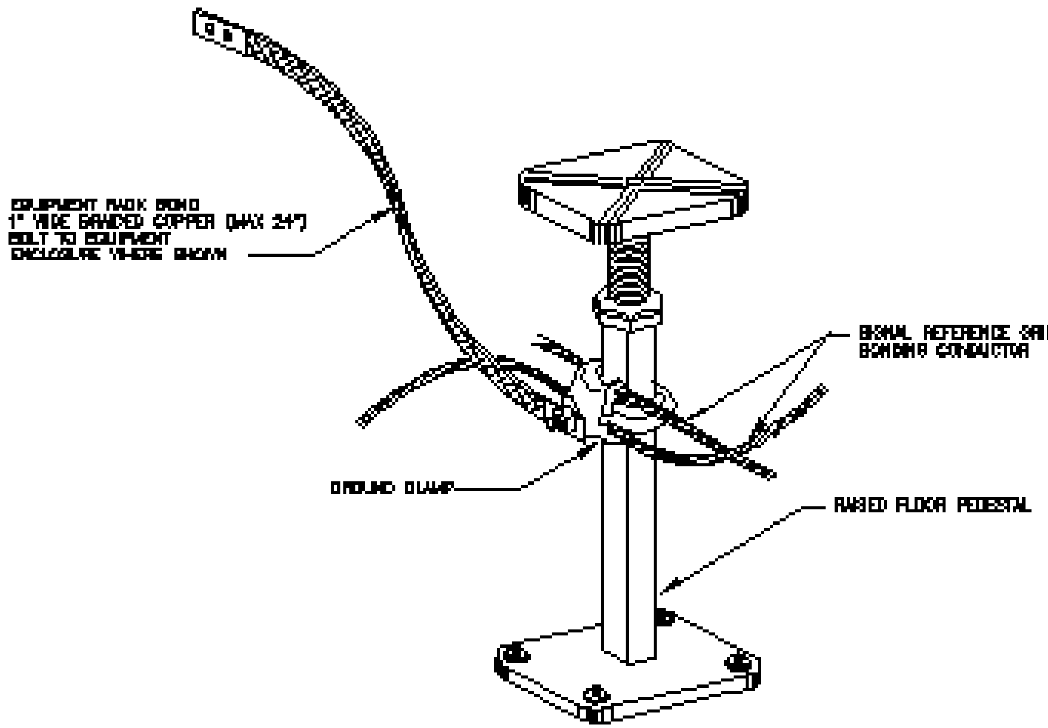


Figure 8-24—Raised access flooring substructure as signal reference grid

Bolted stringer

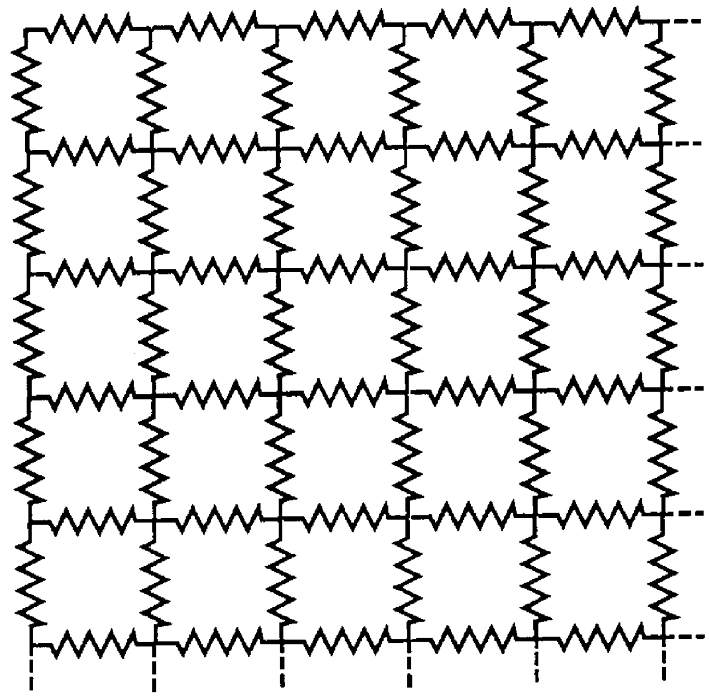


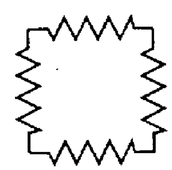
Bonding to the pedestal



Signal Reference Grid

- Signal reference grid takes advantage of many resistances in parallel, so that the overall resistance is low over a broad frequency range
- The impedance of an individual path is much less significant, since there are many in parallel



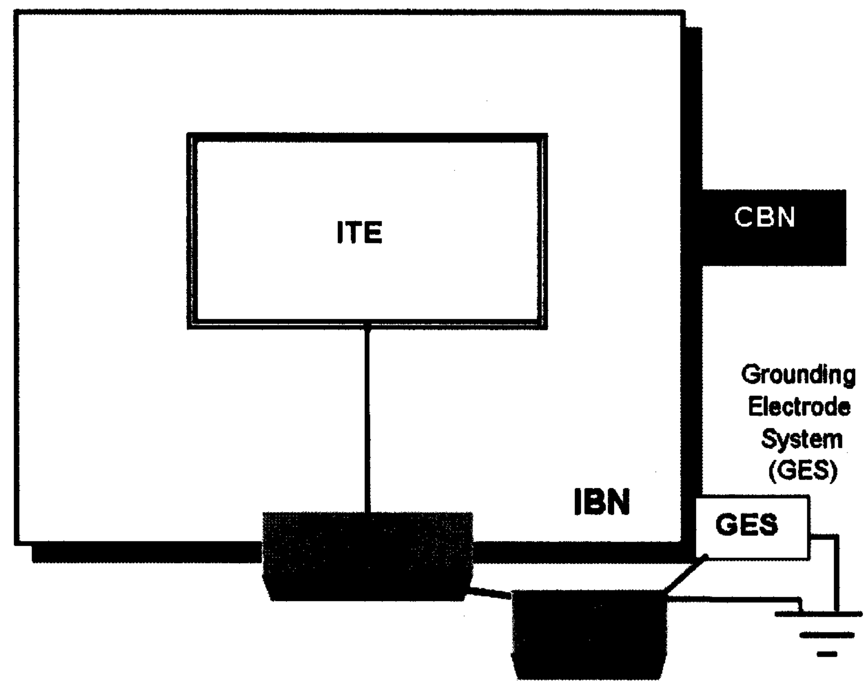


Surface of plane is divided into equal squares of whatever the desired dimension. CM ^{2} is typical. Impedance then represented on this selected per-square basis.

Telecommunications world (Bell Standards) have different grounding terminology

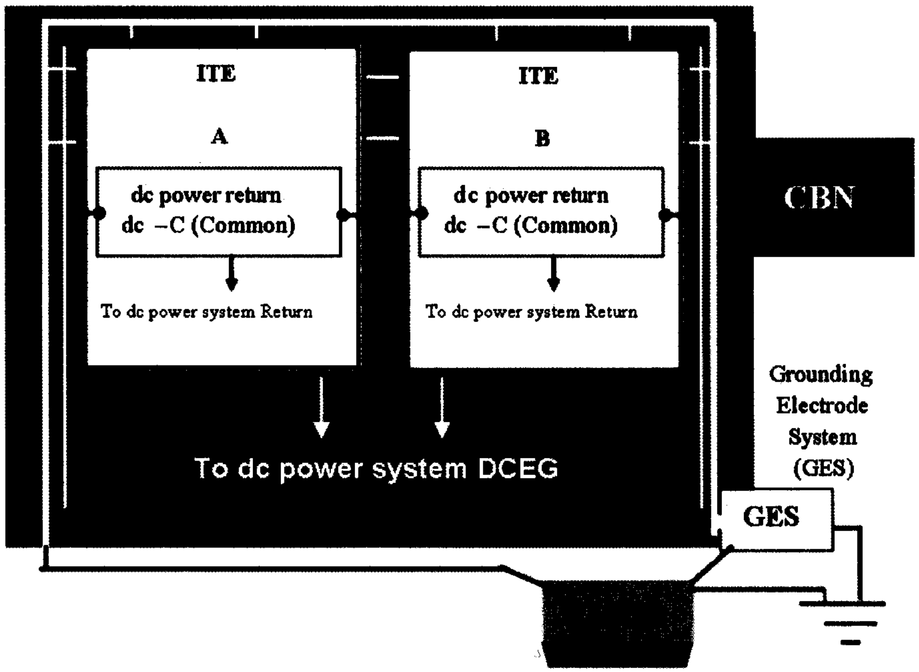
Isolated Bonding Network:

is the equivalent grounding scheme as single point grounding for an AC distribution system



Telecommunications grounding terminology

Common Bonding Network:
  is the equivalent grounding scheme as multi-point grounding for an AC distribution system

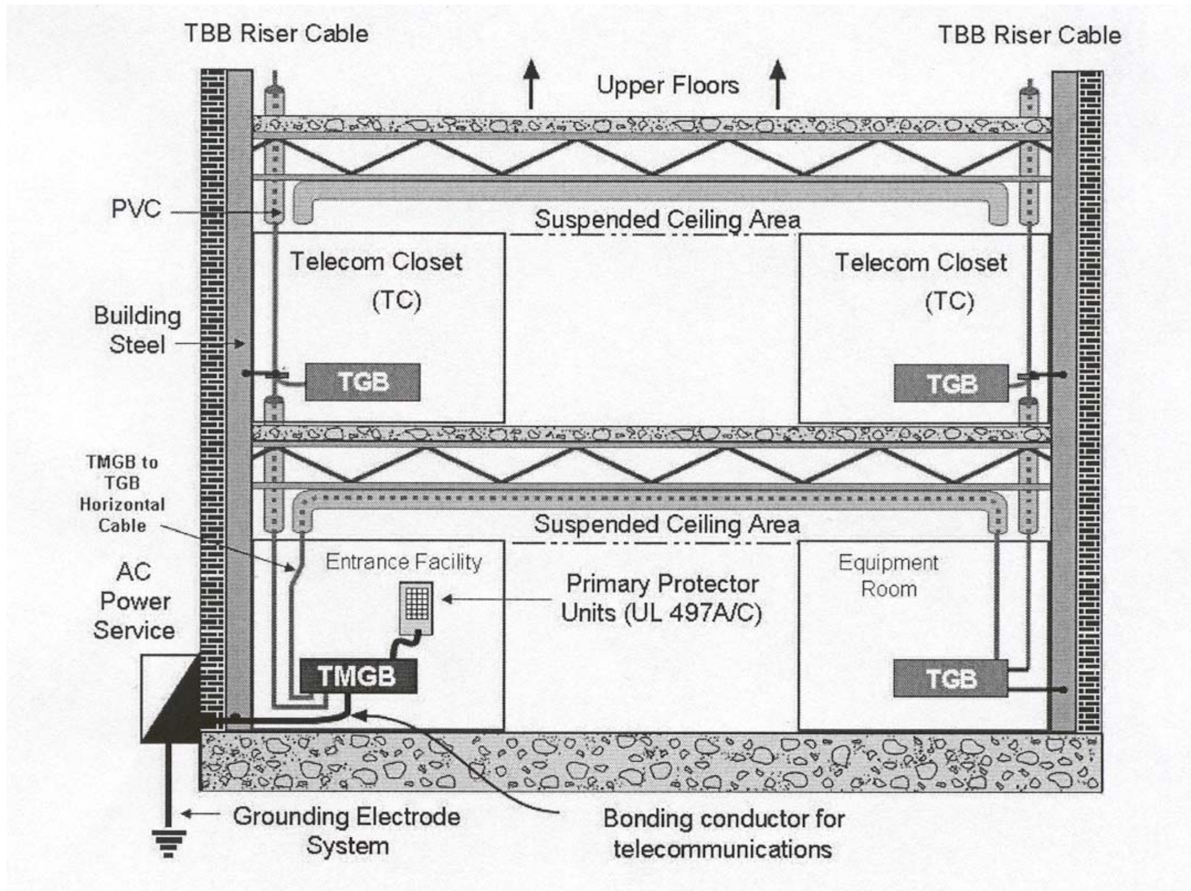


Telecommunications grounding terminology

TBB – telecommunications bonding backbone

TGB - telecommunications grounding busbar

TMGB - telecommunications main grounding busbar



Telecommunications grounding -Isolated bonding network

CDCPS – centralized DC power system

DCG – DC ground

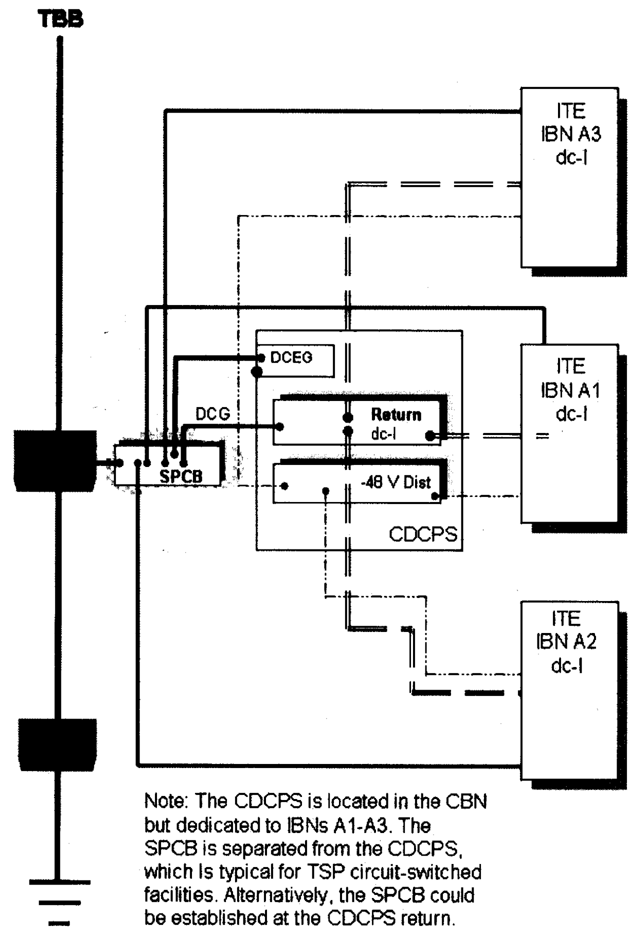
DCEG – DC equipment ground

dc-I – DC return conductor that is insulated from the DCEG

ITE – Information technology equipment

SPCB – Single point connection bar

TBB – telecommunications bonding backbone



Telecommunications grounding -Common bonding network

CDCPS – centralized DC power system

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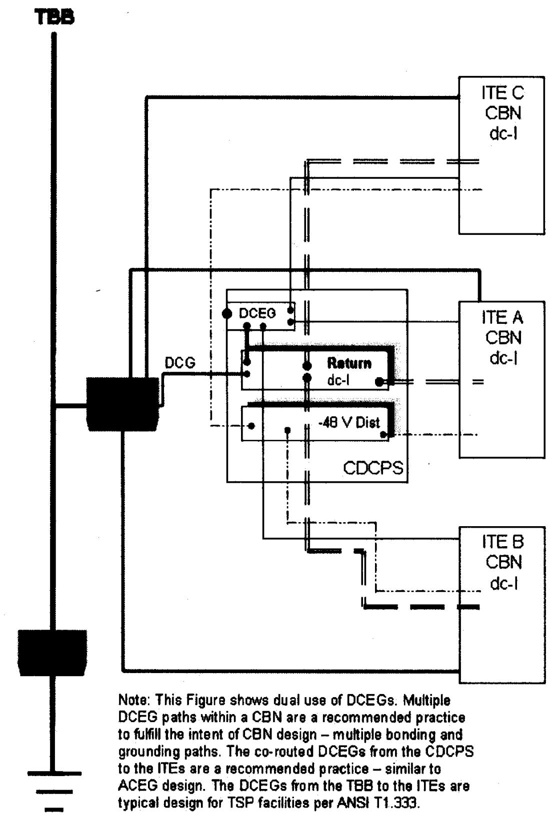
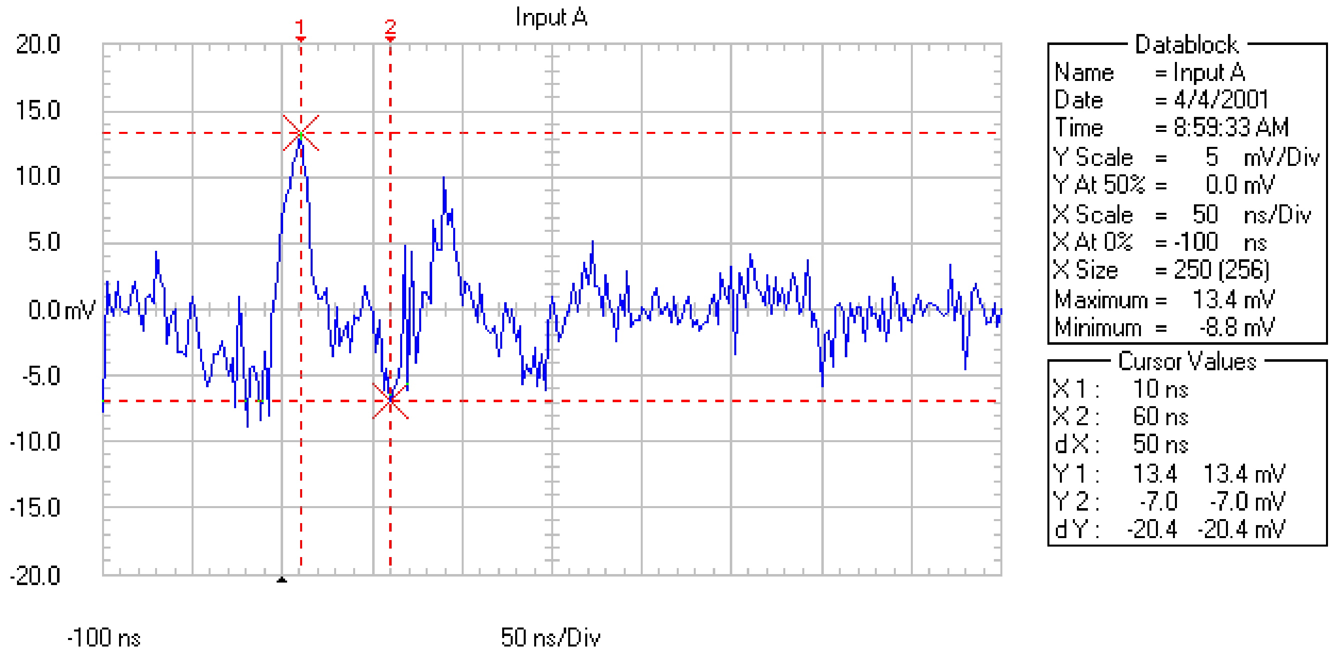


Note: This Figure shows dual use of DCEGs. Multiple DCEG paths within a CBN are a recommended practice to fulfill the intent of CBN design – multiple bonding and grounding paths. The co-routed DCEGs from the CDCPS to the ITEs are a recommended practice – similar to ACEG design. The DCEGs from the TBB to the ITEs are typical design for TSP facilities per ANSI T1.333.

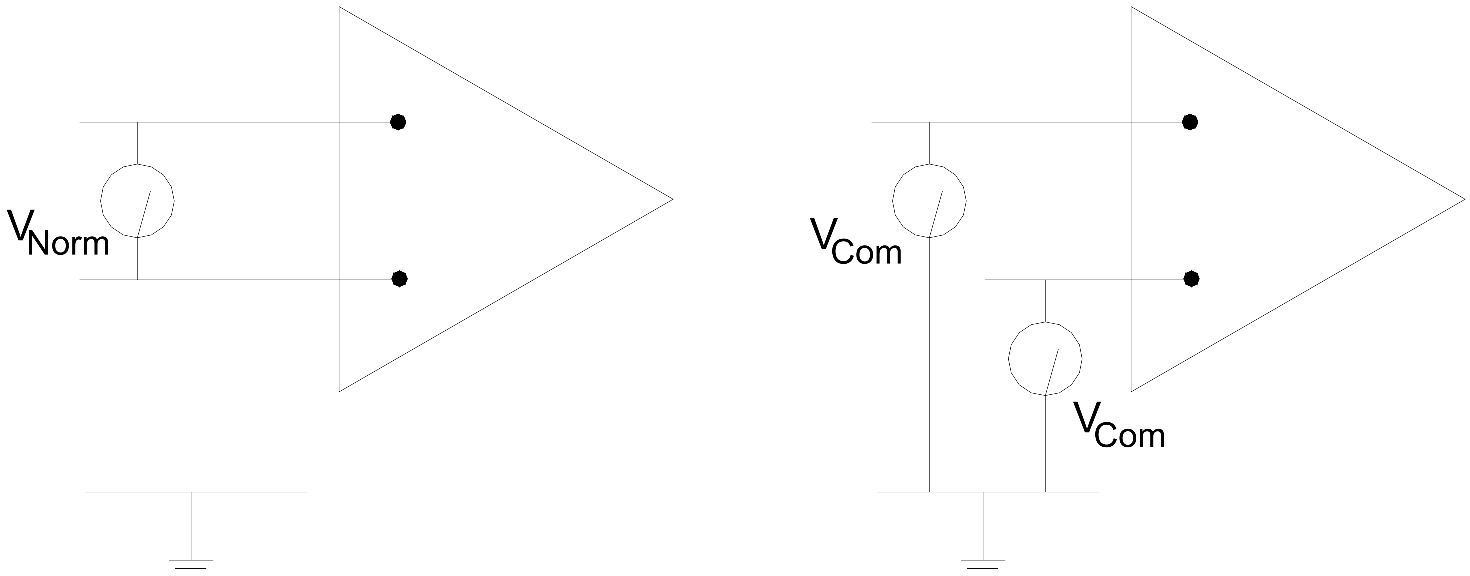
Grounding to deal with interference

- Interference current does not simply drain into "ground" and disappear
- Interference has a source and follows a closed loop (circuit) back to the source
- Part of the "circuit" is often a or several capacitors



Normal mode and Common mode interference

- Part of dealing with the interference is determining the circuit for the interference and whether or not it is referenced to ground

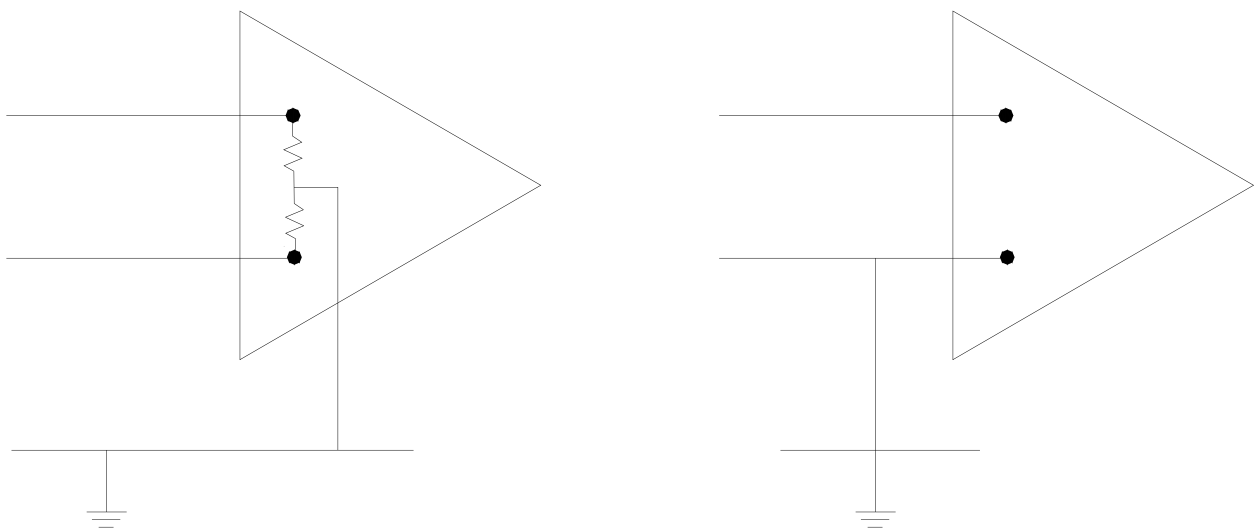


Normal Mode

Common Mode

Grounding to deal with interference

- Unbalanced circuits are much more susceptible to interference from ground based signals than balanced circuits
- For this reason most IT equipment now uses balanced circuits to send digital signals



Balanced Circuit   Unbalanced Circuit

Shield Capacitances, ground voltages

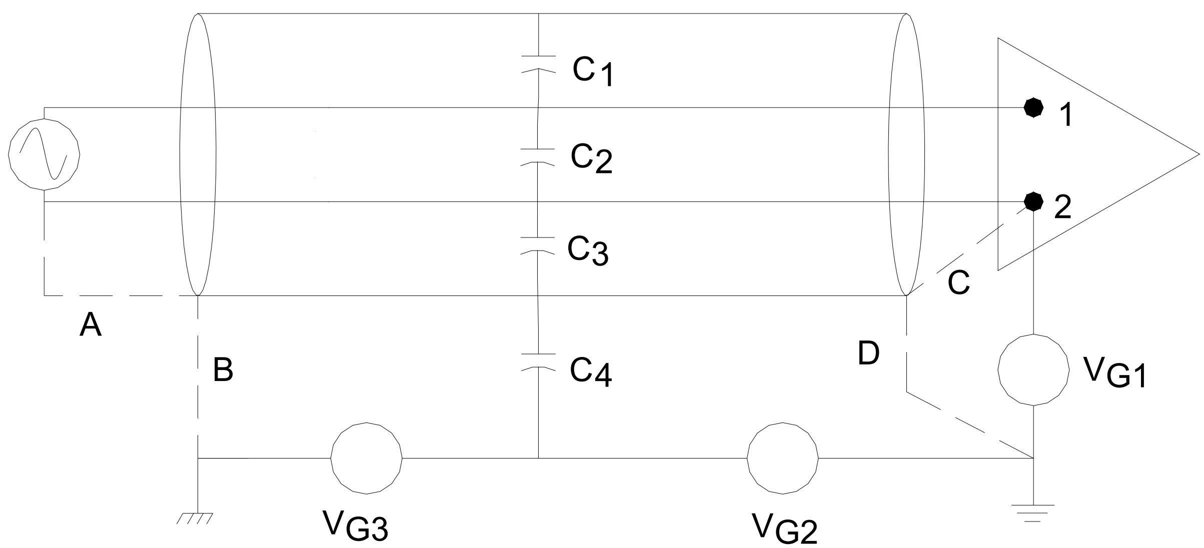


Figure 10.3 Model for analyzing shield effectiveness.

Shield equivalent circuit

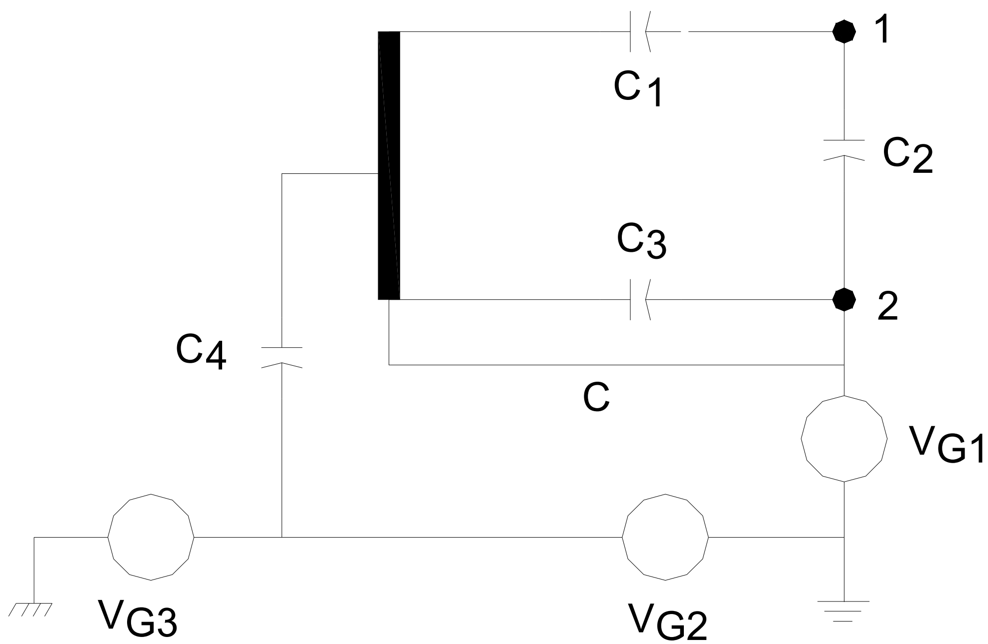


Figure 10.4 Equivalent circuit for model in Figure 10.3

Ground plane for industrial machine

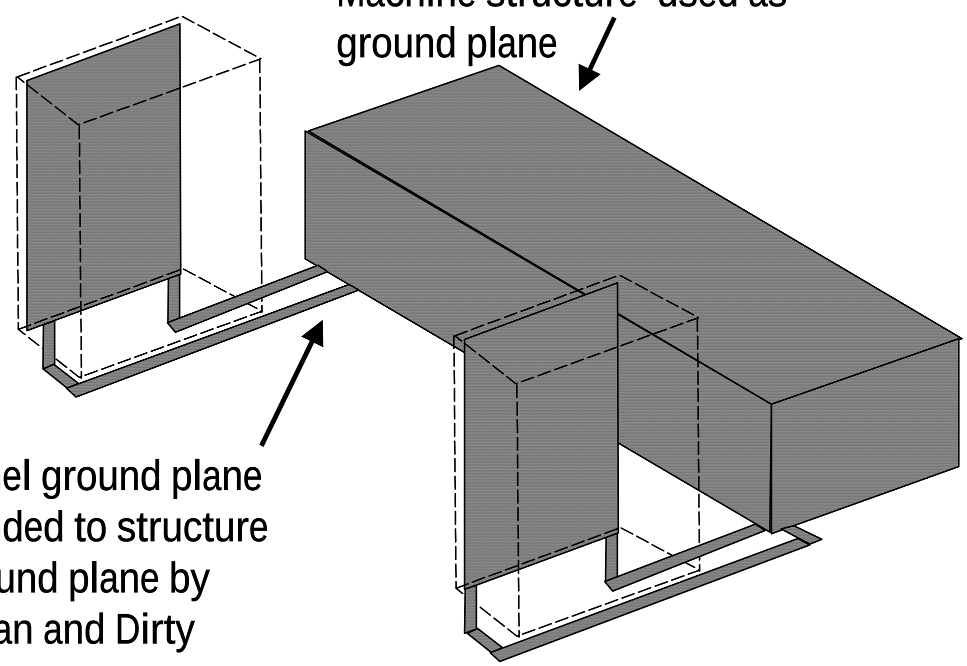


Figure 10.6 Panel ground plane extended to the machine structure

References

IEEE Standard 142-2007, Recommended Practice for Grounding of Industrial and Commercial Power Systems

IEEE Standard 1100-2005, IEEE Recommended Practice for Powering and Grounding Electronic Equipment

NFPA 70-2008, National Electrical Code

NFPA 780-1995, Lightning Protection Code

Questions?

- Robert Schuerger, PE
- Principal Reliability Analysis Corporate Lead
- HP Critical Facilities Services delivered by EYP MCF
- 310-297-4693
- bschuerger@hp.com