Grounding for Industrial Systems

Jim Bowen

2011 IAS Tutorial
December 2011

IEEE
Celebrating 125 Years
of Engineering the Future

IAS
IEEE INDUSTRY
APPLICATIONS
SOCIETY

System Failures on Industrial Power Systems

Failure Mode	Percentage of Failures
Line to Ground	**98%**
Phase to Phase	< 1.5%
*Three Phase	< 0.5%

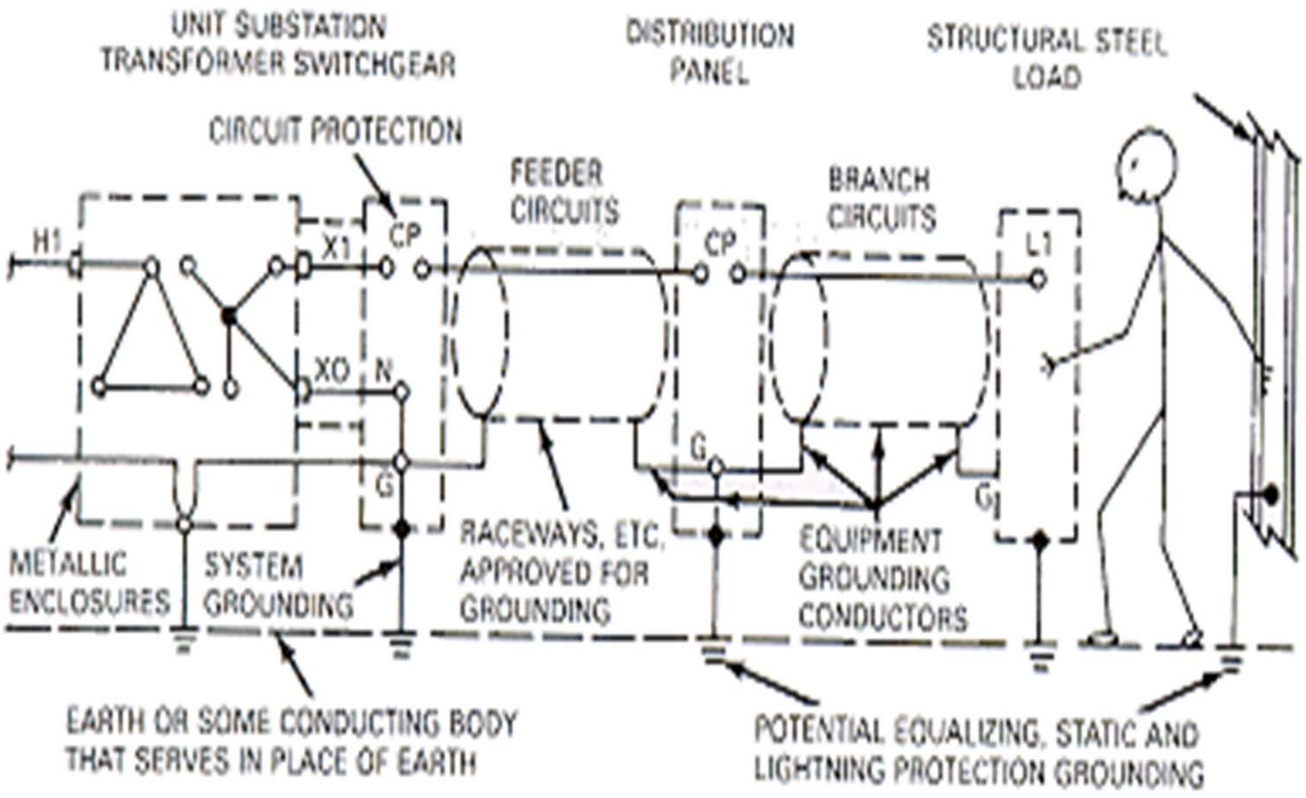
**Most three phase faults are man-made: i.e. accidents caused by improper operating procedure.*

First Half Agenda – System Grounding

- What is a ground fault?
- What happens in an ungrounded system?
- What happens in a solidly grounded system?
- Application of resistance grounding
- Resistance grounding and generators

What is a Ground Fault?

- Contact between ground and an energized conductor
- Unleashes large amount of electrical energy
- Dangerous to equipment and people



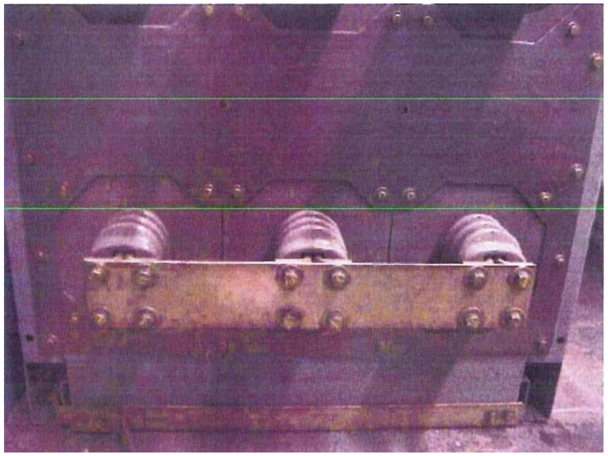
Definitions

- **System Grounding** – An *intentional* ground on the system

- **Resistance Grounding** –A type of grounding using a resistor in the neutral (system or derived) to limit available fault current

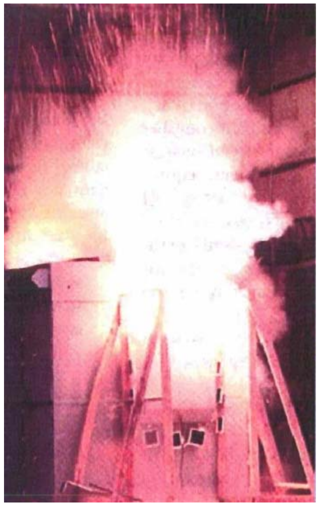
- **Ground Fault Protection** –Detection of an *unintentional* ground on the system and taking appropriate action

Two Types of Faults



Bolted Faults

- Solid connection between two phases or phase and ground resulting in high fault current.
- Stresses are well contained so fault creates less destruction.



Arc Faults

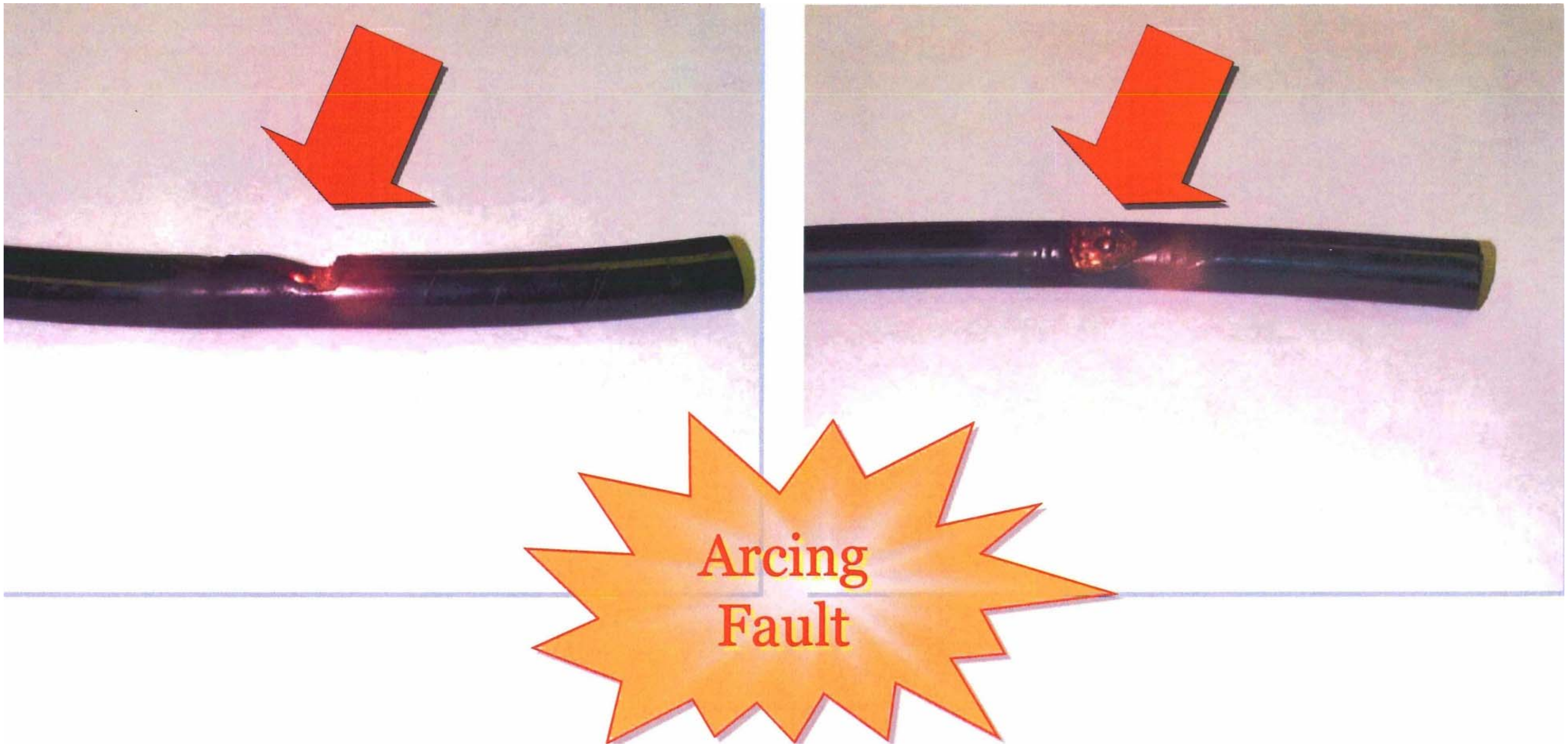
- Usually caused by insulation breakdown, creating an arc between two phases or phase to ground.
- Intense energy is not well contained, and can be very destructive.

Arc Flash Equation Open A
(Above 600 Volts)

- $E = (793 \times F \times V \times t_A)/D^2$

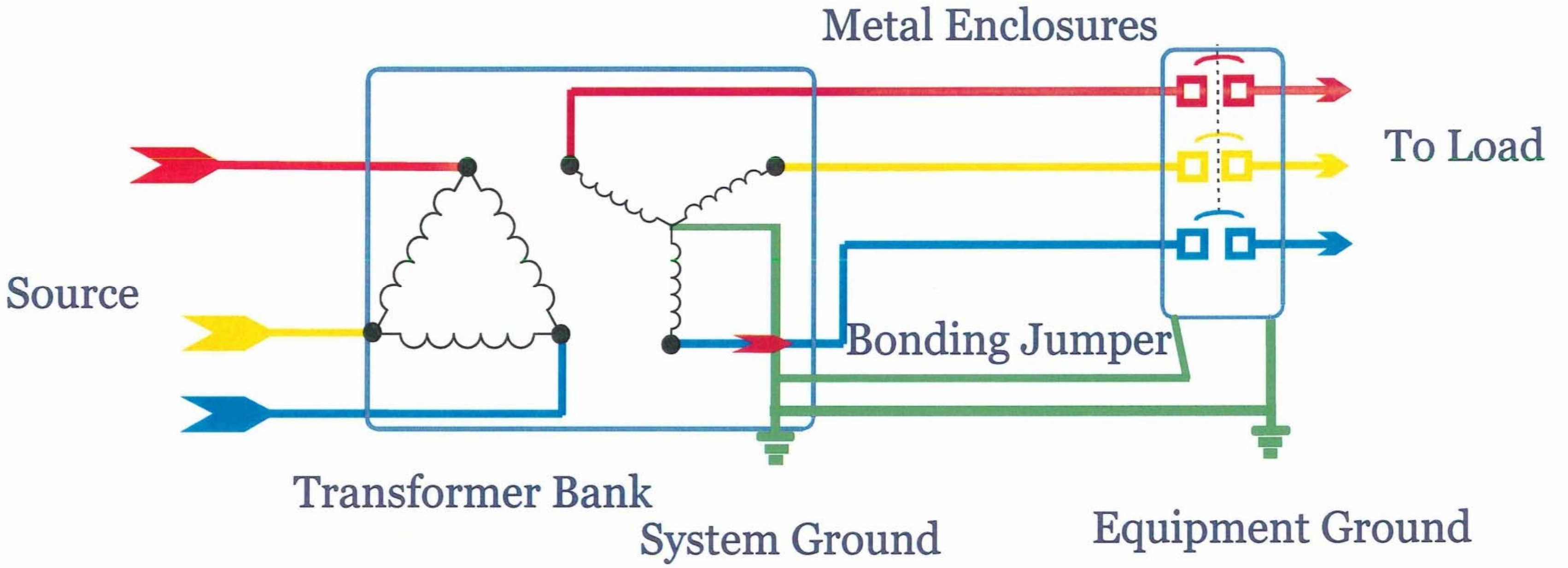
- E = Incident Energy in cal/cm²
- F = Bolted fault short circuit current in kA
- V = phase-to-phase voltage in kV
- t_A = Arc Duration in Seconds
- D = Distance from the arc source in inches

600 Volt "THHN" Power Cable



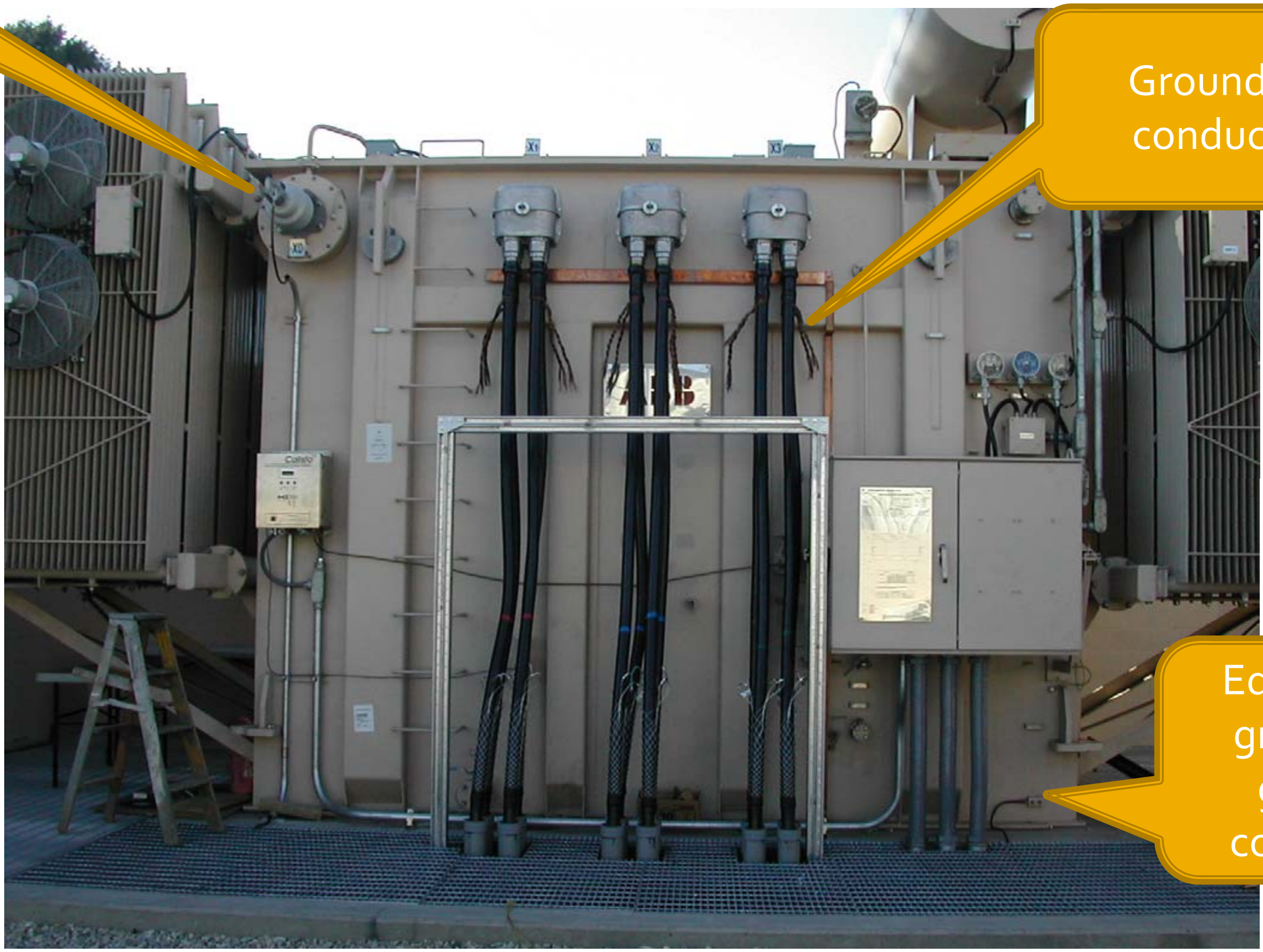
Arcing
Fault

Grounding Definition



Neutral grounding means a permanent and continuous conductive path to the earth with sufficient ampacity to carry any fault current liable to be imposed on it, sufficiently low impedance to limit the voltage rise above ground and to facilitate the operation of the protective devices in the circuit.

Grounding Definitions



System Ground

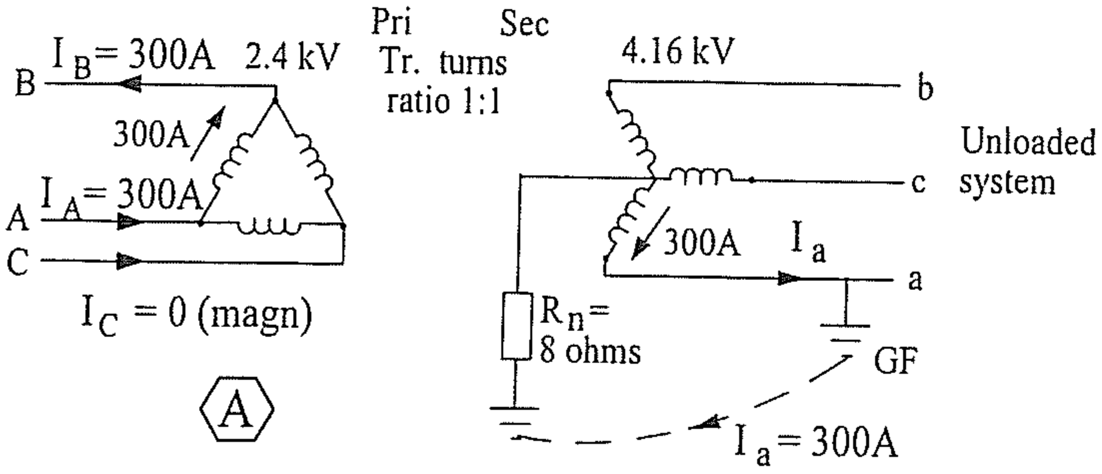
Grounding conductor

Equipment ground or ground conductor

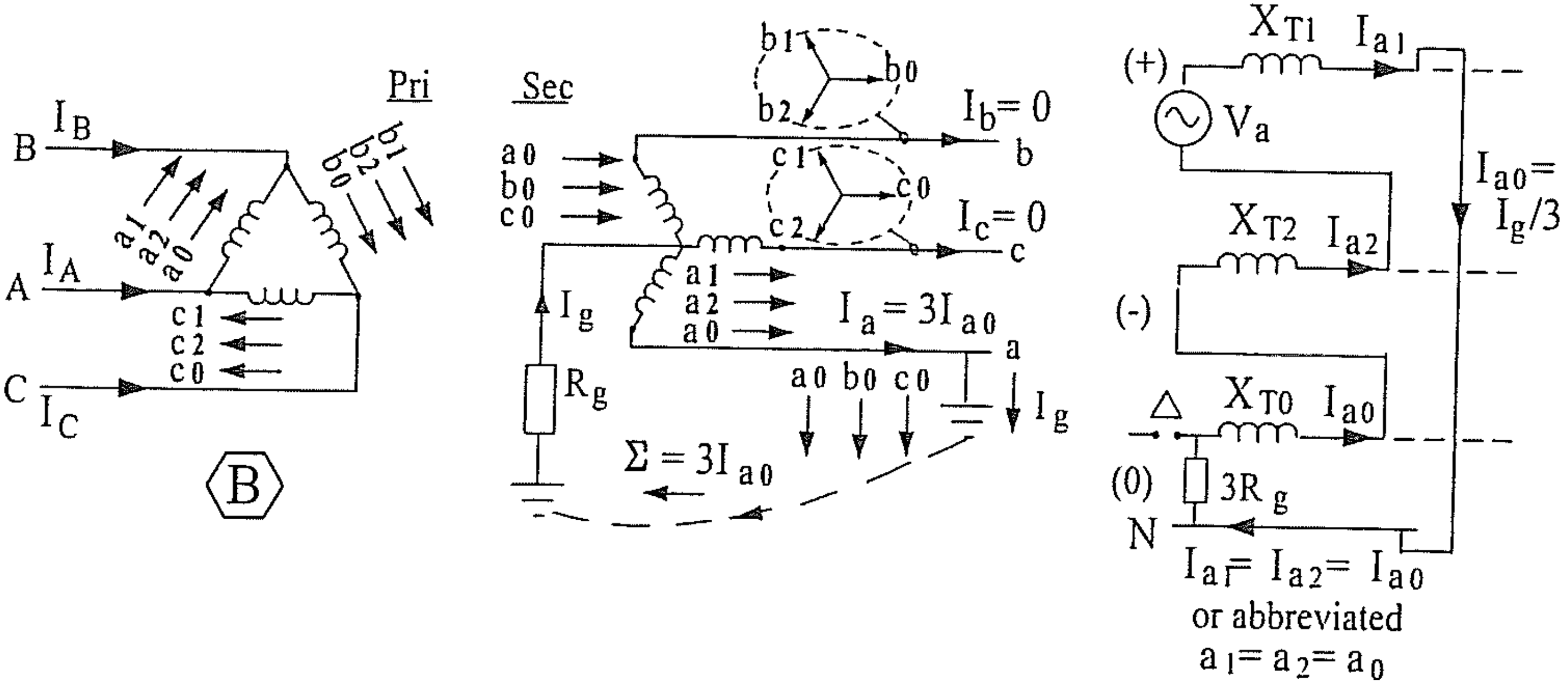
System Grounding

Delta – wye transformer

- 1:1 transfor to make simple
- Medium resistance grounded



Delta-wye Transformer Sequence Diagram



System Grounding Methods

- Ungrounded
- Solidly Grounded
- Impedance Grounded
  - Low Resistance Grounded
  - High Resistance Grounded
  - Reactance Grounded

Ungrounded System

Ungrounded Systems

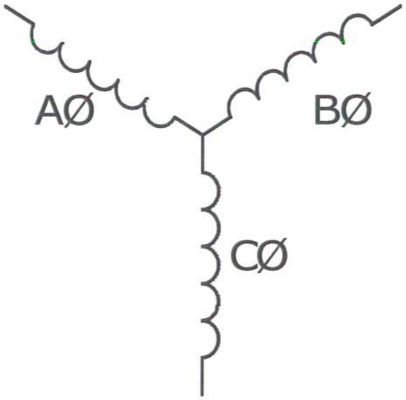
Popular in 3-wire LV systems up to 1950s

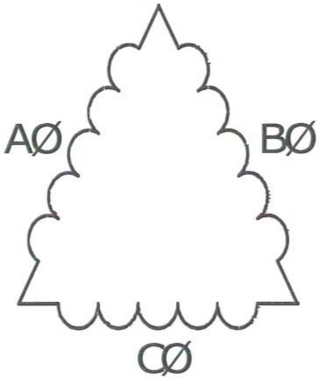
Advantages

- Negligible fault current on first ground fault
- No tripping on first ground fault

Disadvantages

- Difficult to locate ground faults
- 5 to 6 times transient over-voltage on intermittent, sputtering arcing ground faults





Industry Recommendations

IEEE Std 242-2001 (Buff Book)
Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems

Ungrounded Systems
8.2.5 **If this ground fault is intermittent or allowed to continue, the system could be subjected to possible severe over-voltages to ground, which can be as high as six to eight times phase voltage.**
Such over-voltages can puncture insulation and result in additional ground faults. These over-voltages are caused by repetitive charging of the system capacitance or by resonance between the system capacitance and the inductance of equipment in the system.

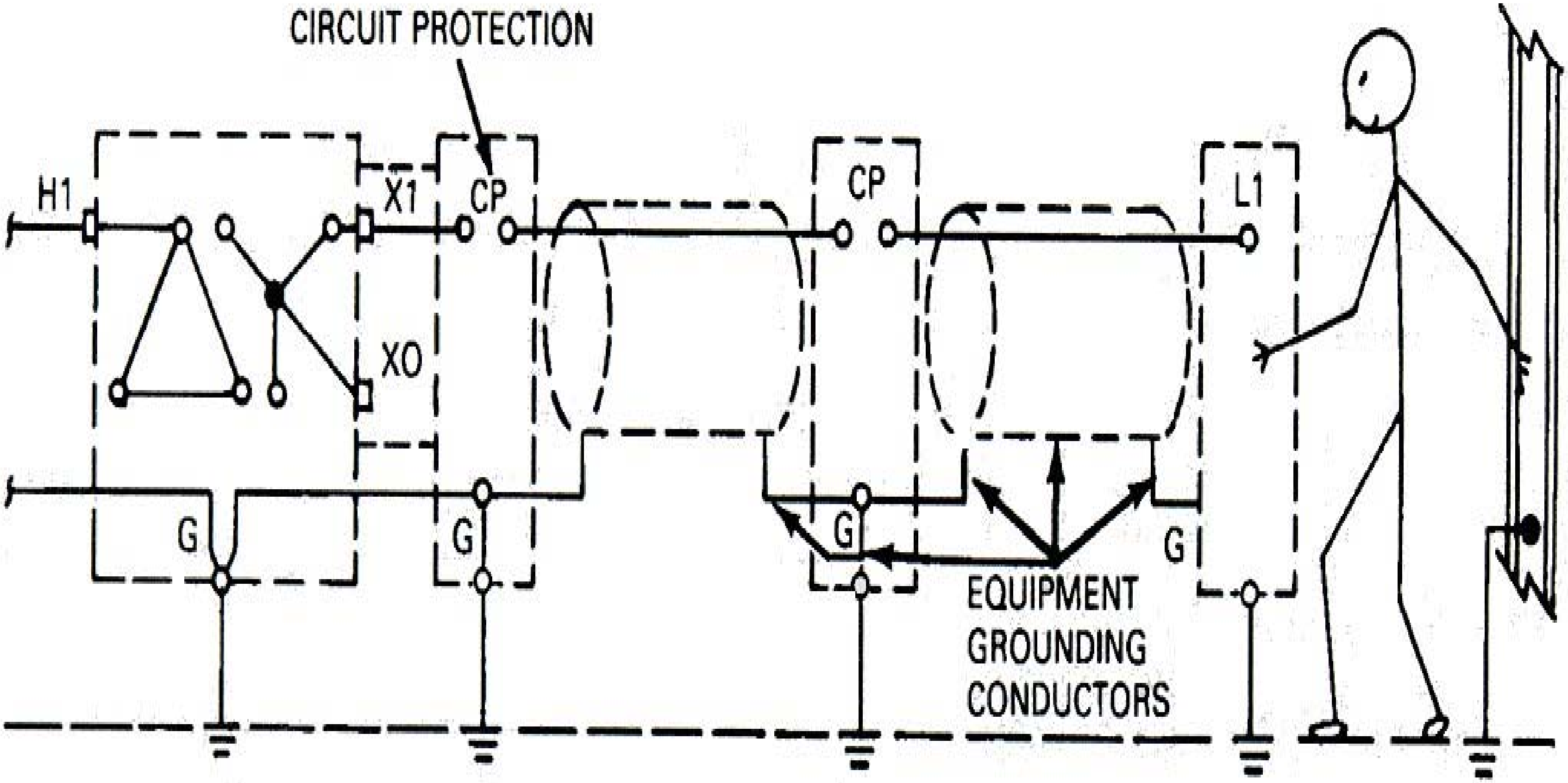
Ungrounded Systems

- No intentional connection to earth ground
- Weakly grounded through system capacitance to ground
- First fault typically 1 -2 amps
- Severe line to ground transient overvoltages

Ungrounded Systems

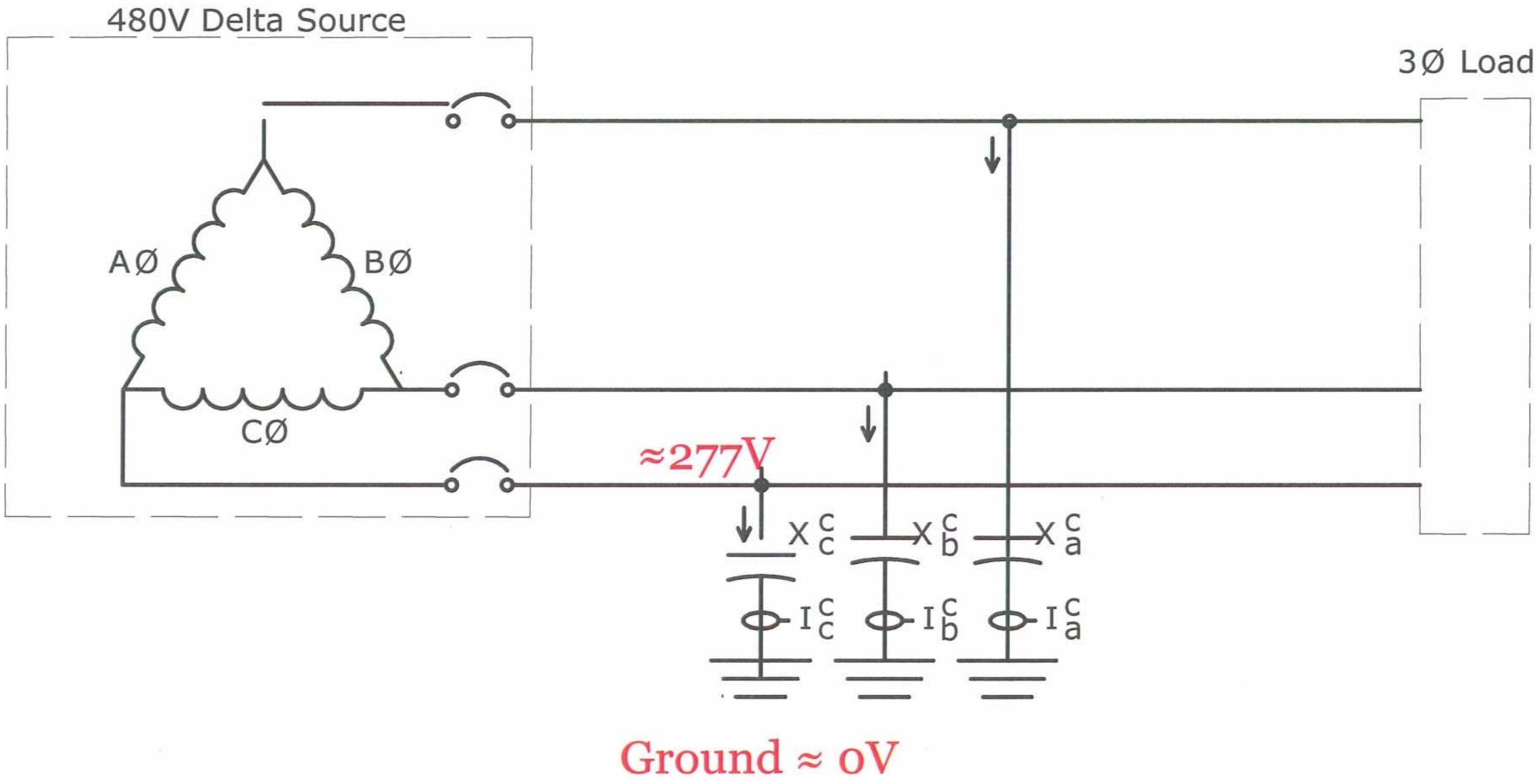
- Seldom used on new systems
- Still relatively common in existing industrial systems
  - Low voltage systems (< 600 V)
  - Medium voltage systems (2.4 - 15 kV)

Ungrounded System



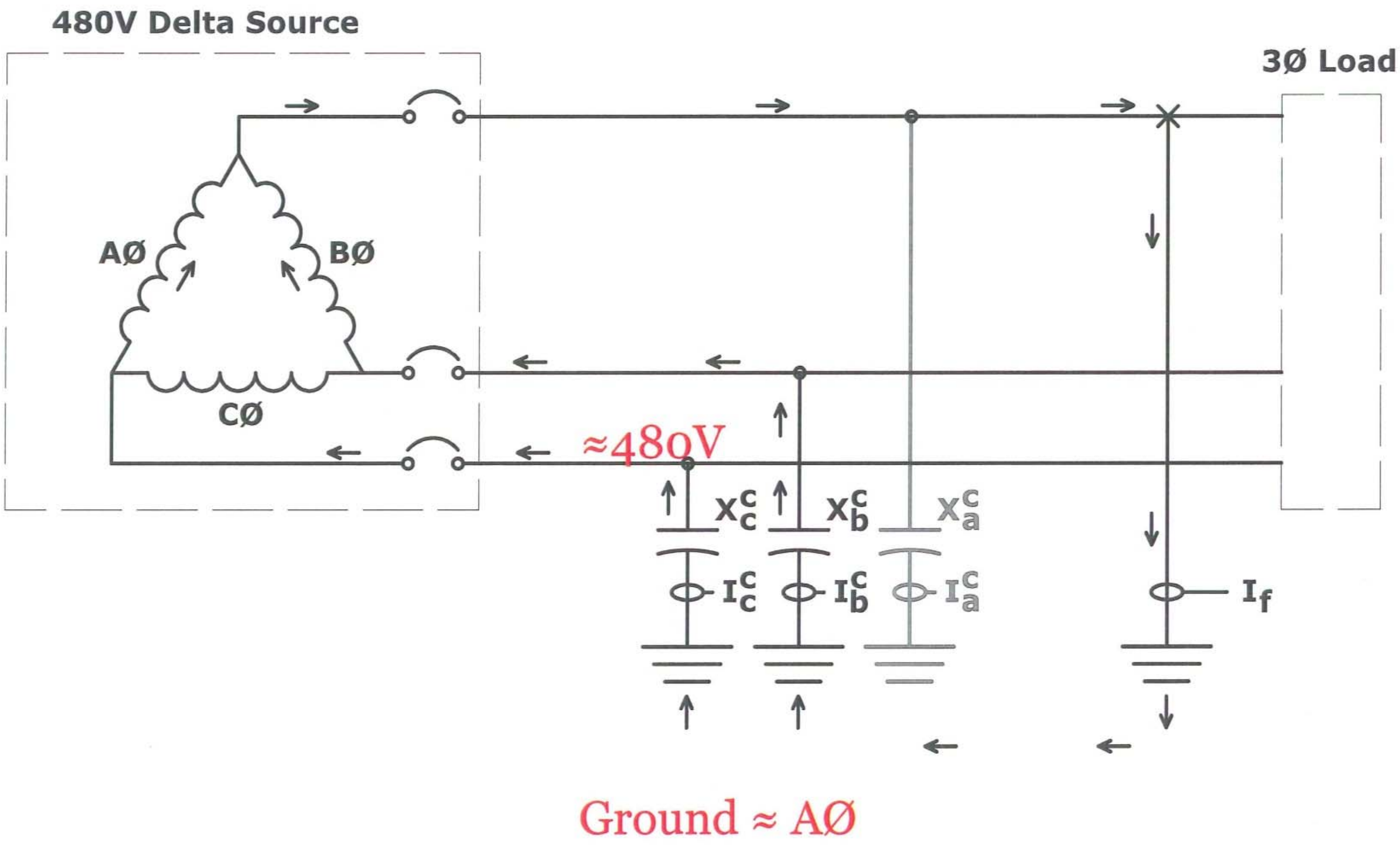
Ungrounded Systems

- Unintentionally grounded through <u>system</u> capacitance
  - Such as cables, transformers, motors, surge suppressors, etc.



Ground Faults

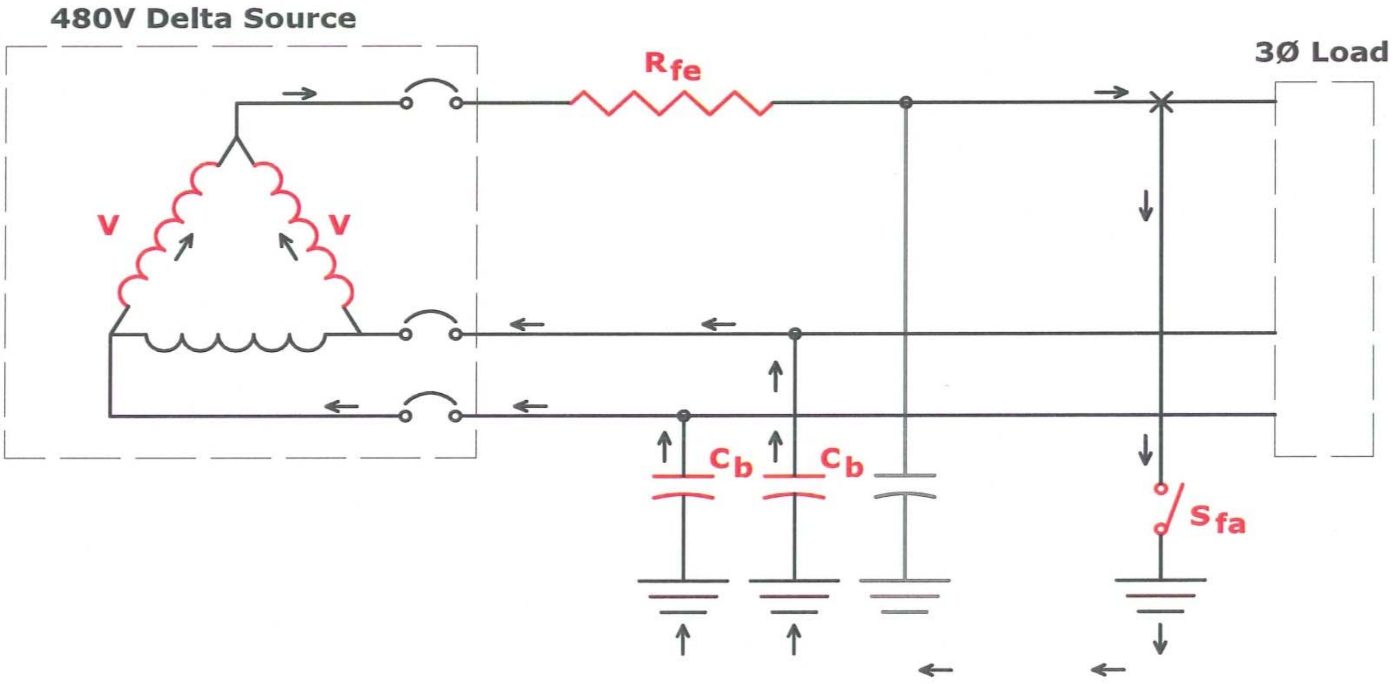
- Ground fault current distribution (minimal current)



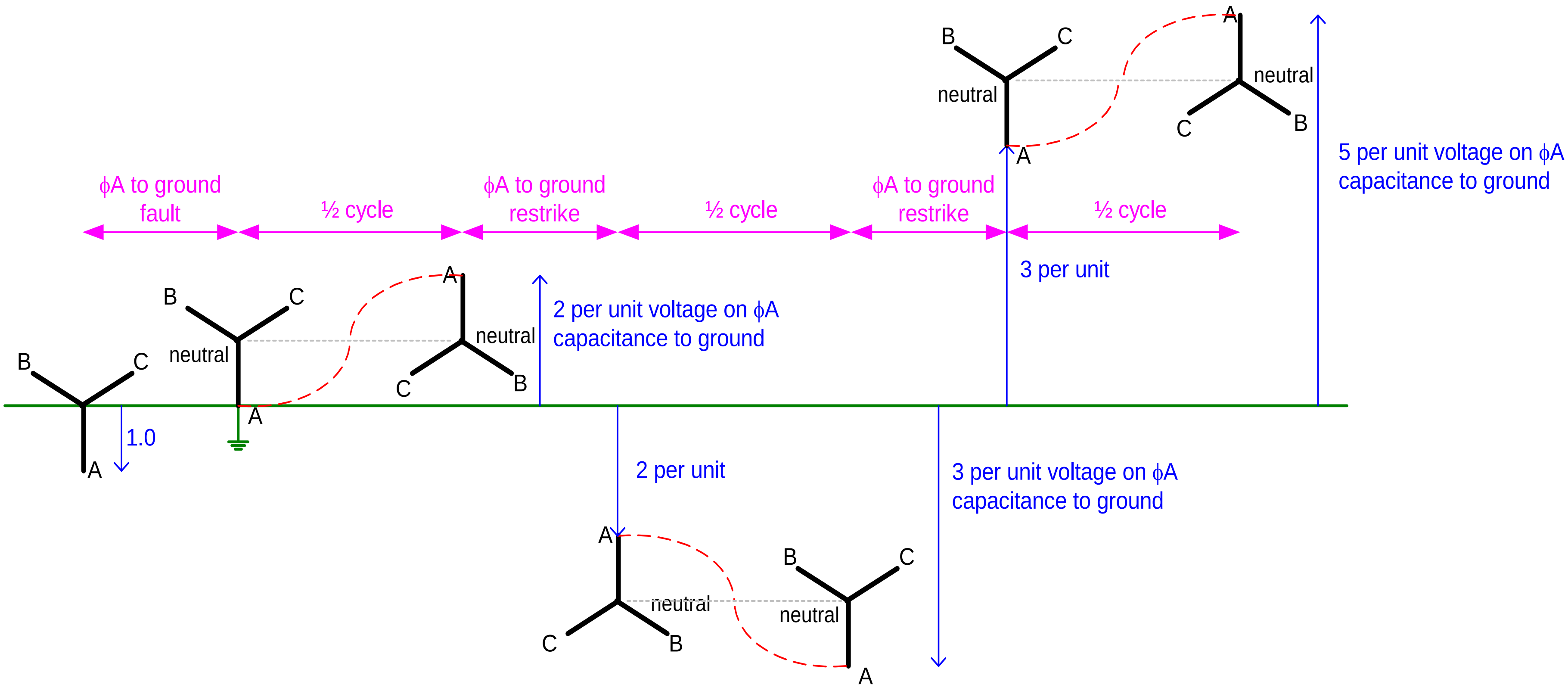
Arc Ground Faults

Intermittent or Re-strike

- **Intermittent ground fault:** A re-striking ground fault can create a high frequency oscillator (RLC circuit), independent of L and C values, causing high transient over-voltages.
    - i.e. re-striking due to ac voltage waveform or loose wire caused by vibration
    - OCPDs do not trip because ground fault current is low due to high value of R_f.



ARCING GROUND FAULTS ON UNGROUNDED SYSTEMS



ϕA to ground fault

½ cycle

ϕA to ground restrike

½ cycle

ϕA to ground restrike

½ cycle

2 per unit voltage on ϕA capacitance to ground

2 per unit

3 per unit voltage on ϕA capacitance to ground

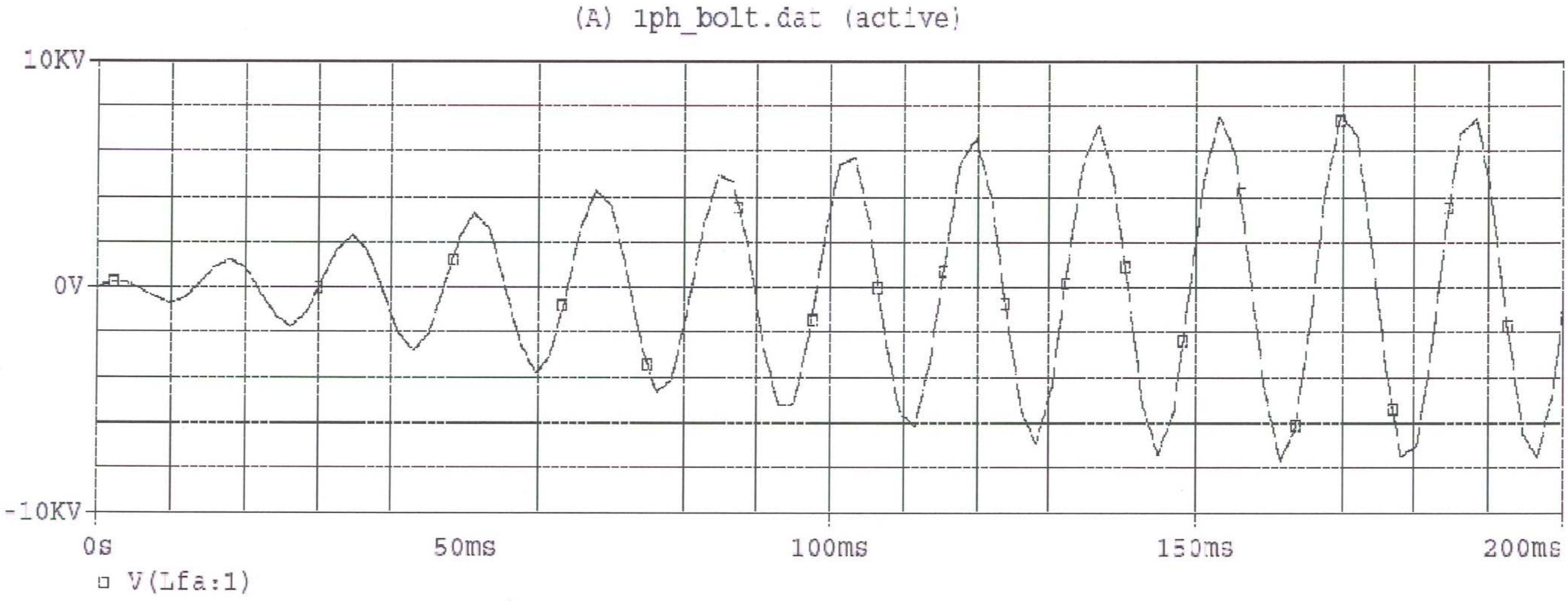
3 per unit

5 per unit voltage on ϕA capacitance to ground

Arc Ground Faults

Intermittent or Re-strike

- Plot of transient over-voltage for a arcing ground fault



Locating Ground Faults

- Good Luck!
  - No direct return to source, only way is through system capacitance.

- Use over-voltage
  - Indicator light and relay method to indicate ground fault.
  - De-energize one feeder at a time.
    - ✓ Very time consuming and dangerous!
      - ➢ Unknown ground fault may be on system for long period of time.
      - ➢ May de-energize vital equipment trying to find fault.

Solidly Grounded Systems

Solidly Grounded Systems

- Connected to earth ground with no intentional additional impedance in circuit
- Arc fault danger zone and flash hazard large
- Ground fault current close to phase current levels
- Minimal transient overvoltage with faults

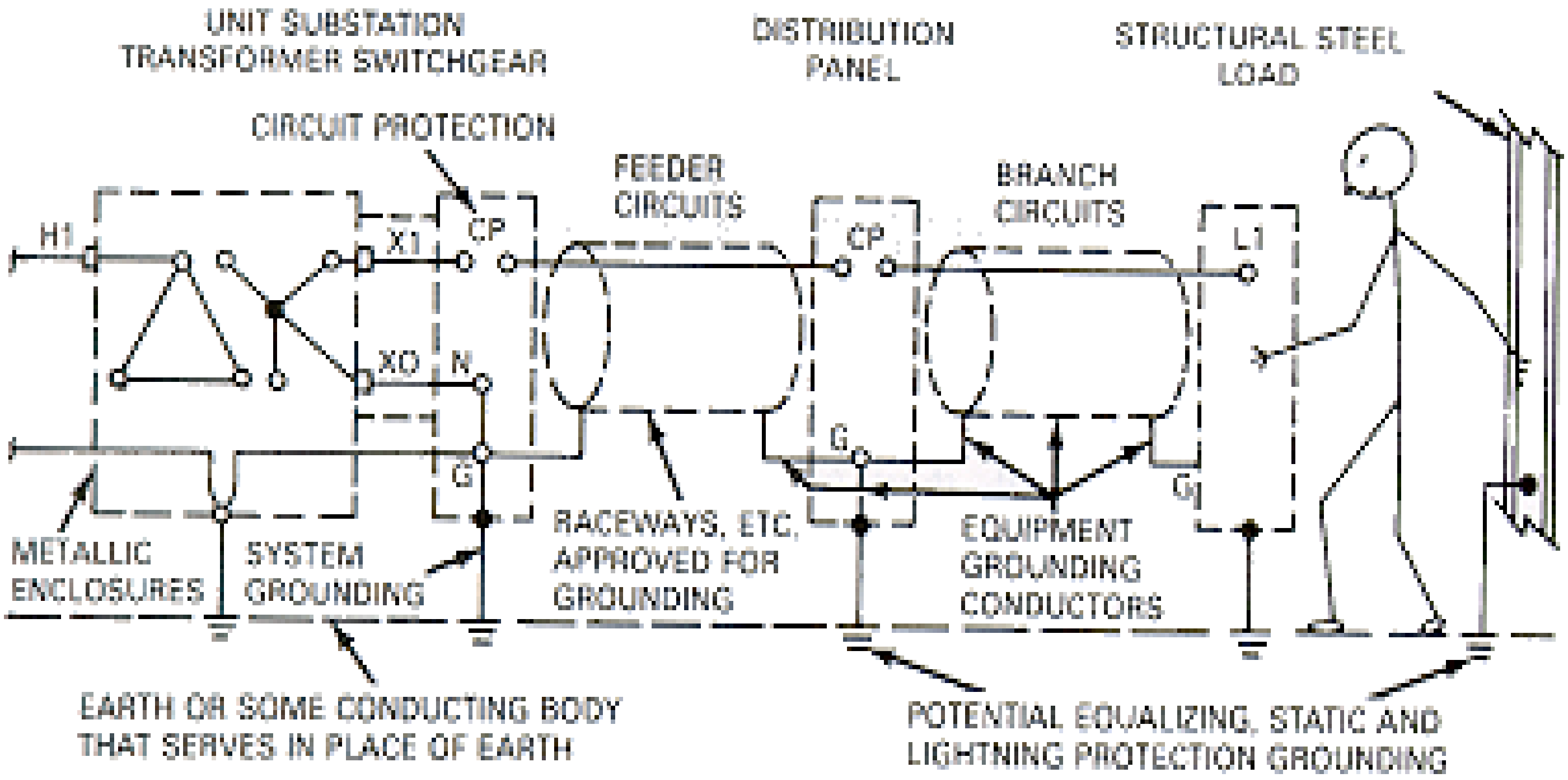
Solidly Grounded

- Almost universally used on high voltage systems (> 72 kV)
- Commonly used on utility distribution systems up to 34.5 kV

Solidly Grounded

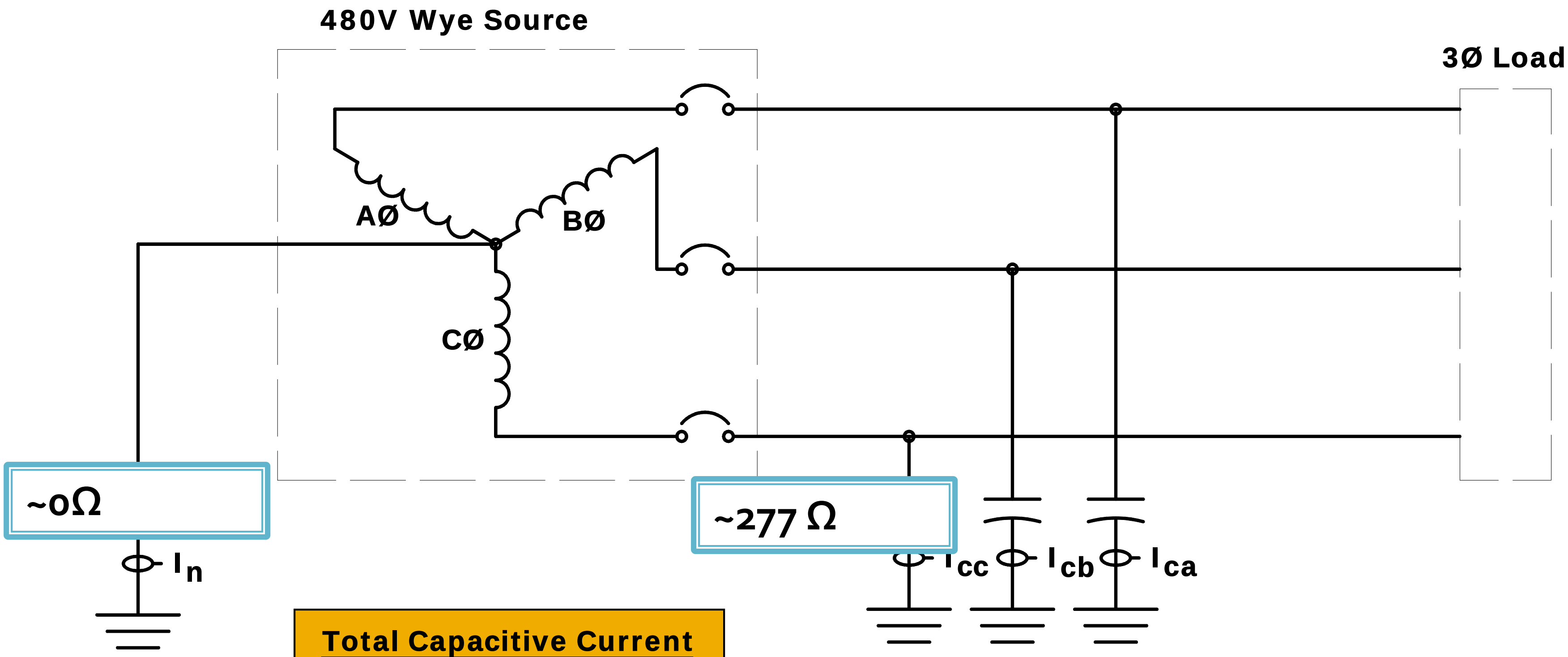
- Commonly used on low voltage (<600 V) commercial, institutional, and residential systems
- Sometimes used on low voltage (<600 V) industrial systems

Solidly Grounded System



Solidly Grounded Systems

- Intentionally grounded through ground wire

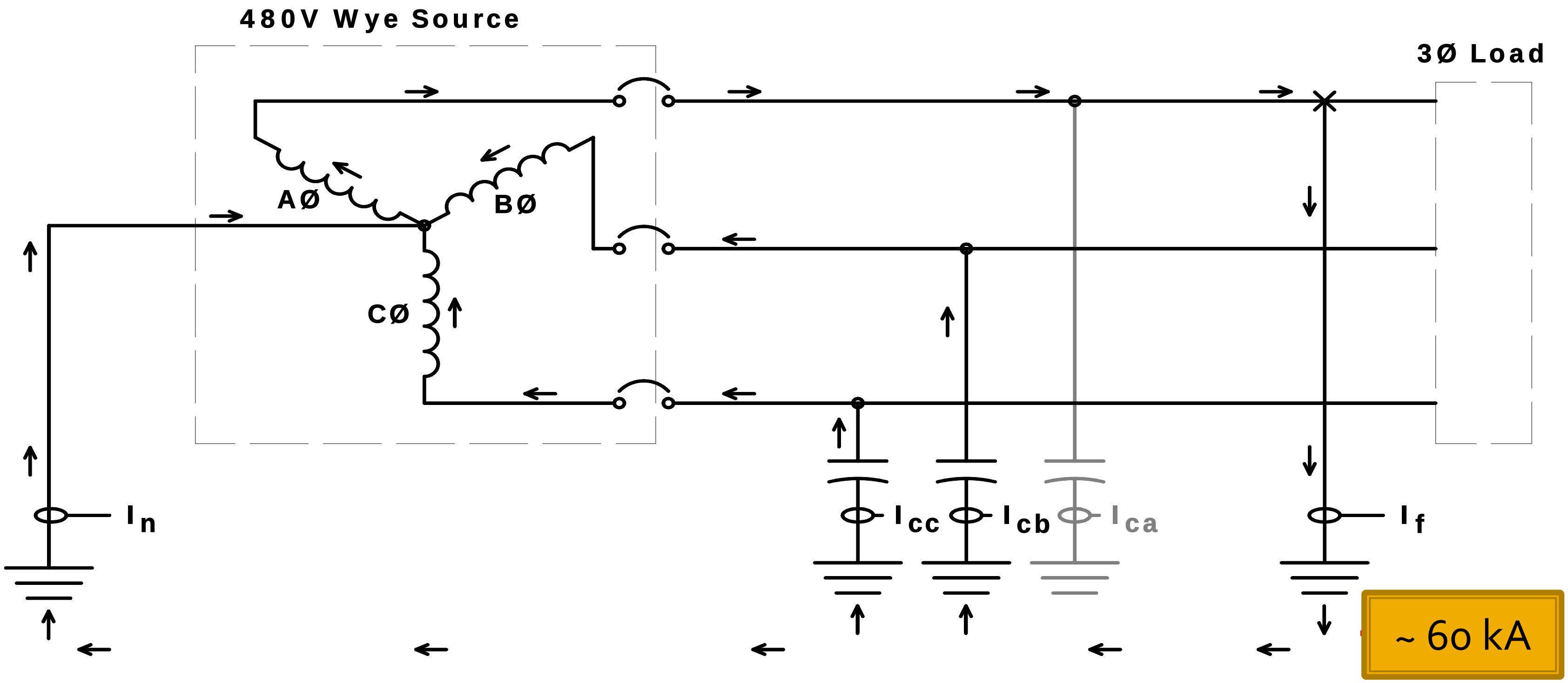


Total Capacitive Current

$I_{ca} + I_{cb} + I_{cc} = 0$

Quick Calc /Bolted Ground Faults

- Ground fault current distribution on AΦ



~ 60 kA

Estimated Total Fault Current

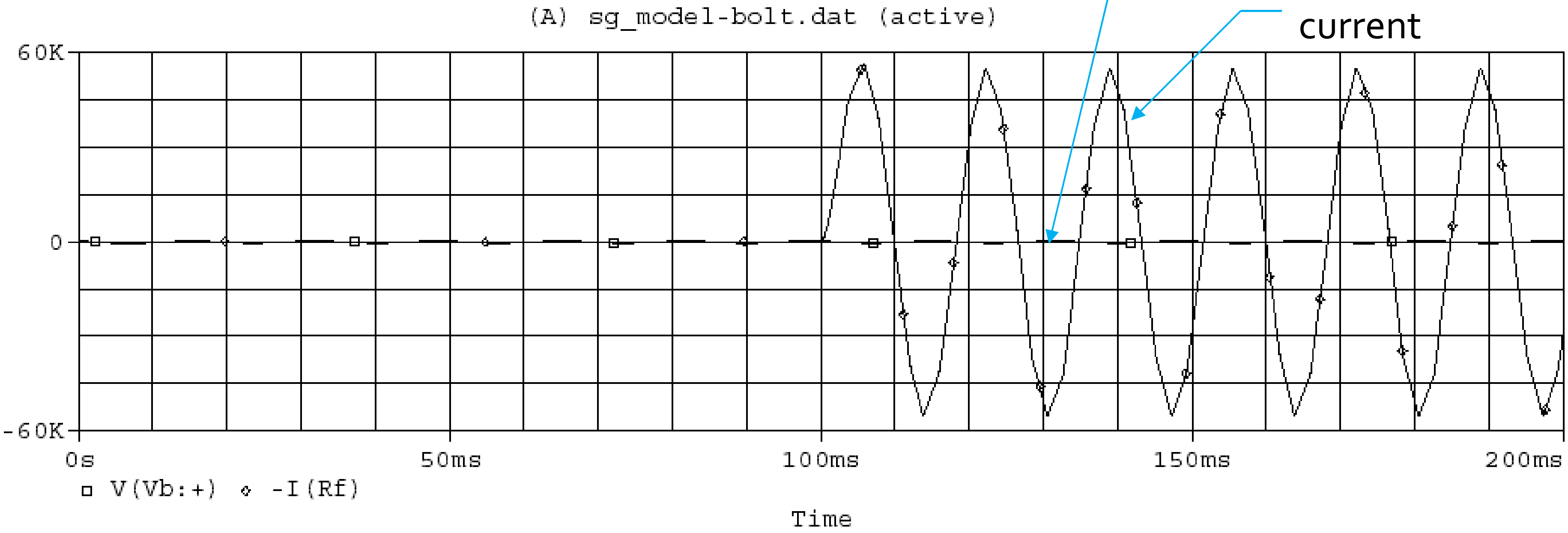
$$I_f = \left(\frac{1}{Z_{pu}}\right) * I_{fla} + (\cancelto{\sim 0A\ (3A)}{I_{cb} + I_{cc}}) = \sim I_n$$

Example (2500kVA, 480V, Z = 5%)

$$I_n = I_f = \left(\frac{1}{0.05}\right) * 3000A = \sim 60{,}000A$$

Bolted Ground Faults

- **Bolted ground fault:** A high fault current causing severe damage. If properly coordinated and installed, OCPD's will clear fault after "acceptable damage".

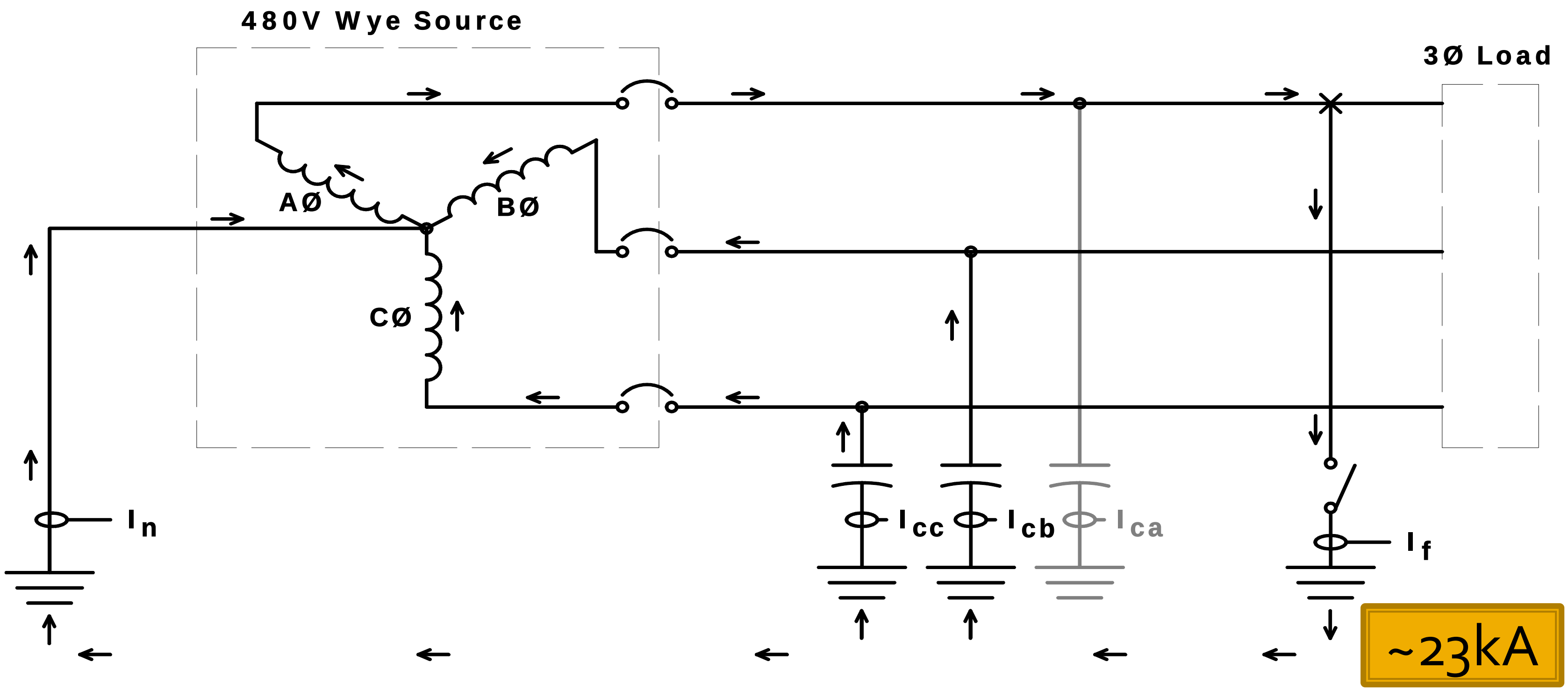


No transient over-voltages

High fault current

Quick Calc / Arcing Ground Faults

- Ground fault current distribution on AΦ



Estimated Total Fault Current

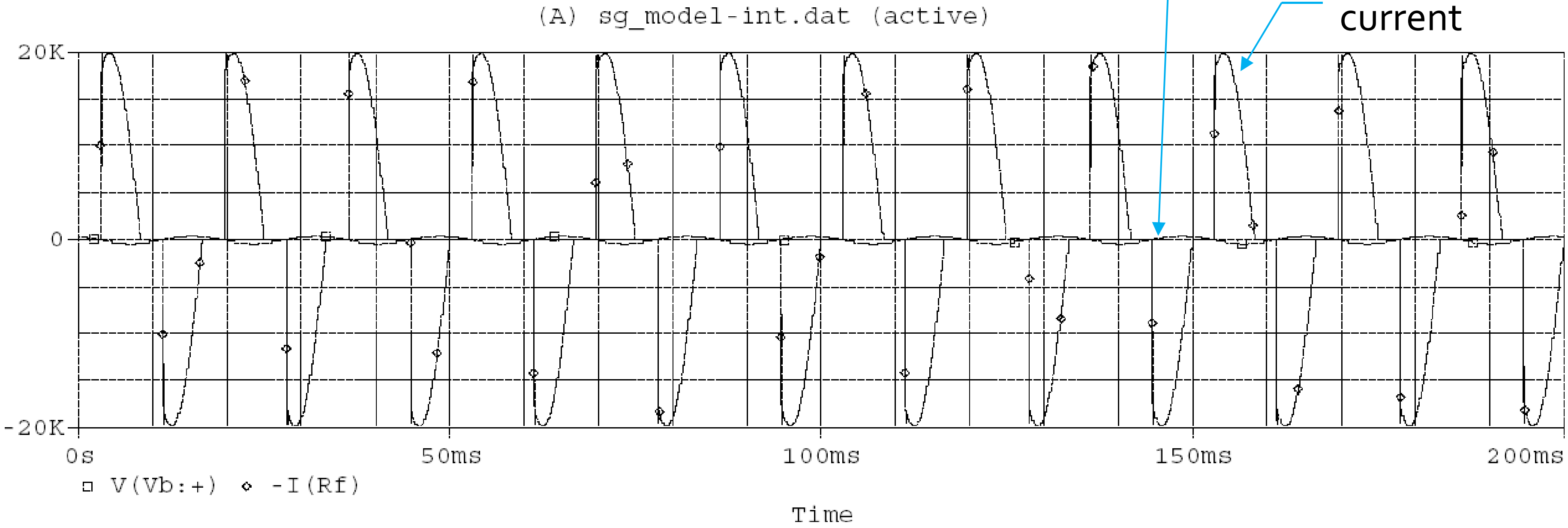
$$I_f = \left(\frac{1}{Z_{pu}}\right) * I_{fla} * .38 + \cancelto{\sim 0A\ (3A)}{(I_{cb} + I_{cc})} = \sim I_n$$

Example (2500kVA, 480V, Z = 5%)

$$I_n = I_f = \left(\frac{1}{0.05}\right) * 3000A * .38 = \sim 23kA$$

Arcing Ground Faults

- **Arcing ground fault:** Lower fault current, so OCPD's may not clear fault. Delay will cause severe equipment and personnel damage due to tremendous amount of energy released.



No transient over-voltages

High fault current

Arcing ground faults are approximately 38% bolted faults.

Solidly Grounded Systems

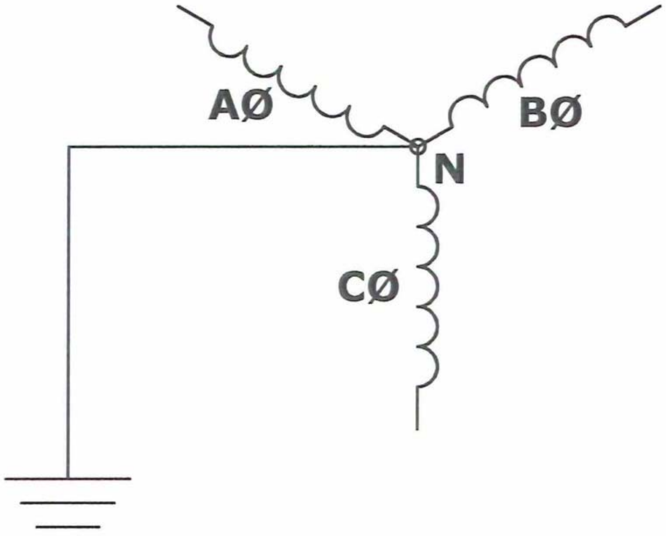
Popular in 4-wire LV systems up to 1950s

Advantages

- Eliminated transient over-voltage problem
- Permit line-to-neutral loads (lighting, heating cables)
- Ground faults easy to locate (follow smoke)

Disadvantages

- Cause unscheduled service interruption
- Danger from low-level arcing ground faults
- Strong shock hazard to personnel
- Coordination issues
- Arc-flash issues



IEEE – Arcing Faults

- **IEEE Std 242-2001 Recommended Practice for the Protection and Coordination of Industrial and Commercial Power Systems**

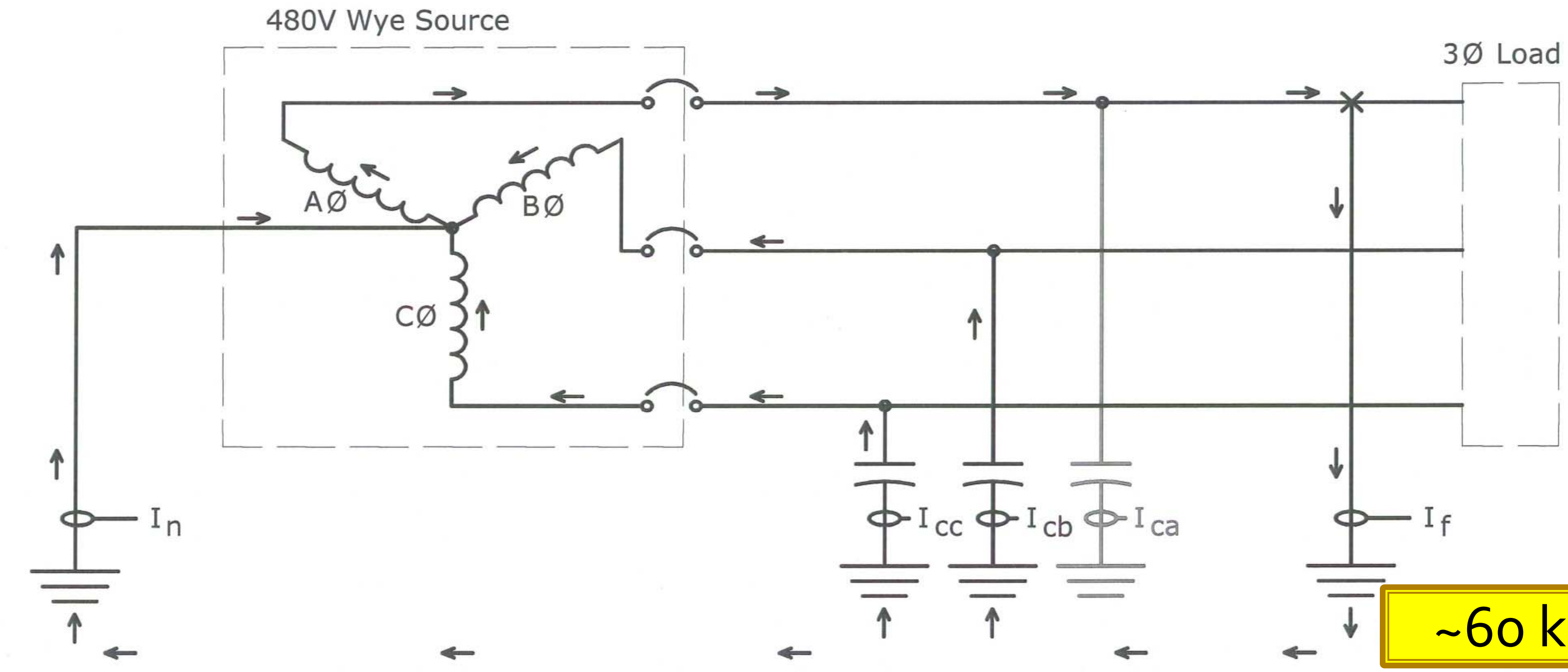
  8.2.2
  One disadvantage of the solidly grounded 480 V system involves the high magnitude of destructive, arcing ground-fault currents that can occur.

- **IEEE Std 141-1993Recommended Practice for Electric Power Distribution for Industrial Plants**

  7.2.4
  The solidly grounded system has the highest probability of escalating into a phase-to-phase or three-phase arcing fault, particularly for the 480 and 600 V systems. The danger of sustained arcing for phase-to-ground fault…is also high for the 480 and 600 V systems, and low or near zero for the 208 V system. A safety hazard exists for solidly grounded systems from the severe flash, arc burning, and blast hazard from any phase-to-ground fault.

Bolted Ground Faults

Estimated Ground fault current distribution on AΦ



~60 kA

Estimated Total Fault Current

$$I_f = \left(\frac{1}{Z_{pu}}\right) * I_{fla} + (\overset{\sim 0A\ (3A)}{\cancel{I_{cb} + I_{cc}}}) = \sim I_n$$

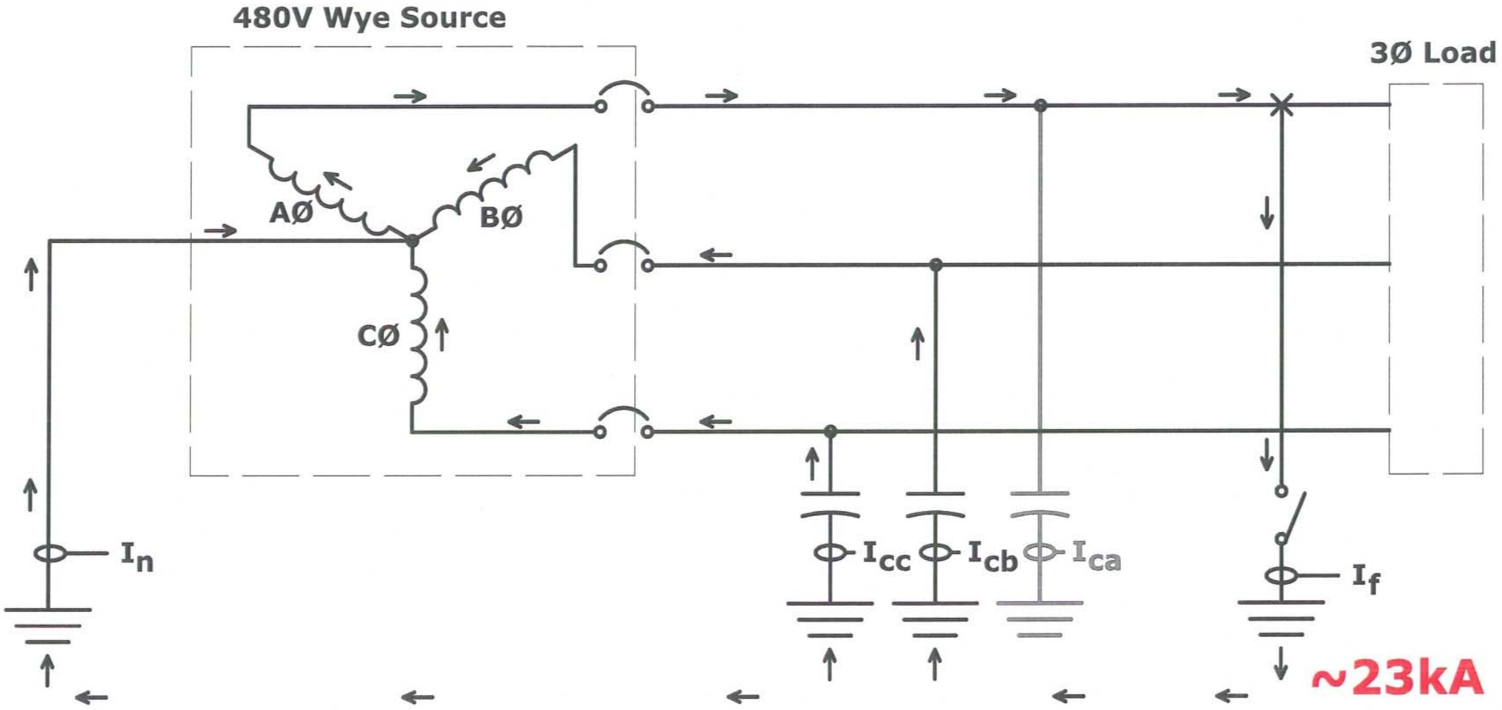
Example (2500kVA, 480V, Z = 5 %)

$$I_n = I_f = \left(\frac{1}{0.05}\right) * 3000A = \sim 60{,}000A$$

Bolted phase to ground 80kA .5sec

Arcing Ground Faults

Estimated Ground fault current distribution on AΦ



Estimated Total Fault Current

$$I_f = \left(\frac{1}{Z_{pu}}\right) * I_{fla} * .38 + \overset{\sim 0A\ (3A)}{\cancel{(I_{cb} + I_{cc})}} = \sim I_n$$

Example (2500kVA, 480V, Z = 5%)

$$I_n = I_f = \left(\frac{1}{0.05}\right) * 3000A * .38 = \sim 23kA$$

Arcing Fault 80kA .5 sec

Hazards with Ungrounded / Solidly Grounded

- **Ungrounded – Method used to ground first power systems**
  - **Very large transient over-voltage conditions may exist.**
    - Insulation not rated, therefore, hazard to personnel and equipment.

  - **Very difficult to locate ground fault.**
    - Good chance of second ground fault on a different phase due to prolonged ground fault.

- **Solidly-Grounded – Replaced Ungrounded Systems**
  - **Very high ground fault currents.**
    - Fault must be cleared, shutting down equipment.
    - Generators may not be rated for ground fault

  - **Tremendous amount of arc flash / blast energy.**
    - Equipment and people are not rated for energy.

Coordination Problems

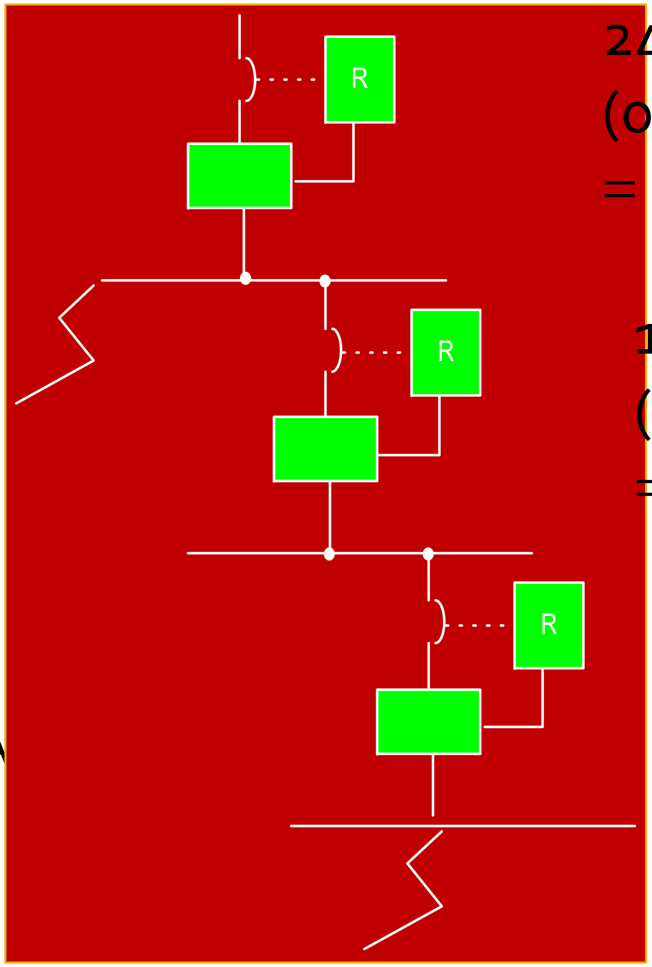
$$KWC = \frac{I_G \times Va \times t}{1000} \approx \frac{I_G \times t}{10}$$

I_G = Fault Current (A)
V_a = 100V (typical)
t = time (cycles)

Typical Transformer

- 2500 kVA, 5% impedance
- Ground condition I_g=23kA
- KWC = 55,200

Acceptable???



24 Cycles
(0.4 seconds)
= 55,200 KWC

12 Cycles
(0.2 seconds)
= 27,600 KWC

6 Cycles
(0.1 seconds)
= 13,800 KWC

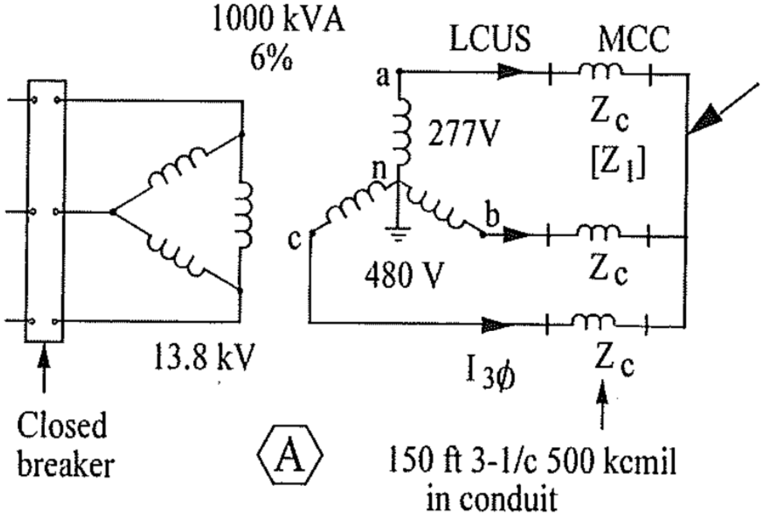
LV Motor Protection

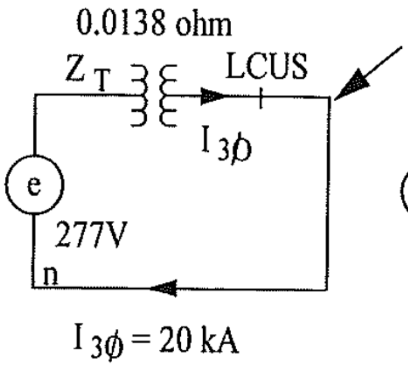
- The 'larger' starters in MCCs must include ground fault trips to reduce nuisance tripping the upstream switchgear breaker

- Use zero sequence CTs, stand-alone ground fault relays, and MCP shunt trips.

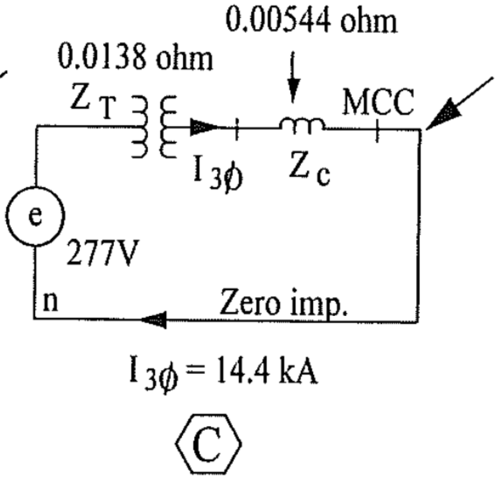
- Experience says all starters size 3 and larger fed from solidly-grounded systems be provided with ground fault protection

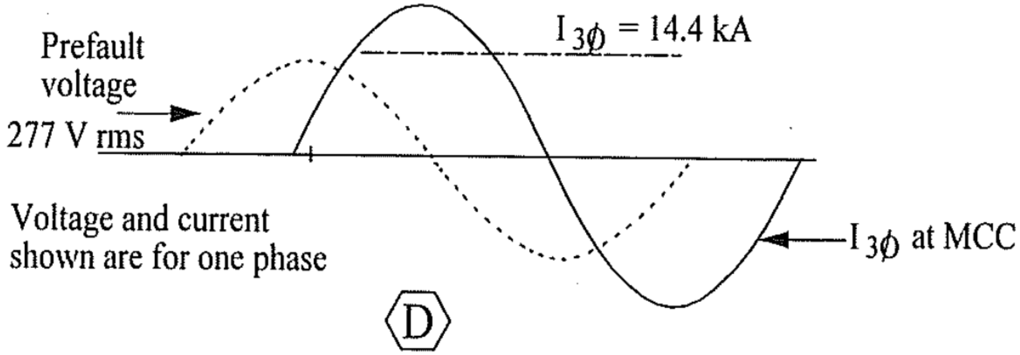
Three phase fault



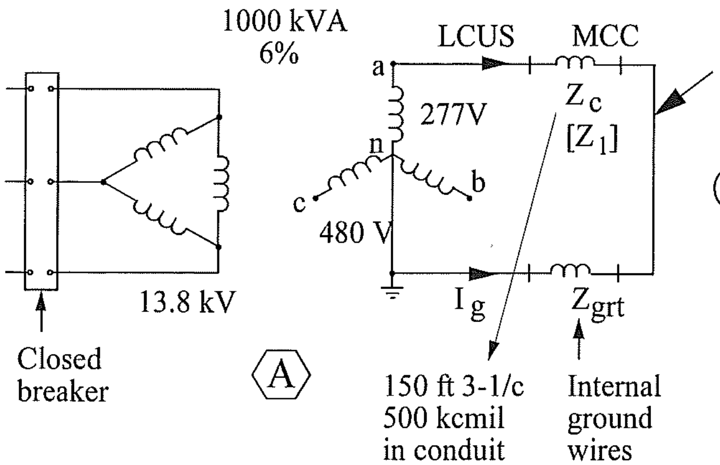


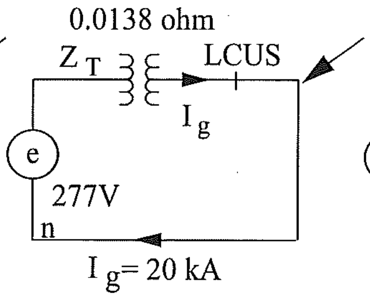
Close
in fault



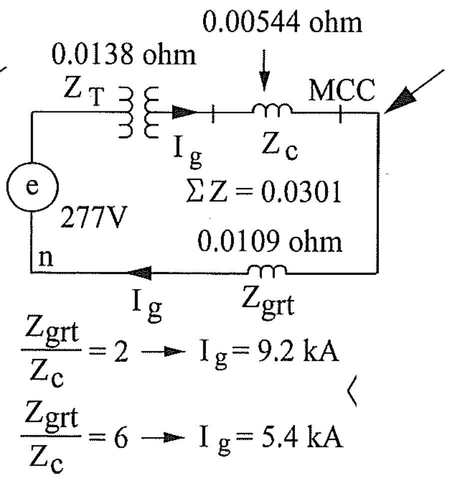


Distance to fault & the effect

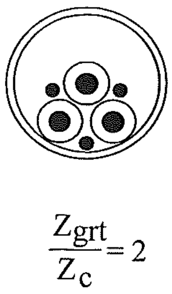




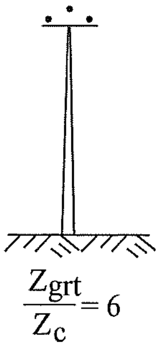
Close in fault



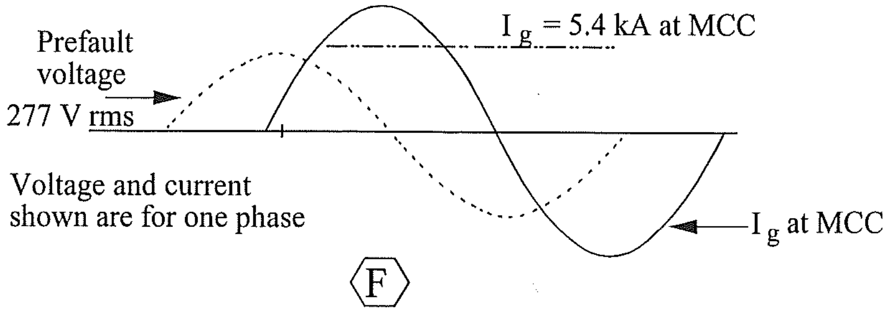
Remote fault



High quality return



Low quality return

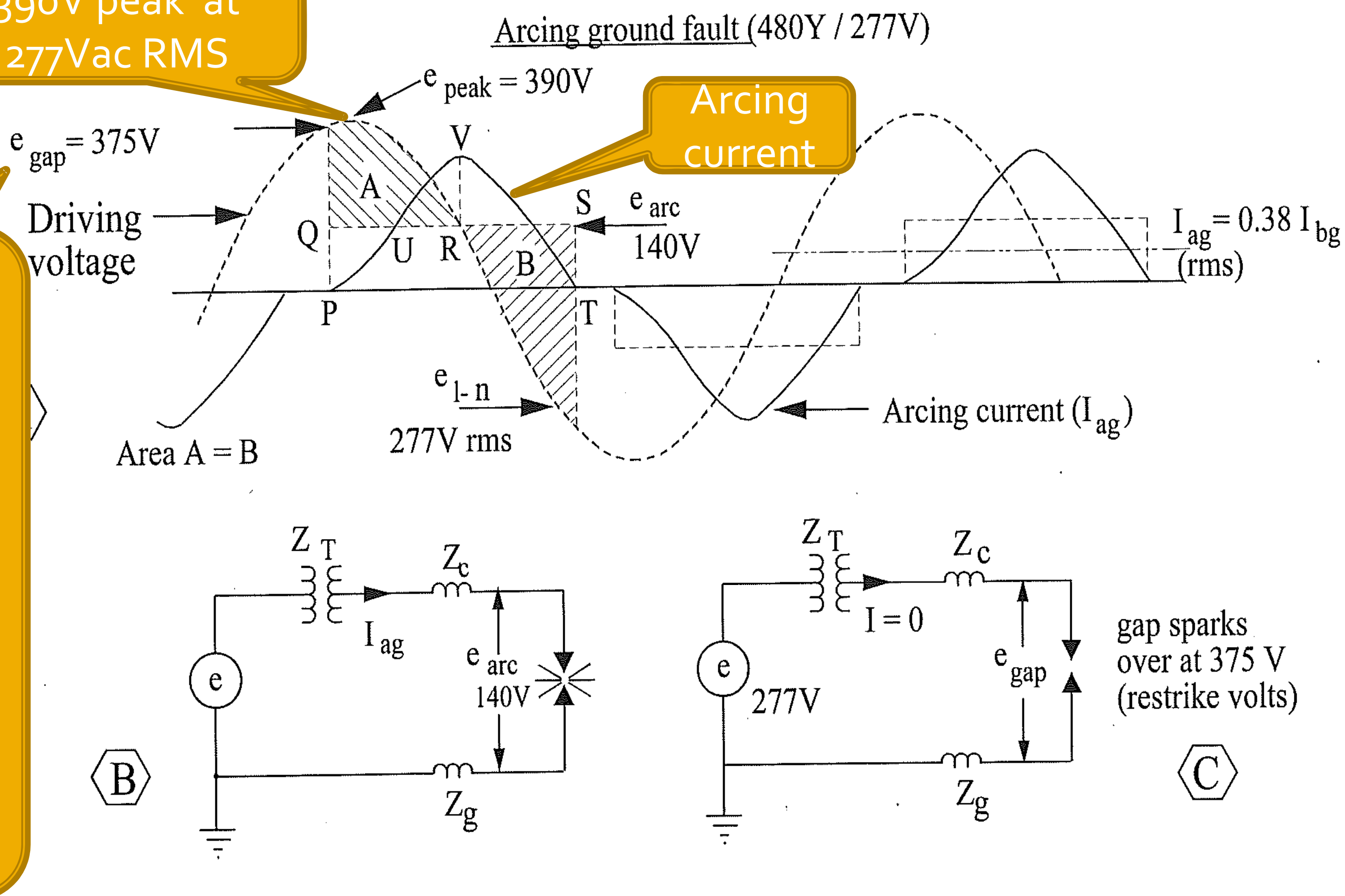


Discontinuous Arcing Ground

Source voltage
390V peak at
277Vac RMS

Arcing
current

375V=Max
voltage
required to
start current
flow.
70 to 140V=
volt required
to sustain arc
across gap



Spark gap phenomenon – arc strikes once voltage achieves spark over and extinguishes when cathode and anode switch

Arcing fault as a % of bolt fault

	480Y/277V
Three phase	89%
Phase to Phase	74%
Phase to Ground	38%

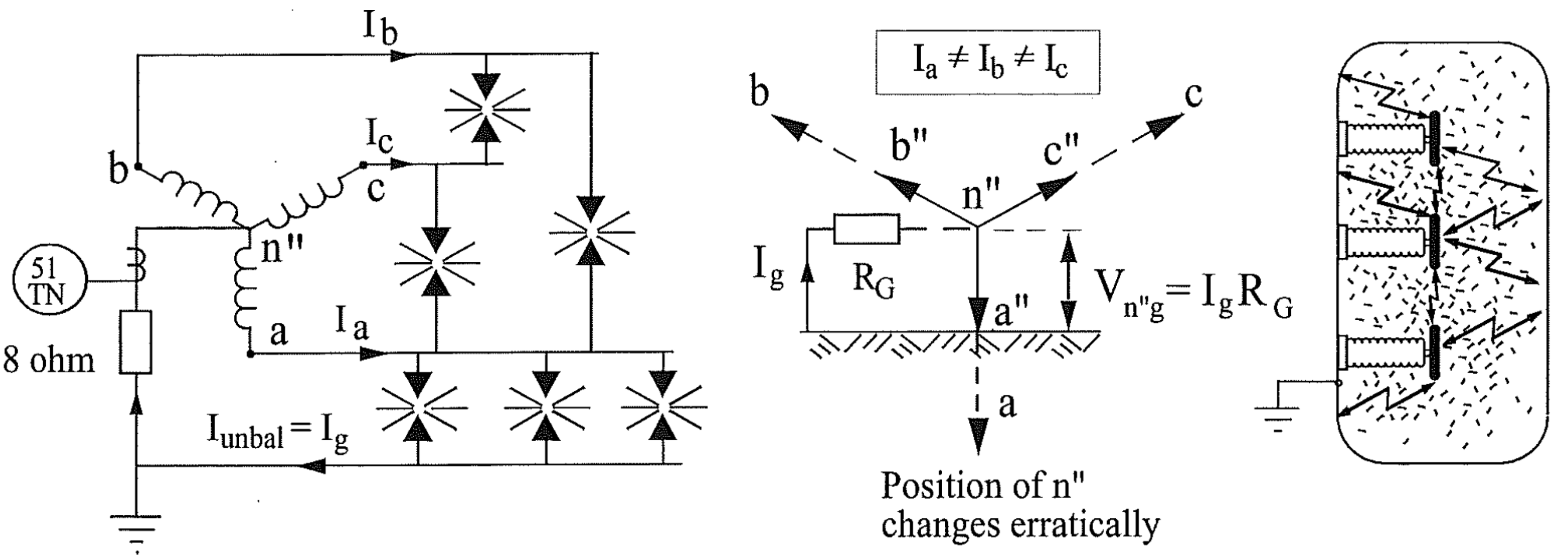
Medium Voltage Faults

Medium Voltage Arc faults

- Resistance grounded
- Insulated bus
- BIL rating
- Sensitive ground fault protection 20Amp pick
- MV arcing ground can be sustained at 200A

Voltage pattern of Arcing Ground fault MV 200A grounding resister

- Drops about 150 volts per inch across arc gap



Arc travel in equipment

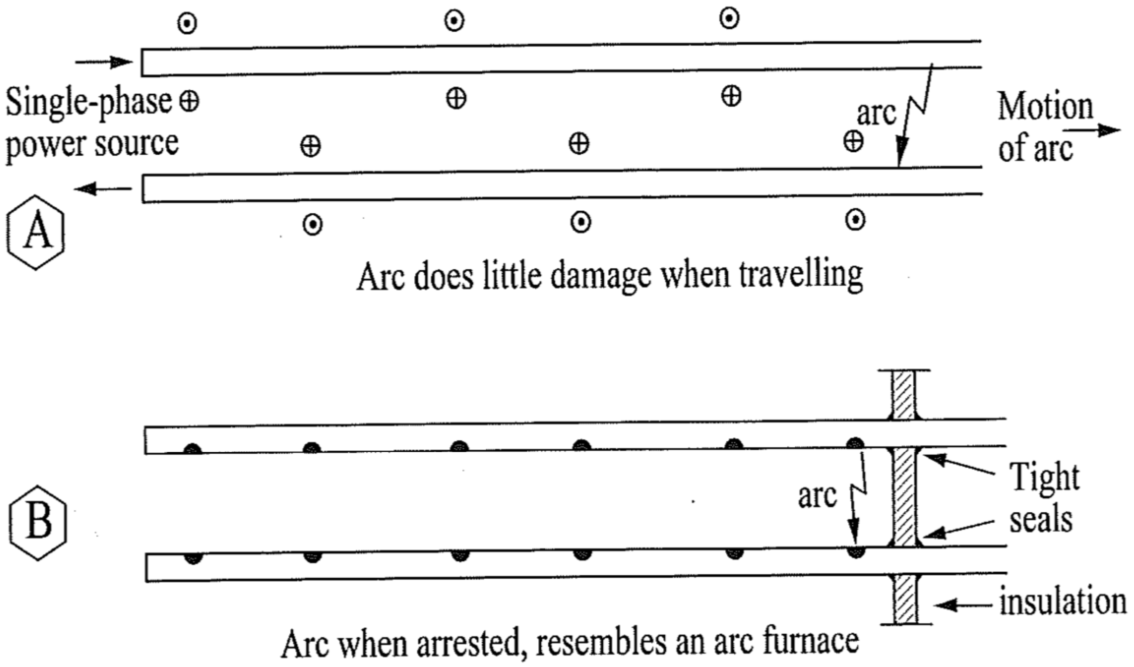
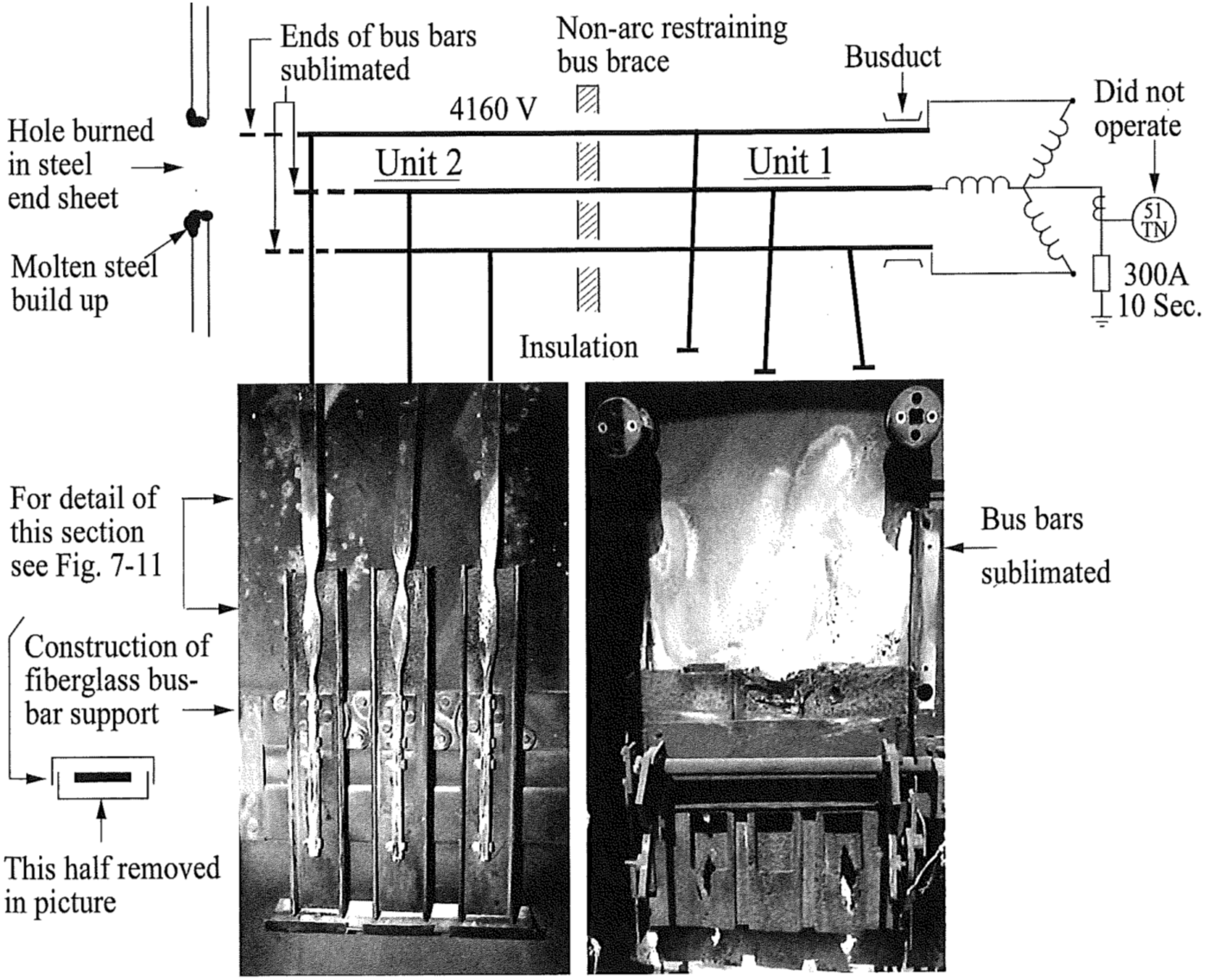


Fig. 7.9 Self-sustaining arc travels away from power source due to interaction of current and flux, the exact interaction that also causes a motor to turn.

MCC without insulated bus



Ground fault in motor

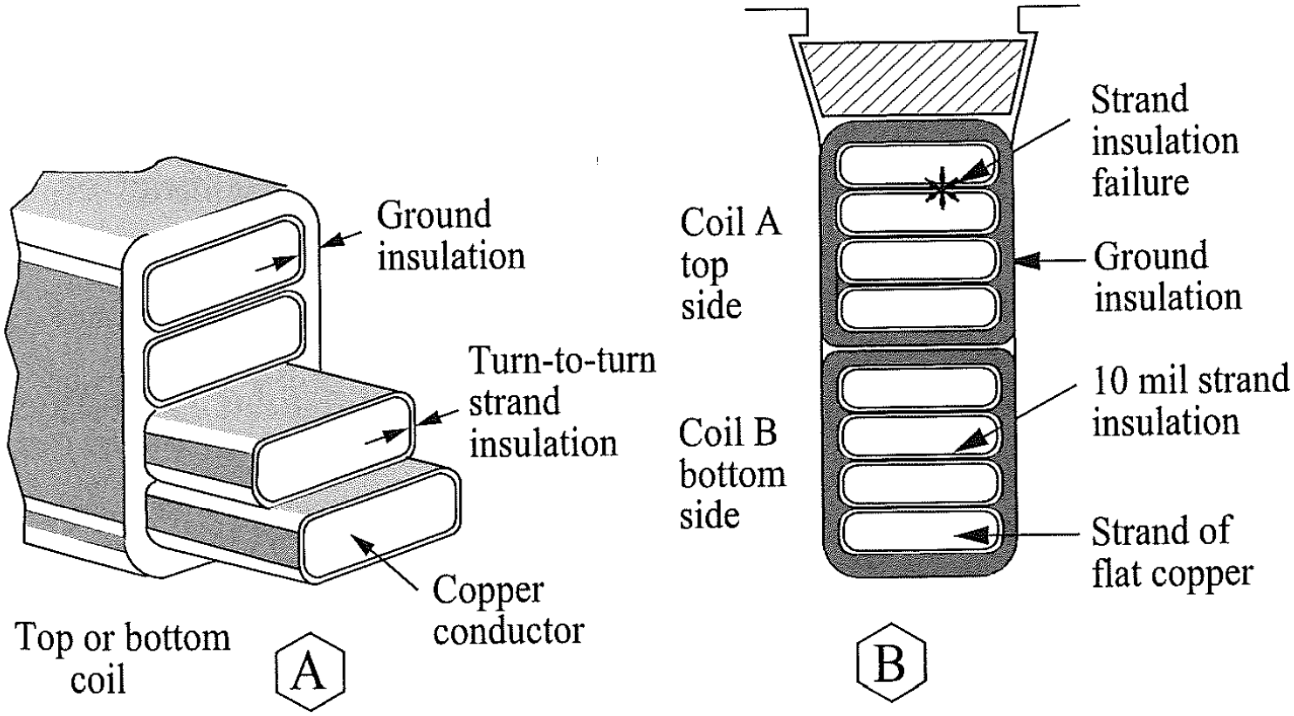
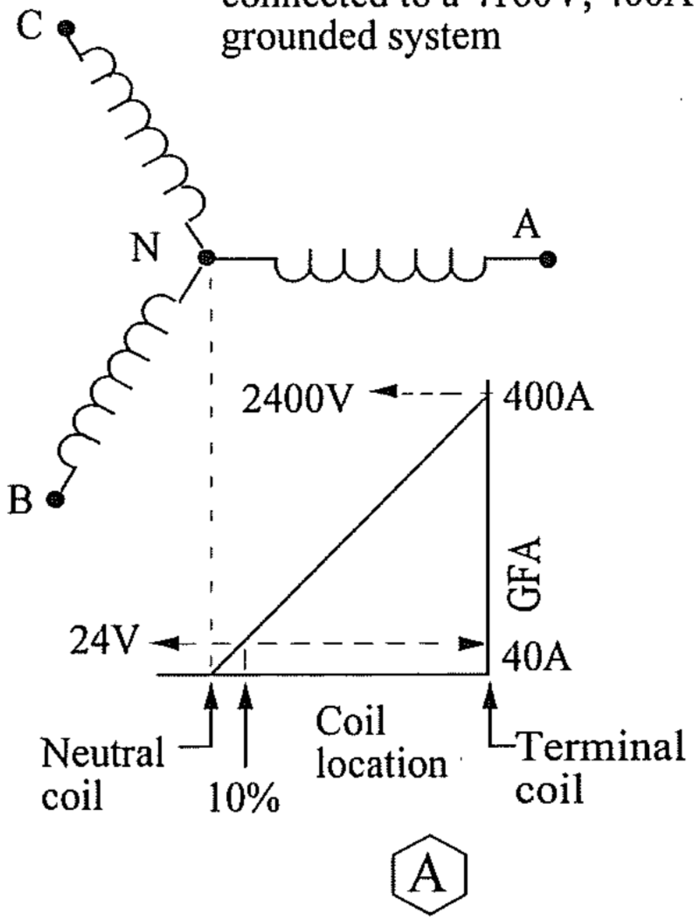


Fig. 7.13 (A) Isometric view of cross section of elemental form-wound 4-kV coil, consisting of 4 single-strand turns, (B) Cross section of coil slot with two four-turn coils of figure A, where strand insulation failure causes a shorted turn, resulting in turn-to-turn fault in machine winding.

Current Distribution Through Ground Fault in Motor Windings

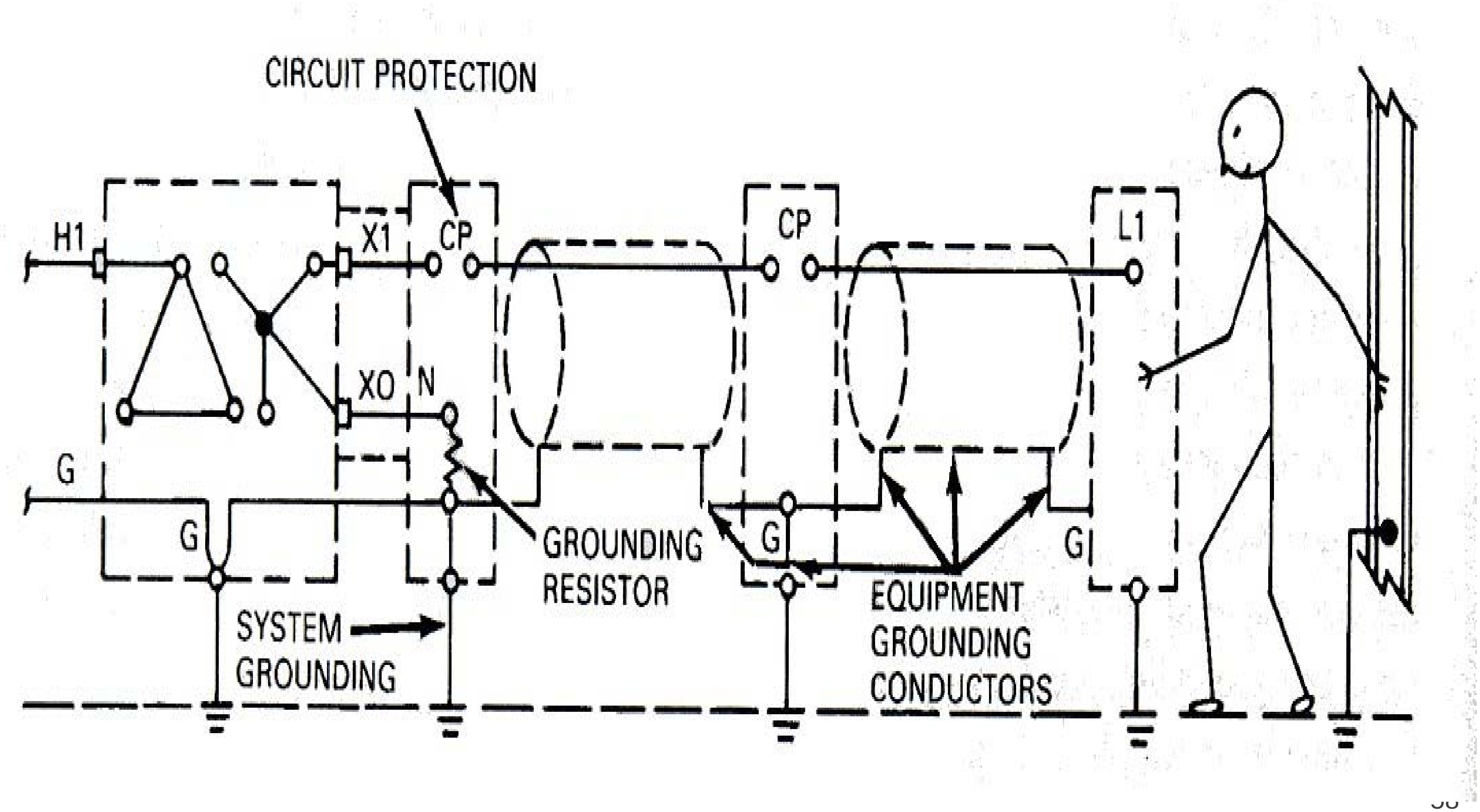


These motor windings are connected to a 4160V, 400A grounded system

24

Resistance Grounded Systems

Resistance Grounded System



Resistor Ratings for Low Resistance Ground

- Voltage rating is system line-to-neutral voltage
- *Resistors available for all common system voltages up to 13,800V*
- Current ratings available for medium voltage systems are from 25A to 2000A
- *Choose resistor current based on system configuration and relaying*

Resistor Ratings for Low Resistance Ground

- Time ratings available are 10 seconds, 60 seconds, and extended time
- *Most installations take either 10s or 60s rating.*
- *Choose based on system ground fault clearing time.*
- *Extended time ratings rarely used; for special conditions where resistor will be energized for 10 minutes or more.*

Resistor Construction
Low Resistance Ground

- Suitable for indoor or outdoor use
- Resistor elements are usually stainless steel

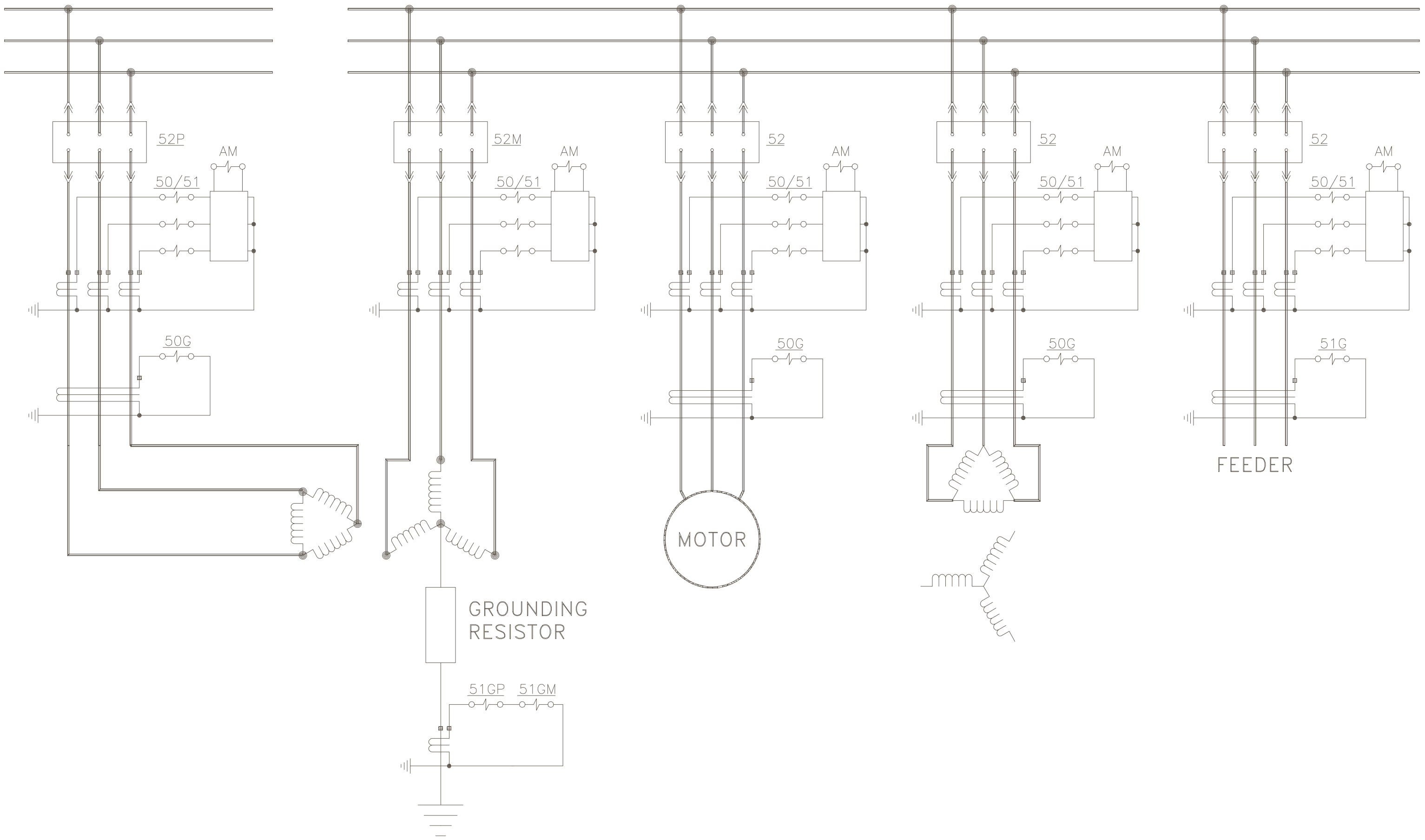
  Check material against ambient atmosphere to prevent possible corrosion damage
- Temperature rise may be 760°C

  Resistor must be well ventilated and must be kept away from combustible material

Resistor Construction
Low Resistance Ground

- Frame of resistor is often connected to middle of resistor element
- *Under fault conditions, frame is energized at 1/2 line-to-ground voltage*
- *Frame must be insulated from ground*
- *Frame must be inaccessible to personnel*

Relaying for Low Resistance Ground



Relaying for Low Resistance Ground

- Motor and transformer feeders

  Use zero-sequence (ground sensor) relaying with 50/5 or 100/5 CT and instantaneous overcurrent relay

  Pickup will be about 15A

- Other feeders

  Use similar relaying, but relay may need to be time delay to coordinate with downstream devices

Relaying for Low Resistance Ground

- Mains
- *Use CT in neutral grounding resistor circuit*
- *Use time delay relay to coordinate with feeder relays*
- *Choose CT ratio and relay setting to pick up at about 10% of grounding resistor current rating, provided that coordinates with feeders*
- *Trip main breaker*

Relaying for Low Resistance Ground

- Backup relaying

  Use CT in neutral grounding resistor circuit

  This may be same CT used for main relay or it may be a second CT

  Use time delay relay and set to coordinate with main relays

  Trip backup breaker, usually the breaker that feeds the transformer

Bus Differnetials

- Difficult to set buss differential relaying to be sensitive to many ground faults

Resistance Grounding

Popular in 3-wire LV systems up to 1970s

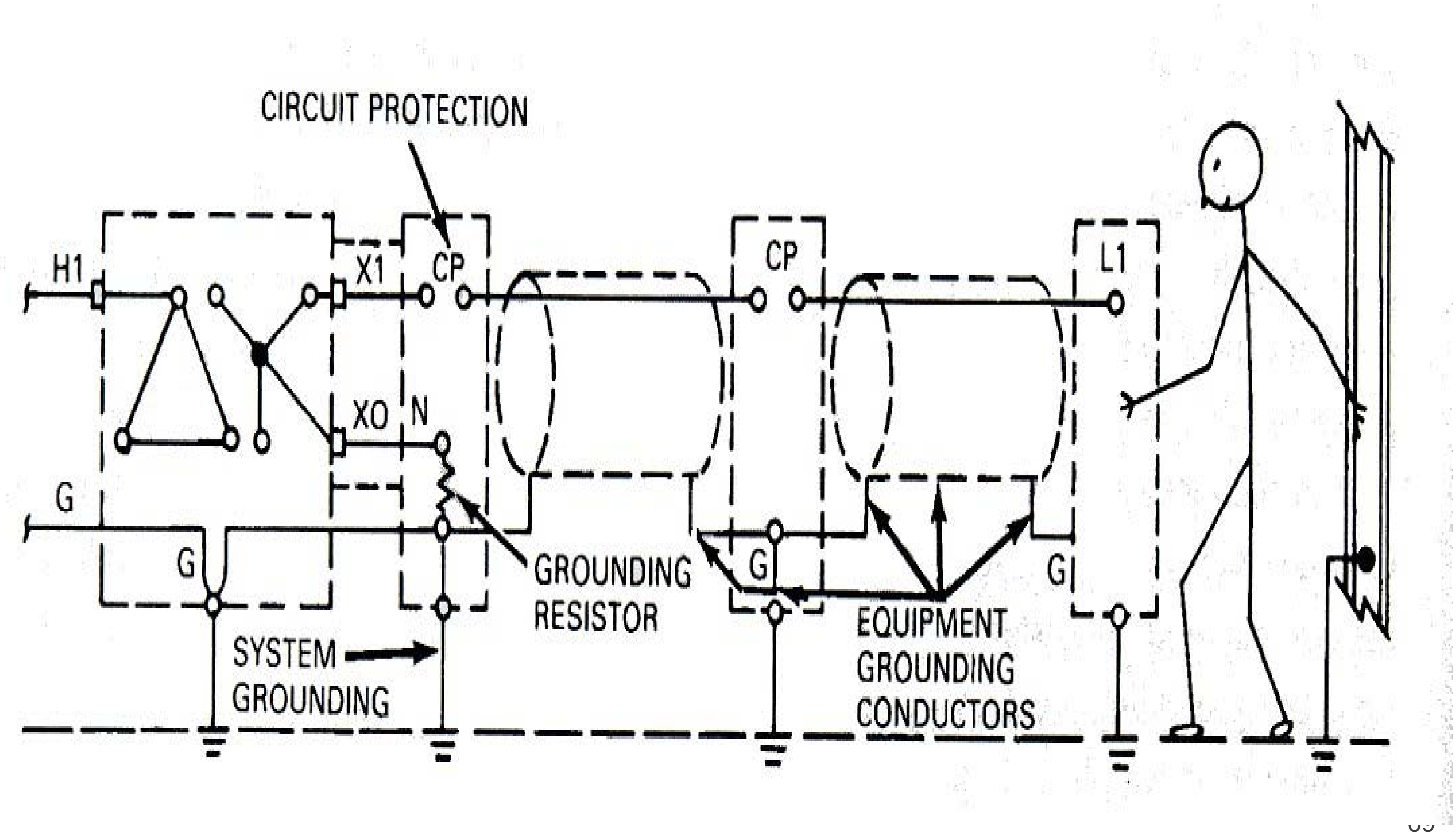
Advantages

- No transient over-voltages
- Easy fault location method
- No Arc Flash Hazards (with ground faults)
- No coordination issues; ground fault current is consistent
- May be possible to use higher gauge wires for grounding

Disadvantages

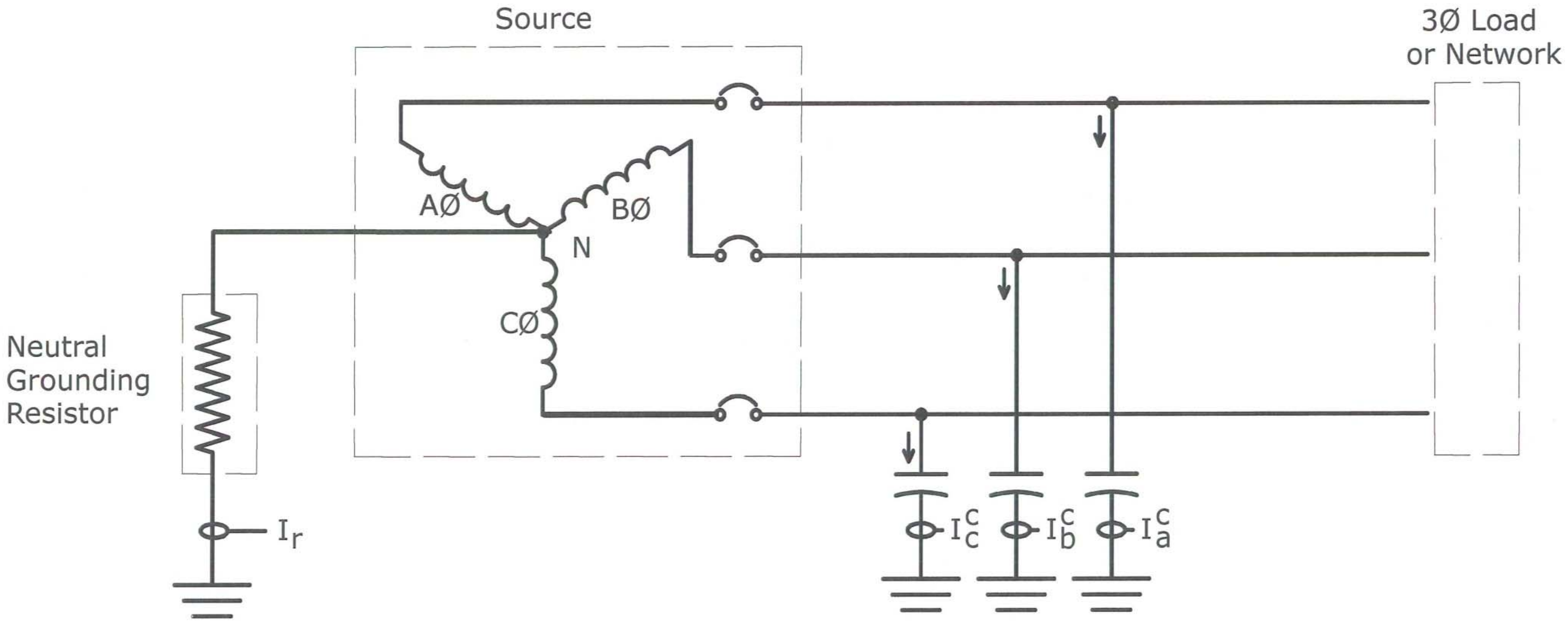
- No directly connected line-to-neutral loads
- Personnel must be trained
- Requires different arrester ratings
- Requires higher cable insulation ratings

Resistance Grounded System



Resistance Grounding

Intentionally grounded through neutral resistor



Low Resistance Grounding (LRG)

- Used on Medium Voltage
  - Some 5kV systems
  - Mainly 15kV systems

- System charging current may be too high for High Resistance Grounding (HRG)Indicator light and relay method to indicate ground fault.

- Ground Fault
  - Current typically limited to 25 –400A
  - Typically Trip within 10 -30 seconds to reduce damage

Duty Rating for NGR's

IEEE Std 32

Time Rating and Permissible Temperature Rise for Neutral Grounding Resistors

Time Rating (On Time)	Temp Rise (deg C)
10 sec	760
1 min	760
10 min	610
Continuous	385

Duration Must Be Coordinated With Protective Relay Scheme

Low Resistance Grounding (LRG)

- **Application Notes**
  - Line-to-neutral voltage for Resistor
    - **Line-to-line voltage for Grounding Transformer**
  - Rated current
    - **Consider change of resistance due to heat rise**
    - **Consider harmonics, leakage, etc.**
    - **Re-striking faults**
  - Vented Enclosure type (NEMA vs. IEC)
    - **Resistor must 'breathe'**
  - CTs and Relays
    - **Neutral or Ground side of Resistor**

Common Options

- Enclosure rating
- Enclosure finish
- Current transformer
- Potential transformer
- Disconnect switch
- Entrance/exit bushings
- Elevating stand
- Seismic rating
- Hazardous area classification
- Third party certification

15kV System Design

- 400A Resistance grounded wye connected system
- Greatly reduce fault energy for ground faults
- Table assumes 25MVA 7% transformer with .3 sec clearing time

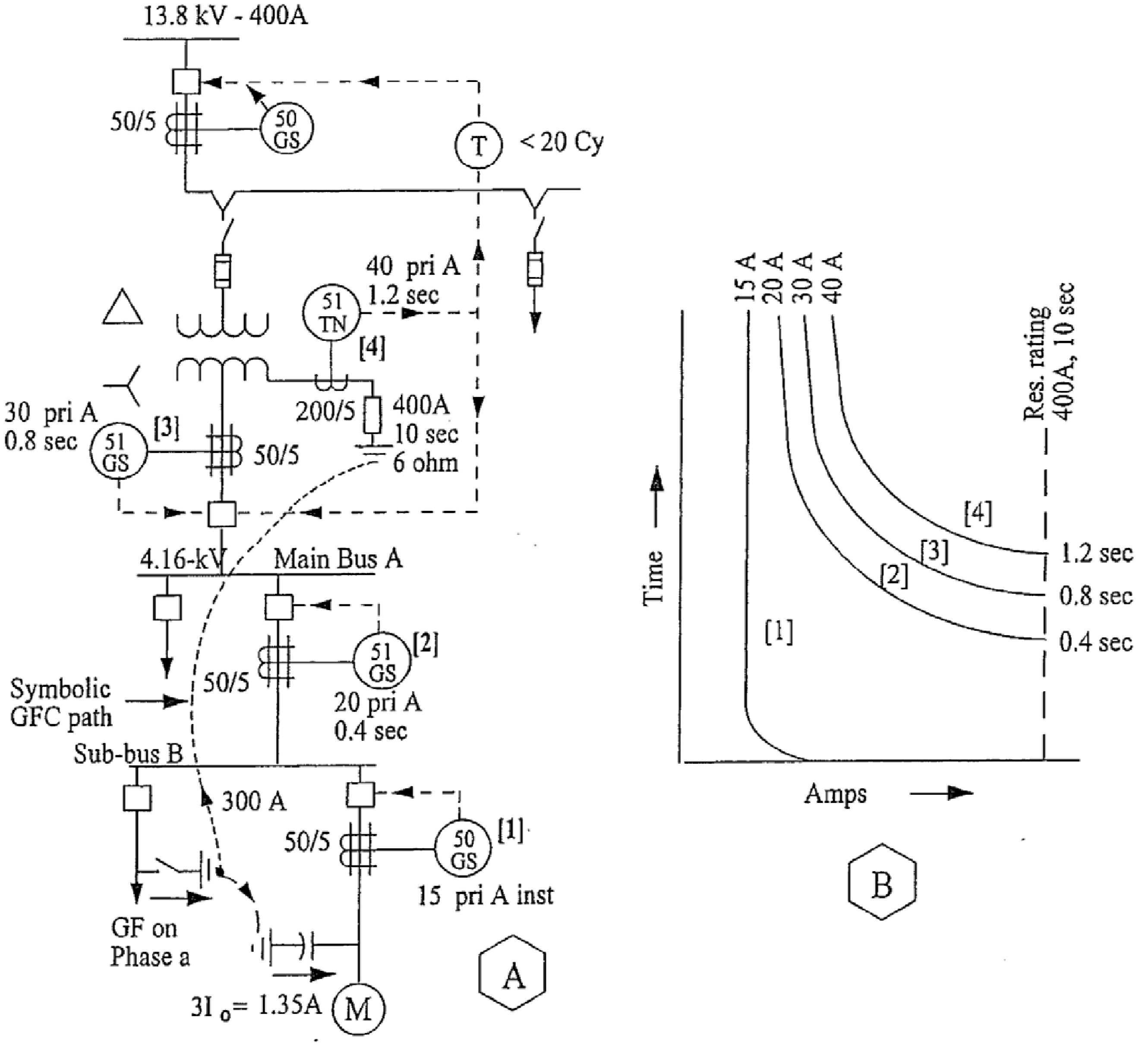
	watt sec	Cal/CM^2
Solid grounded 15kA fault	107,000 MW-sec	151
Resistance grounded 400A Limit	2.8MW-sec	4

Cheat Code # 1

- Resistor mass proportional to rated current, duty and temperature rise
- Shorter duration or higher temperature rise equates to lower cost

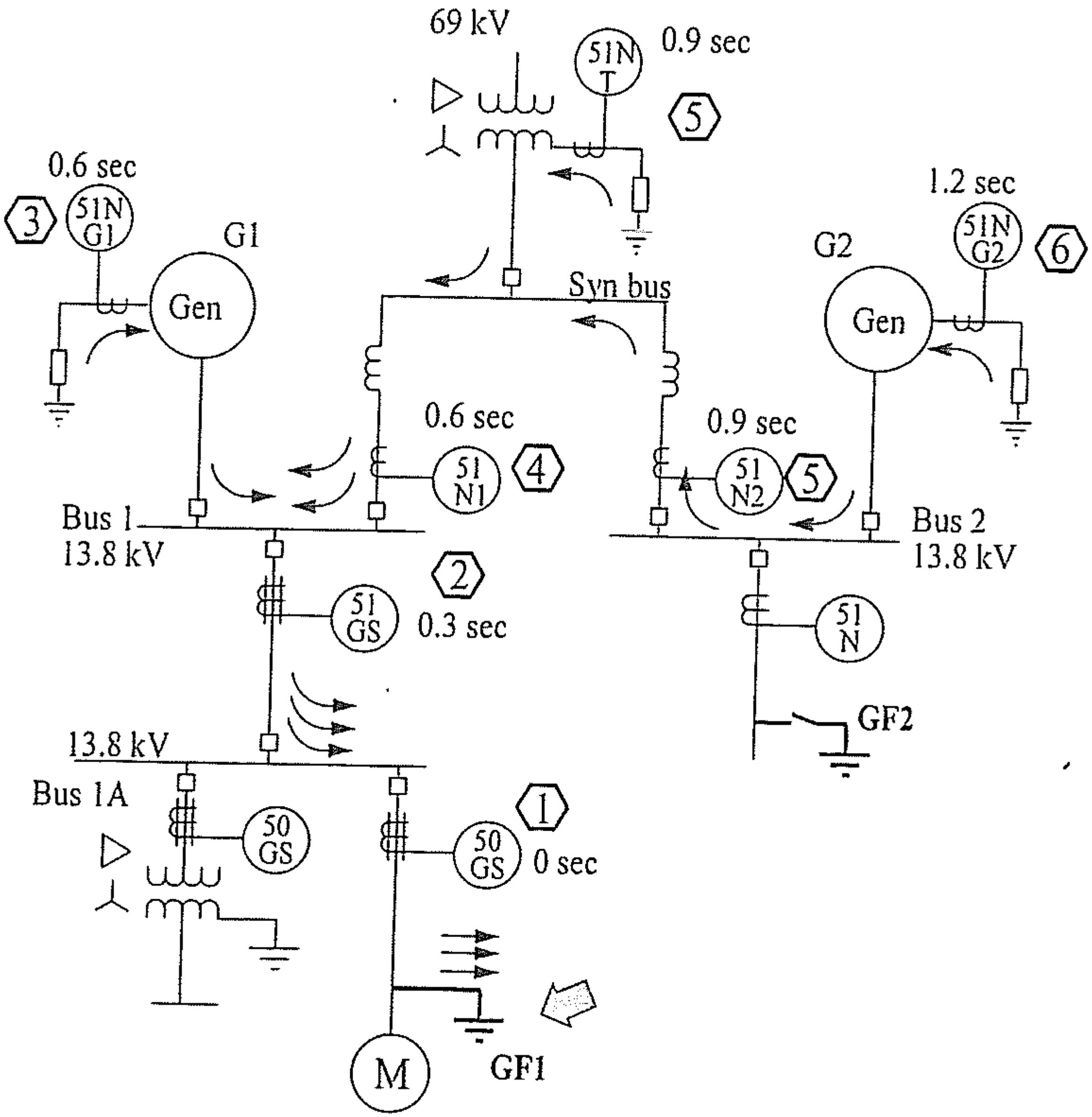
$$\text{Resistor mass} = \frac{\text{Watt} \bullet \text{seconds}}{\Delta T \bullet C_p}$$

400 Amp Ground fault protection



Multiple Grounds

- Additive nature of magnitude



High Resistance Grounded Systems

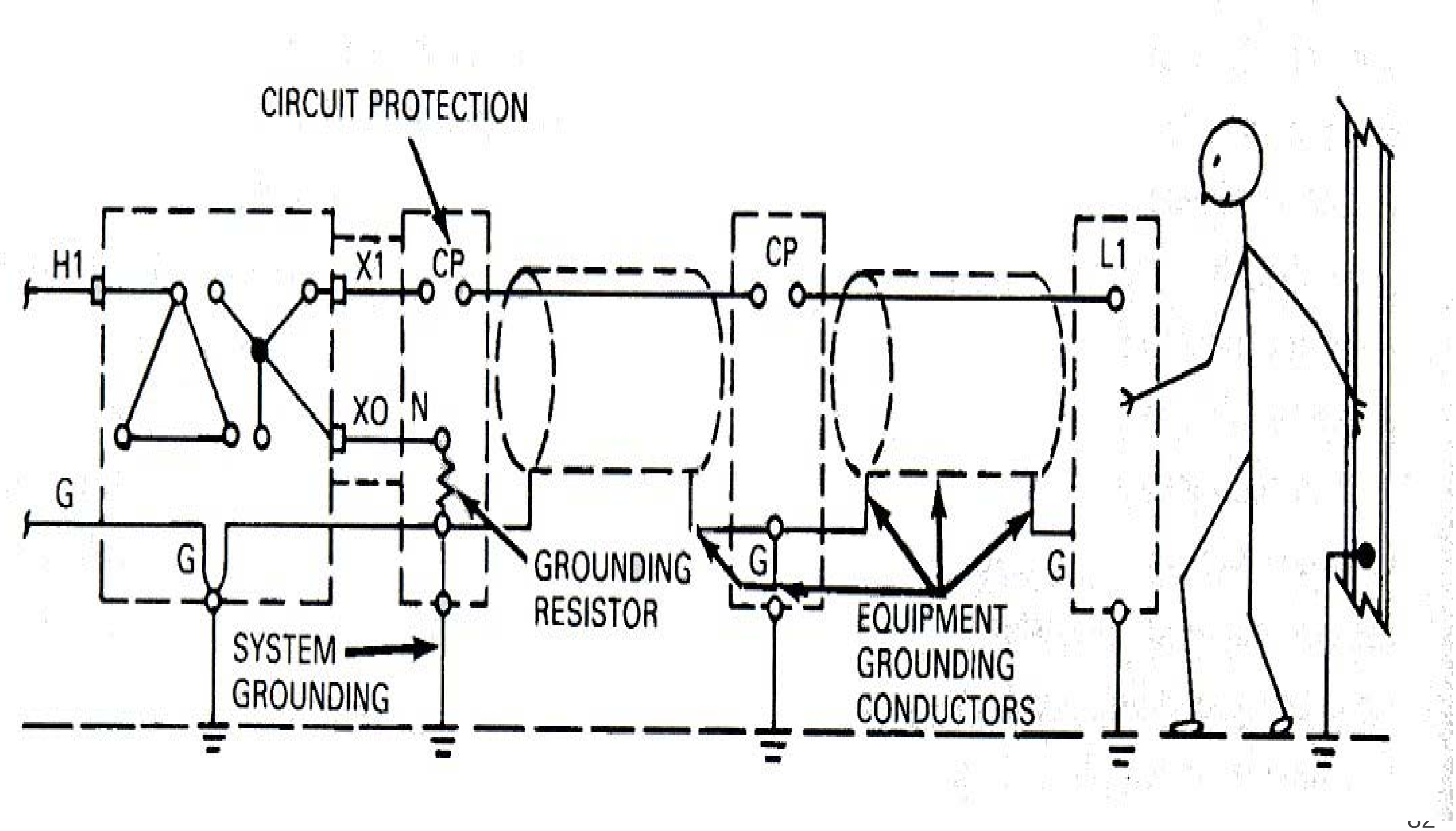
High Resistance Ground

- Commonly used on low voltage systems in industrial plants
- Becoming popular on advanced medium voltage systems in industrial plants
- Used by utilities for large generators

High Resistance Grounding

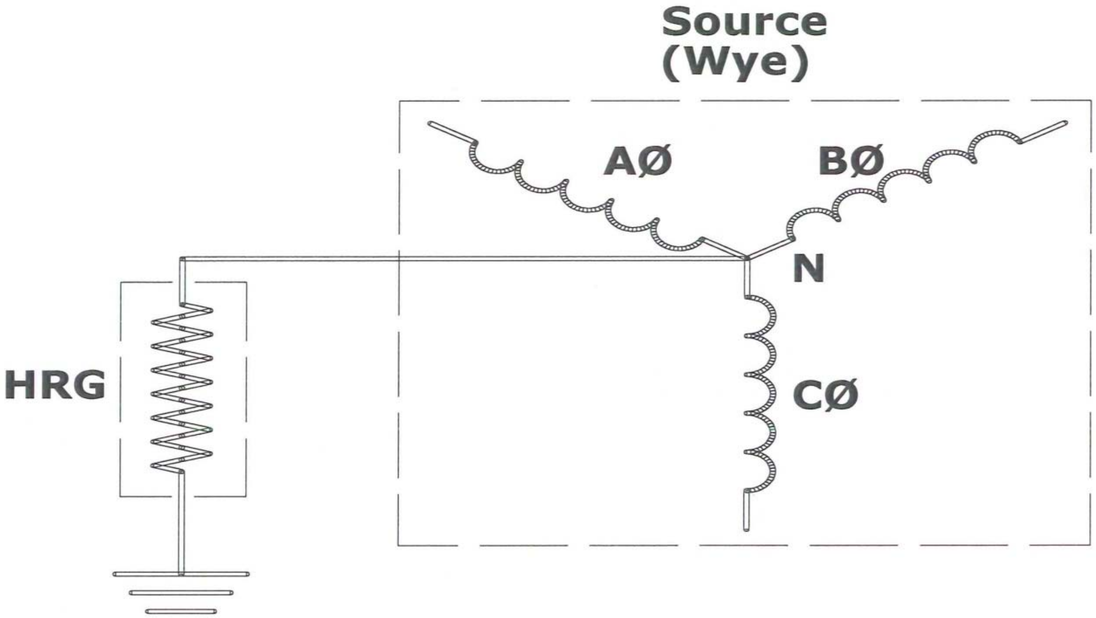
- Connected to earth ground through a high resistance
- Limits ground fault current to a few amperes (1-10 A is common)
- Protective schemes alarm only
- To be effective, $R_o > X_{C\,o}$ and $R_o < 2X_o$

Resistance Grounded System



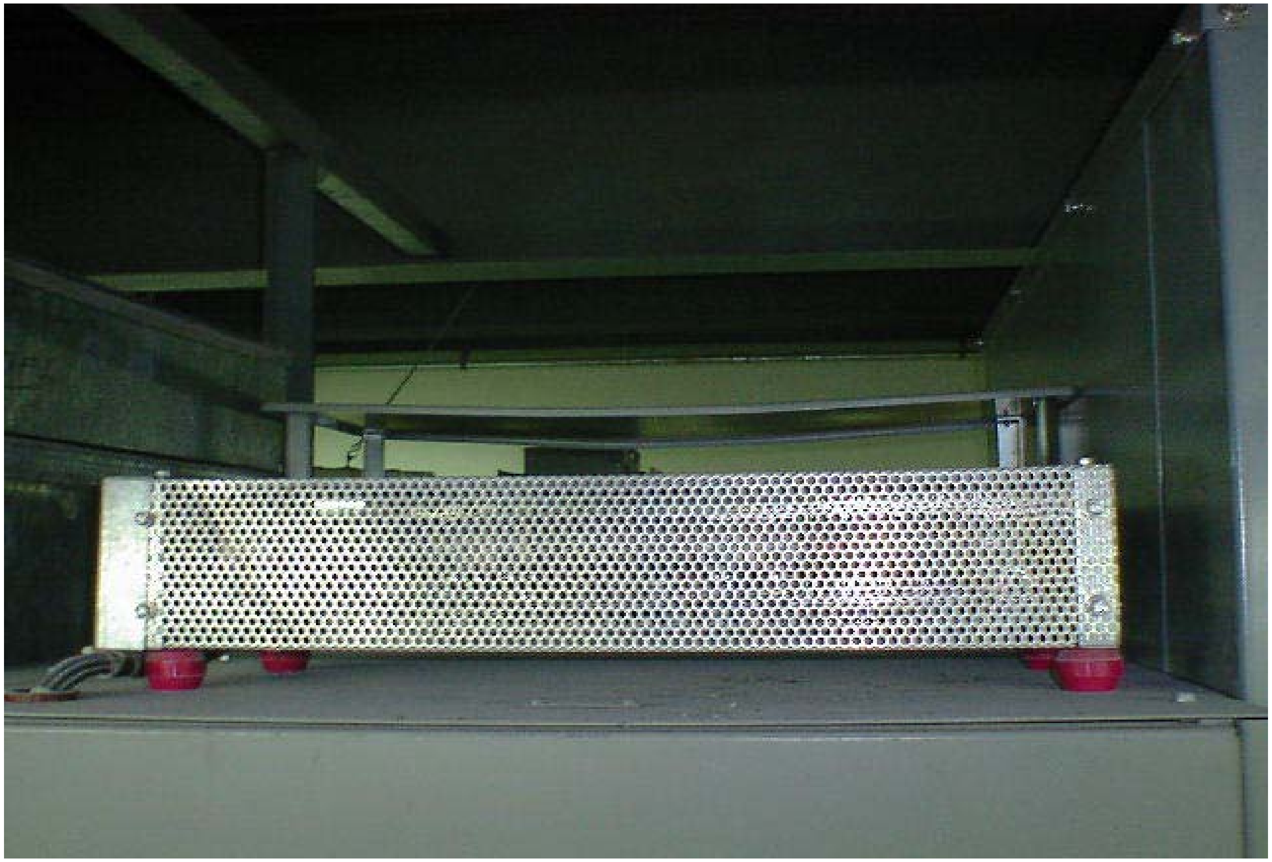
High Resistance Grounding

- **How does HRG improve safety and reliability?**
  - Inserts a resistor between neutral and ground
  - Dramatically reduces risk of Electrocution
  - Eliminates approximately 95% of Arc Flash / Blast Injuries



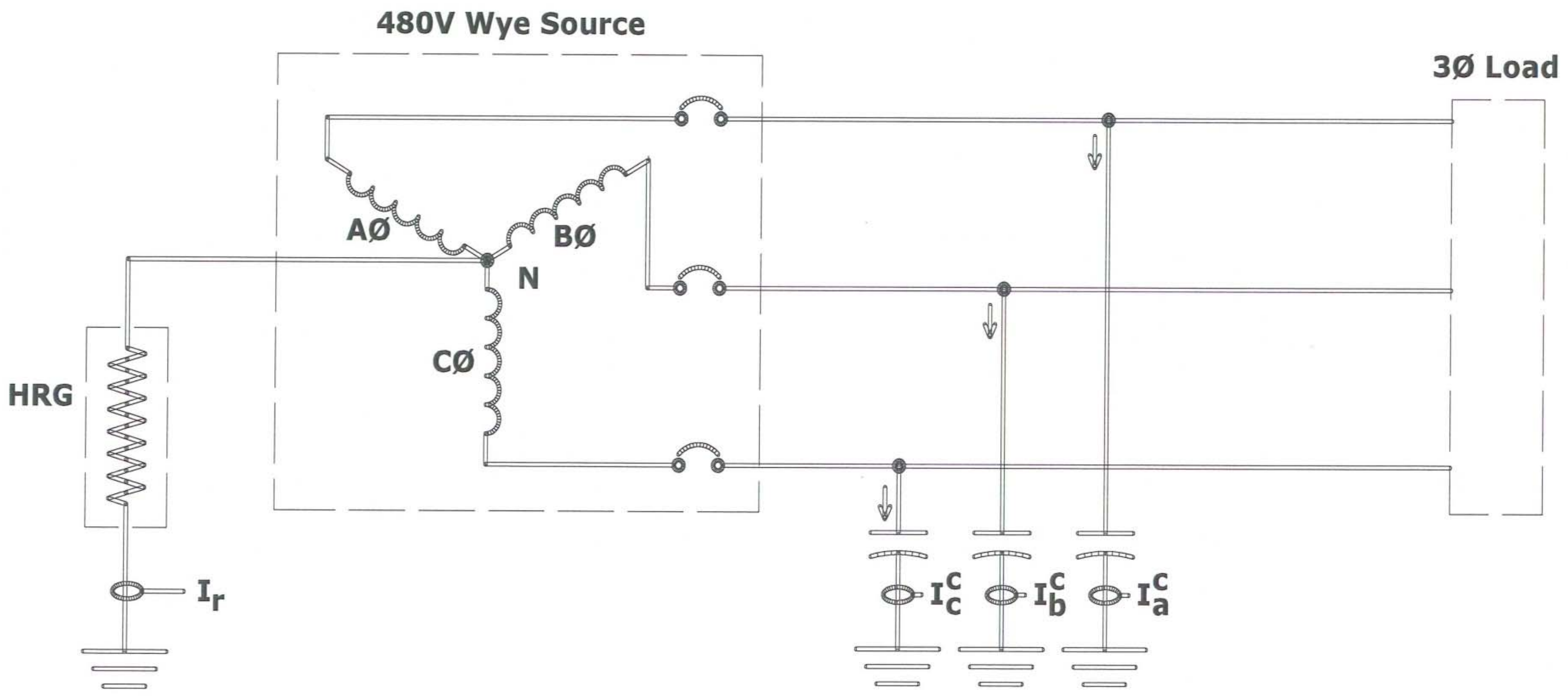
Pictures of HRG System

- Resistor – Mounted on top of Swgr

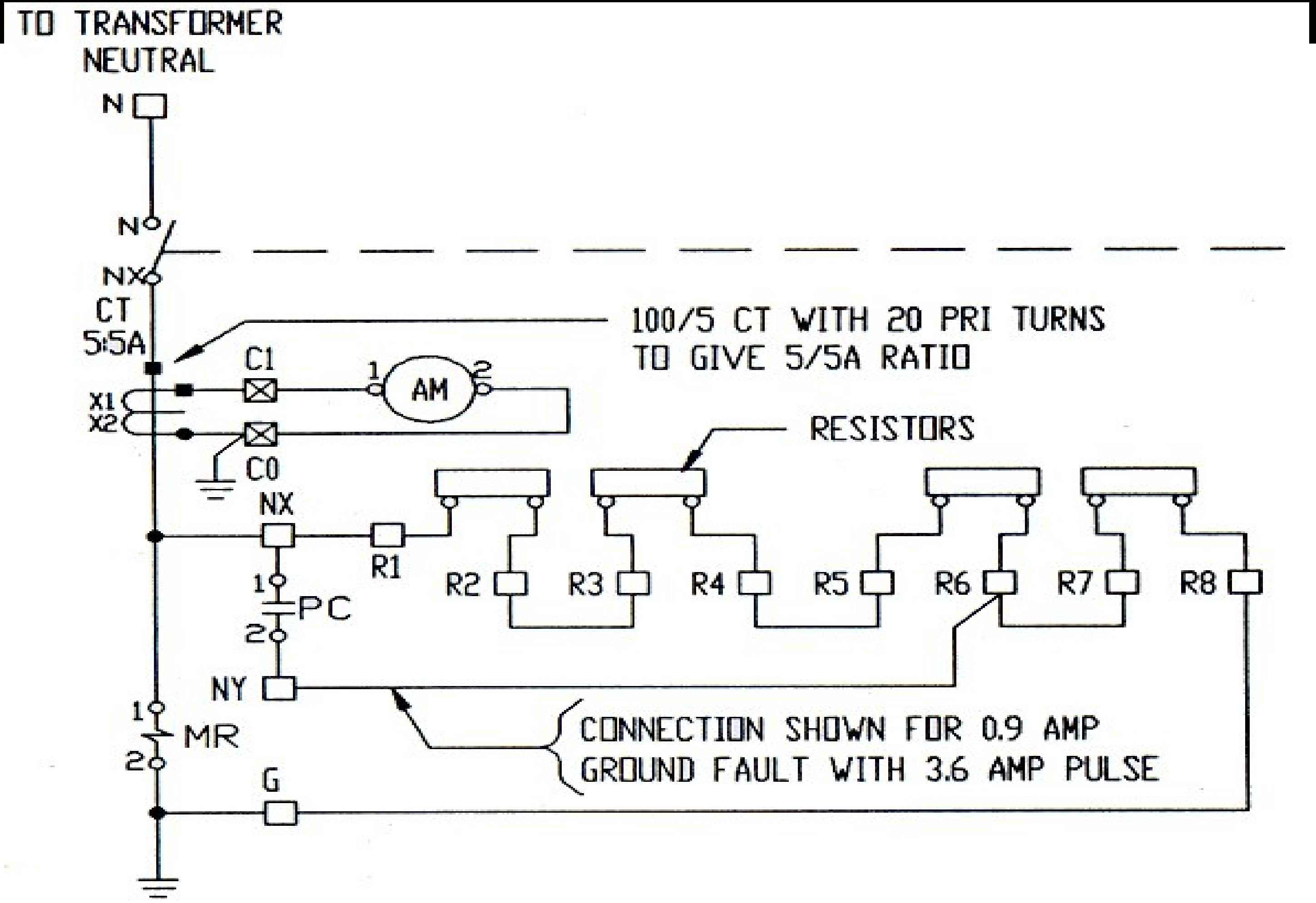


High Resistance Grounding

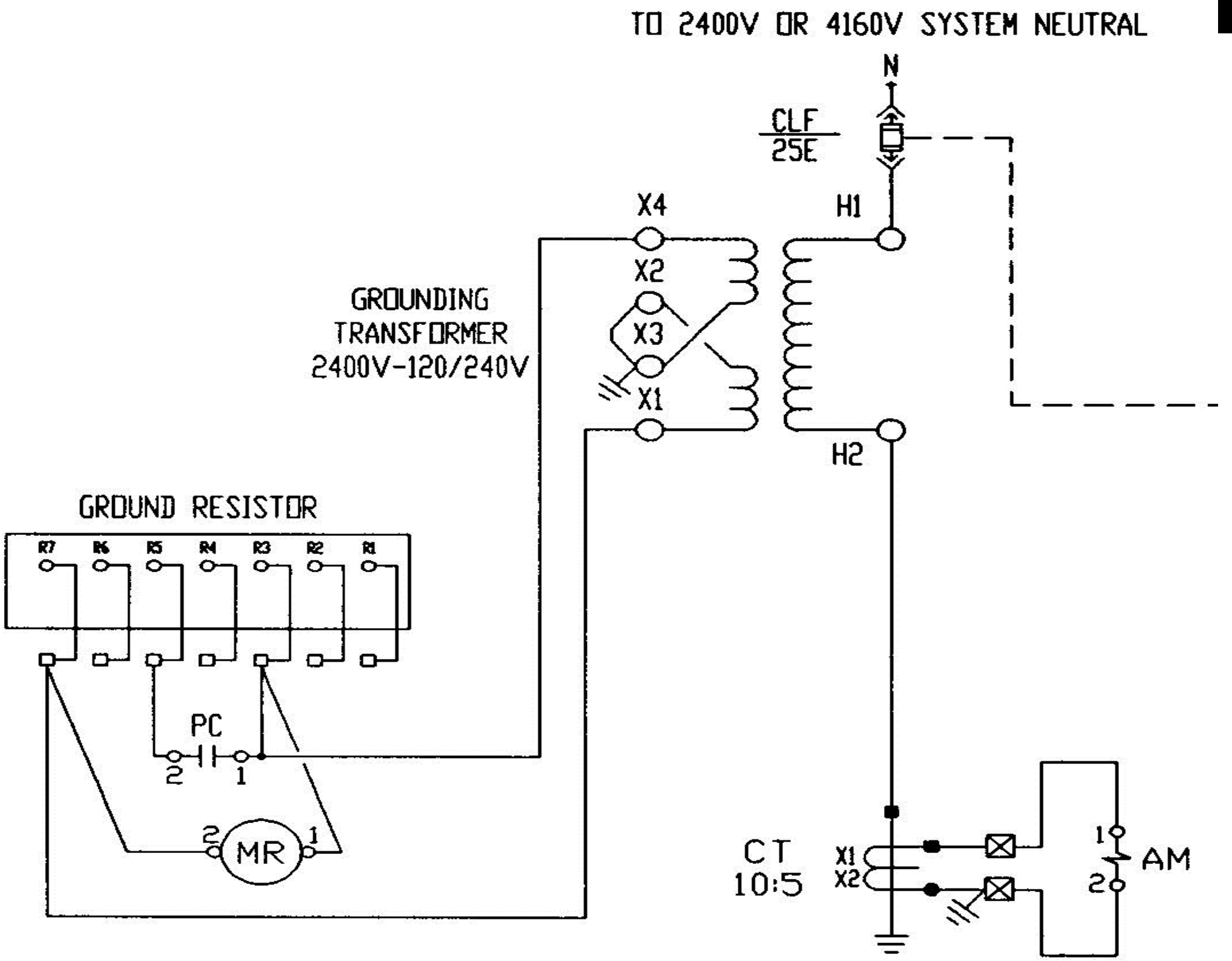
Intentionally grounded through neutral resistor



Low Voltage


TO TRANSFORMER
NEUTRAL
N
N
NX
CT
5:5A
100/5 CT WITH 20 PRI TURNS
TO GIVE 5/5A RATIO
C1
AM
1
2
X1
X2
C0
RESISTORS
NX
R1
R2
R3
R4
R5
R6
R7
R8
1
PC
2
NY
1
MR
2
G
CONNECTION SHOWN FOR 0.9 AMP
GROUND FAULT WITH 3.6 AMP PULSE

Medium Voltage HRG



Resistor Current Rating

- Setting must be higher than charging current
- Current rating for low voltage systems is typically from 0.9A to 3.6A
- Current rating for medium voltage systems is typically from 2A to 7A or from 5A to 20A at primary voltage

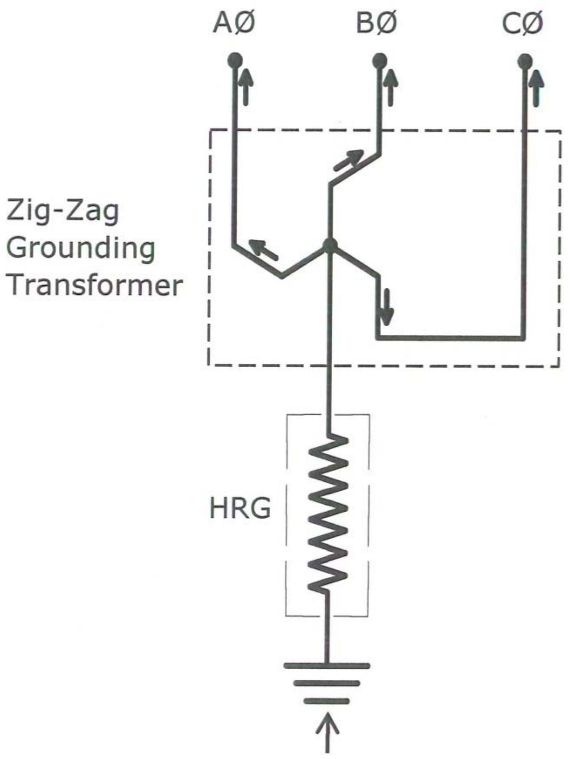
High Resistance Grounding

- Advantages
    - Eliminates overvoltage transients
    - Allows faulted circuit to continue operation

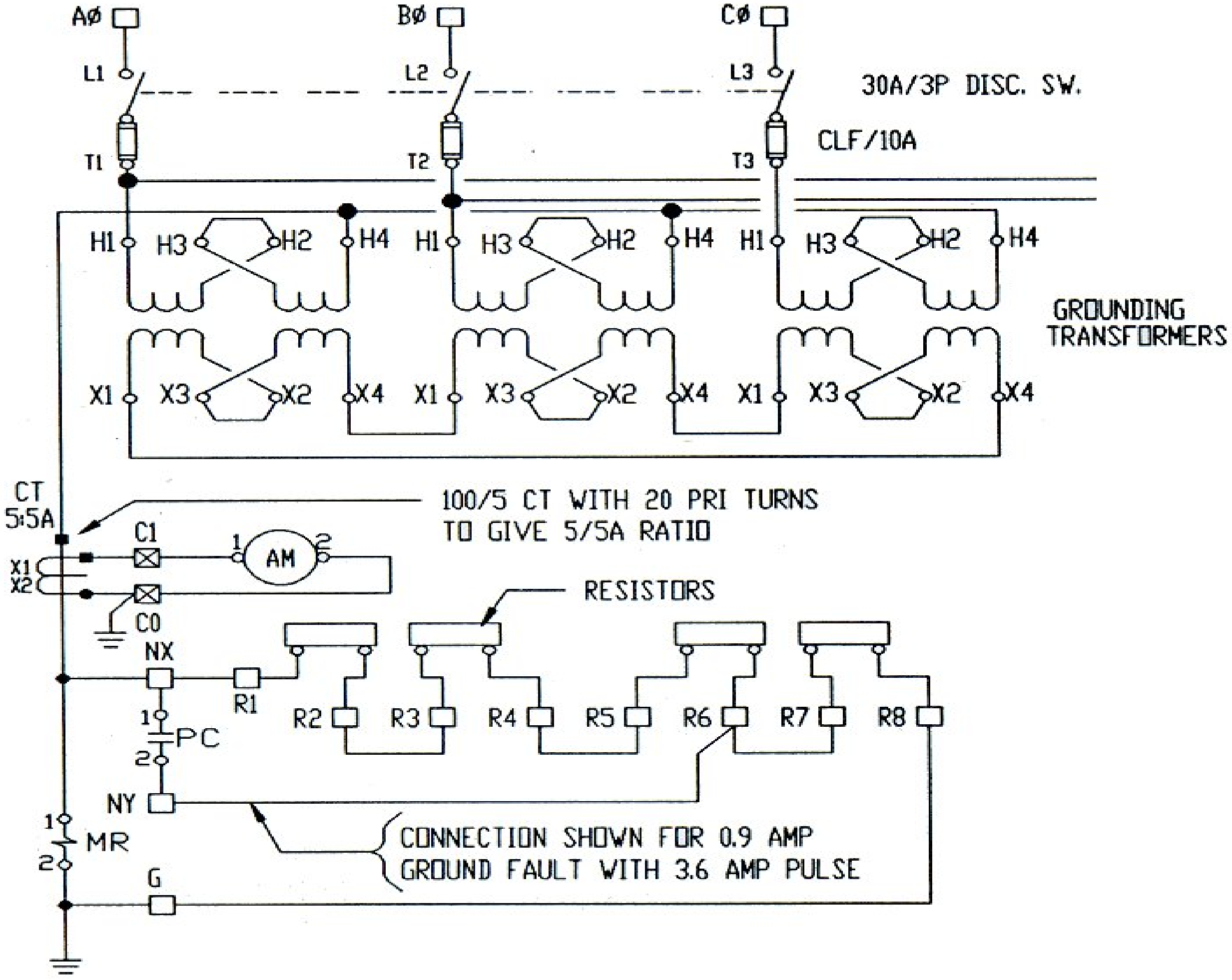
- Disadvantages
    - Potential for nuisance alarming
    - Maintenance personnel may ignore first fault

What if no neutral exists?

- Can HRG be used on Delta connected systems?
  - A grounding transformer is installed (either a zig-zag or a wye-delta) from all three phases to create an artificial neutral for grounding purposes only.



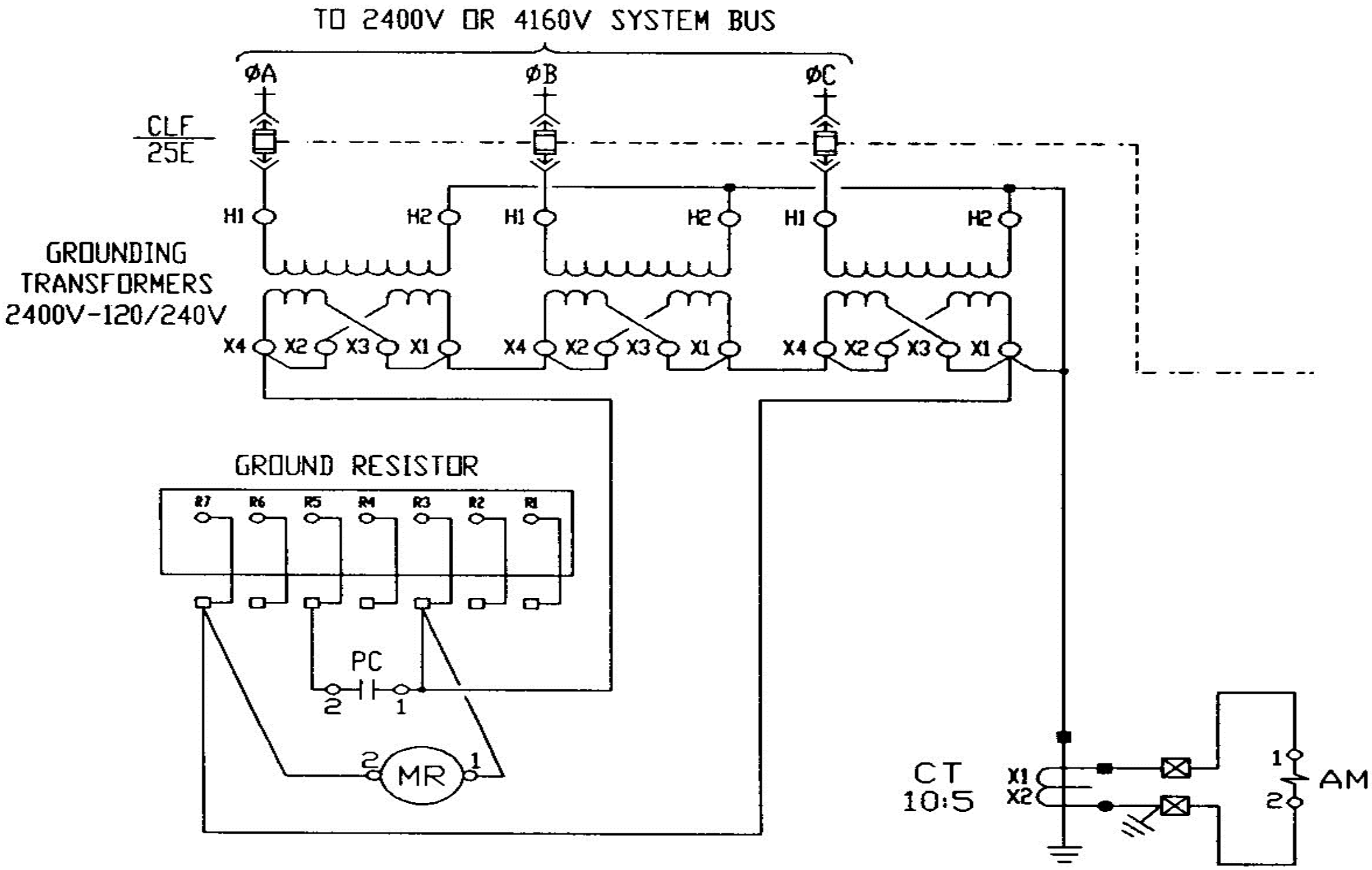
Low Voltage Derived Neutral HRG



100/5 CT WITH 20 PRI TURNS TO GIVE 5/5A RATIO

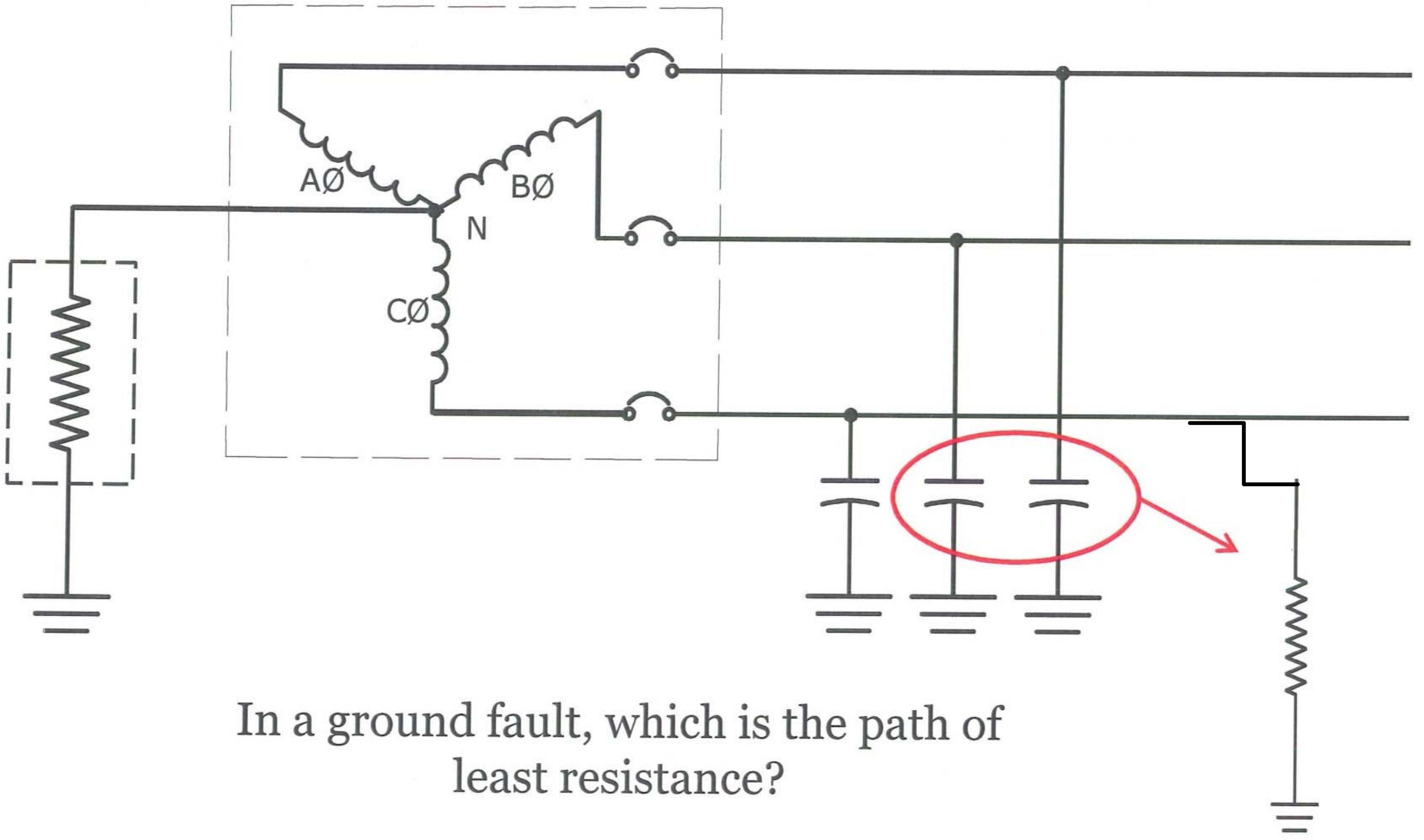
CONNECTION SHOWN FOR 0.9 AMP GROUND FAULT WITH 3.6 AMP PULSE

Medium Voltage Derived Neutral



System Capacitance

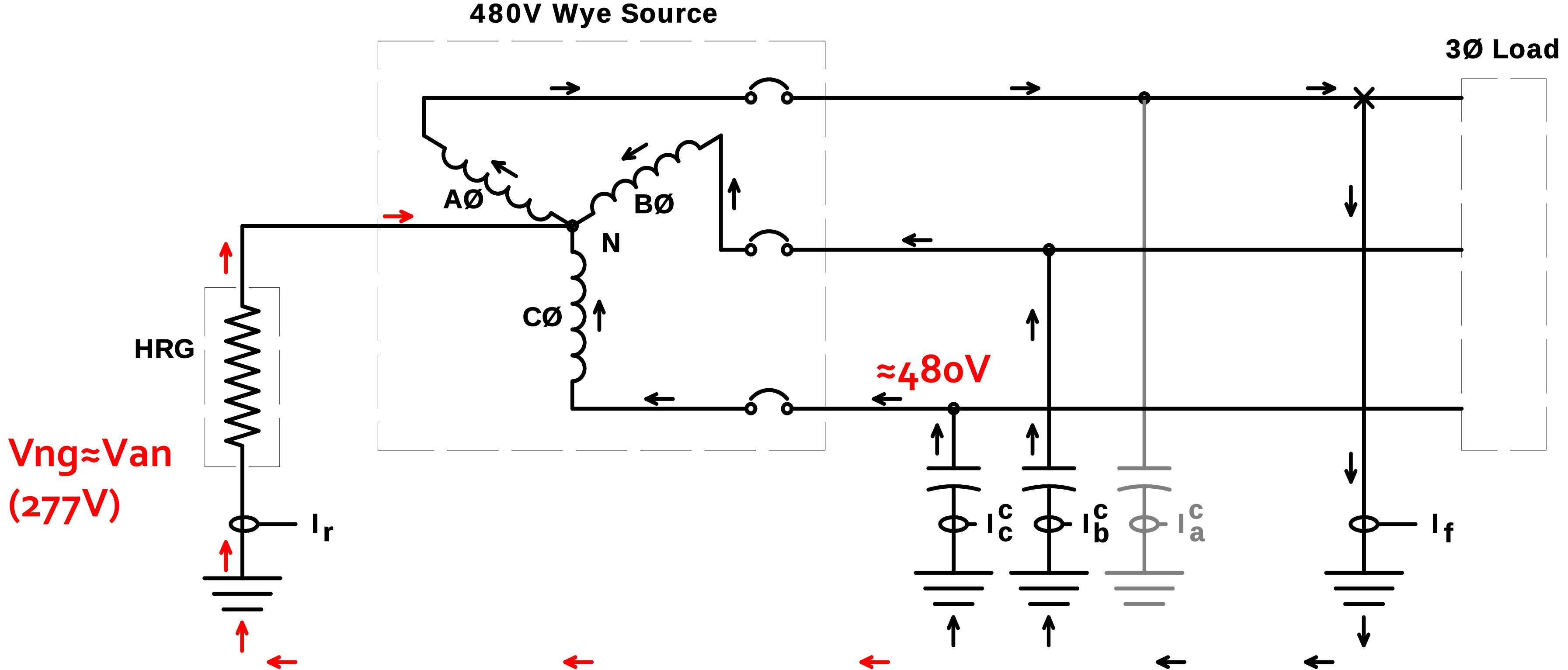
In a ground fault, which is the path of least resistance?



In a ground fault, which is the path of least resistance?

High Resistance Grounding

- Compared to Ungrounded Systems (voltage rise)



Vng≈Van (277V)

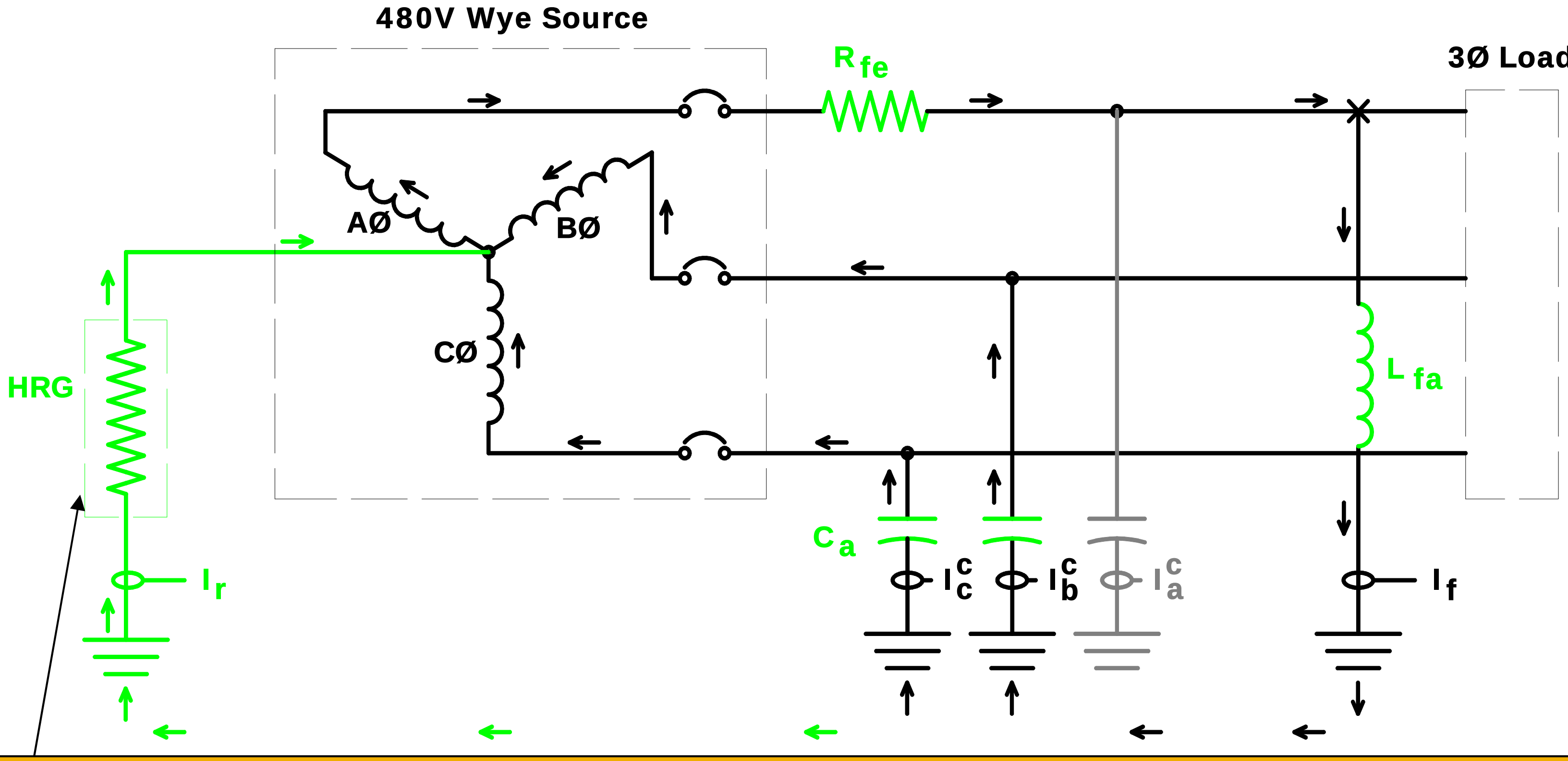
≈480V

Ground ≈ AØ

Additional return path, only difference between Ungrounded and HRG!

High Resistance Grounding

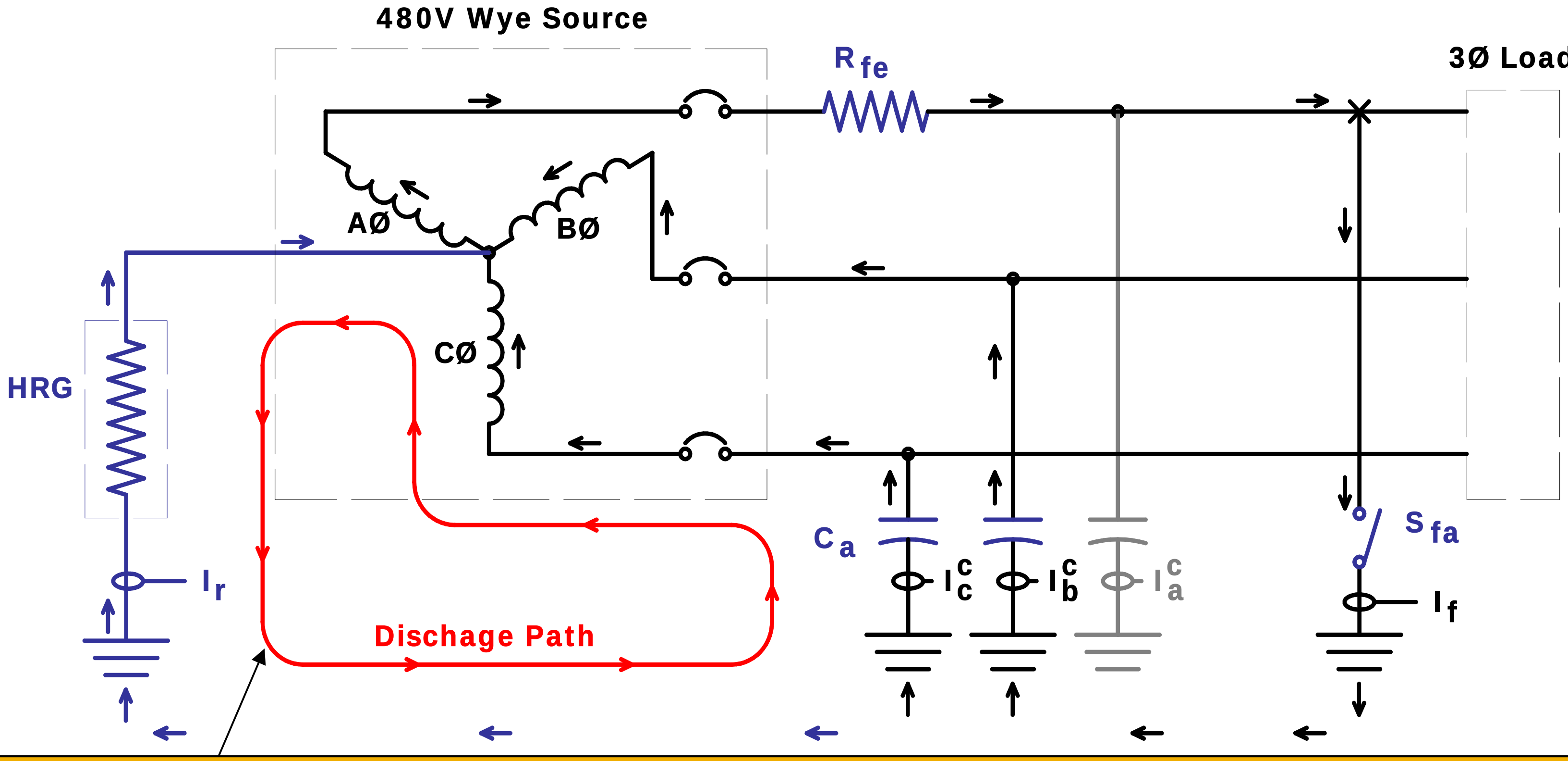
- Importance of additional path versus Ungrounded



RLC circuit no longer exists! System Capacitance (capacitors) causing resonance cannot occur due to dampening resistor (HRG) preventing transient over-voltage!

High Resistance Grounding

- Importance of additional path versus Ungrounded



Intermittent arcing cannot build up a charge (transient over-voltage) in the System Capacitance. Capacitors are discharging during non-strike to the resistor (HRG)!

High Resistance Grounding

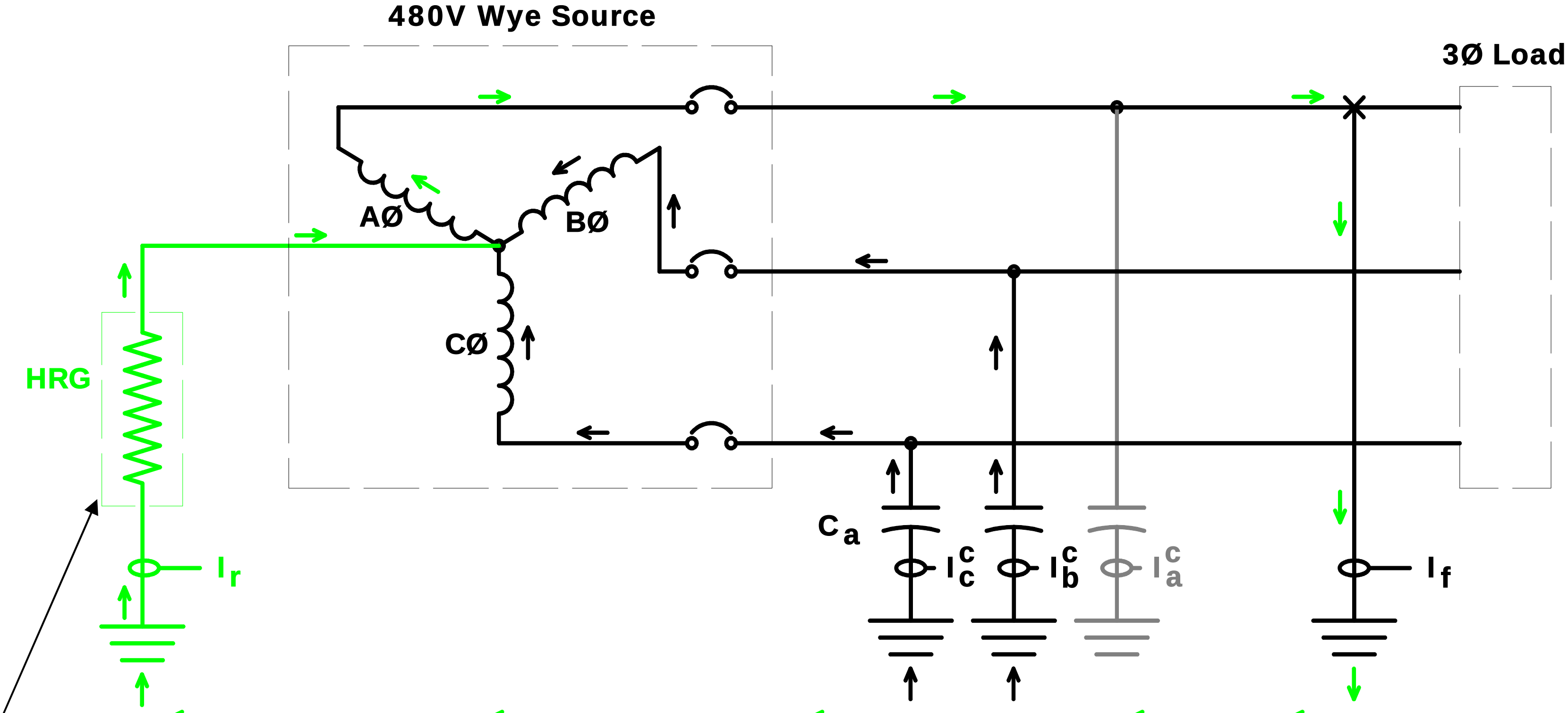
- Only discharges if $R_0 < X_{co}$, so $I_r > I_{xco}$
  - That is, resistor current must be greater than capacitive charging current.
  - Here are 'rule of thumb' numbers for estimation

Transformer (kVA)	Charging Current (A)
1000	0.2 - 0.6
1500	0.3 - 0.9
2000	0.4 - 1.2
2500	0.5 - 1.5

  - See Appendix F for method to measure capacitive current

High Resistance Grounding

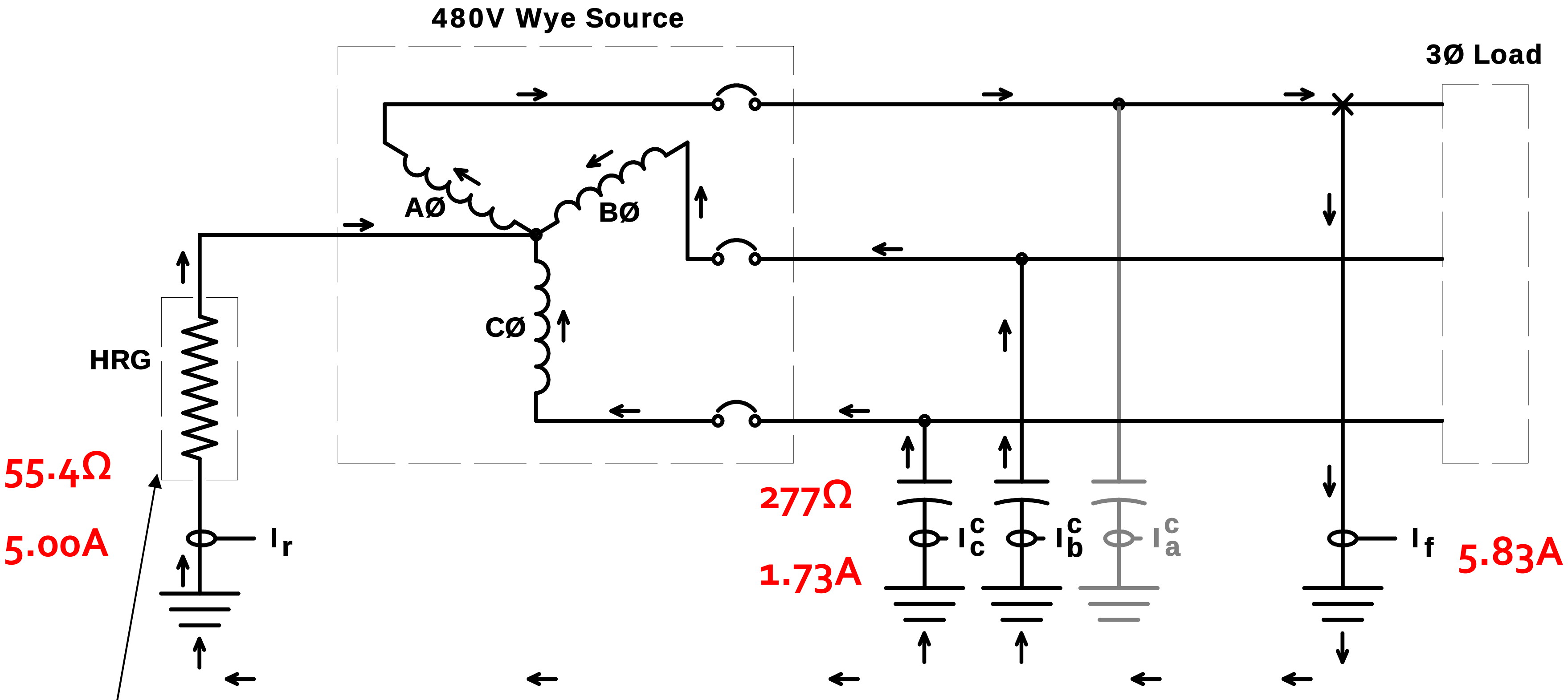
- Importance of additional path versus Solidly Grounded



Resistor (HRG) in lieu of wire adds significant amount of resistance to lower ground fault to a predetermined value preventing destructive fault currents and shut-down!

High Resistance Grounding

- Compared with Solidly Grounded (current rise)



Resistor in return path, only difference between Solidly Grounded and HRG!

5.83A ≠ 3.00A + 5.00A

GARD

High Resistance Grounding

- Currents:
  - Normal Operation

$$(I_a{}^c + I_b{}^c + I_c{}^c) = 0A$$

$$I_r = \frac{V_{ng}}{R_r} = \frac{0V}{55.4\Omega} = 0A$$

$$I_f = \sqrt{I_r{}^2 + (I_a{}^c + I_b{}^c + I_c{}^c)^2} = 0A$$

  - Fault conditions

$$(I_a{}^c + I_b{}^c + I_c{}^c) = (0 + 1.73\angle 60^\circ + 1.73\angle 120^\circ) = 3.00\angle 90^\circ A$$

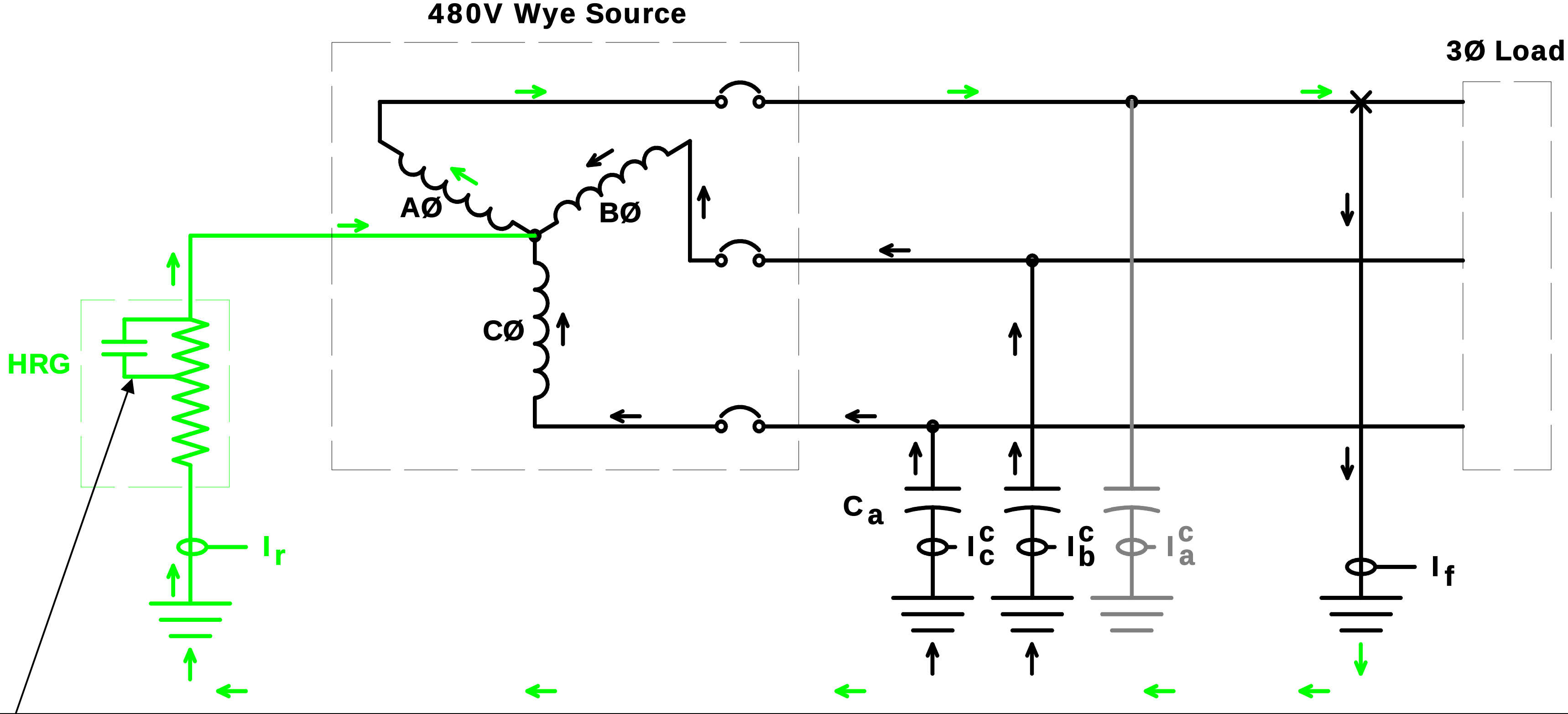
$$I_r = \frac{V_{ng}}{R_r} = \frac{277V}{55.4\Omega} = 5.00\angle 0^\circ A$$

$$I_f = \sqrt{I_r{}^2 + (I_a{}^c + I_b{}^c + I_c{}^c)^2} = 5.83A$$

$$I_f = 3.00\angle 90^\circ + 5.00\angle 0^\circ = 5.83\angle 31^\circ A$$

High Resistance Grounding

- Another advantage of return path: ground fault location



Contactor shorts out part of the resistor changing the resistance, hence, changing the current. Ground fault current now is a pulse signal that allows for detection!

System Charging Current

- **Only discharges if $R_0 < X_{C0}$, so $I_r > I_{XC0}$**

  (per IEEE 142-1991 1.4.3)

  - That is, resistor current must be greater than capacitive charging current.
  - **'Rule of thumb' for 480V system:**

Transformer (kVA)	Charging Current (A)
1000	0.2 -0.6
1500	0.3 -0.9
2000	0.4 -1.2
2500	0.5 -1.5

Estimating Charging Current

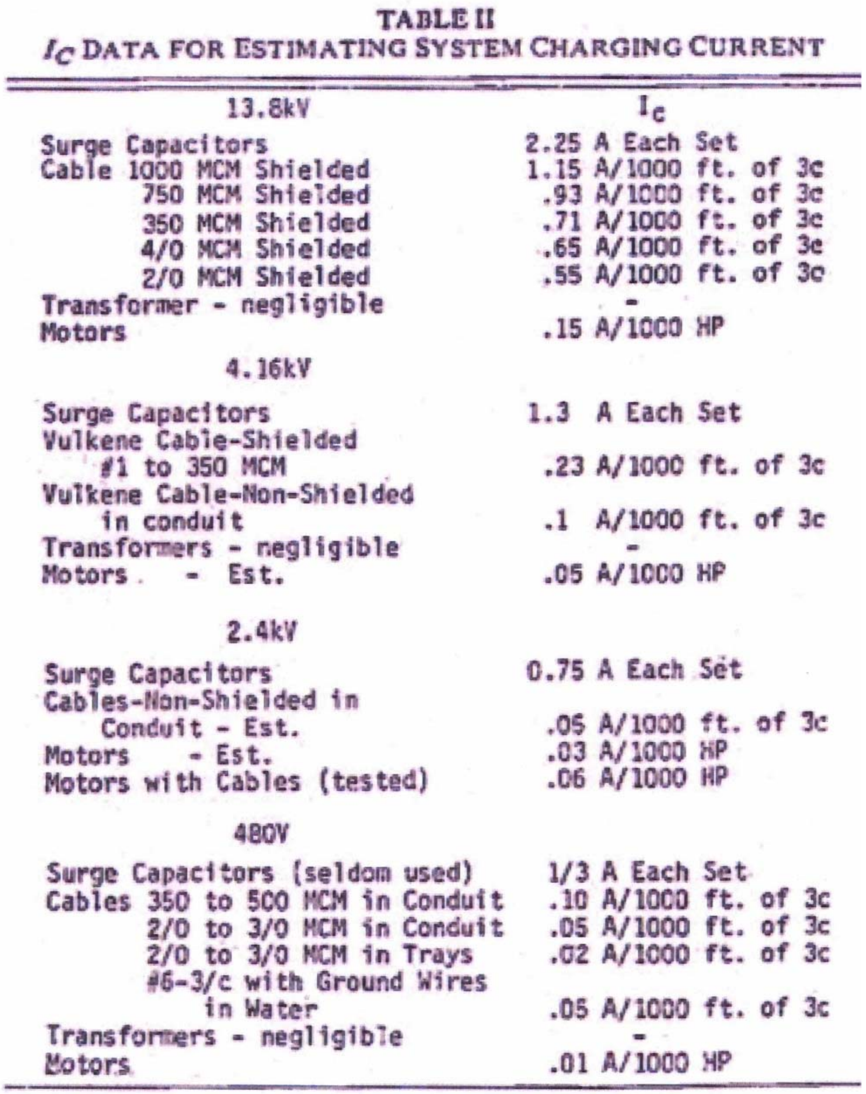


TABLE II

I_C DATA FOR ESTIMATING SYSTEM CHARGING CURRENT

13.8kV	I_c
Surge Capacitors	2.25 A Each Set
Cable 1000 MCM Shielded	1.15 A/1000 ft. of 3c
750 MCM Shielded	.93 A/1000 ft. of 3c
350 MCM Shielded	.71 A/1000 ft. of 3c
4/0 MCM Shielded	.65 A/1000 ft. of 3c
2/0 MCM Shielded	.55 A/1000 ft. of 3c
Transformer - negligible	-
Motors	.15 A/1000 HP
4.16kV	
Surge Capacitors	1.3 A Each Set
Vulkene Cable-Shielded #1 to 350 MCM	.23 A/1000 ft. of 3c
Vulkene Cable-Non-Shielded in conduit	.1 A/1000 ft. of 3c
Transformers - negligible	-
Motors - Est.	.05 A/1000 HP
2.4kV	
Surge Capacitors	0.75 A Each Set
Cables-Non-Shielded in Conduit - Est.	.05 A/1000 ft. of 3c
Motors - Est.	.03 A/1000 HP
Motors with Cables (tested)	.06 A/1000 HP
480V	
Surge Capacitors (seldom used)	1/3 A Each Set
Cables 350 to 500 MCM in Conduit	.10 A/1000 ft. of 3c
2/0 to 3/0 MCM in Conduit	.05 A/1000 ft. of 3c
2/0 to 3/0 MCM in Trays	.02 A/1000 ft. of 3c
#6-3/c with Ground Wires in Water	.05 A/1000 ft. of 3c
Transformers - negligible	-
Motors	.01 A/1000 HP

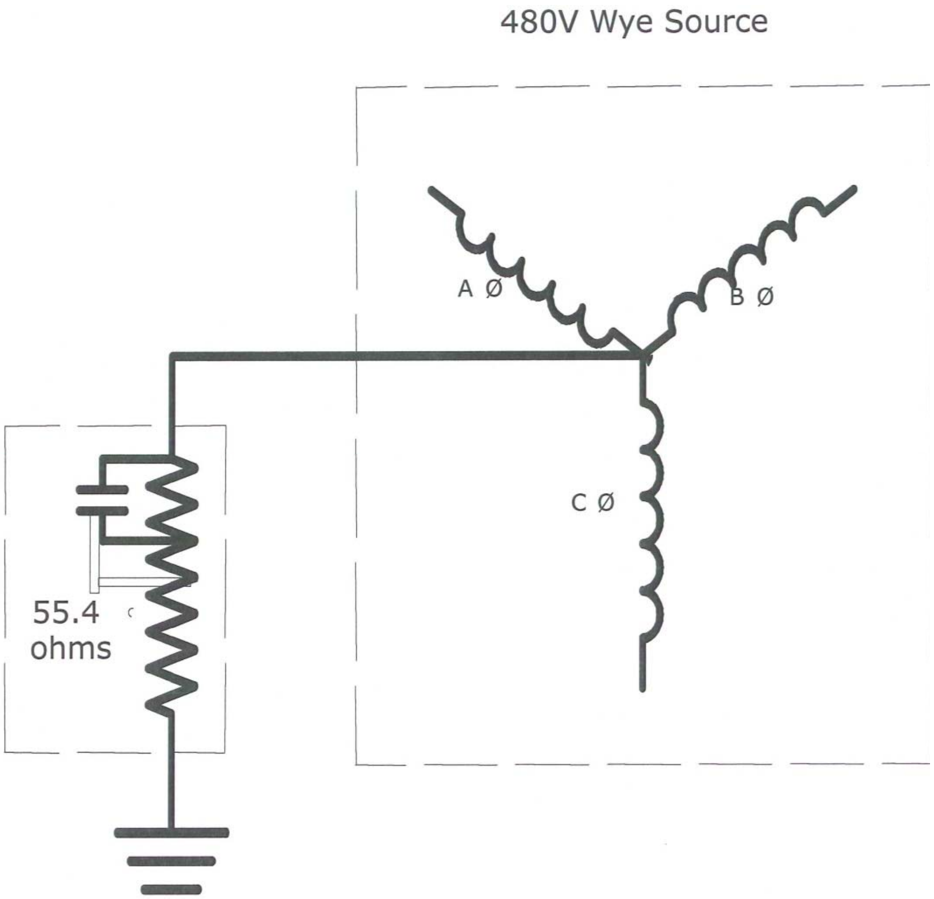
Cheat Code # 2

- Resistance increases as resistor heats up
- Cheaper stainless steel alloys may produce undesirable results

Resistance change per degree C	
Nickel Chromium	0.01%
18SR/1JR SS	0.02 – 0.04%
304SS	0.22%

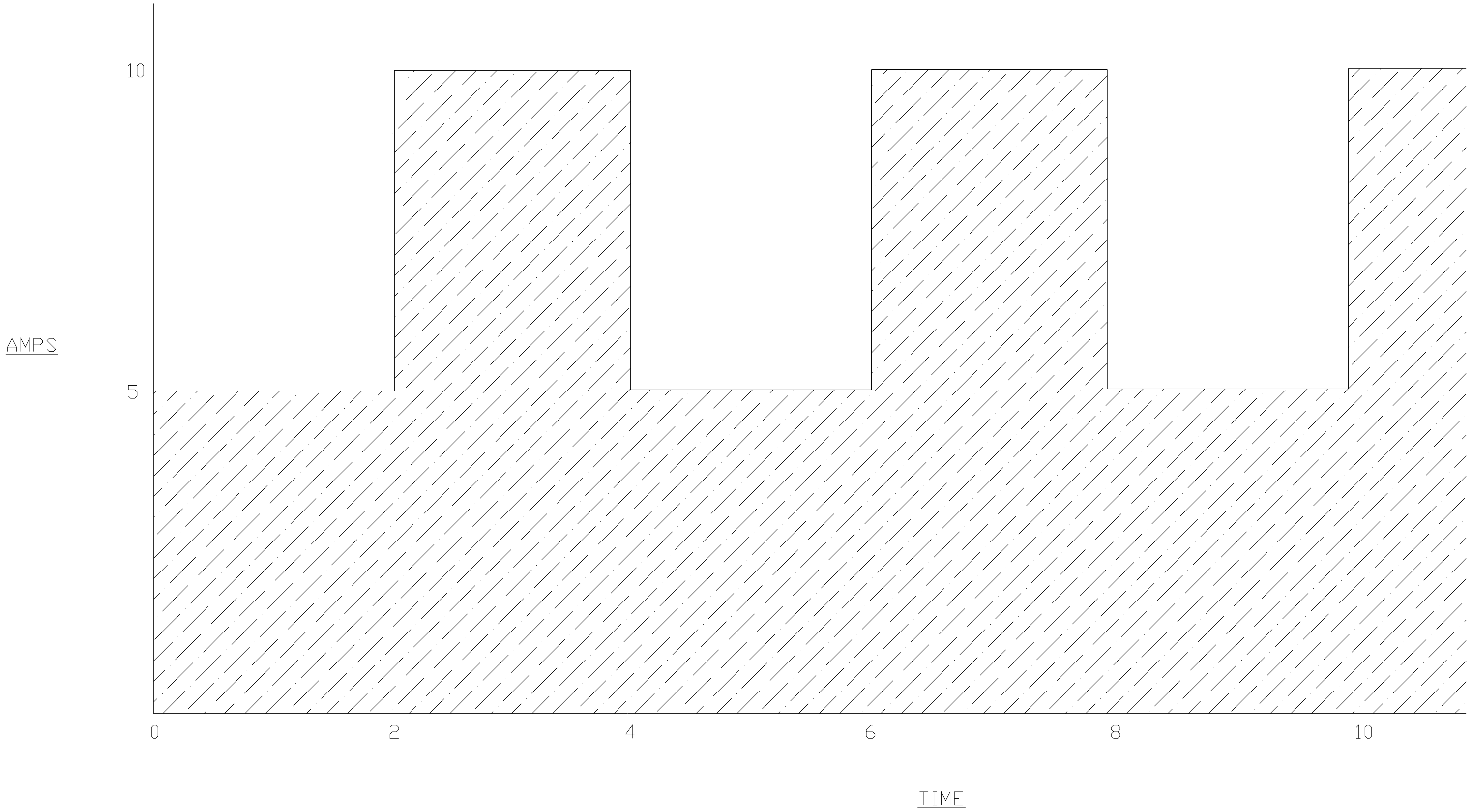
Fault Location

- Operator controlled contactor connected across half the grounding resistor
- When activated, contactor alternately shorts half the resistor and forces the current to double
- Possible to use ammeter to track the current fluctuation



High Resistance Grounding

- Contactor shorts out ½ resistance, thus, doubling current to 10A at ~30 pulses / minute.



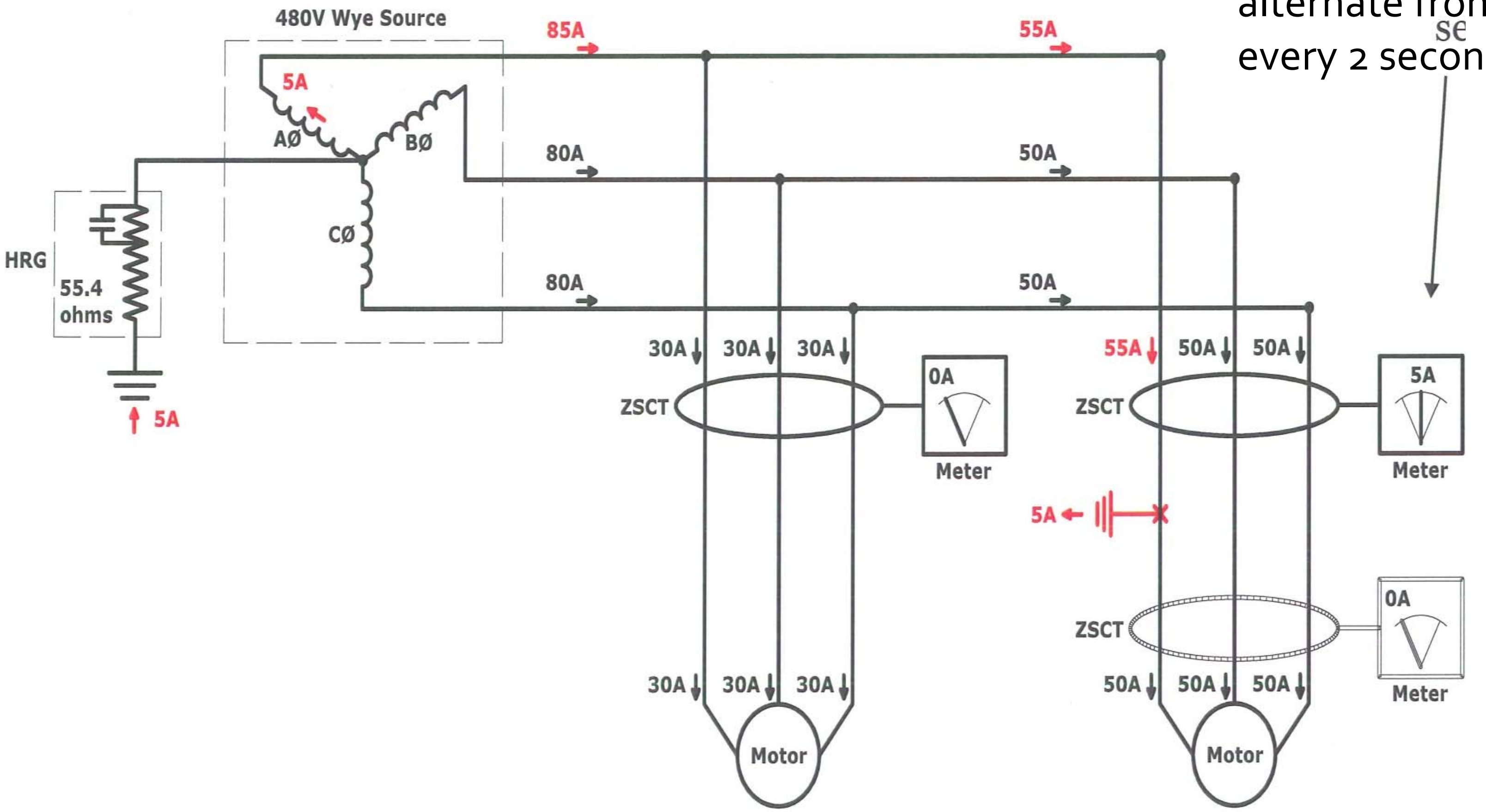
Ground Fault Location Method

NOTE: *Tracking a ground fault can only be done on an energized system. Due to the inherent risk of electrocution this should only be performed by trained and competent personnel. Appropriate PPE measures should be taken into consideration as well.*

Fault Location

- Method to quickly locate ground faults

Meter reading will alternate from 5A to 10A every 2 seconds.



Design Considerations with HRG Systems

- Very few potential hazards with HRG, however…
  - Elevated Voltages
  - Trained Personnel
  - Cables, TVSSs, VFDs Insulation

- Line-to-Neutral Loads

- Loss of Ground
  - System becomes Ungrounded or Solidly Grounded introducing more Hazards

High Resistance Ground

- Surge protection must be rated based on line to ground potential rise
- High frequencies can appear as nuisance alarms
- Ground fault may be left on system for an extended time

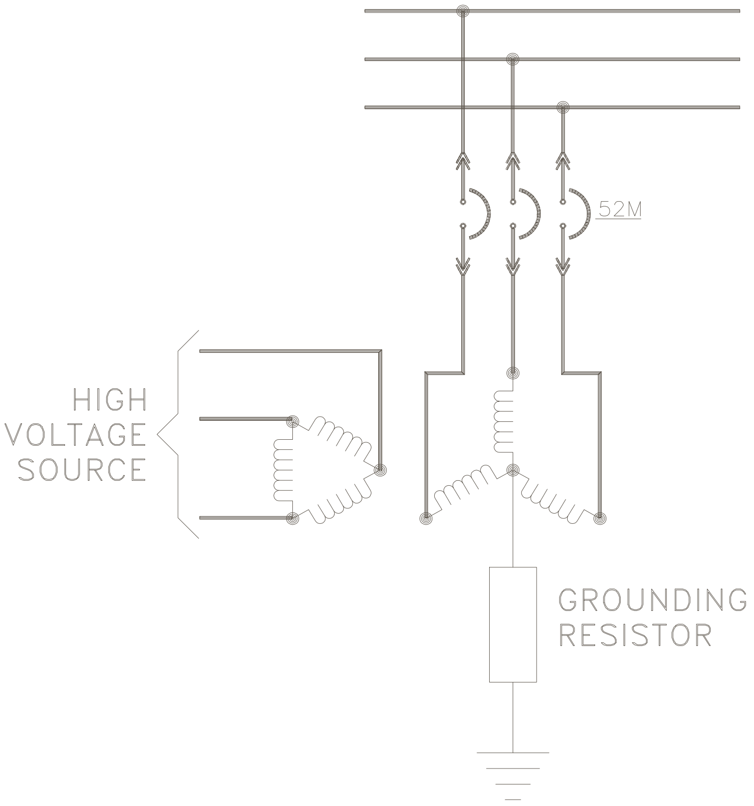
VFD and HRG

- Harmonics travel the coupling capacitance system
  - Band pass filters around the fault sensing unit
  - Size resister for total watts
- DC Faults are a problem that the new generation of drives are addressing

Where Do We Ground?

- Single transformer feeding bus
- Transformer secondary Y connected

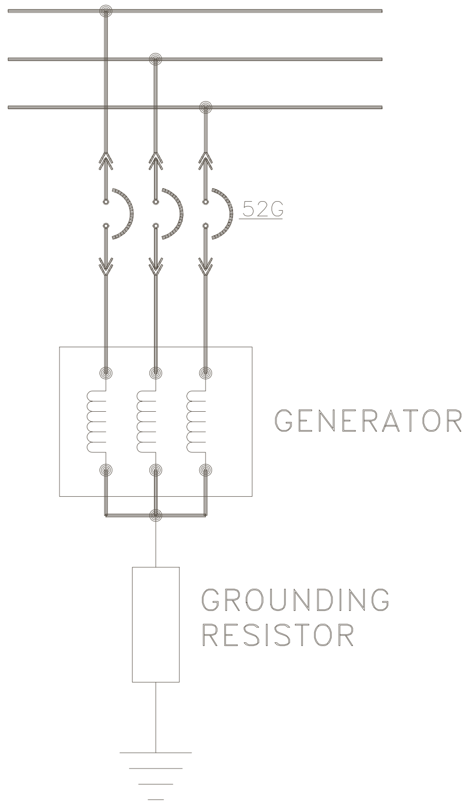
Connect grounding resistor to neutral of transformer



Where Do We Ground?

- Single generator feeding bus
- Generator Y connected

Connect grounding resistor to neutral of generator

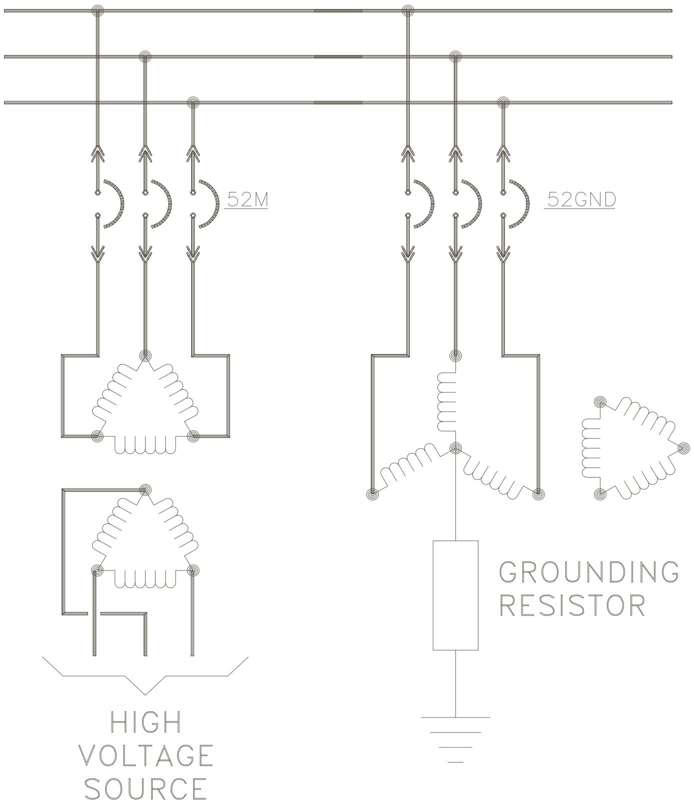


Where Do We Ground?

- Single source feeding bus
- Source Δ connected

Derive neutral with Y-Δ or zig-zag transformer

Connect grounding resistor to this derived neutral

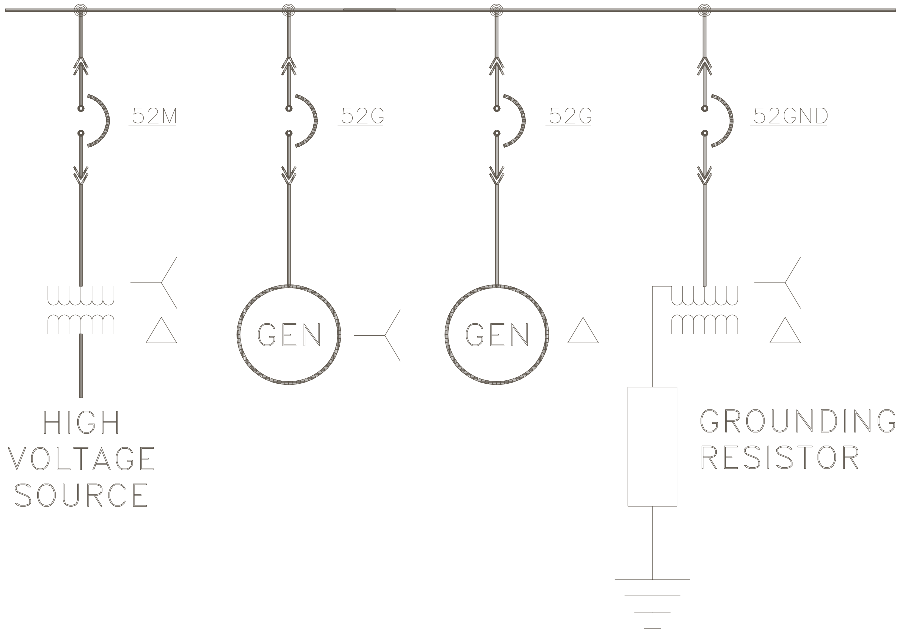


Where Do We Ground?

- Multiple sources feeding bus
- Sources Y or Δ connected

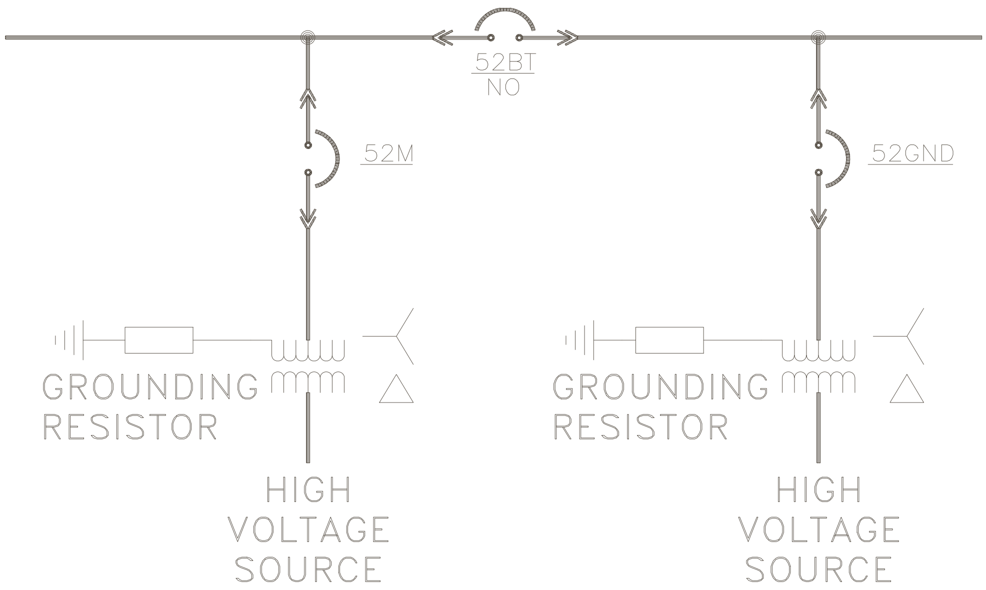
Derive neutral with Y Δ or zig-zag transformer

Connect grounding resistor to this derived neutral



Where Do We Ground?

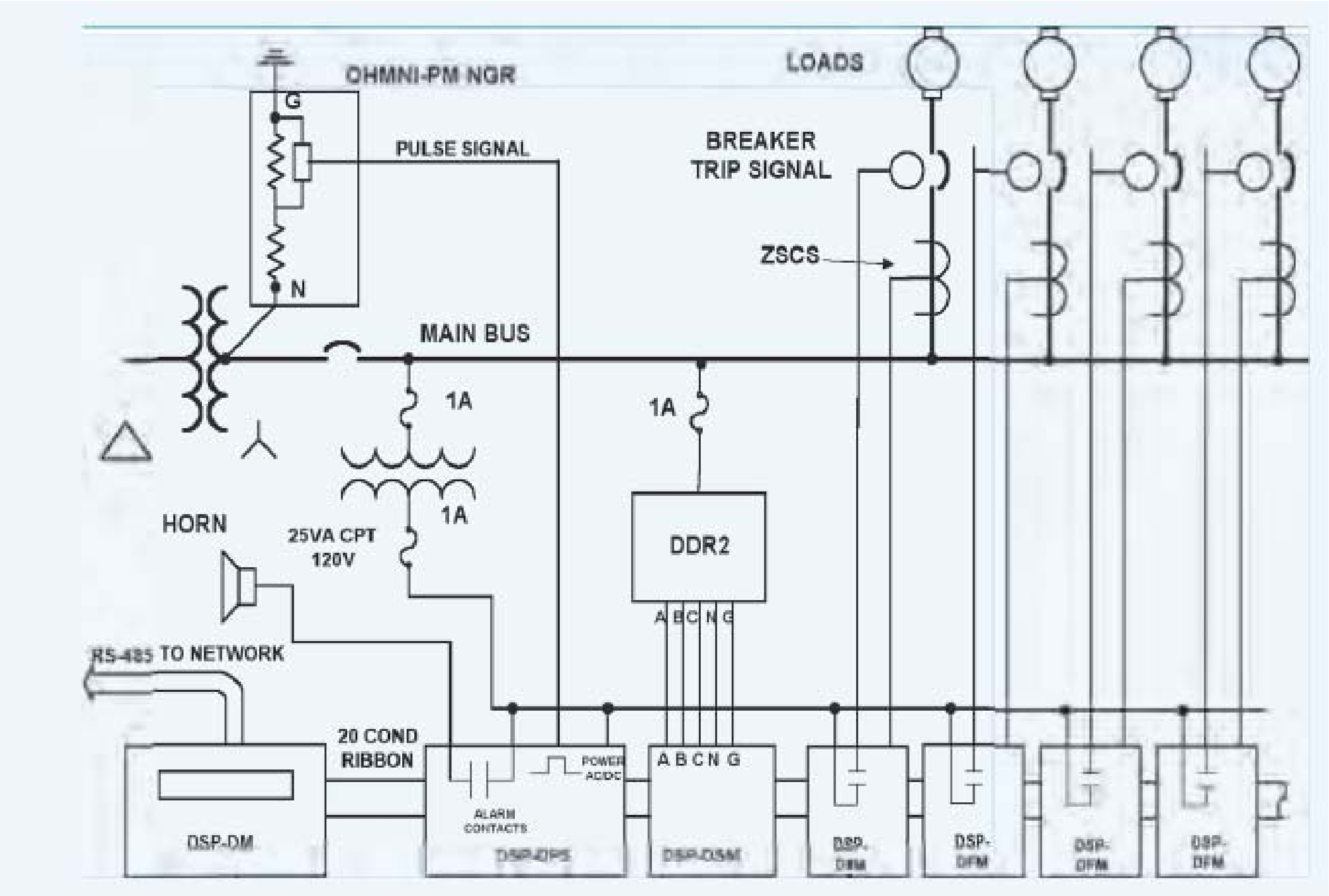
- Double-ended substation with normally open tie
- Transformers Y connected



Connect grounding resistor to each transformer neutral

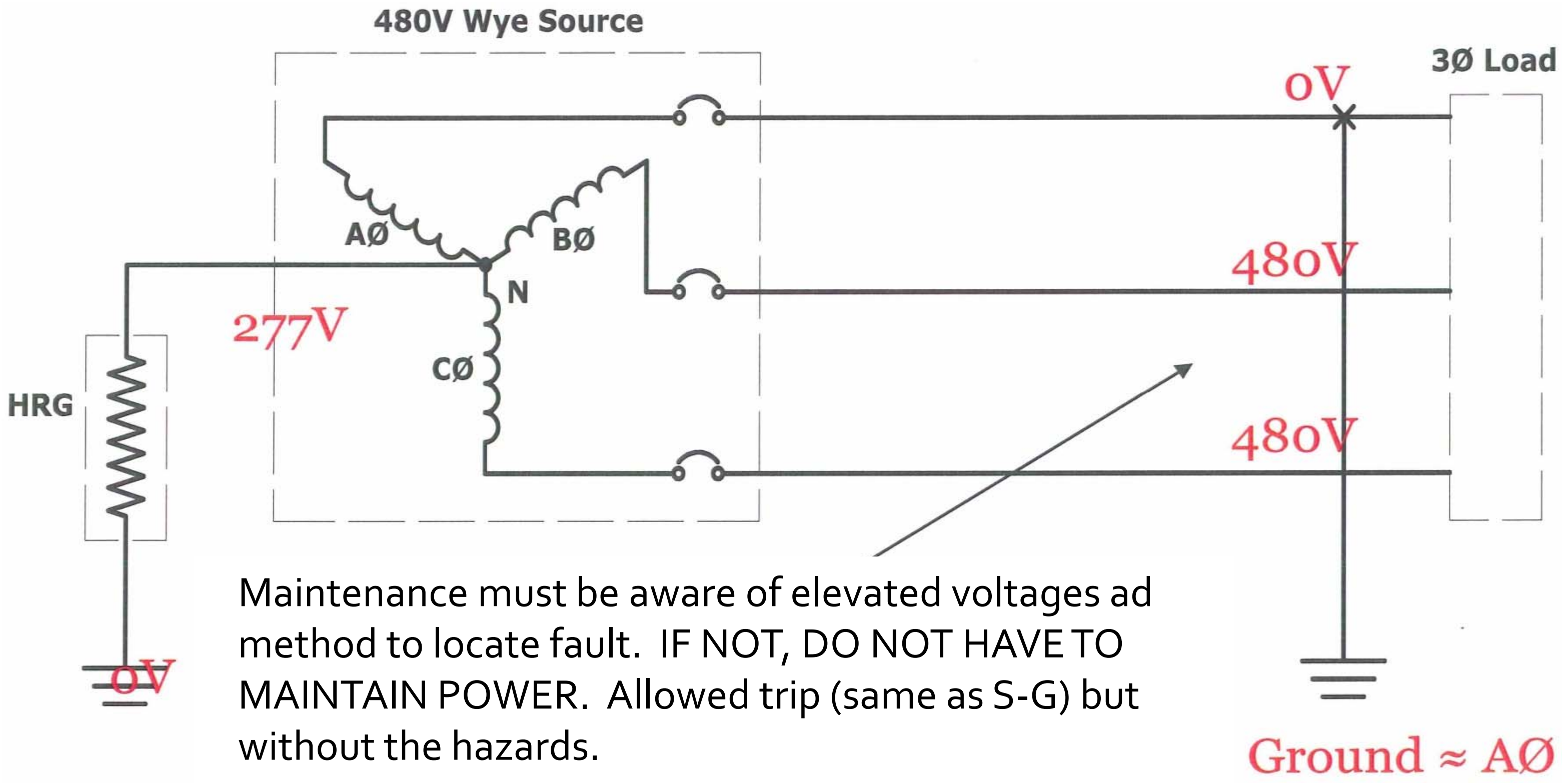
Pictures of HRG System

- Schematic of tripping HRG System



Elevated Voltage Hazard

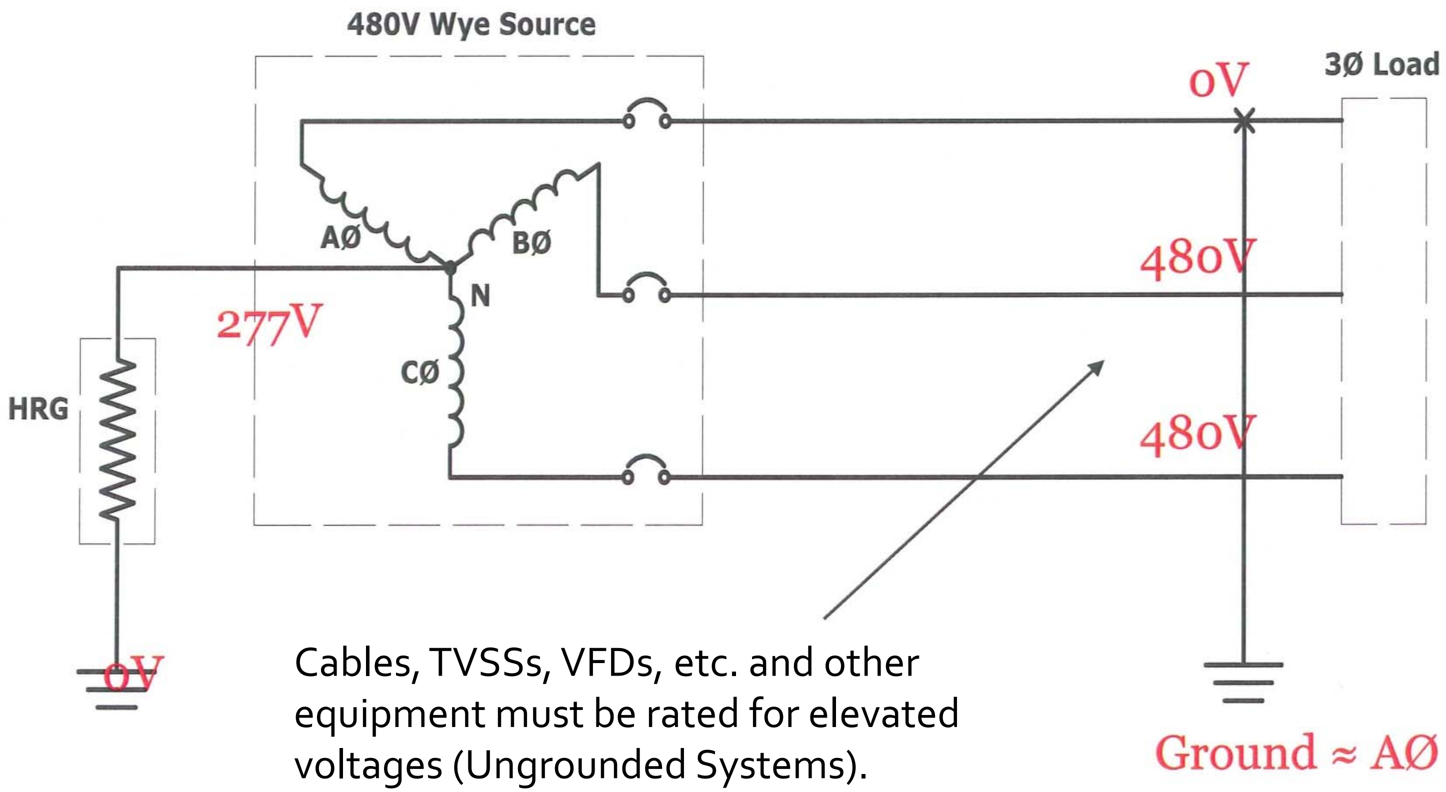
- Properly rated equipment prevents Hazards



Maintenance must be aware of elevated voltages ad method to locate fault. IF NOT, DO NOT HAVE TO MAINTAIN POWER. Allowed trip (same as S-G) but without the hazards.

Elevated Voltage Hazard

- Properly rated equipment prevents Hazards



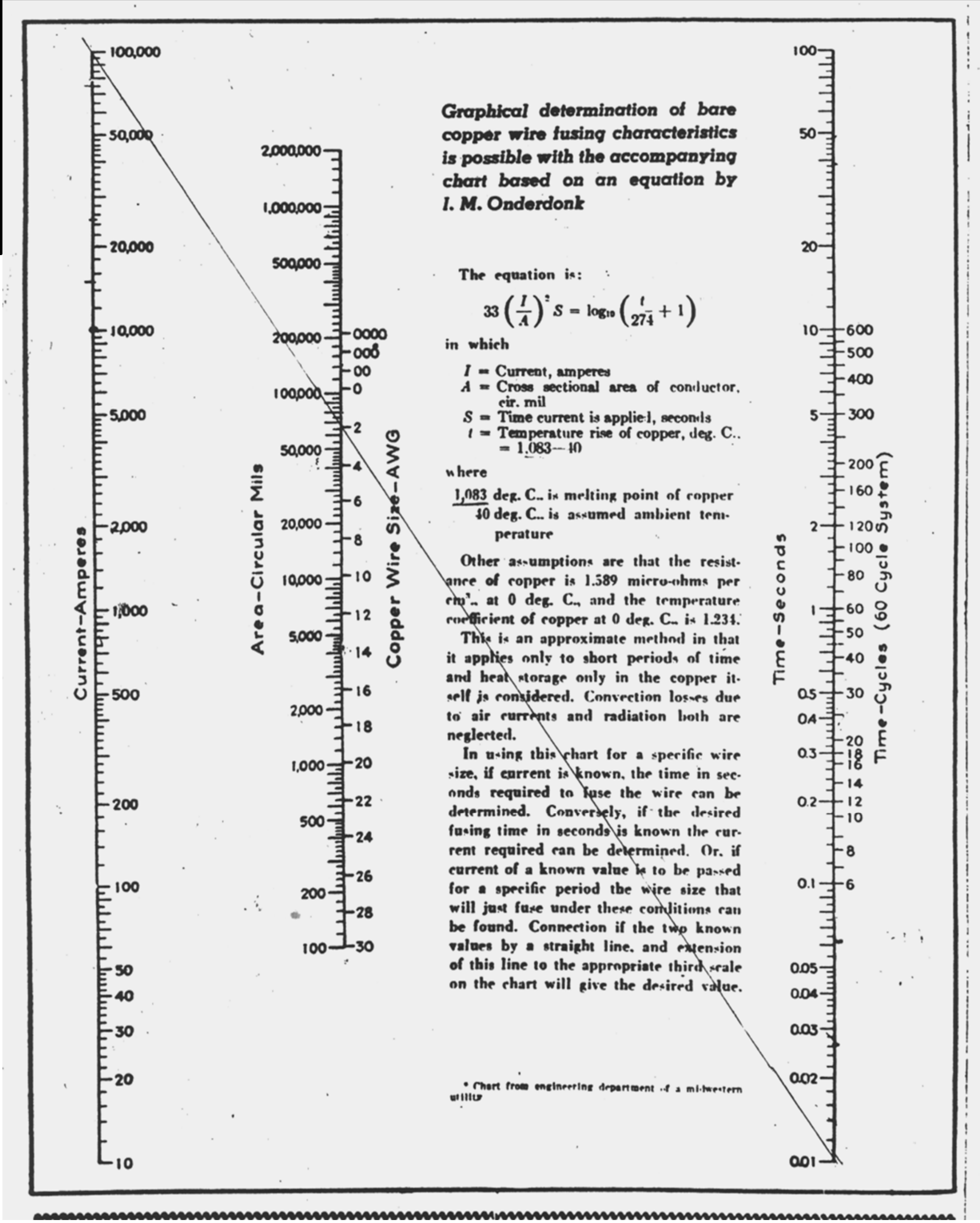
Cables, TVSSs, VFDs, etc. and other equipment must be rated for elevated voltages (Ungrounded Systems).

Retrofitting High Resistance Grounding

	LV	MV
Solidly Grounded	•Insert resistor in Xo •Use isolation transformers to support line to neutral loads	•Insert transformer and resistor at Xo •Install zero sequence ct's and meters •Surge arrestors •Cable voltage rating •Grounded Neutral Cap Bank
Un-Grounded	•Derive neutral	•Derive neutral •Install zero sequence meters

Why HRG

Time to melt copper at 10 amps



Graphical determination of bare copper wire fusing characteristics is possible with the accompanying chart based on an equation by I. M. Onderdonk

The equation is:

$$33\left(\frac{I}{A}\right)^2 S = \log_{10}\left(\frac{t}{274}+1\right)$$

in which

I = Current, amperes
A = Cross sectional area of conductor, cir. mil
S = Time current is applied, seconds
t = Temperature rise of copper, deg. C., = 1,083—40

where

1,083 deg. C., is melting point of copper
40 deg. C., is assumed ambient temperature

Other assumptions are that the resistance of copper is 1.589 micro-ohms per cm³., at 0 deg. C., and the temperature coefficient of copper at 0 deg. C., is 1.234.

This is an approximate method in that it applies only to short periods of time and heat storage only in the copper itself is considered. Convection losses due to air currents and radiation both are neglected.

In using this chart for a specific wire size, if current is known, the time in seconds required to fuse the wire can be determined. Conversely, if the desired fusing time in seconds is known the current required can be determined. Or, if current of a known value is to be passed for a specific period the wire size that will just fuse under these conditions can be found. Connection if the two known values by a straight line, and extension of this line to the appropriate third scale on the chart will give the desired value.

---

* Chart from engineering department of a mid-western utility

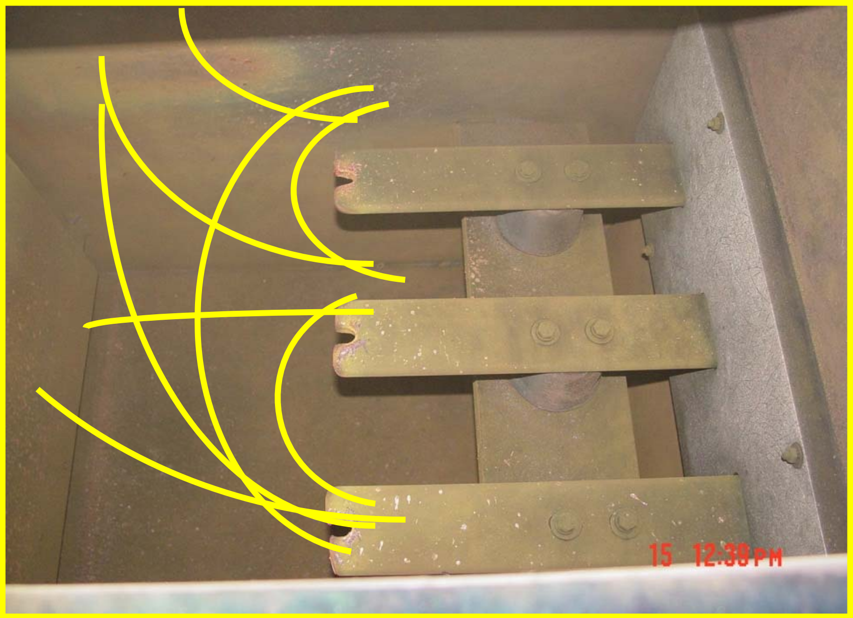
Arc Propagated

- 8kV line-line with bare conductors and varying ground fault currents
- Varied grounding resistor
- Ground fault initiator should be thought of like a fuse (large enough “fuse” never blows)

Evidence of Multiple Arcs

- Multiple arc paths
- Arc can move from columnar arc to diffuse arc and back
- Arcs will wink out when they can not be sustained
- Always high Ground current involved

Bar conductors and the available arc paths

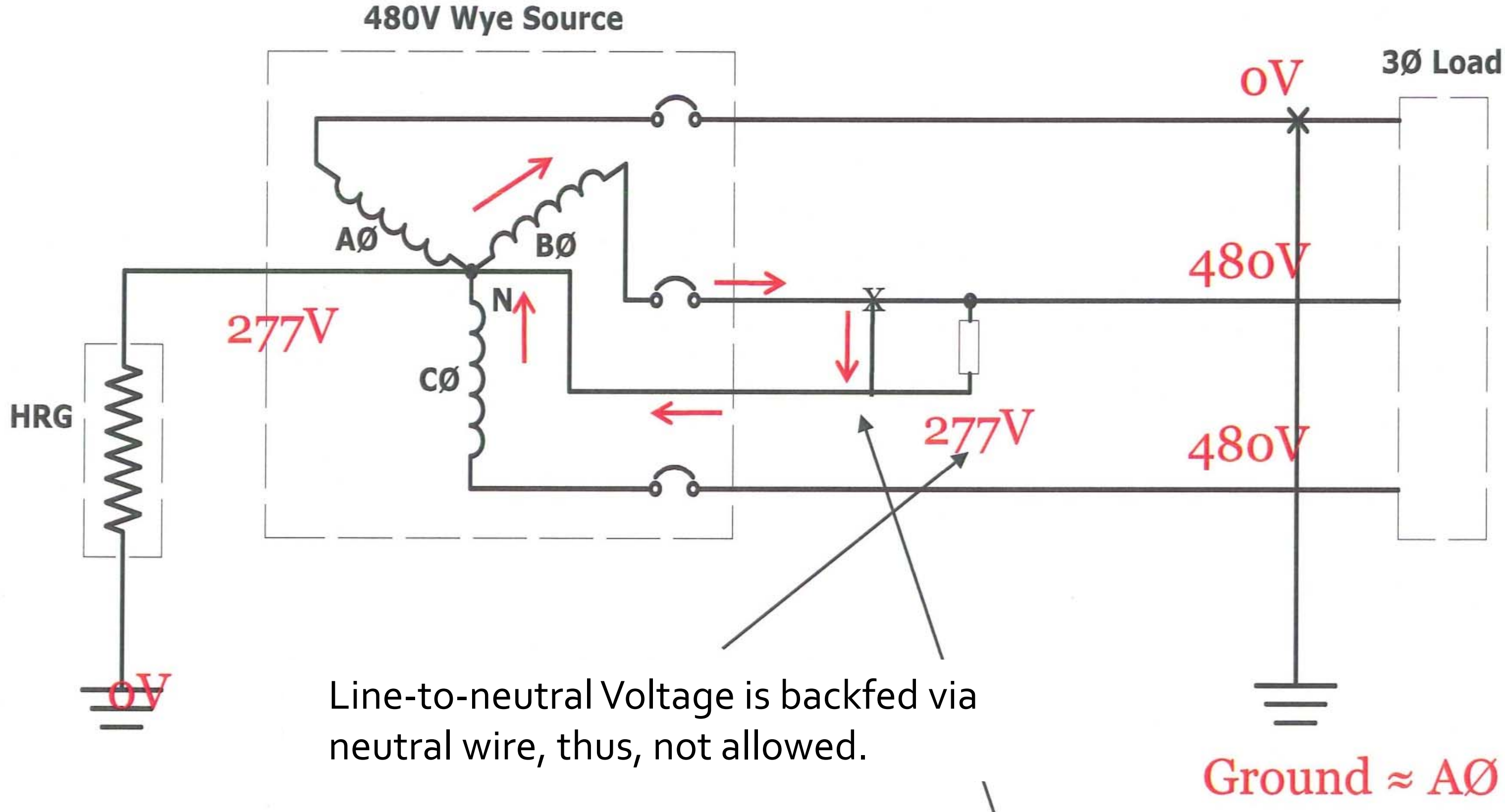


Test Results

Test #	Ground current (A)	Fault self clearing	Propagated to a phase fault	Duration of ground current (msec)	Fuse wire (mm)
12	225	No	Yes	3	.5
13	153	No	No	80	.5
14	153	No	No	80	.5
15	119	No	Yes	93	.3
16	182	No	Yes	5	.5
17	110	No	Yes	6.4	.3
18	105	No	Yes	5.9	.5
19	33	No	Yes	4.7	.5
20	10.4	No	Yes	4.4	.5

No Single Phase Loads

- No line-to-neutral loads allowed, prevents Hazards.

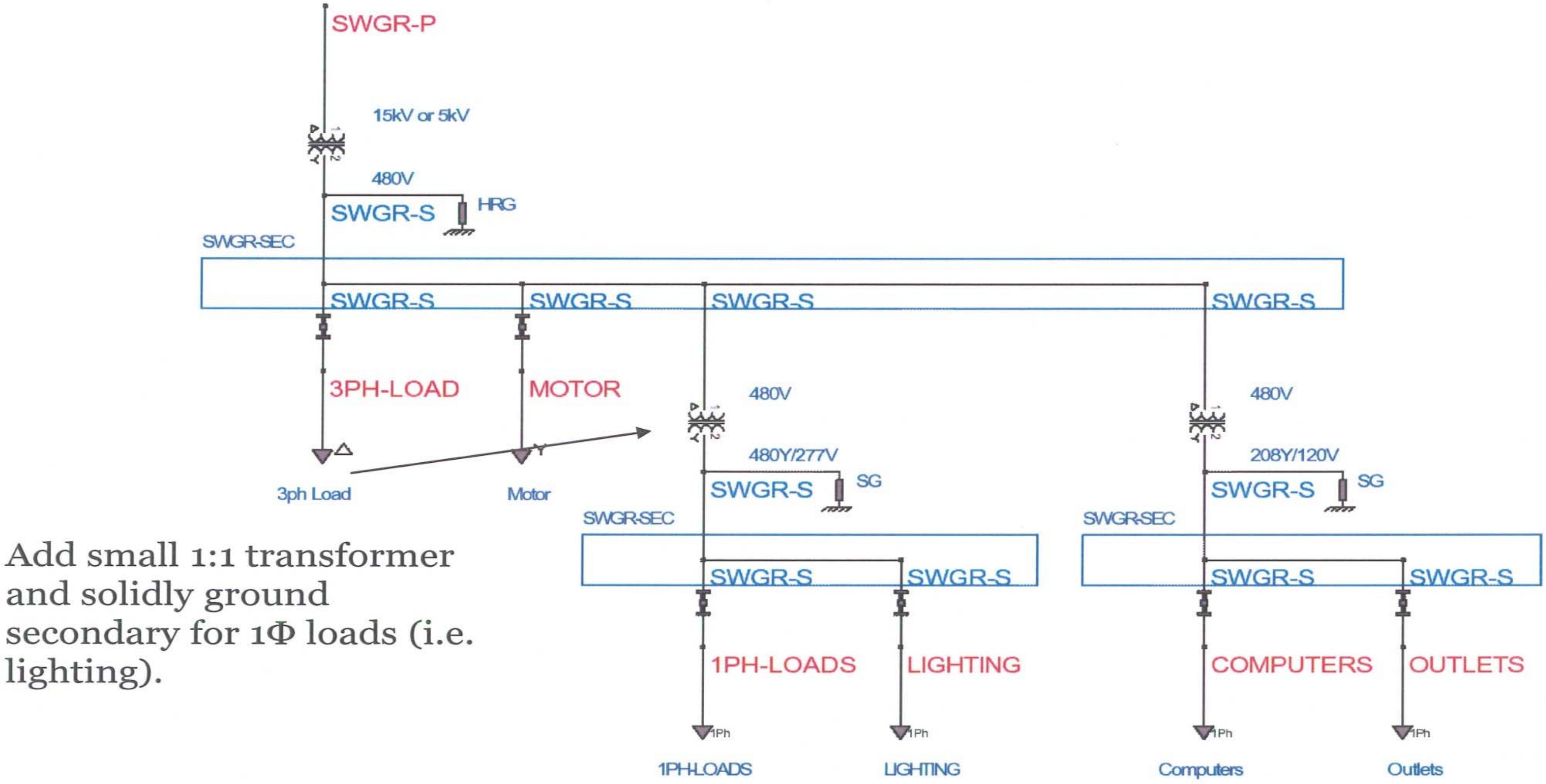


Line-to-neutral Voltage is backfed via neutral wire, thus, not allowed.

Phase and Neutral wires in same conduit. If faulted, bypass HRG, thus, Φ-G fault.

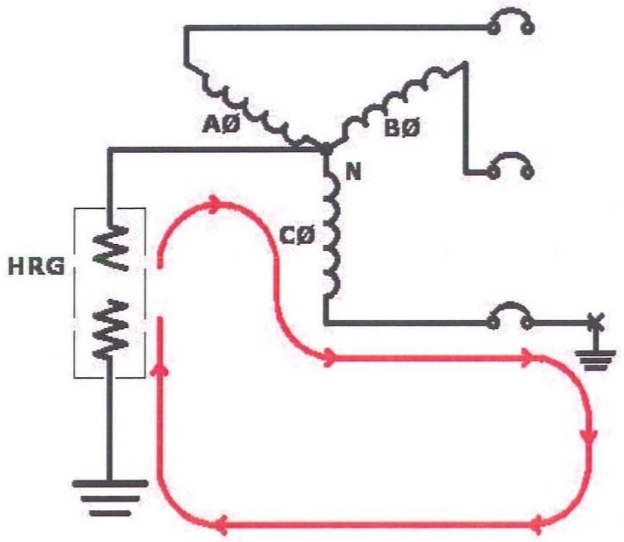
Resolve NEC requirement

- Add small 1:1 transformer and solidly ground secondary for 1Φloads (i.e. lighting).



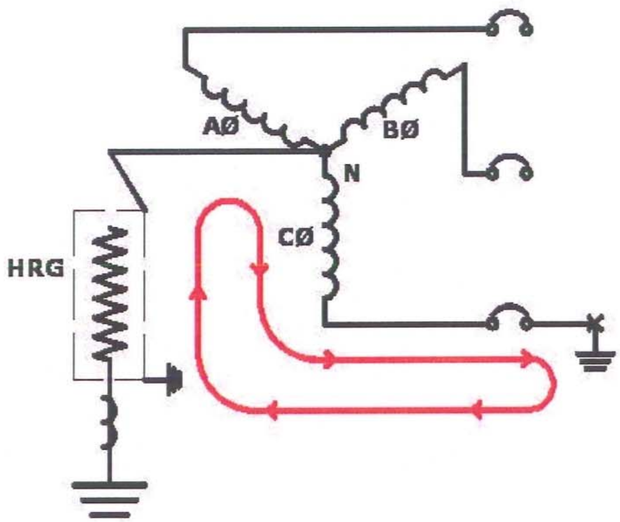
Add small 1:1 transformer and solidly ground secondary for 1Φ loads (i.e. lighting).

Loss of Ground Hazard



Open Circuit:

- Desired fault current cannot flow.
- Ungrounded System.

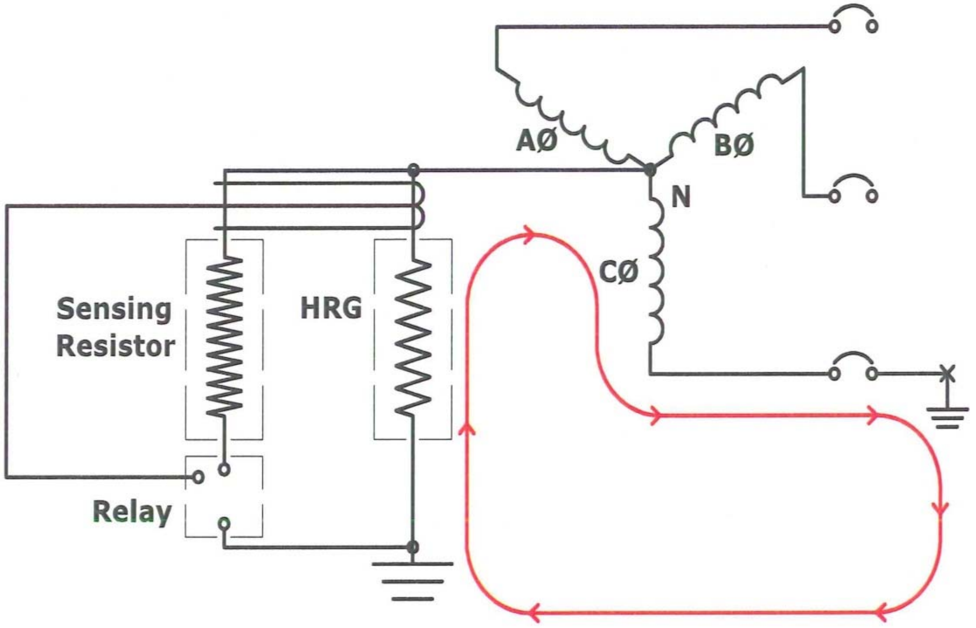


Short Circuit:

- Undesired fault current can flow.
- Solidly Grounded System.

Resolving Hazard

- Undercurrent and undervoltage relay
  - Relies on inherent system imbalances
  - Detects Open/Short Circuits
- Ground Fault Relay & Sensing Resistor
  - Detects Open / Short Circuits



Relaying for High Resistance Ground

- For voltages up through 4,160V, ground faults are usually not cleared immediately
- For medium voltage, zero sequence CT and meter are provided for each feeder

Why Convert

- Trips Vs alarm - impact on Operations
- Limit damage due to faults
- Reduced Arc Flash zones
- Control of Voltage transients

Ground Faults

Damage to Power System Components:

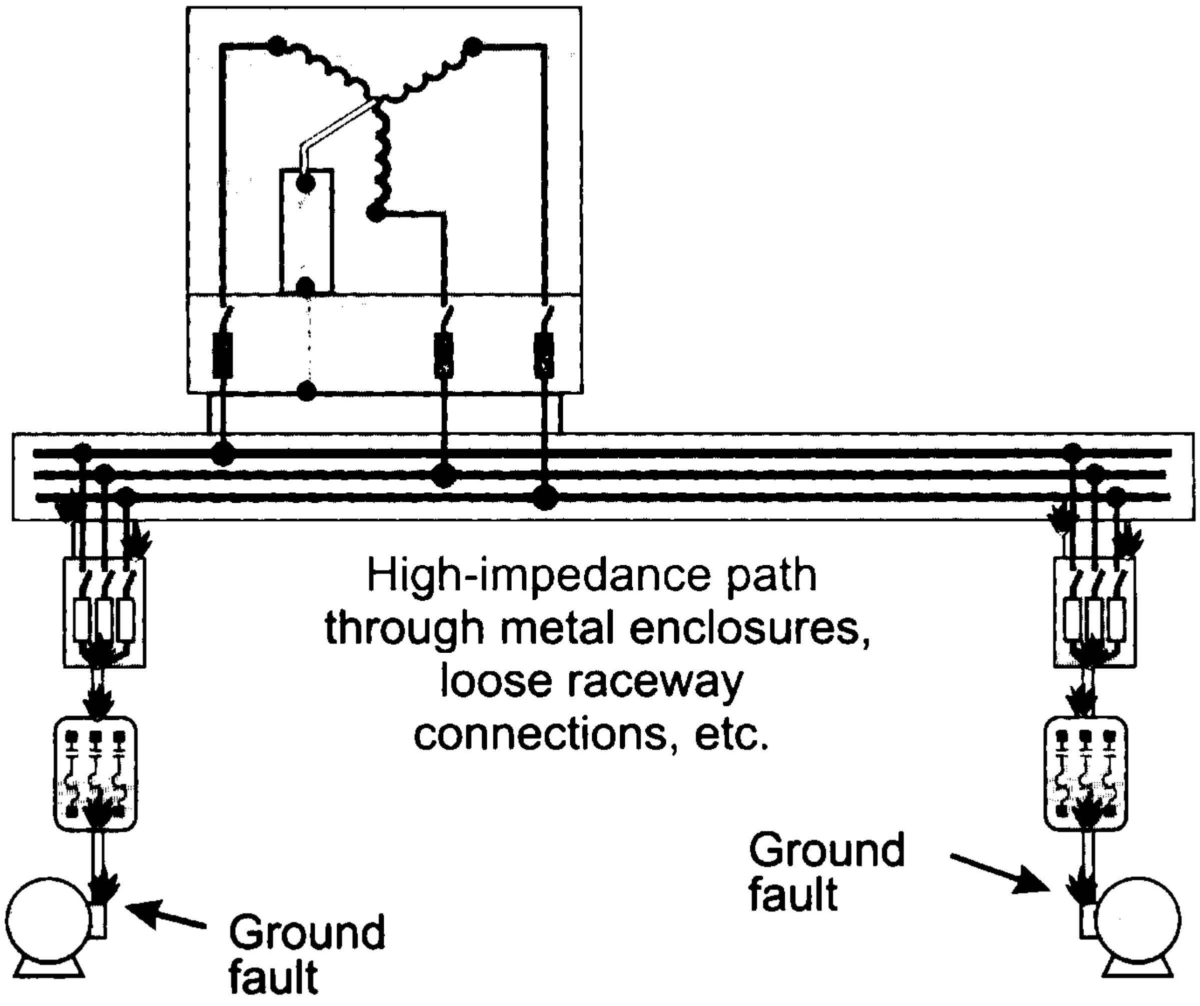
- Thermal Damage $(I_{rms})^2 * t$
- Mechanical Damage $(I_p)^2$

Comparison between S-G example and HRG

System Grounding	Ground Fault (A)	Damage to Equipment (1 sec)
HRG	5	1 per unit
S-G	22,800	$(22{,}800 / 5)^2 = 20.8\text{x}10^6$ p.u.

Solidly-Grounded Systems have 20.8 million times more damage than HRG!!!

Second Ground Fault on High-Impedance Grounded System



High-impedance path through metal enclosures, loose raceway connections, etc.

Per IEEE…

IEEE Std 142-1991 (Green Book)
Recommended Practice for Grounding of Industrial and Commercial Power Systems

1.4.3 The reasons for limiting the current by resistance grounding may be one or more of the following:

- To reduce burning and melting effects in faulted electric equipment, such as switchgear, transformers, cables, and rotating machines.
- To reduce mechanical stresses in circuits and apparatus carrying fault currents.
- To reduce electric-shock hazards to personnel caused by stray ground-fault currents in the ground return path.
- To reduce the arc blast or flash hazard to personnel who may have accidentally caused or who happen to be in close proximity to the ground fault.

Per IEEE…

TO HRG OR NOT TO HRG?

IEEE Std 141-1993 (Red Book)
Recommended Practice for Electric Power Distribution for Industrial Plants

7.2.2 There is no arc flash hazard, as there is with solidly grounded systems, since the fault current is limited to approximately 5A.

Another benefit of high-resistance grounded systems is the limitation of ground fault current to prevent damage to equipment. High values of ground faults on solidly grounded systems can destroy the magnetic core of rotating machinery.

Bare Main vs. Insulated Main

Bare main bus 85kA 3 phase .5 sec

Insulated main bus 85kA 3 phase .5 sec

Solidly Grd vs. High Resitance Grd

Solid grounded 3 phase 80kA .5 sec

High Resistance Grounded 3 phase 80kA .5 sec

Objective

- Minimize the damage for internal ground faults
- Limit mechanical stress in the generator from external ground faults
- Provide a means of system ground fault detection
- Coordinate with other system/equipment requirements

Generator Grounding – IEEE

IEEE Std. 142-1991 (Green Book)
1.8.1 Discussion of Generator Characteristics

Unlike the transformer, the three sequence reactances of a generator are not equal. The zero-sequence reactance has the lowest value, and the positive sequence reactance varies as a function of time. Thus, a generator will usually have higher initial ground-fault current than a three-phase fault current if the generator is solidly grounded. According to NEMA, the generator is required to withstand only the three-phase current level unless it is otherwise specified…

A generator can develop a significant third-harmonic voltage when loaded. A solidly grounded neutral and lack of external impedance to third harmonic current will allow flow of this third-harmonic current, whose value may approach rated current. If the winding is designed with a two-thirds pitch, this third-harmonic voltage will be suppressed but zero-sequence impedance will be lowered, increasing the ground-fault current…

Internal ground faults in solidly grounded generators can produce large fault currents. These currents can damage the laminated core, adding significantly to the time and cost of repair…Both magnitude and duration of these currents should be limited whenever possible.

Single Generator

NEMA Std MG 1-2003 Motors & Generators
32.34 Neutral Grounding

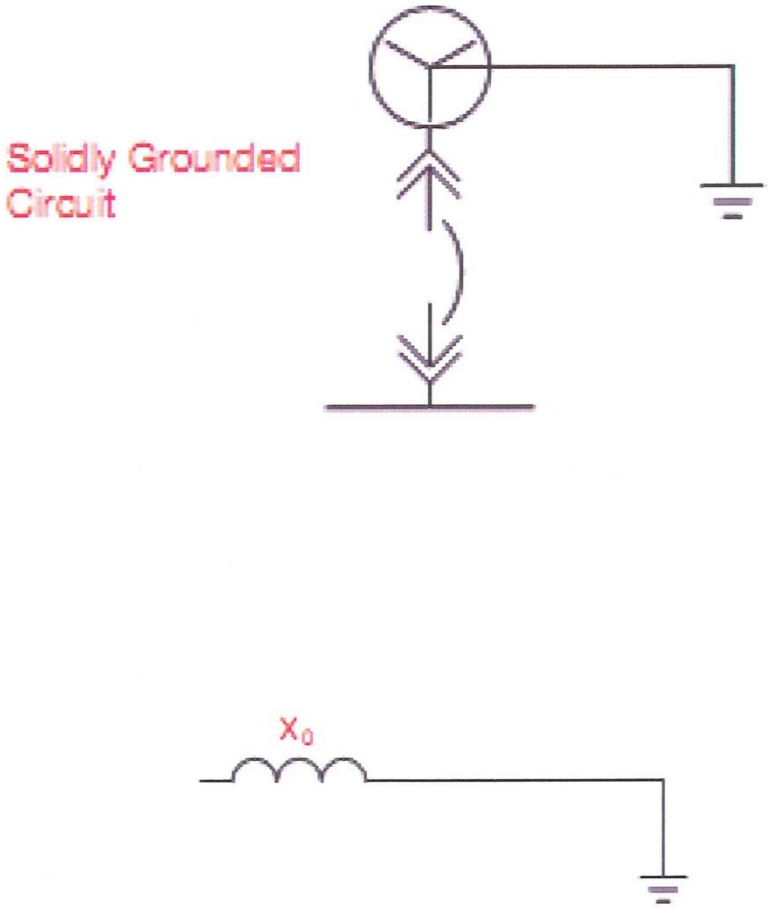
- For safety of personnel and to reduce over-voltages to ground, the generator neutral is often either grounded solidly or grounded through a resistor or reactor.
- The neutral may be grounded through a resistor or reactor with no special considerations required in the generator design or selection unless the generator is to be operated in parallel with other power supplies.
- The neutral of a generator should not be solidly grounded unless the generator has been specifically designed for such operation

IEEE Std 242-2001 (Buff Book)
12.4 Generator Grounding

- Generators are not often operated ungrounded. While this approach greatly limits damage to the machine, it can produce high transient overvoltages during faults and also makes it difficult to locate the fault.

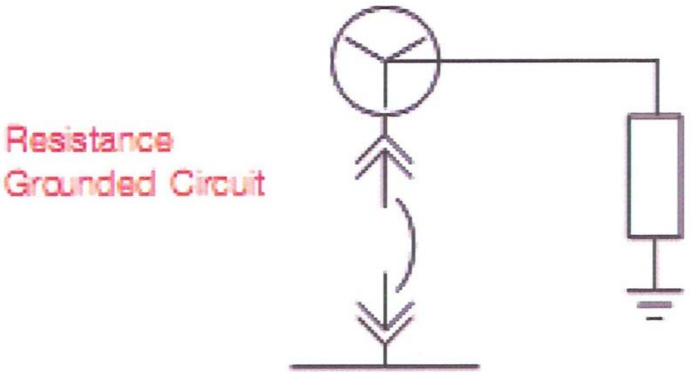
Solidly Grounded Systems

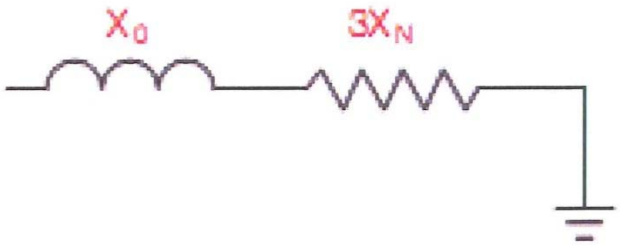
- Best suited for LV 3Ø, 4W systems
- Generator must be rated for use as solidly grounded
- System trips on first fault
- Coordinated relay scheme may be difficult



Resistance Grounding

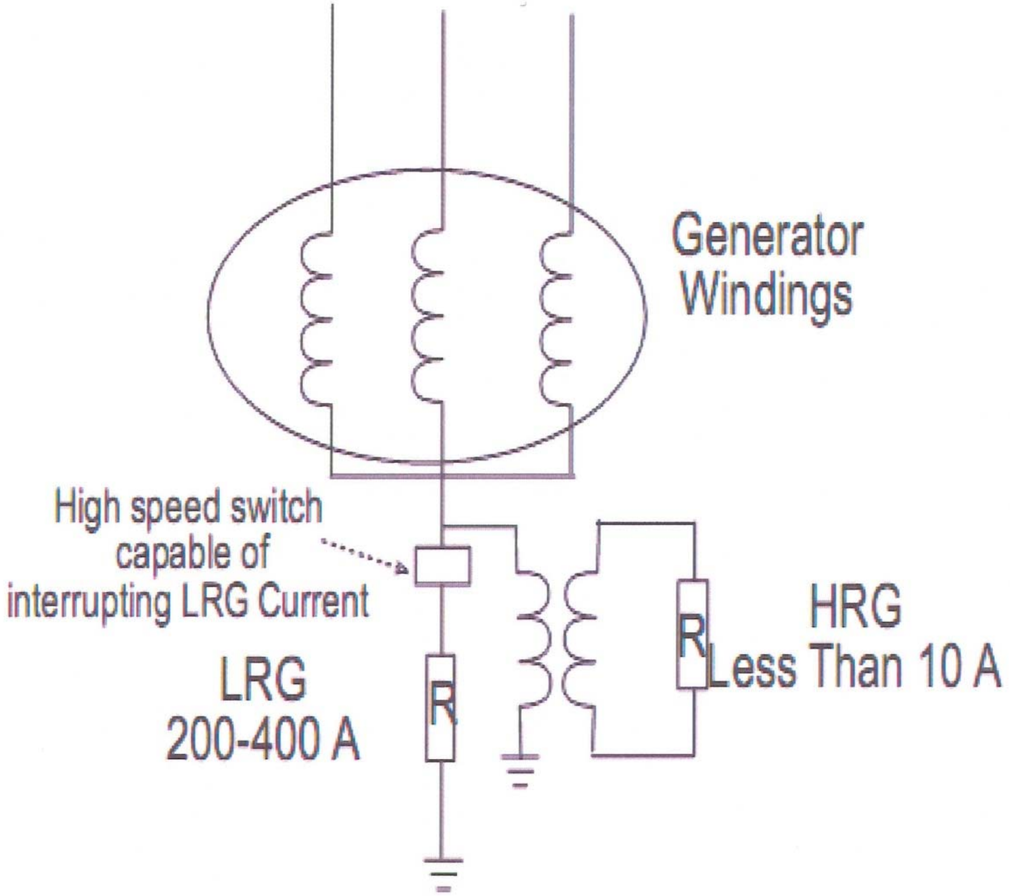
- Best suited for 3Ø, 3W systems
- Capacitive charging current important
- Higher resistance limits damage on internal fault





Hybrid Grounding

- Low resistance grounding overcomes capacitive charging current
- After generator is isolated the LRG is removed, limiting fault current to 5 A



Generator System Grounding

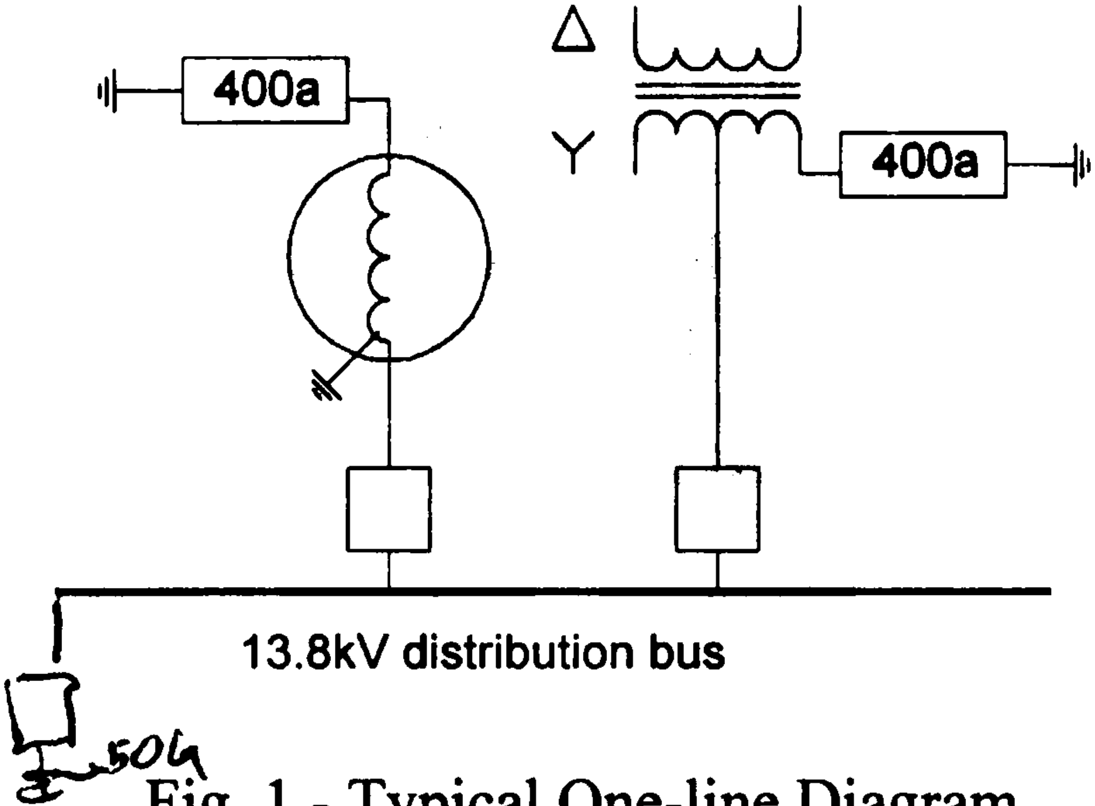


Fig. 1 - Typical One-line Diagram

Stator Damage Due to Transformer vs. Groun Resistance

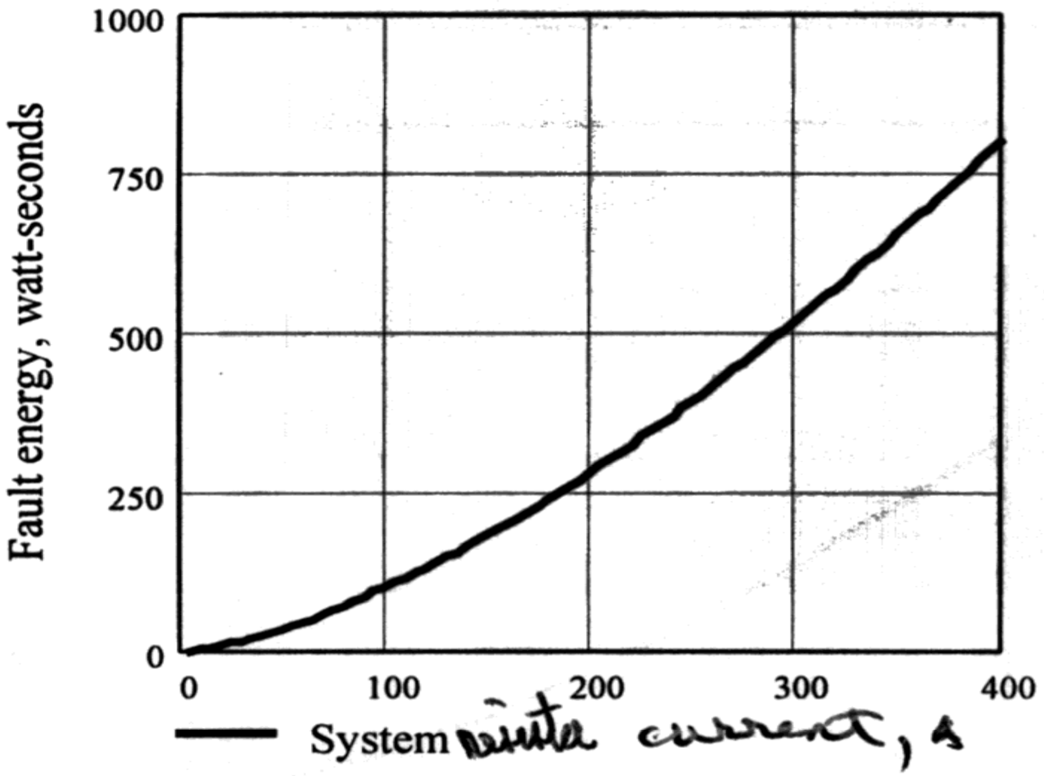


Fig 2a. Energy due to “system current” – for various magnitudes of current

Accumulated Damage due to Transformer

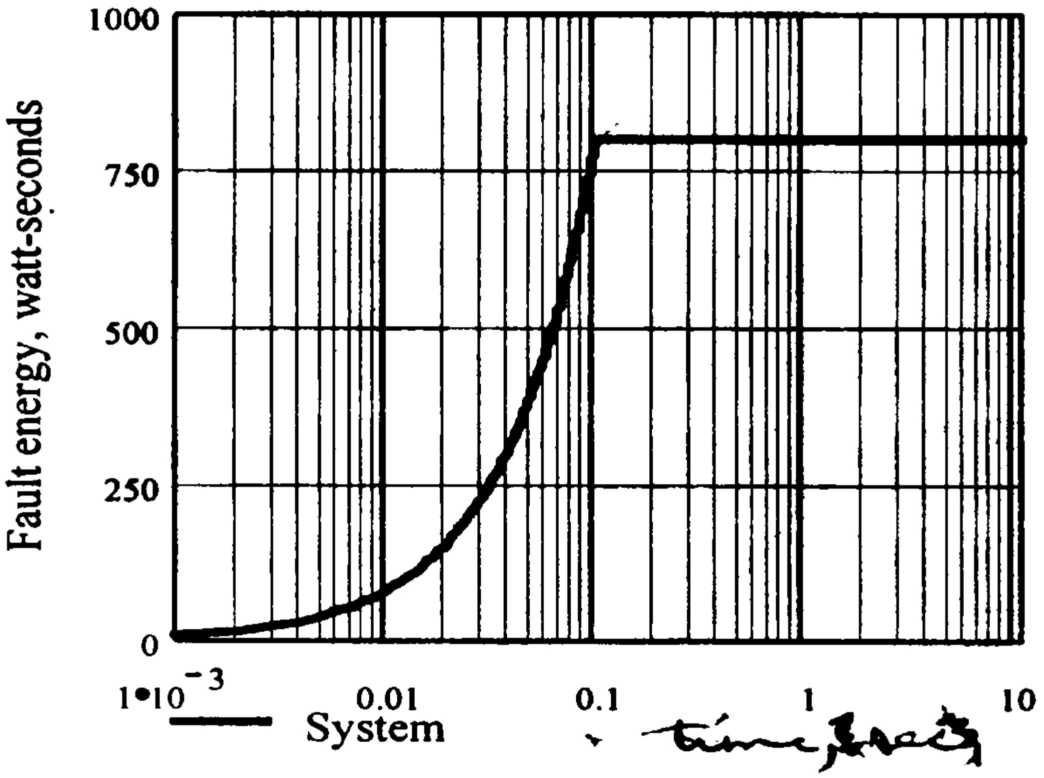


Fig 2b. Arc energy due to 400a. “system current” over time

Stator Damage Due to Generator vs. Ground Resistance

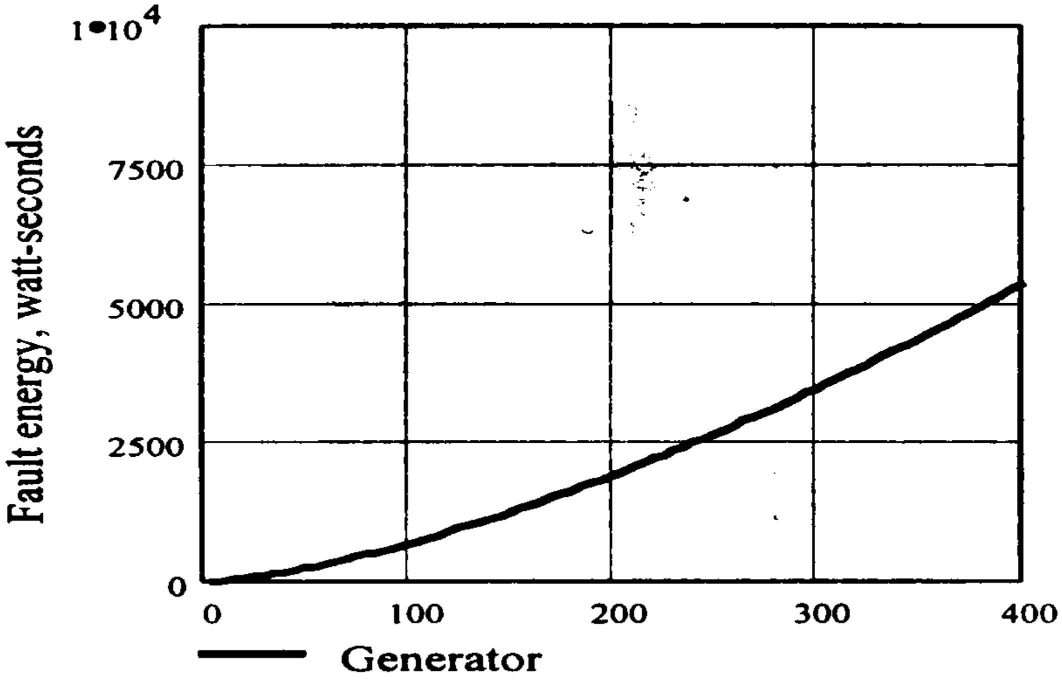


Fig 3a. Fault energy due to “machine current” – for various magnitudes of current

Accumulated Damage due to Generator at 400A

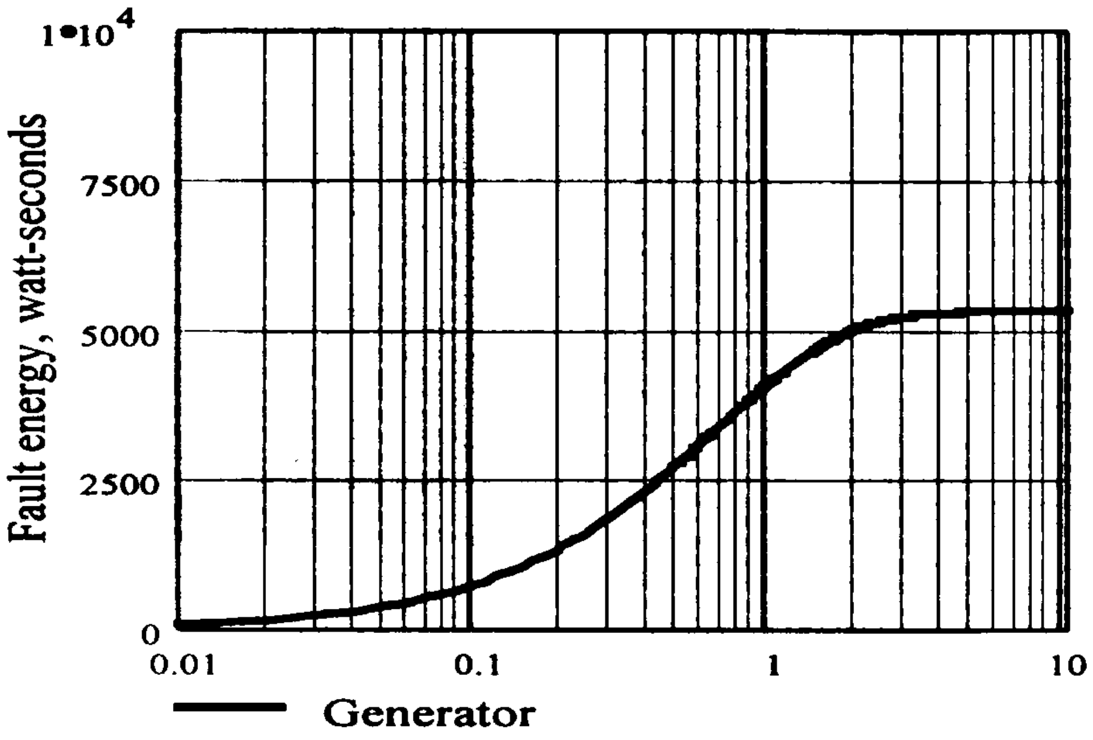


Fig 3b. Arc energy due to 400a. “machine current” over time

Accumulated Damage due to Generator at 10A

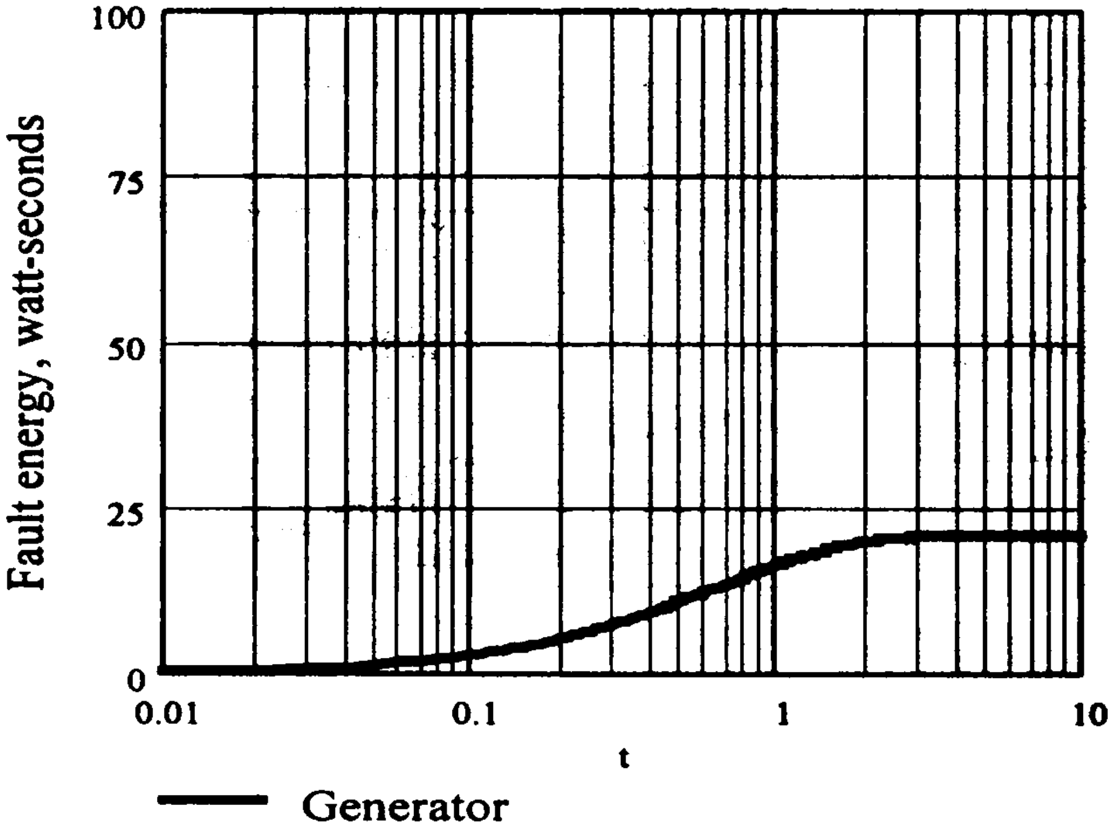
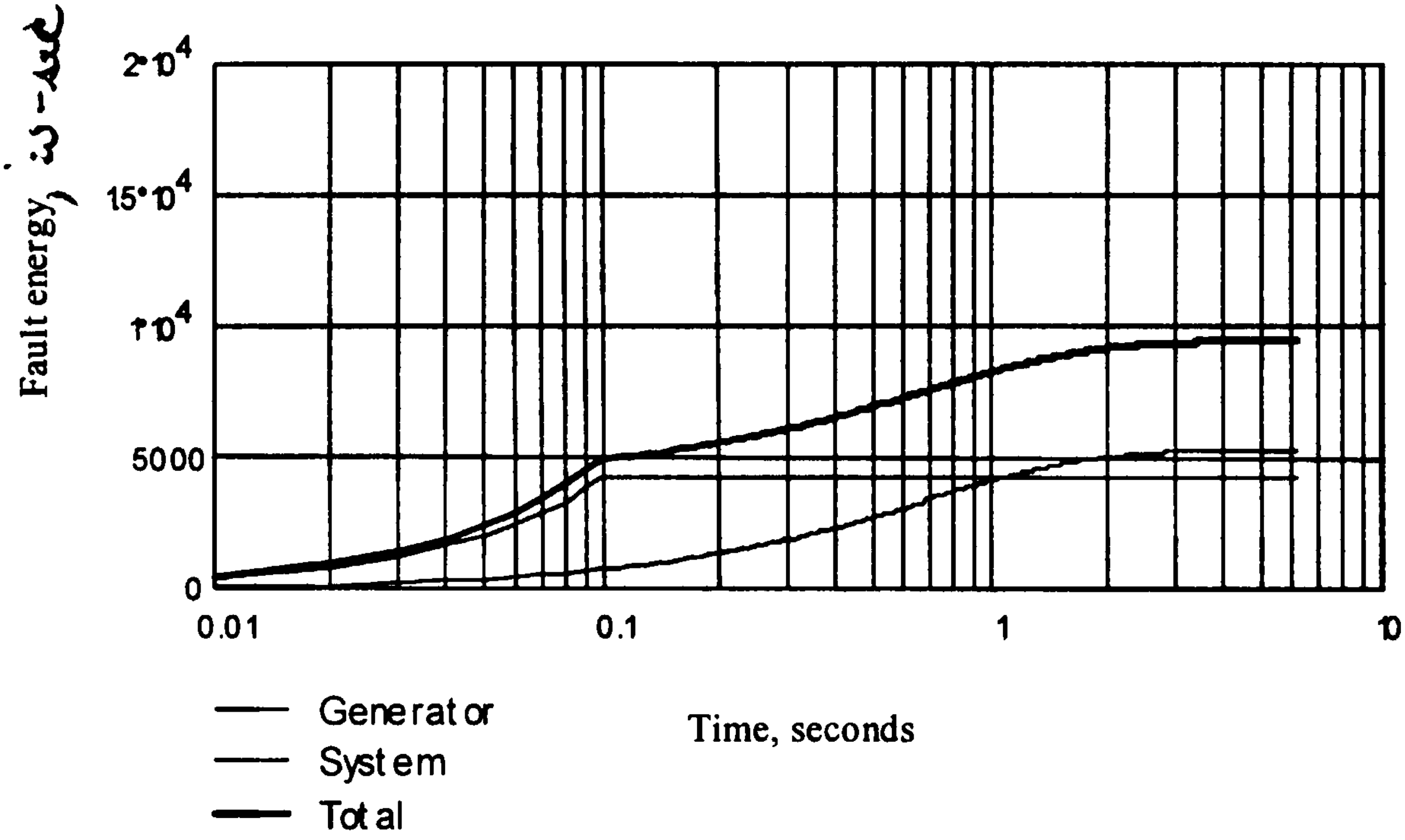


Fig 4 – Fault energy versus time with 10a. grounding

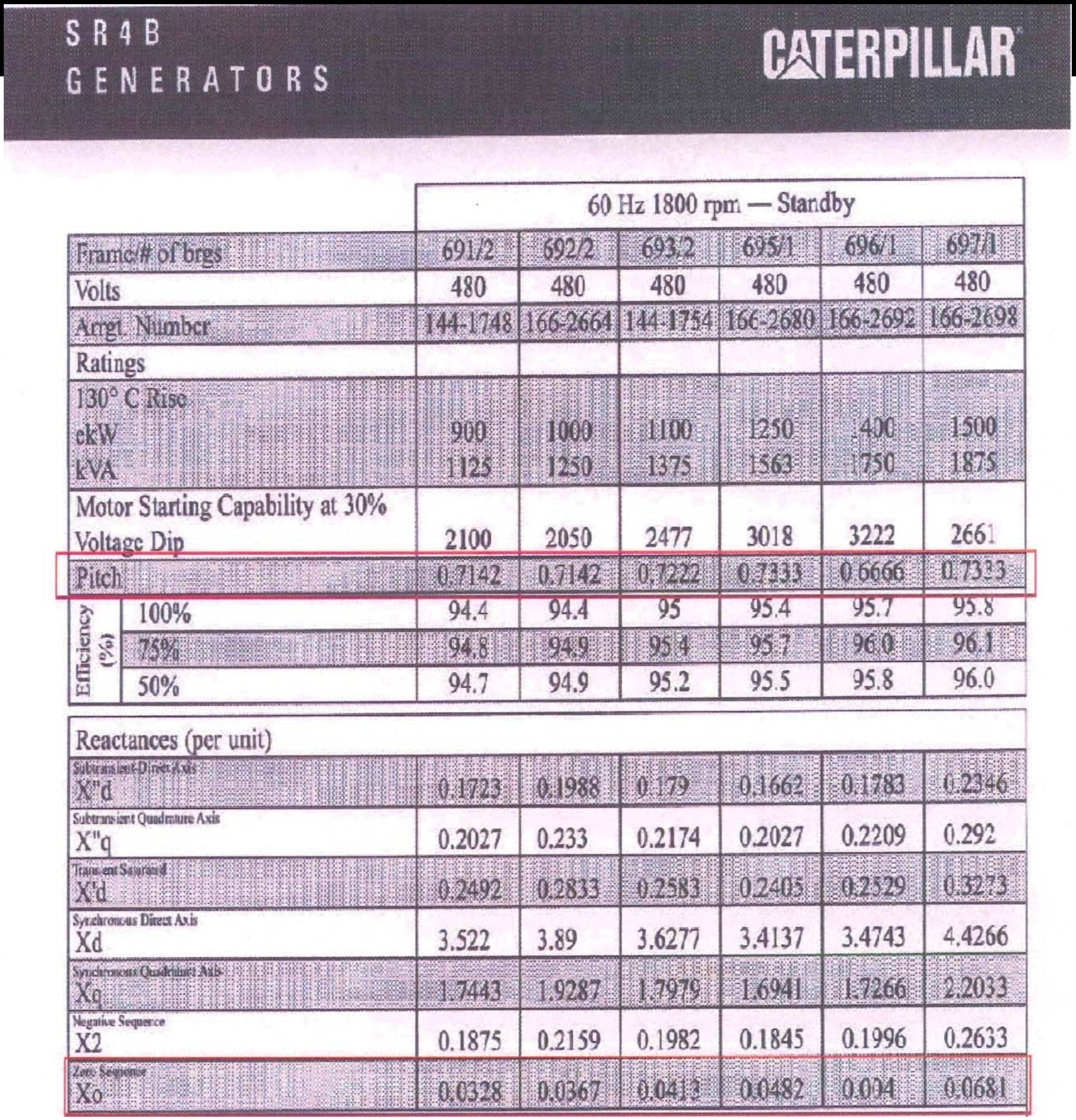
Total Fault Energy



Paralleled Generators

- Easy if all generators are same design and pitch, always operated at equal loading and are not switched with three pole transfer switch

Generator Impedance Example



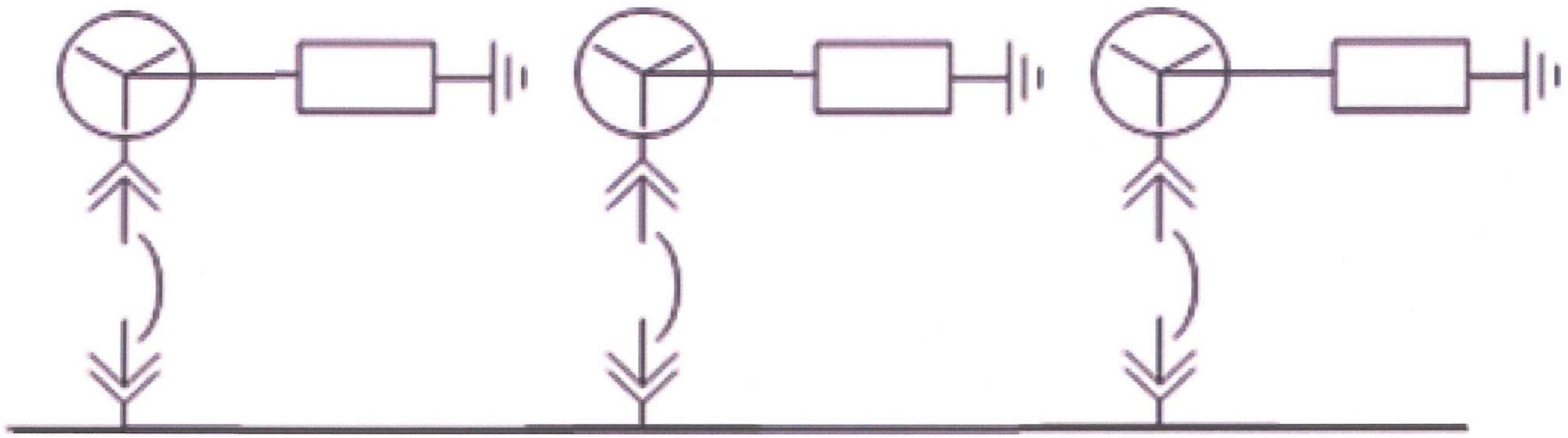
SR4B
GENERATORS

CATERPILLAR

	60 Hz 1800 rpm — Standby					
Frame/# of brgs	691/2	692/2	693/2	695/1	696/1	697/1
Volts	480	480	480	480	480	480
Arrgt. Number	144-1748	166-2664	144-1754	166-2680	166-2692	166-2698
Ratings						
130° C Rise ekW kVA	 900 1125	 1000 1250	 1100 1375	 1250 1563	 1400 1750	 1500 1875
Motor Starting Capability at 30% Voltage Dip	2100	2050	2477	3018	3222	2661
Pitch	0.7142	0.7142	0.7222	0.7333	0.6666	0.7333
Efficiency (%) 100%	94.4	94.4	95	95.4	95.7	95.8
Efficiency (%) 75%	94.8	94.9	95.4	95.7	96.0	96.1
Efficiency (%) 50%	94.7	94.9	95.2	95.5	95.8	96.0

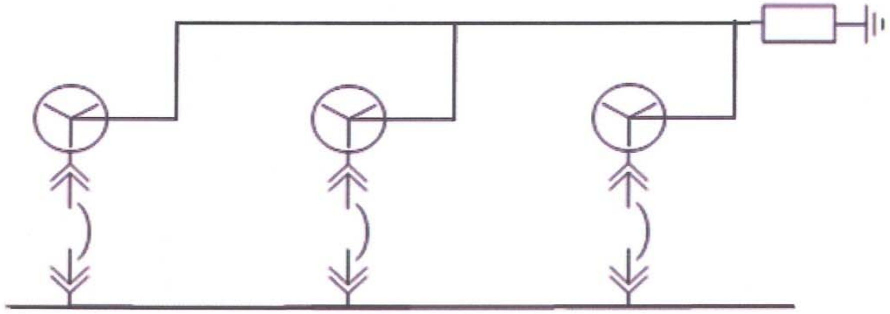
Reactances (per unit)						
Subtransient Direct Axis X"d	0.1723	0.1988	0.179	0.1662	0.1783	0.2346
Subtransient Quadrature Axis X"q	0.2027	0.233	0.2174	0.2027	0.2209	0.292
Transient Saturated X'd	0.2492	0.2833	0.2583	0.2405	0.2529	0.3273
Synchronous Direct Axis Xd	3.522	3.89	3.6277	3.4137	3.4743	4.4266
Synchronous Quadrature Axis Xq	1.7443	1.9287	1.7979	1.6941	1.7266	2.2033
Negative Sequence X2	0.1875	0.2159	0.1982	0.1845	0.1996	0.2633
Zero Sequence Xo	0.0328	0.0367	0.0413	0.0482	0.004	0.0681

Separate Grounding Resistors

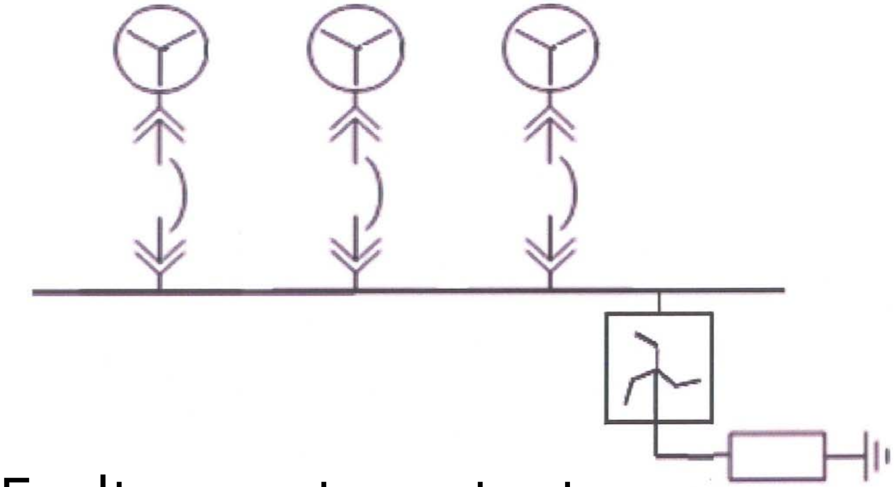


- Separately grounding prevents circulating 3rdharmonic current
- Must have means of disconnecting neutral if generator is being serviced
- Multiple NGR’s has cumulative effect on ground fault current

Common Grounding Path

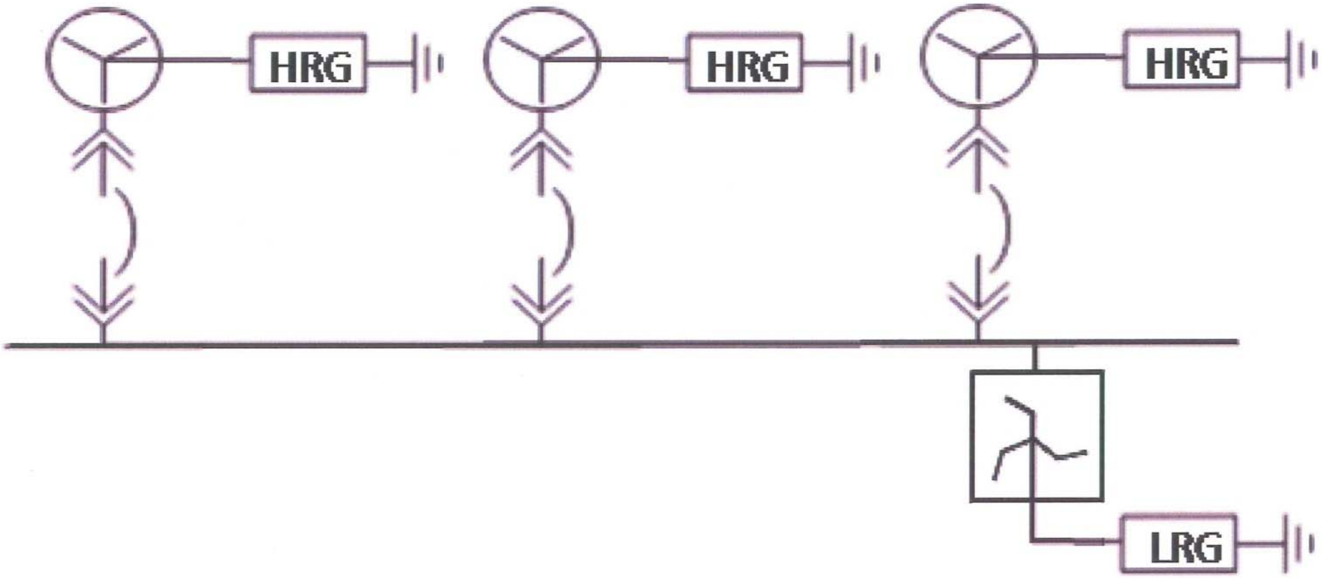


- Fault current constant
- Requires disconnect in each neutral for service
- Path for circulating 3rd harmonic currents
- Not protected against faults in stator windings



- Fault current constant
- Generators safe to service
- No path for circulating 3rd harmonic currents
- Generators ungrounded until synchronized and connected

Hybrid Grounding

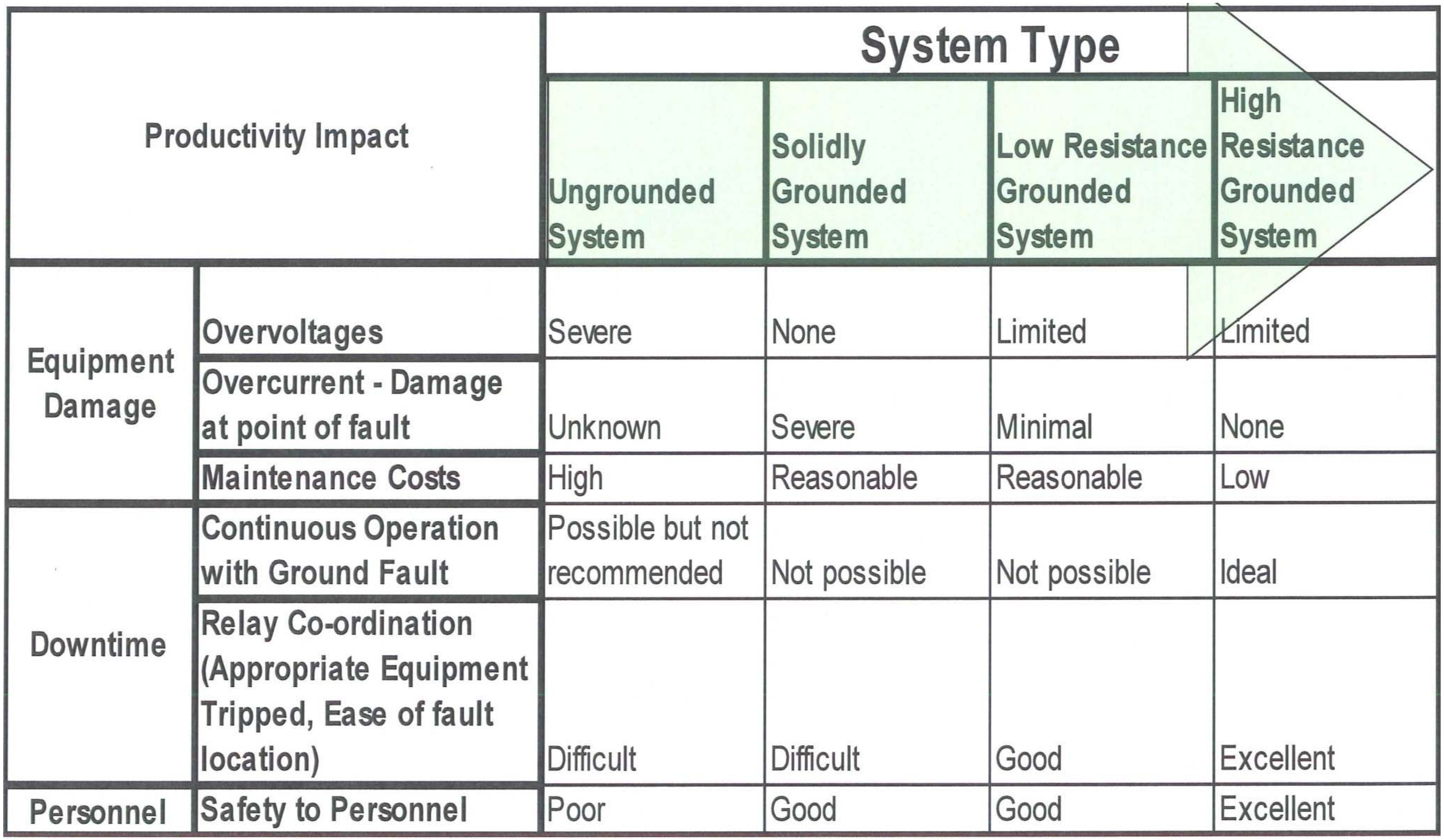


A neutral deriving transformer holds the fault current on the main bus to a consistent 400 amps. Each generator is protected by HRG.

Recommendation

- Solidly ground only at LV when generator permits, loads are non-critical and primarily single phase
- HRG at LV
- LRG combined with HRG at MV or where charging current is excessive

Benefits of Grounding



Productivity Impact		System Type			
		Ungrounded System	Solidly Grounded System	Low Resistance Grounded System	High Resistance Grounded System
Equipment Damage	Overvoltages	Severe	None	Limited	Limited
	Overcurrent - Damage at point of fault	Unknown	Severe	Minimal	None
	Maintenance Costs	High	Reasonable	Reasonable	Low
Downtime	Continuous Operation with Ground Fault	Possible but not recommended	Not possible	Not possible	Ideal
	Relay Co-ordination (Appropriate Equipment Tripped, Ease of fault location)	Difficult	Difficult	Good	Excellent
Personnel	Safety to Personnel	Poor	Good	Good	Excellent

Second Half Agenda

- Equipment Grounding
    - Ground Systems and GEC
    - Bonding
    - Component Grounding
    - Ground Fault Protection

- Substation
    - Criteria for Ground Grid Design
    - Designing Safe and Effective Ground Systems
        - ✓Soil
        - ✓System
        - ✓Conductors
        - ✓Arrangement

Equipment Grounding

Significant Domestic Codes and Standards

- **NFPA 70 –National Electrical Code**
  - General grounding provisions
  - Certain definitions

- **ANSI C2 –National Electric Safety Code**
  - General grounding provisions for electric supply stations

- IEEE 142-2007 –IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems The Green Book
  - System Grounding
  - Equipment Grounding
  - Static and Lightning Protection Grounding
  - Connection to Earth
  - Electronic Equipment Grounding

Equipment Grounding

- System Grounding –Part 1
  - Includes Grounded Conductor

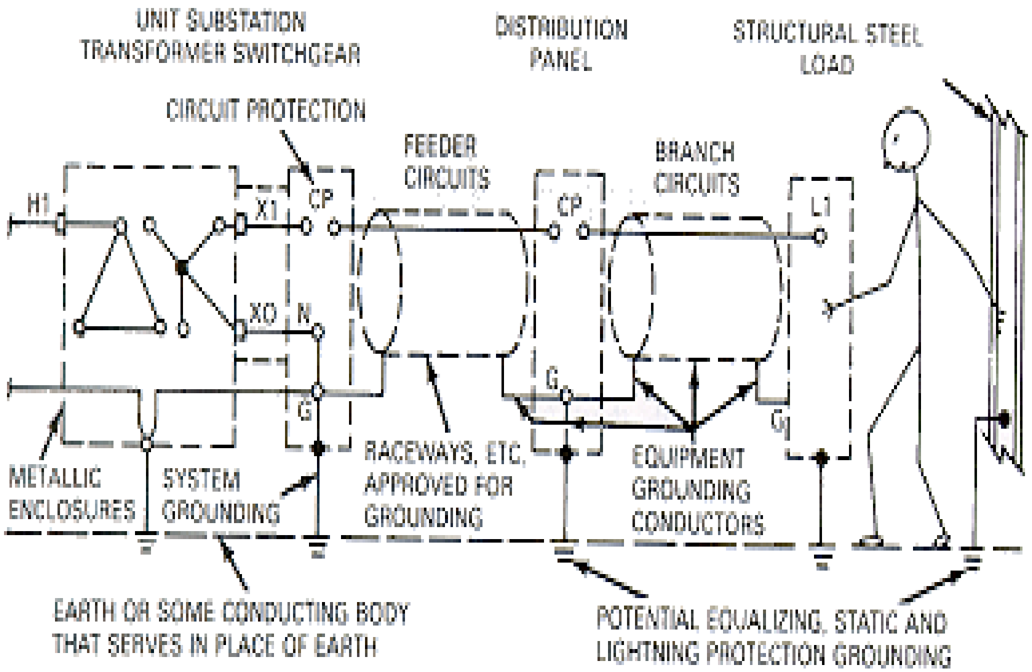
- Equipment Grounding –Part 2
  - Includes GEC and bonding/grounding of system components
  - GEC required for HRG, LRG and solidly grounded systems

Objectives of Equipment Grounding

- To reduced shock hazard to personnel
- To provide adequate current carrying capability (impedance and duration) to handle ground fault current w/o fire or hazard
- To provide a low-impedance return path for ground fault current to ensure operation of overcurrent device

Risk of a Poor Grounding System

- Panel is 20 Ω to ground
- Transformer ground
  = 10 Ω to ground
- No ground return path
- Ig=Ground Fault

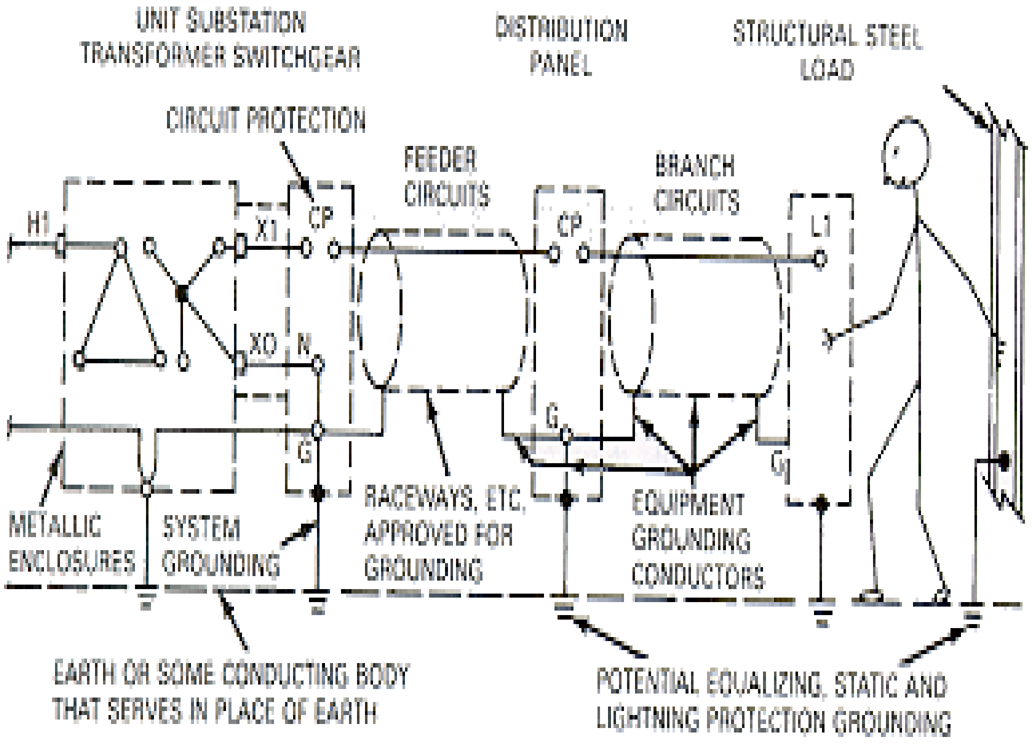


$$I_g = \frac{\text{Volts}}{\text{R of the ground path}} = \frac{277\text{Vac}}{20\ \Omega + 10\ \Omega} = 9.233\text{A}$$

Panel touch potential with 9.23Amps of fault current

- V=IgR
- V=(9.233A)(20 Ω)
- V= 184Vac

- If a good return path - 0 volts across panel



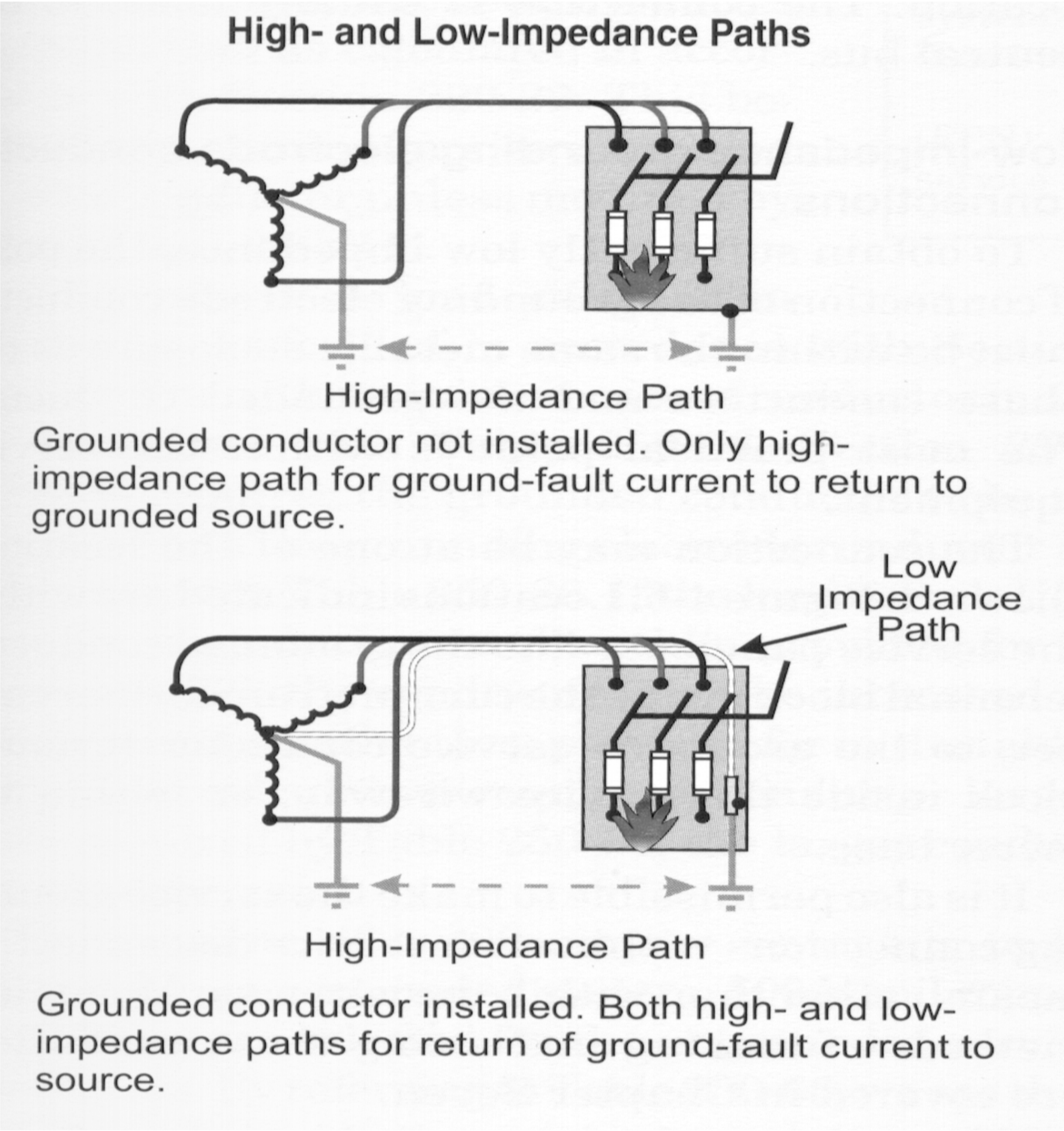
Equipment Grounding Requirements

- Conductive Materials enclosing conductors or equipment (e.g. conduit, motor frames) shall be connected to earth to limit voltage to ground on these items. These shall be:
  - Connected together (bonded)
  - Connected to the grounded conductor
- For LRG or HRG or ungrounded systems, these items must still be bonded together
- Earth cannot be sole EGC or fault current path

Grounding Electrode Conductor (GEC)

- Defined in NEC as "The conductive path installed to connect normally non-current-carrying metal parts of equipment together and to the system grounded conductor or the grounding electrode conductor, or both."

- Characteristics:
  - Copper or corrosion resistant material
  - Accessible (generally)
  - Sized per NEC Table 250.66



High- and Low-Impedance Paths

Grounded conductor not installed. Only high-impedance path for ground-fault current to return to grounded source.

Grounded conductor installed. Both high- and low-impedance paths for return of ground-fault current to source.

Risk of a Poor Grounding System

- Tray is 20 Ω to ground
- Transformer ground is 10 Ω to ground
- No ground return path
- Ig=Ground Fault

$$Ig = \frac{\text{Volts}}{\text{R of the ground path}}$$

$$= \frac{277\text{Vac}}{20\,\Omega + 10\,\Omega}$$

$$= 9.233\text{A}$$

Tray touch potential with 9.23Amps of fault current

- V=IgR
- V=(9.233A)(20 Ω)
- V= 184Vac

- If a good return path 0 volts across tray

System Bonding Jumper

- Defined in NEC as “The connection between the grounded circuit conductor and the equipment grounding conductor at a separately derived system.”

- Differs from main bonding jumper because main jumper is specific to service

- Characteristics:
  - Copper or corrosion resistant material
  - Accessible (generally)
  - Unspliced
  - Wire, bus or screw
  - Sized per NEC 250.28D, based on phase conductor size -See Table 250.66

GEC and Bonding Jumper

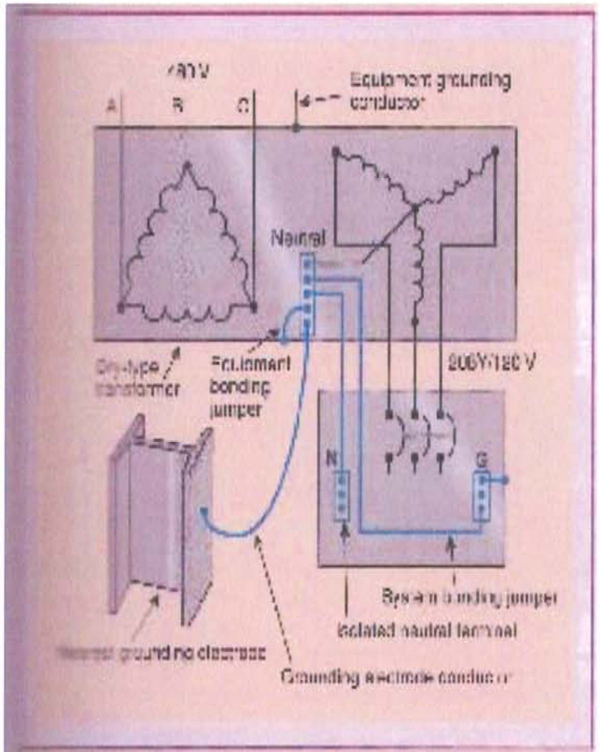


Exhibit 250.13 A grounding arrangement for a separately derived system in which the grounding electrode conductor connection is made at the transformer.

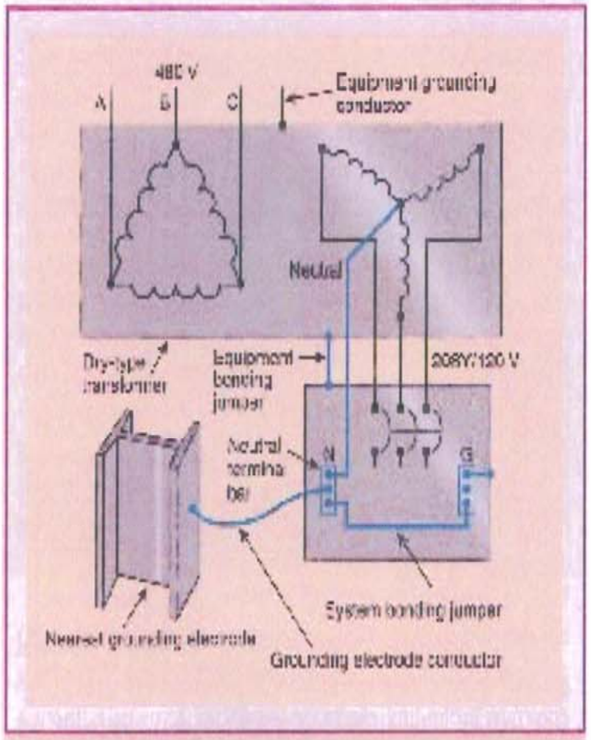


Exhibit 250.14 A grounding arrangement for a separately derived system in which the grounding electrode conductor connection is made at the first disconnecting means.

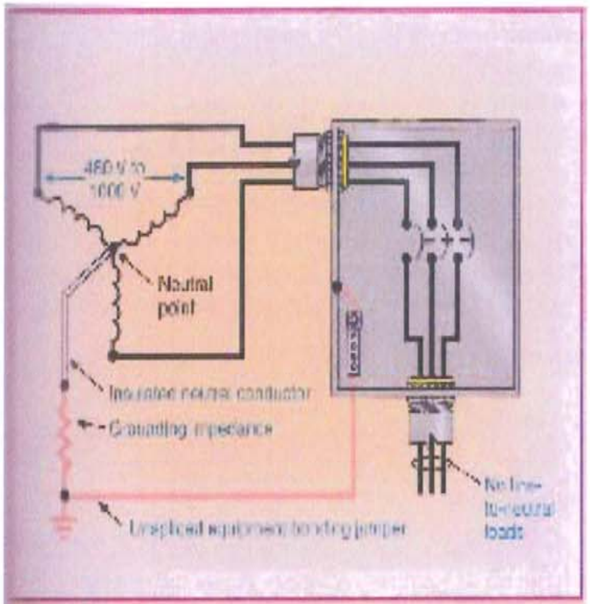


Exhibit 250.21 Schematic diagram of a high-impedance grounded neutral system

Grounding Electrode System

- All of the following present at a building or structure served shall be bonded together:
  - Metal Underground Water Pipe
  - Metal Frame of the Building or Structure
  - Concrete Encased Electrode
  - Ground Ring
  - Rod and Pipe Electrodes
  - Other Listed Electrodes
  - Plate Electrodes

Grounding Electrode System

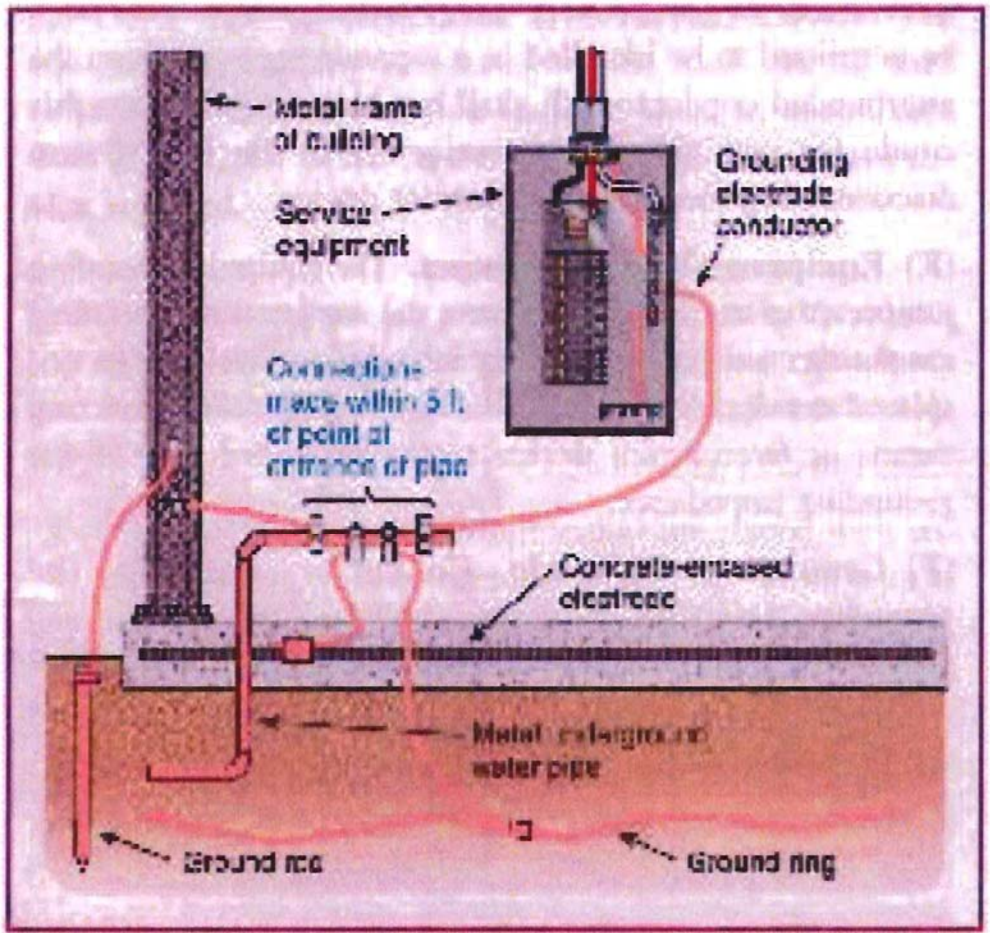


Exhibit 250.22 A grounding electrode system that uses the metal frame of a building, a ground ring, a concrete-encased electrode, a metal underground water pipe, and a ground rod.

Bonding

- Bonded, per NEC: Connected to establish electrical continuity and conductivity

- NEC gives bonding requirements
  - Metal raceways, trays, cable armor, enclosures, etc. and other non-current carrying metal parts shall be bonded

- NEC gives acceptable bonding means
  - Threaded couplings or bosses
  - Threadless couplings where made up tight for raceways
  - Other listed devices such as bonding locknuts, bushings or bushings with jumpers

Equipment Grounding Conductor

- Types of EGC are given in NEC article 250.118
  - Copper or Al wire
  - RMC
  - IMC
  - EMT
  - Listed Flex (with conditions)
  - Listed Liquidtight Flex (with conditions)
  - Type AC cable
  - Mineral Insulated Cable
  - Type MC cable
  - Cable tray (with conditions)
  - Cablebus framework (with conditions)
  - Other raceways (e.g. listed gutters)

ECG Identification

- EGC can be bare, covered or insulated
  - Insulation must be green or green with one or more yellow stripes
  - Green or green with yellow stripes are not permitted to be used for ungrounded or grounded conductors

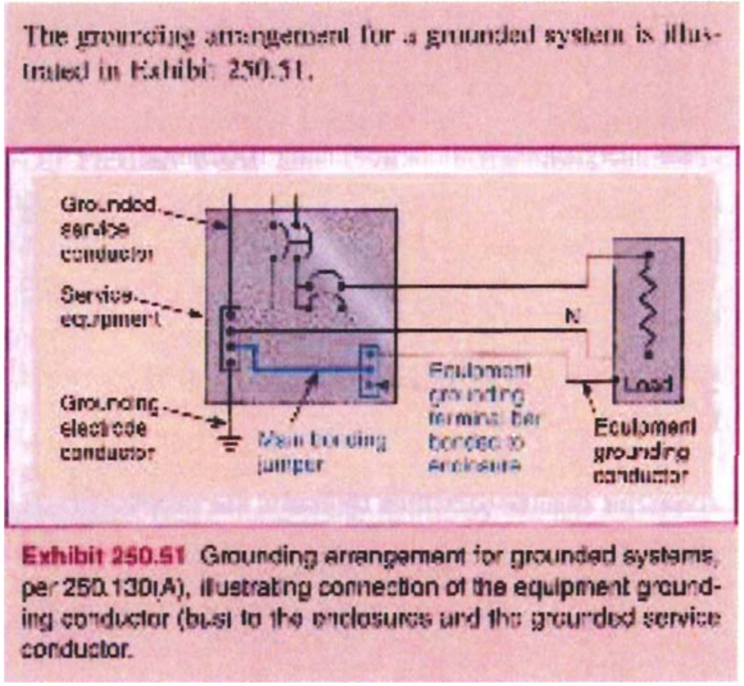
- Conductor #6 or larger, or conductors in multi-conductor cable can be reidentified by:
  - Stripping insulation
  - Coloring exposed portions green
  - Marking exposed insulation with green tape or adhesive labels

Size of ECG

- **Refer to NEC table 250.122**
  - Size based on overcurrent protection
  - Never must be larger than circuit conductor
  - Where a single EGC is run with multiple circuits in same raceway, cable or tray, it shall be sized based on the largest OC device
  - For parallel cables, EGC must be run with both sets, with each sized per 250.122

Methods of Equipment Grounding

- For grounded systems, the connection by bonding the EGC to the grounded service conductor and the GEC
- For fixed equipment connected with permanent wiring, EGC shall be routed with circuit conductors



The grounding arrangement for a grounded system is illustrated in Exhibit 250.51.

Exhibit 250.51 Grounding arrangement for grounded systems, per 250.130(A), illustrating connection of the equipment grounding conductor (bus) to the enclosures and the grounded service conductor.

Equipment Grounding Conductors

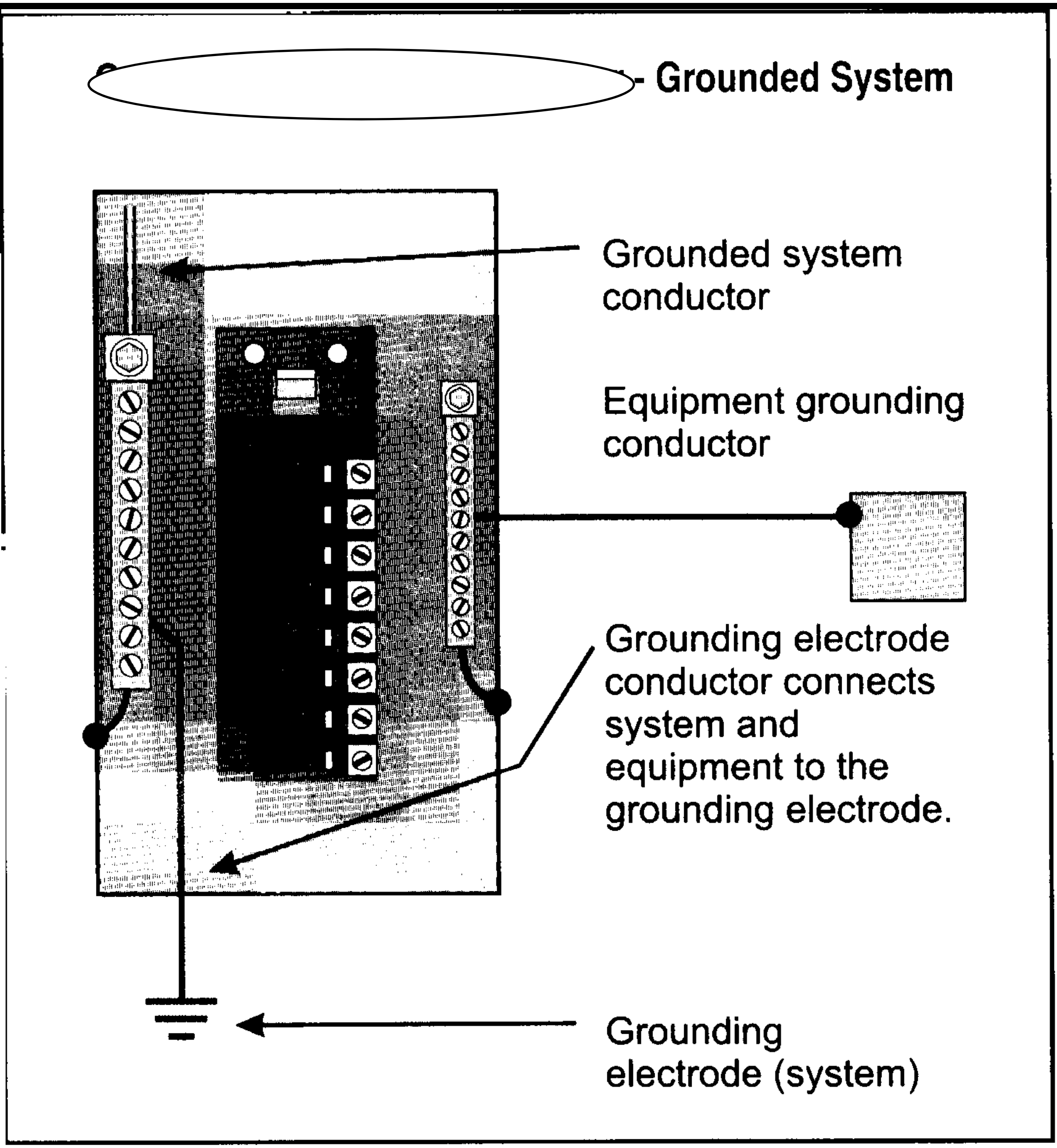
- Required for every piece of the equipment in a substation
- Conductor, be it a raceway or cable, is limited in the allowable current-carrying capability by a series of rules in the NEC
  - Copper conductors (see NEC Table 250-122 for ampacity)
  - Cable Tray (if listed for grounding) (see NEC Table 318-7 for ampacity)

Equipment Grounding Conductor

Connect non-current carrying metal parts to system grounded conductor

Fault Current return path

NEC250-118

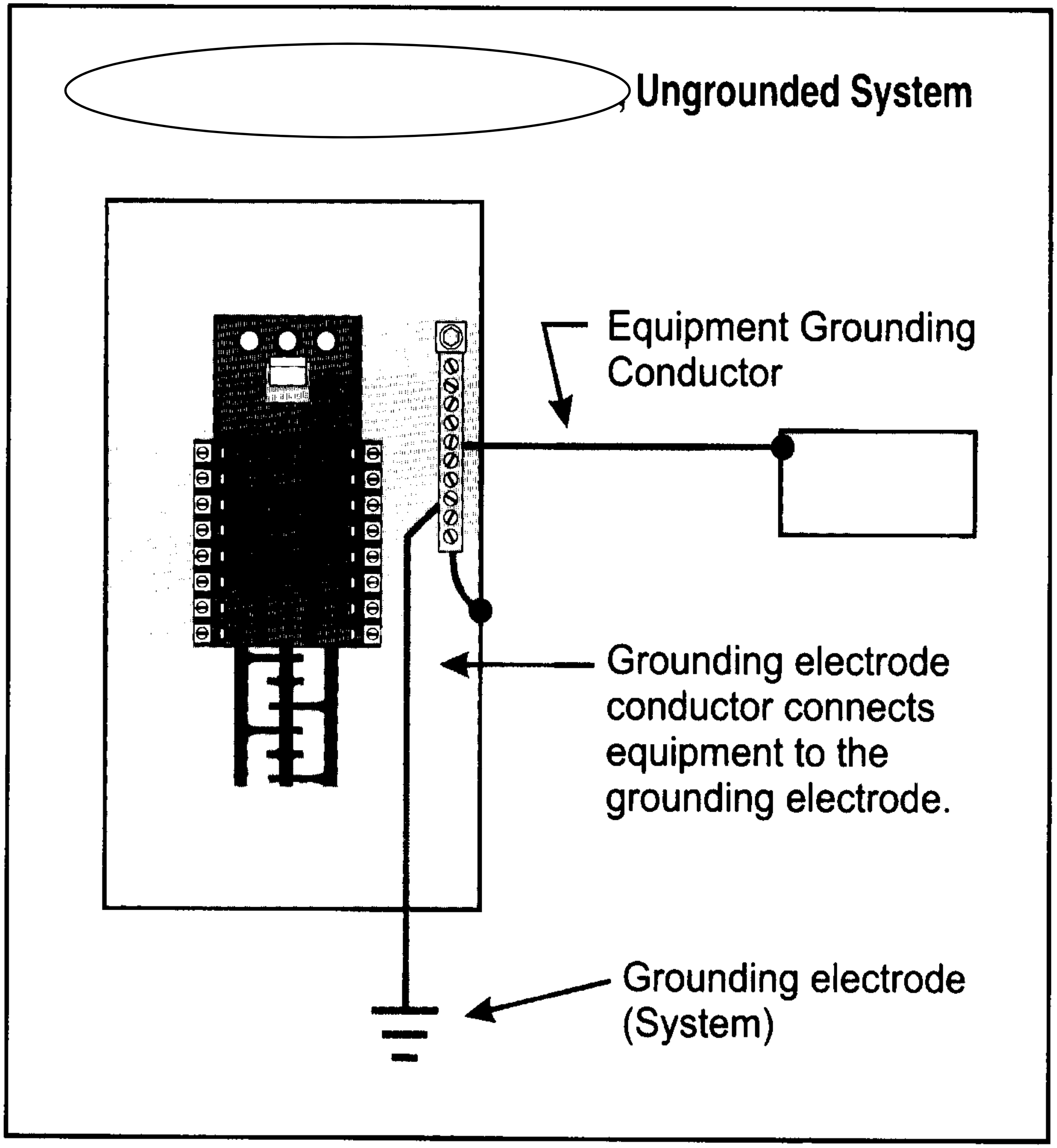


Equipment Grounding Conductor

Connection is the current path

Same size as grounded case

NEC Table 250-122



Equipment Grounding Conductors (cont.)

  - RGS conduit and Electrical Metallic Tubing
  - Liquid-tight flex and Greenfield flex under certain conditions
  - Cable armor of AC and MC cables
  - Metallic Sheaths of shielded cables
- NEC Sections 250-110 through 250-148 for the rules pertaining to the installation of the equipment grounding conductor

Grounding w/ Tray

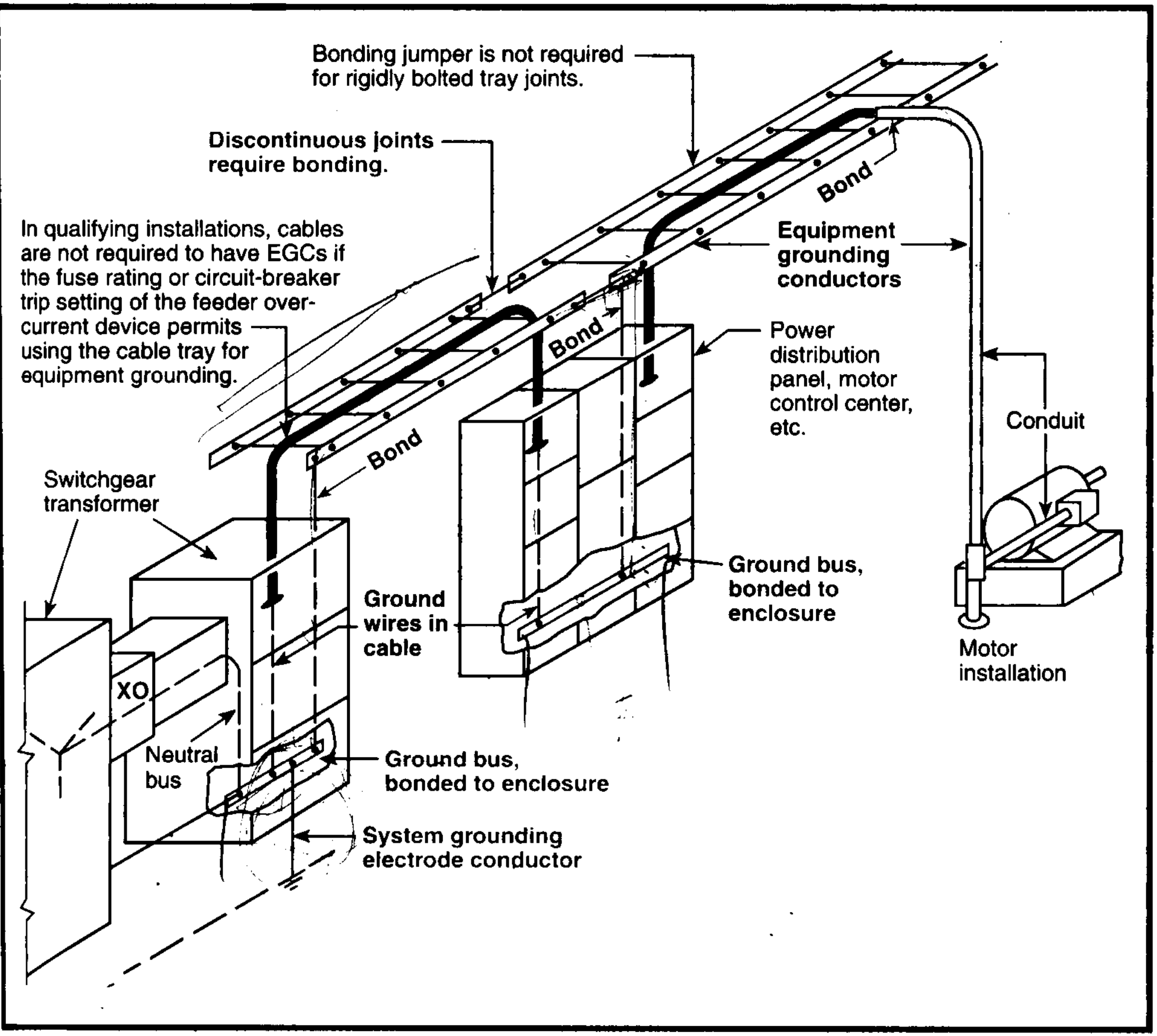


Figure 318.2 An example of multiconductor cables in cable trays with conduit runs to power equipment where bonding is provided in accordance with Section 318-7(b)(4). (Cable Tray Institute)

Tray Current Carrying Capacity

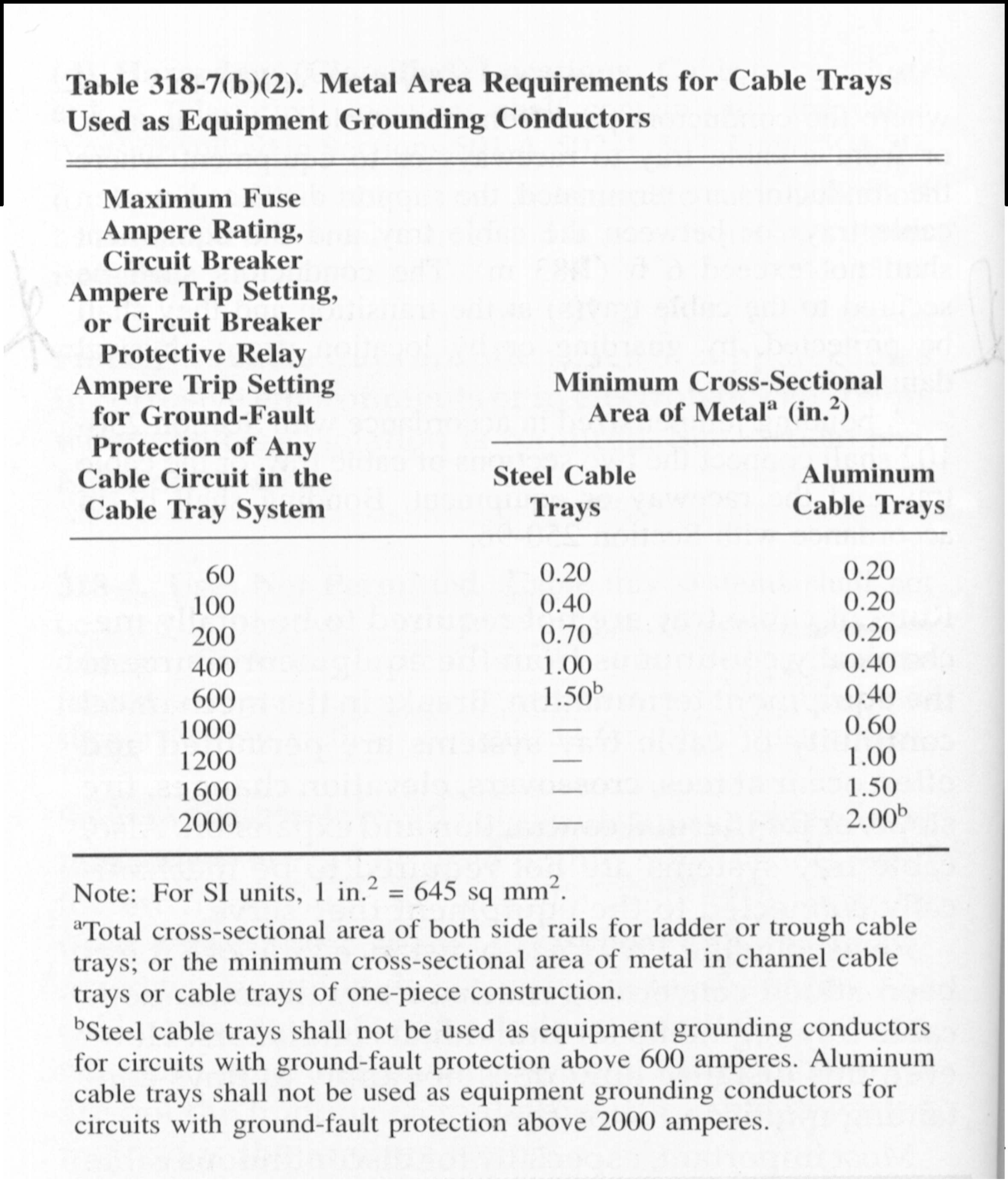


Table 318-7(b)(2). Metal Area Requirements for Cable Trays Used as Equipment Grounding Conductors

Maximum Fuse Ampere Rating, Circuit Breaker Ampere Trip Setting, or Circuit Breaker Protective Relay Ampere Trip Setting for Ground-Fault Protection of Any Cable Circuit in the Cable Tray System	Minimum Cross-Sectional Area of Metal[a] (in.^{2})	
	Steel Cable Trays	Aluminum Cable Trays
60	0.20	0.20
100	0.40	0.20
200	0.70	0.20
400	1.00	0.40
600	1.50[b]	0.40
1000	—	0.60
1200	—	1.00
1600	—	1.50
2000	—	2.00[b]

Note: For SI units, 1 in.^{2} = 645 sq mm^2.

[a] Total cross-sectional area of both side rails for ladder or trough cable trays; or the minimum cross-sectional area of metal in channel cable trays or cable trays of one-piece construction.

[b] Steel cable trays shall not be used as equipment grounding conductors for circuits with ground-fault protection above 600 amperes. Aluminum cable trays shall not be used as equipment grounding conductors for circuits with ground-fault protection above 2000 amperes.

Equipment Grounding Conductor NEC250-122(f)

- For parallel conductors to be based on the trip rating of the ground fault protection
- NEC requires High Impedance Grounding still sized on trip
- For HRG Frame size of the largest breaker to size the ground return conductor even though this will greatly exceed the 10 amps

[redacted]

- Must be run with the phase conductors. Bonding jumpers have to be direct connections for the raceway. NEC Section 250-118
- Must be permanently identified at each end and every point where the conductor is accessible NEC Section 280-119

Equipment Grounding Conductor

- For grounded systems, the connection are required:
  - The **equipment ground conductor** to the ground bus
  - The ground bus to the case
  - The ground bus via the **grounding electrode** to the floor or to a PCR ground loop if one has been specified. See NEC Section 250-130(a)

Equipment Grounding Conductor

- Any lug or connection used in the grounding conductor path must be listed for the purpose. NEC Section 250-8

Unit Substations

- Much more simple than outdoor, open-frame substations (lots more on that later)
  - Voltage gradients are typically not a significant problem
  - Generally dealing with a metal-enclosed package, all bonded together
  - All grounding circuits to and from unit substation must be properly connected
  - Use of impedance grounding greatly reduces risk to personnel

Unit Substations with Transformers

- Unique problems because two systems are present
  - Must have EGC running back to line-side source
  - Secondary is separately-derived system and is subject to all rules (recall system grounding, GEC, system bonding jumper, etc.)

- Line-side and load side systems are interconnected due to EGC requirements but are functionally separate

Utilization Equipment

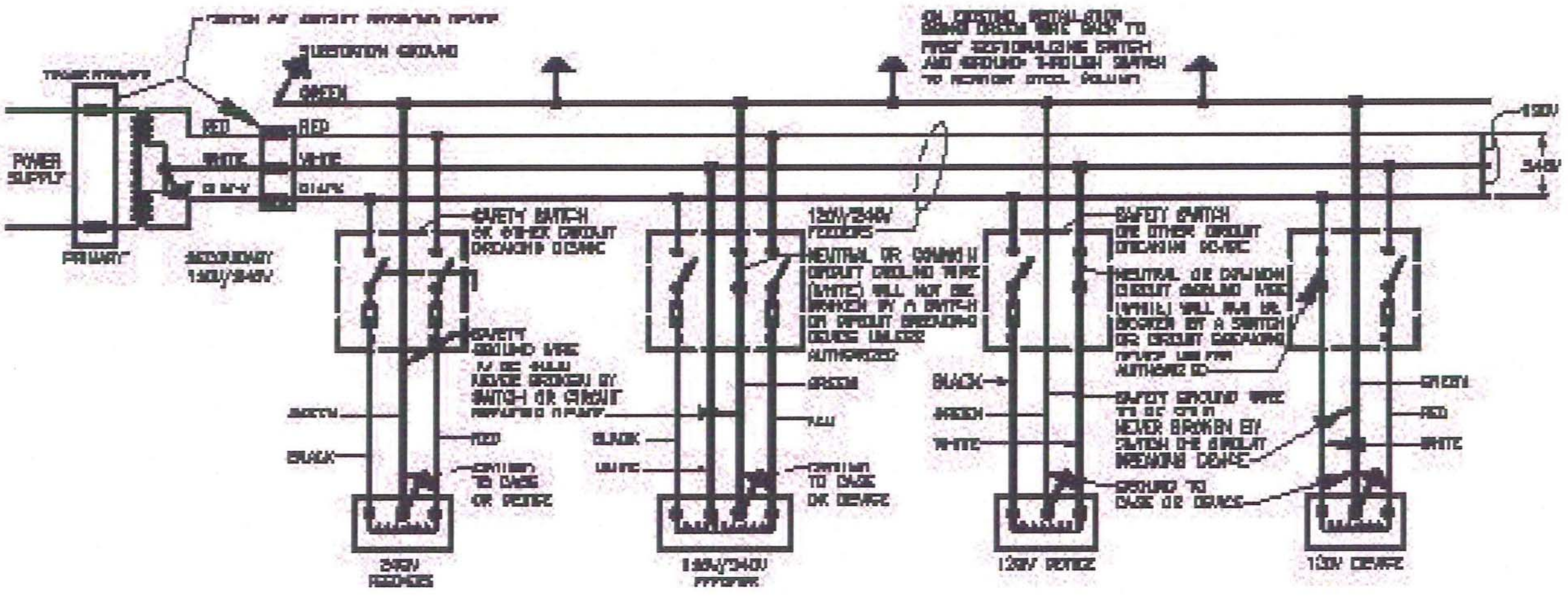


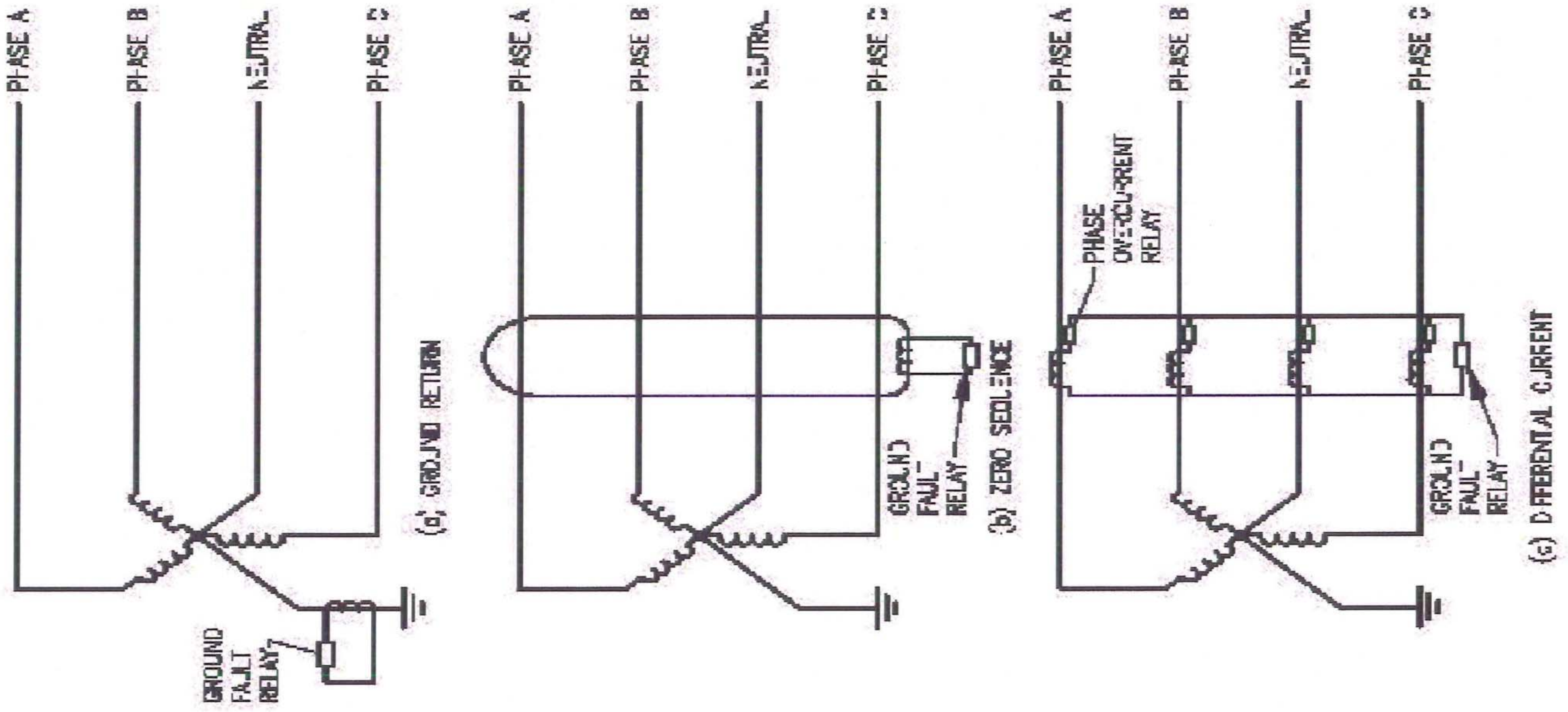
Figure 2-14—Typical supply conductor patterns of power circuits of utilization apparatus with emphasis on a distinction between grounding and grounded conductors of fixed equipment

Ground Fault Protection

- Use of phase overcurrent devices is not ideal
  - Can produce less current than device rating thus trip times can be extremely long (e.g. fuse) with LRG system
  - Ground faults often are arcing and are intermittent in nature not allowing thermal elements to operate quickly

- Separate ground fault protection is recommended

Ground Fault Sensing



(a) GROUND RETURN

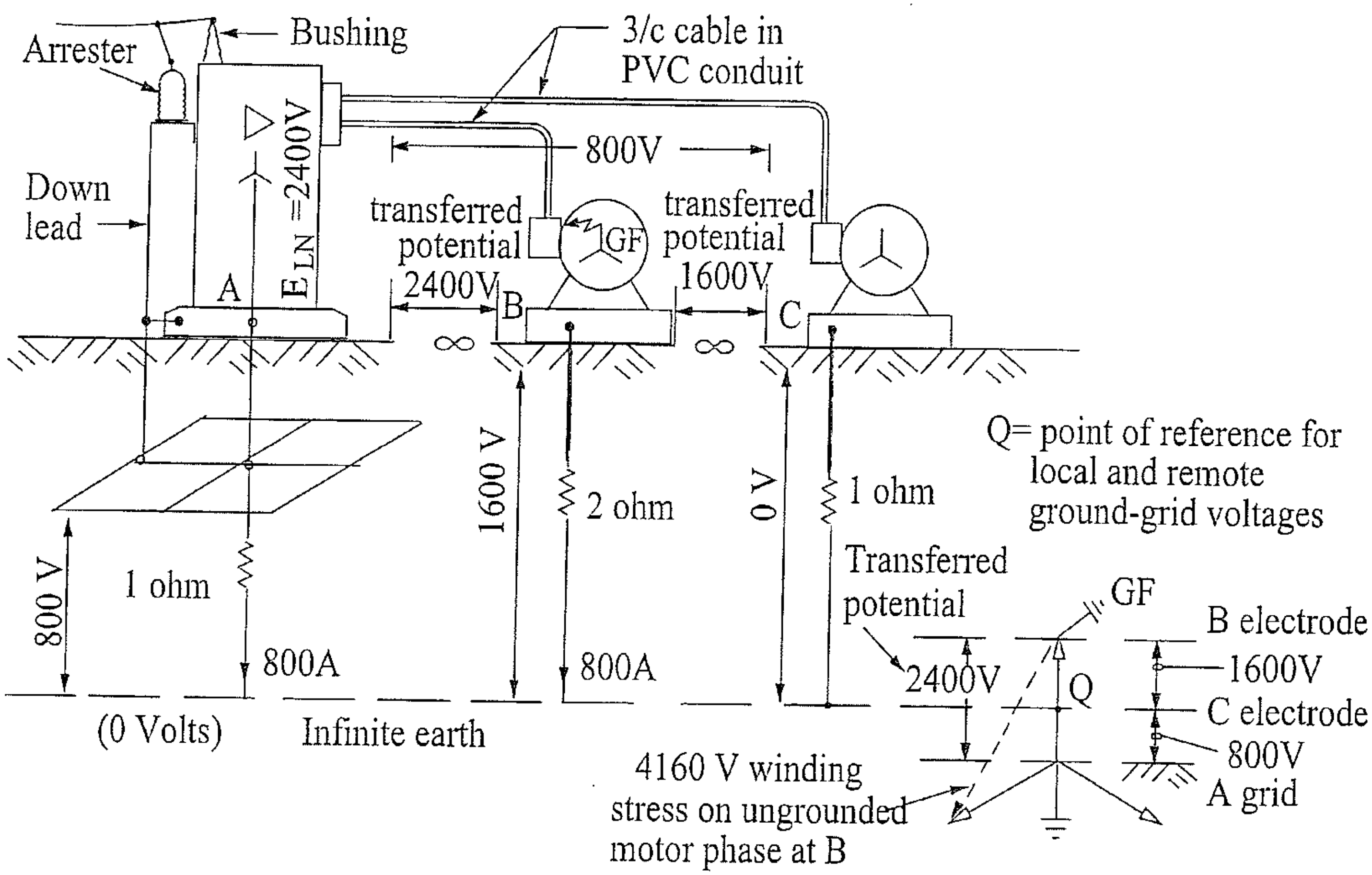
(b) ZERO SEQUENCE

(c) DIFFERENTIAL CURRENT

Figure 2-13—Ground-fault sensing

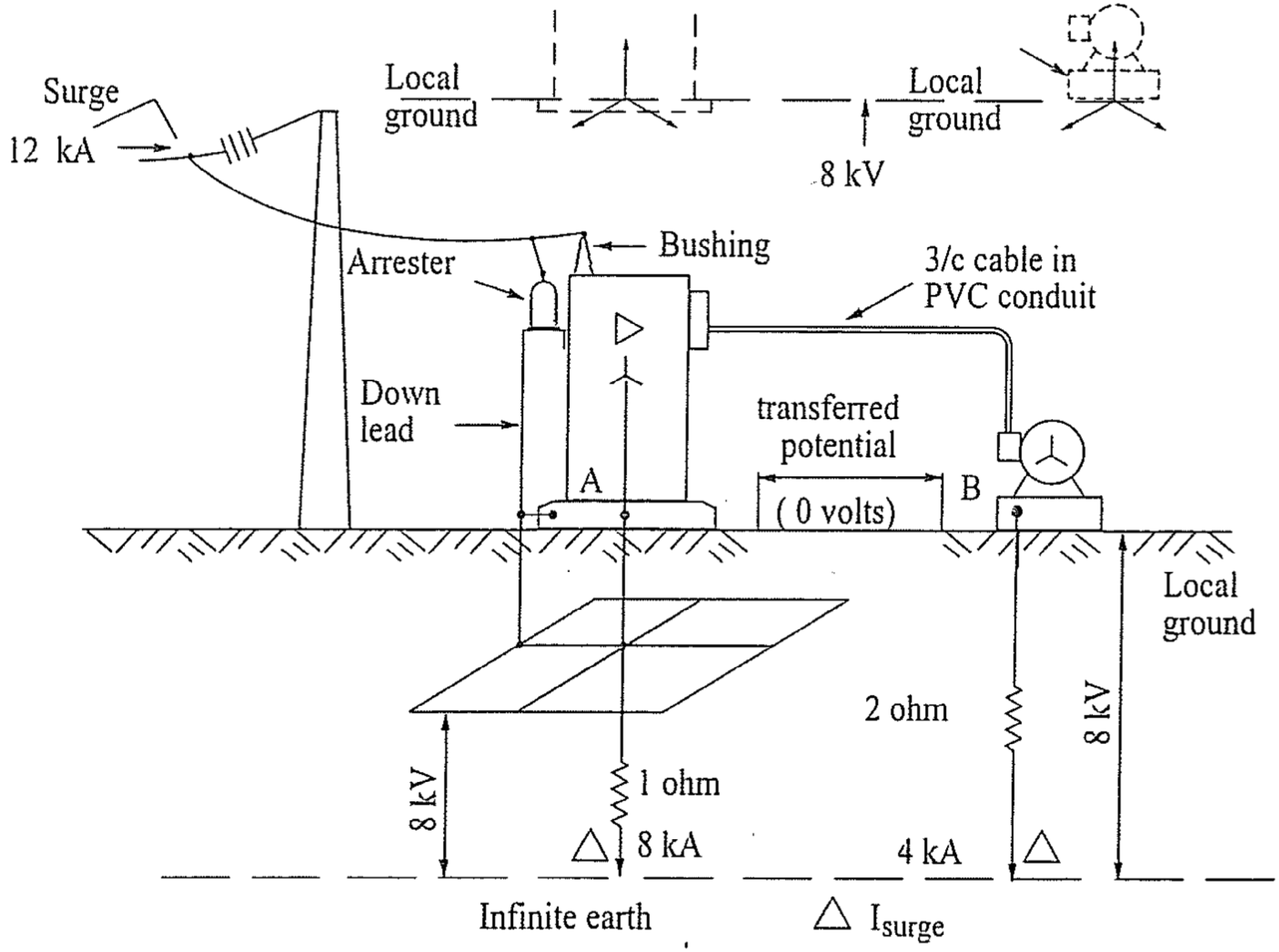
Inter-grid Conductors

- Absense of inter-grid connection in presence of high H-G current



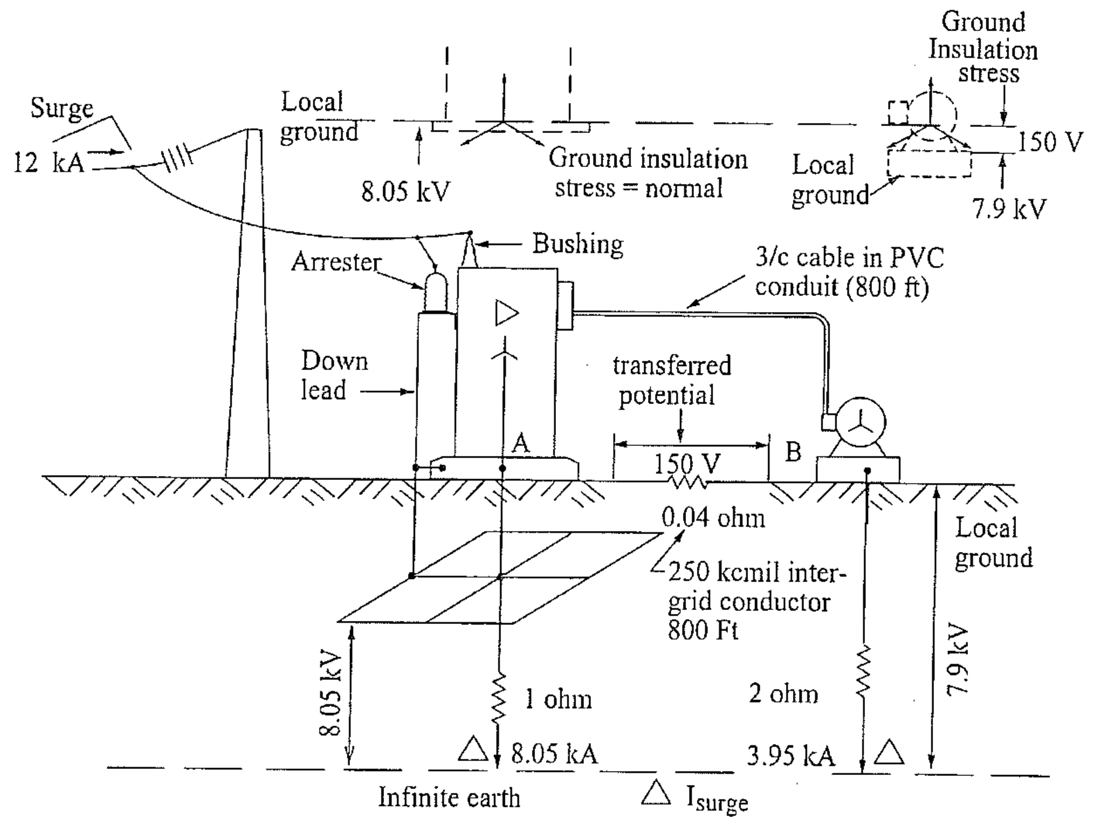
Inter-grid Connections

- Zero resistance inter-grid connectior minimizes line to ground insulation stress



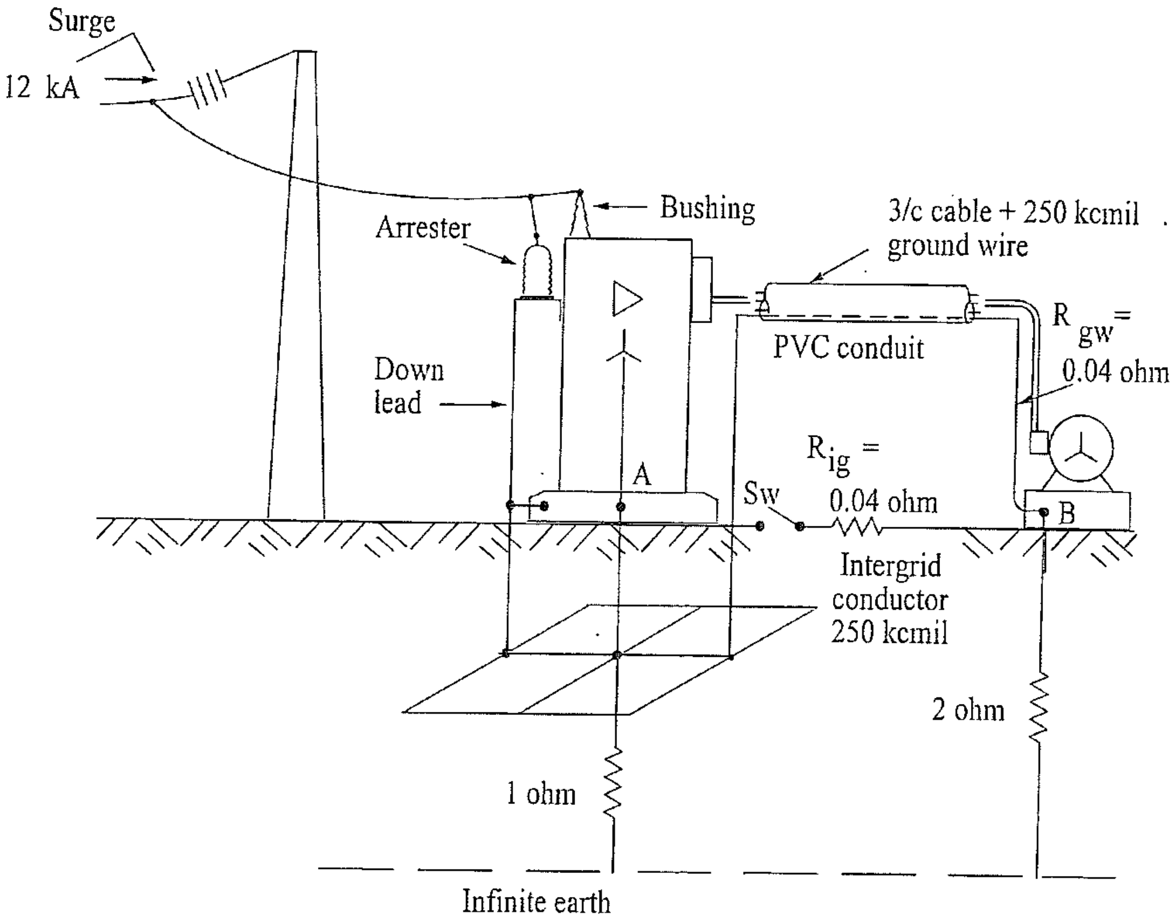
Transfer potential for Surge Arrestor

- Typical inter-grid conductor reduces transfer potential



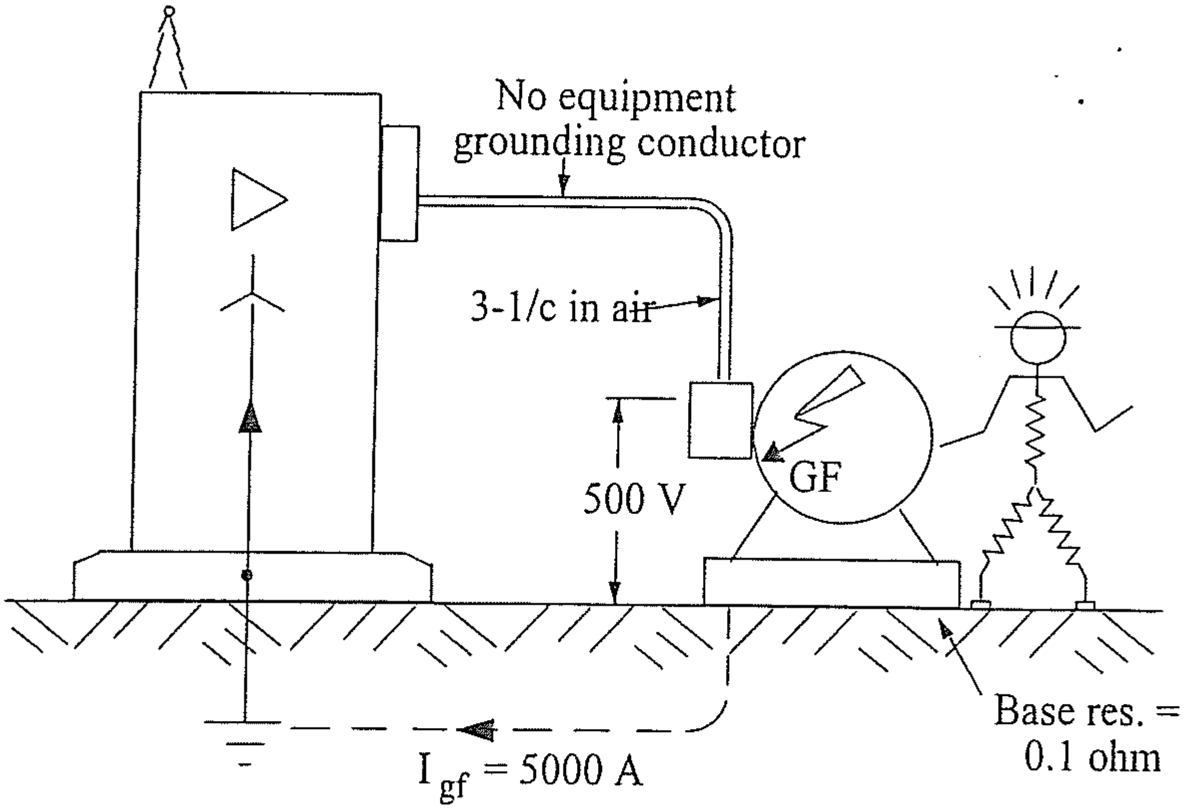
Typical Petrochemical Installation

- Earth return
- Inter-grid connection



Solid ground and equipment grounding

- Problem when we loose the equipment ground



- Earth return low impedance path back
- Higher current but much lower touch potential

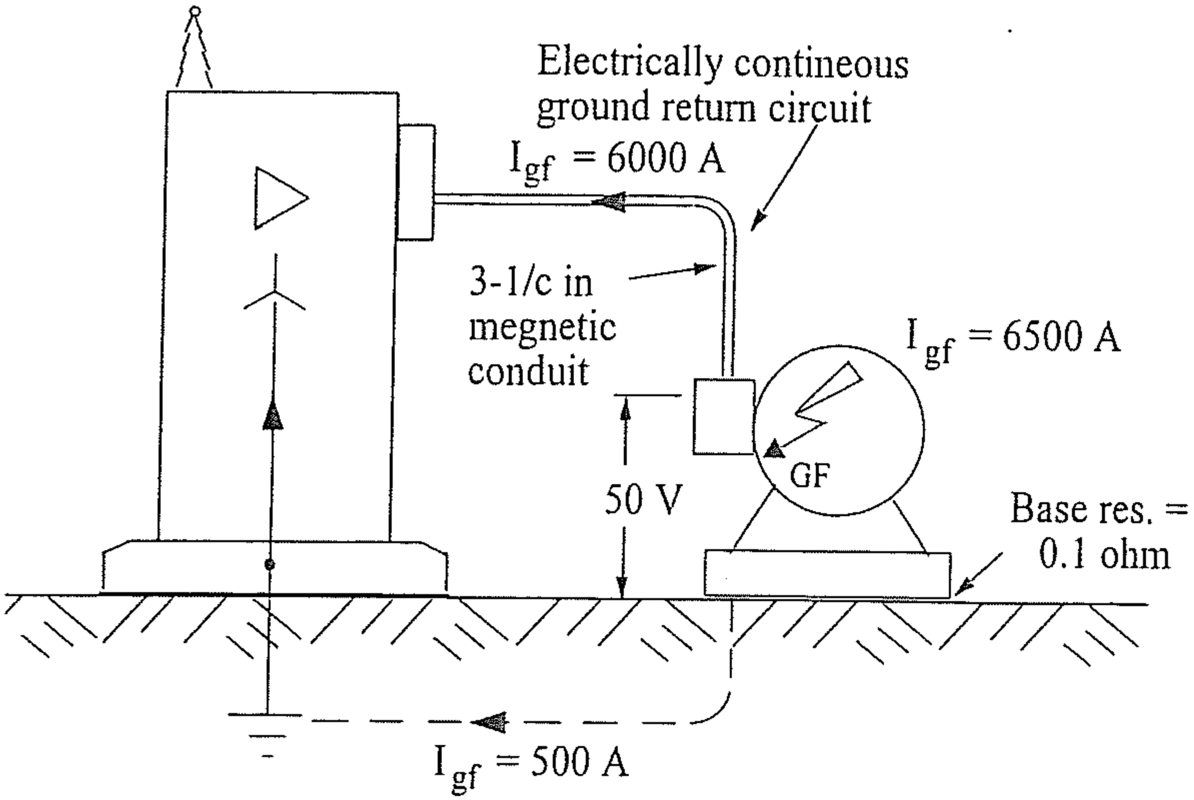


Fig. 2.16 Majority of motor ground-fault current returns to transformer neutral using any channels (as metallic conduit) in close proximity to outgoing conductors.

Substation Grounding

Substation Grounding Outline

- **Part 1** — Criteria for Ground Grid Design
  - Applicable Codes, Standards and Guides
  - Safety Criteria and Exposure Mechanisms
- **Part 2** — Designing Safe and Effective Ground Systems
  - General Criteria
  - Soil Parameters
  - System Parameters
- **Part 3** — Designing Safe and Effective Ground Systems
  - Conductor Properties
- **Part 4** — Designing Safe and Effective Ground Systems
  - Grounding System Arrangement
  - Computer Simulation
  - Problem Areas
  - Testing

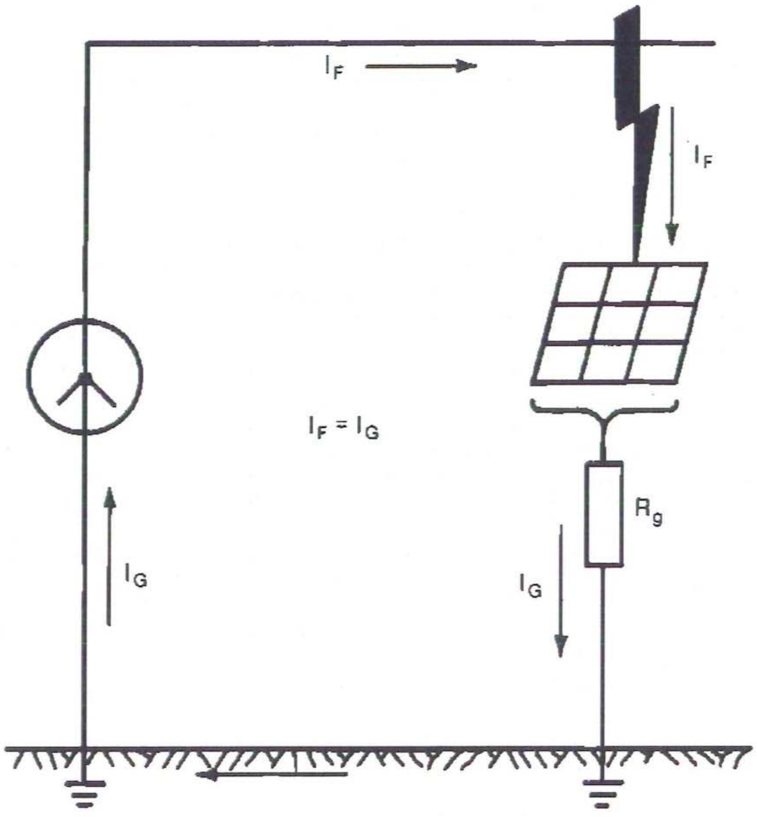
Significant Domestic Codes and Standards

- **NFPA 70** – National Electrical Code
  - General grounding provisions
  - Certain definitions
- **ANSI C2** – National Electric Safety Code
  - General grounding provisions for electric supply stations
- **IEEE 837** – IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding
  - Specific to connectors
  - Written in procedure form
- **IEEE 81** – IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System
- **IEEE 80** – IEEE Guide for Safety in AC Substation Grounding
  - Comprehensive and Absolutely Indispensable

Hazardous Conditions

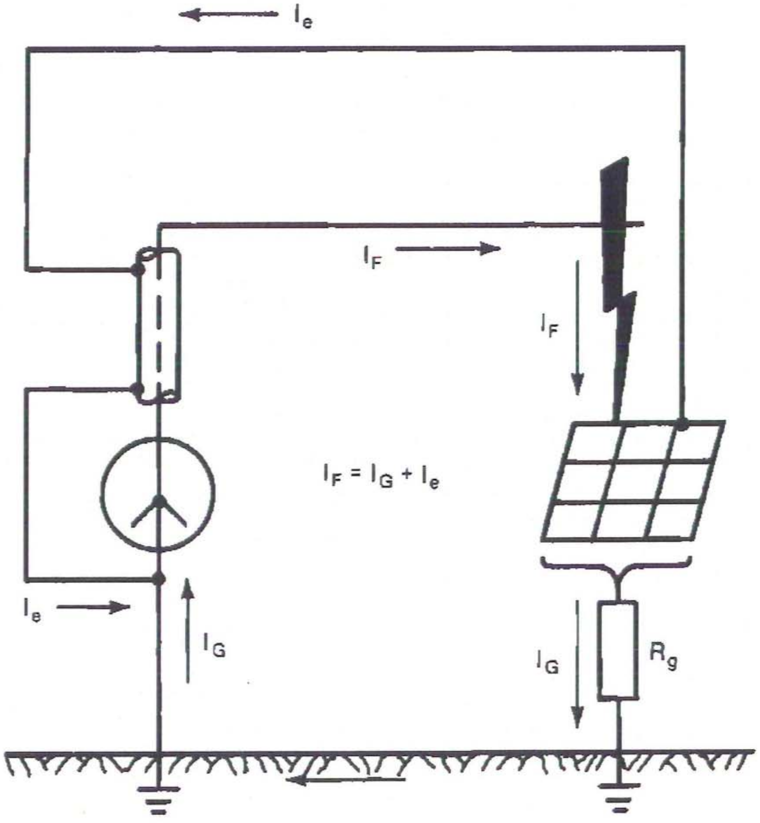
- Shock
  - Not necessarily caused by contact with an intentionally energized object (that's what insulation is for)
  - Caused by potential gradients
  - Requires the following simultaneous conditions
    - ✓ Current, typically high in relation to the grounding area and resistance
    - ✓ Current distribution through soil resistance causing gradients at earth's surface
    - ✓ Absence of insulating material that could mitigate current flow through the body
    - ✓ Duration of contact and fault sufficient to develop harmful current flow through the body
    - ✓ Bad luck -Presence of human at wrong place at the wrong time, bridging two points of potential difference caused by the above items

Current Return Paths



(a)

Figure (a): $I_F = I_G$
Total fault current returns through ground



(b)

Figure (b): $I_F = I_G + I$
Fault current splits

Specific Susceptibility

- Physiological Effects of Electric Current
  - As current increases, the following effects occur
    - ✓ 1 mA: threshold of perception
    - ✓ 1 to 6 mA: let-go current –unpleasant but can be released
    - ✓ 9 –25 mA: pain and hard to release; may require secondary treatment
    - ✓ 60 –100 mA: highly dangerous; ventricle fibrillation, stoppage of cardio-pulmonary system; immediate treatment required

- Fibrillation Current is the Criterion on Which Analysis is Based

Determining Body Current Limits

- Depends on Current and Time (Energy absorbed)
  - The energy absorbed by the body is expressed as follows:

$$S_B = (I_B)^2 \cdot t_s$$

where:
I_B is the exposure current (rms amperes)
t_s is the exposure duration (seconds)
S_B is an empirical constant related to tolerable shock energy

  - Further, research indicates that 99.5% of all persons can withstand current as expressed below without suffering ventricular fibrillation:

$$I_B = \frac{k}{\sqrt{t_s}}$$

where:
k is the square root of S_B

Current vs. Time

- Alternate Analysis
  - Biegelmier's Curve
- Summary
  - Eat, drink, survive shocks better

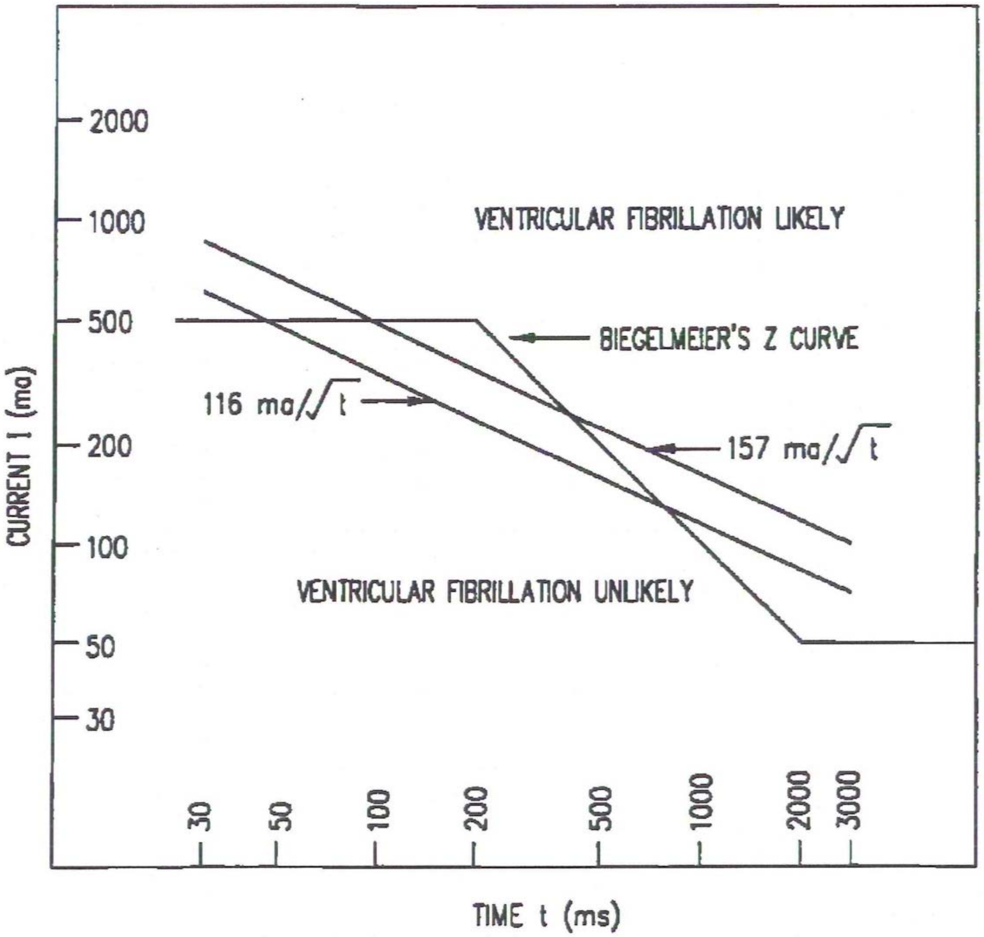


Figure 5—Body current versus time

Don’t Try to Resist It

- For 50 and 60 Hz Currents the Human Body is Approximated as a Resistor
  - Current path assumptions
    - ✓ One hand to both feet
    - ✓ One foot to the other
  - Resistance (from experimental data)
    - ✓ Body resistance is 300 Ω
    - ✓ Body resistance including skin is 500 Ω to 3000 Ω

- IEEE 80 Makes the Following Critical Assumptions
  - Hand and foot contact resistance is equal to zero
  - Glove and shoe resistance are equal to zero
  - R_B (resistance of a human body) = 1000 Ω for:
    - ✓ Hand-to-hand
    - ✓ Hand-to-feet
    - ✓ Foot-to-foot

Body Current Paths

- Hand-to-Hand
  - Vital organs (heart) exposed

- Hand-to-Foot
  - Vital organs (heart) exposed

- Foot-to-Foot
  - Vital organs not specifically exposed
    - ✓ Depends on one's definition of "Vital"
    - ✓ Takes 25 times more current to produce same heart current

- Despite the above, IEEE 80 recommends:
  - Use of 1000 Ω for all calculations (conservative)
    - ✓ Person could fall into energized equipment
    - ✓ Person could be resting in prone position

Developing Voltage Criteria

For the next few slides:

R_A total effective resistance of the accidental circuit in Ω

V_A total effective voltage (step or touch) of the accidental circuit

I_B tolerable body current from previous

U, Z and I_f are system parameters

Terminal H is a point in system at same potential as grid

R_B is resistance of body

I_b body current in A, flows from H to F through the unfortunate individual

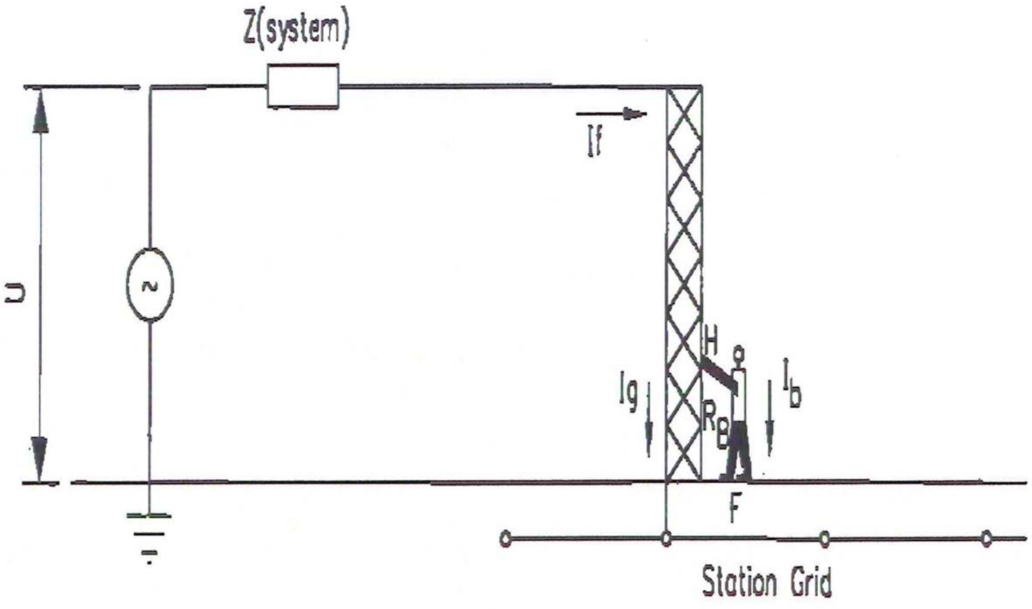


Figure 6—Exposure to touch voltage

Touch Voltage Criteria

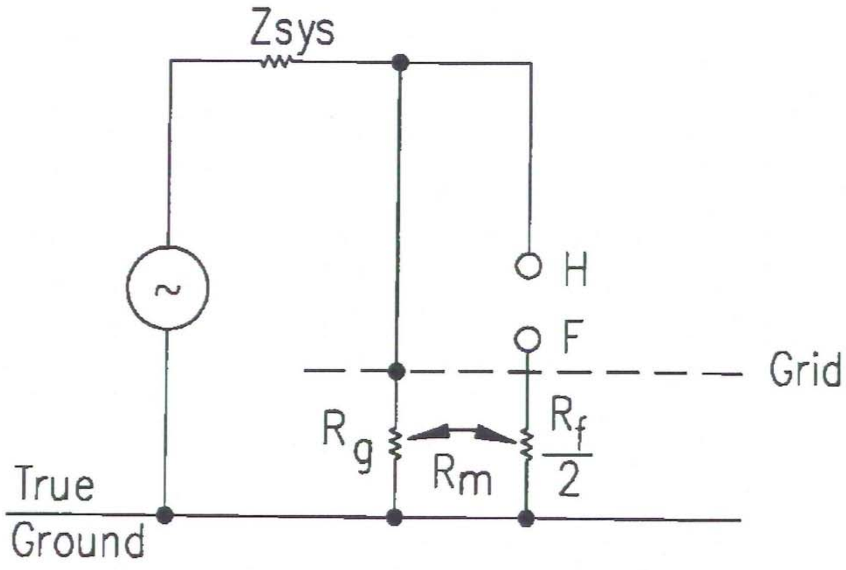


Figure 7—Impedances to touch voltage circuit

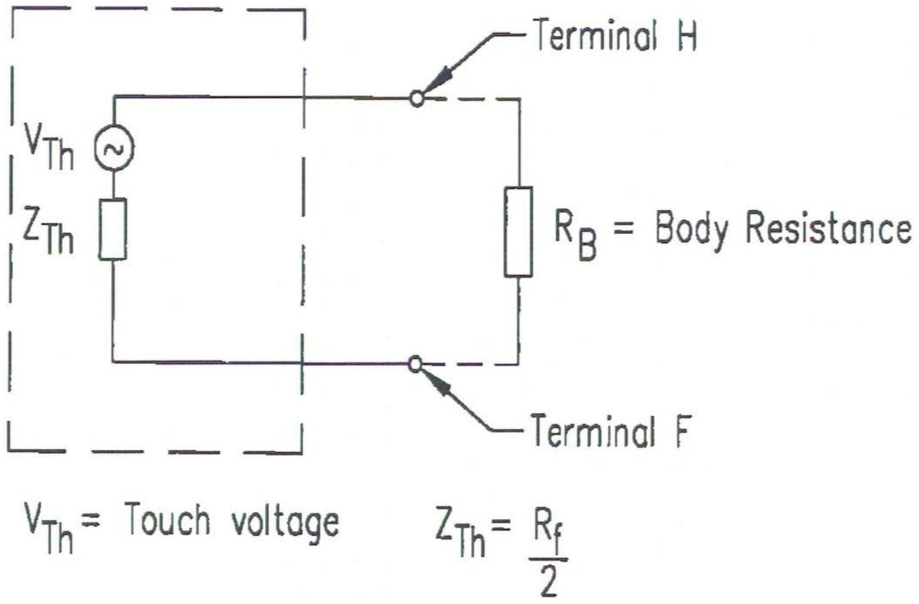


Figure 8—Touch voltage circuit

Step Voltage Criteria

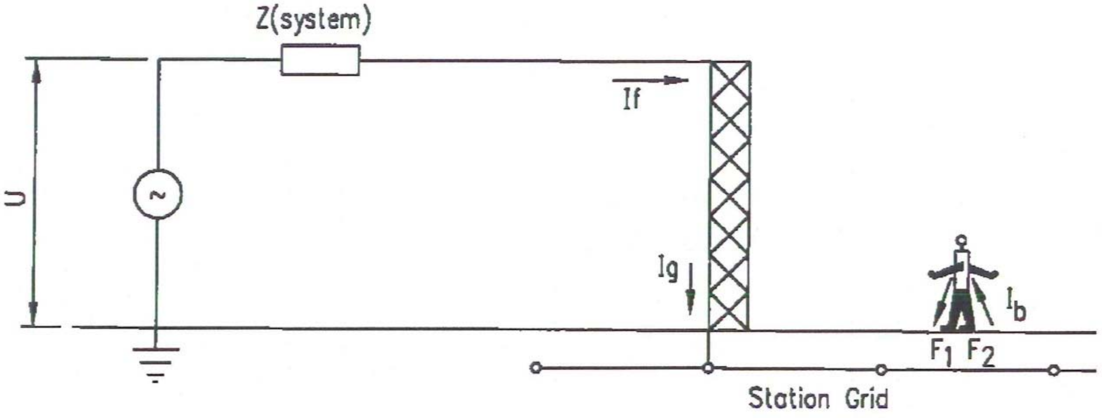


Figure 9—Exposure to step voltage

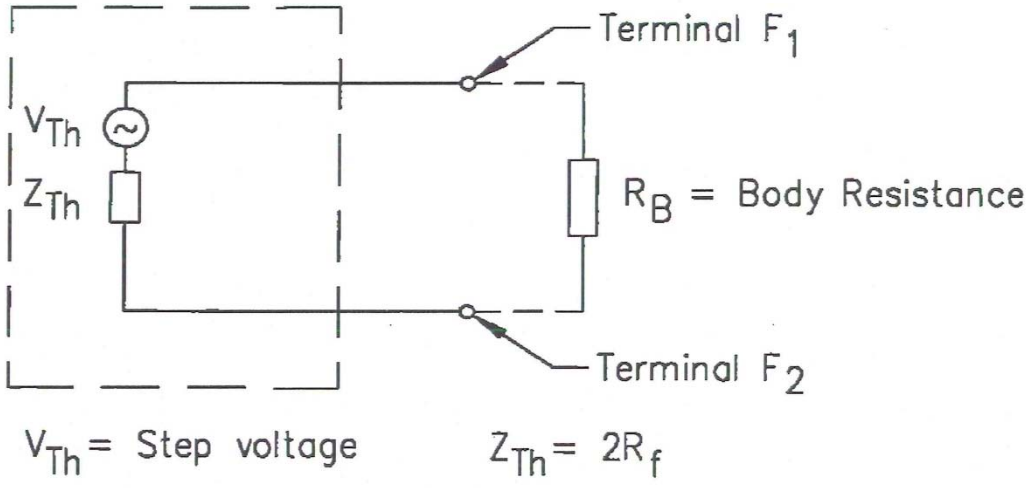


Figure 10—Step voltage circuit

Putting it All Together

- The maximum driving voltages of the accidental step circuits are:

$$E_{step} = \left(R_B + 2R_f\right)I_B$$

For a 50 kg body weight –

$$E_{step50} = (1000 + 6C_s \,.\, P_s)\,\frac{0.116}{\sqrt{t_s}}$$

For a 70 kg body weight –

$$E_{step70} = (1000 + 6C_s \,.\, P_s)\,\frac{0.157}{\sqrt{t_s}}$$

- The maximum driving voltages of the accidental touch circuits are:

$$E_{touch} = \left(R_B + \frac{R_f}{2}\right) I_B$$

For a 50 kg body weight –

$$E_{touch50} = (1000 + 1.5C_s \,.\, P_s)\,\frac{0.116}{\sqrt{t_s}}$$

For a 70 kg body weight –

$$E_{touch70} = (1000 + 1.5C_s \,.\, P_s)\,\frac{0.157}{\sqrt{t_s}}$$

E_{step} is the step voltage in V
E_{touch} is the touch voltage in V
C_s is the surface layer derating factor
R_s is the resistivity of the surface in $\Omega\text{-m}$
T_s is the duration of the shock in seconds

Shocking Situations

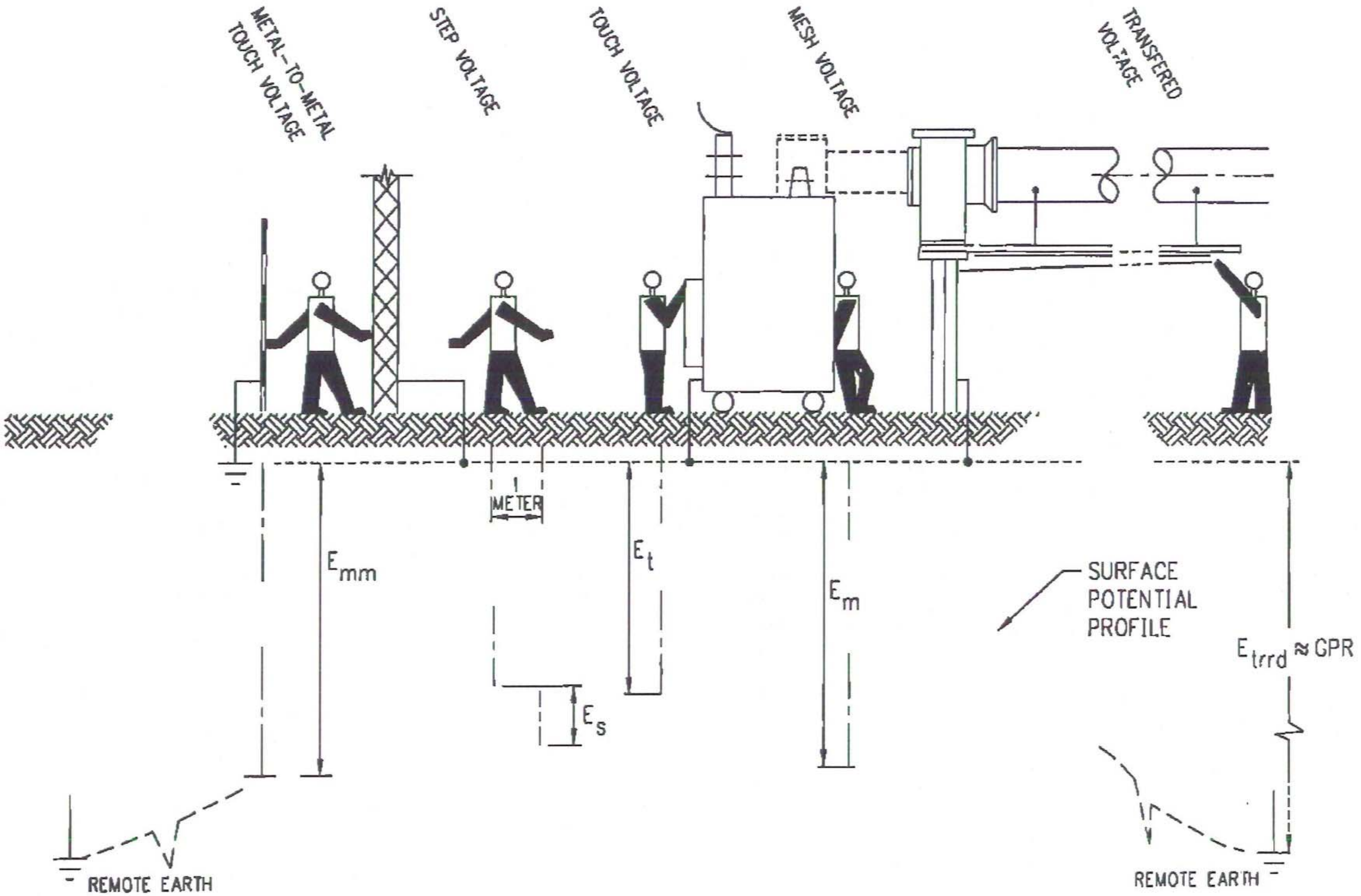


Figure 12—Basic shock situations

Transferred Potential

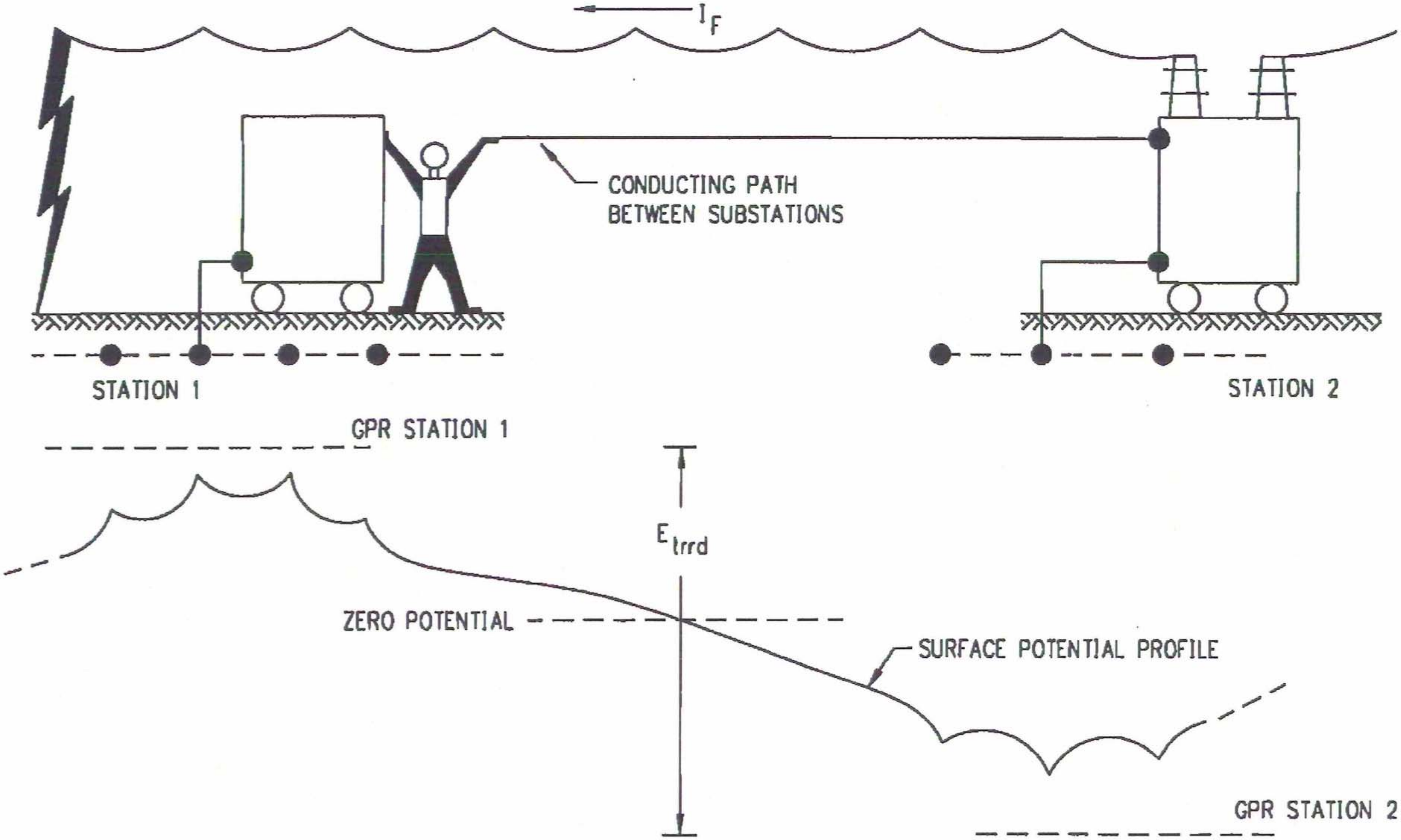


Figure 13—Typical situation of extended transferred potential

Designing Safe Grounding Systems

- The Ground System Must
  - Assure continuity of service
  - Limit the effects of potential gradients to safe levels under normal and fault conditions
  - Limit voltage imposed by lightning, line surges or unintentional contact with higher voltage lines
  - Stabilize the voltage to earth during normal operation
  - Provide an effective ground fault current path

Select Definitions

- Ground Potential Rise (GPR) – The maximum electrical potential that a substation grounding grid may attain relative to a distant point assumed to be remote earth.
  - GPR = grid resistance x maximum grid current
  - Safety not necessarily dependent on GPR; a safe system could have a high GPR with low gradients

- Step Voltage – The difference in surface potential experienced by a person bridging a distance of 1 meter with the feet without contacting any grounded object

- Touch Voltage – The potential difference between the GPR and the surface potential where a person is standing with one hand on a grounded surface

Select Definitions Continued

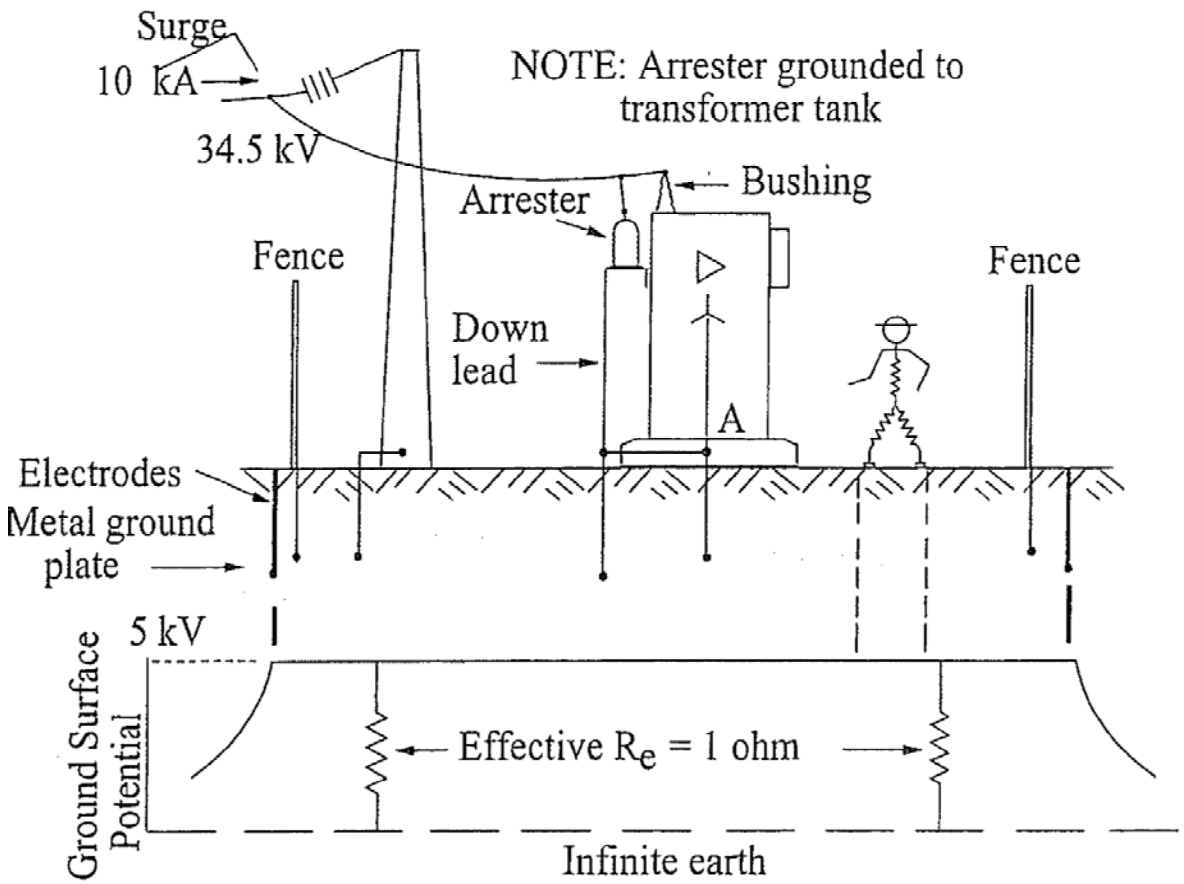
- Metal-to-Metal Touch Voltage –The potential difference between metallic objects within the substation site that may be bridged by direct contact
  - Assumed negligible in conventional substations if both items are tied to the grid
  - Could be substantial with contact between grounded and ungrounded object such as an isolated fence, water pipe or rail line

- Transferred Voltage –Special case where a voltage is transferred into or out of a substation

- Touch Voltage –The potential difference between the GPR and the surface potential where a person is standing with one hand on a grounded surface

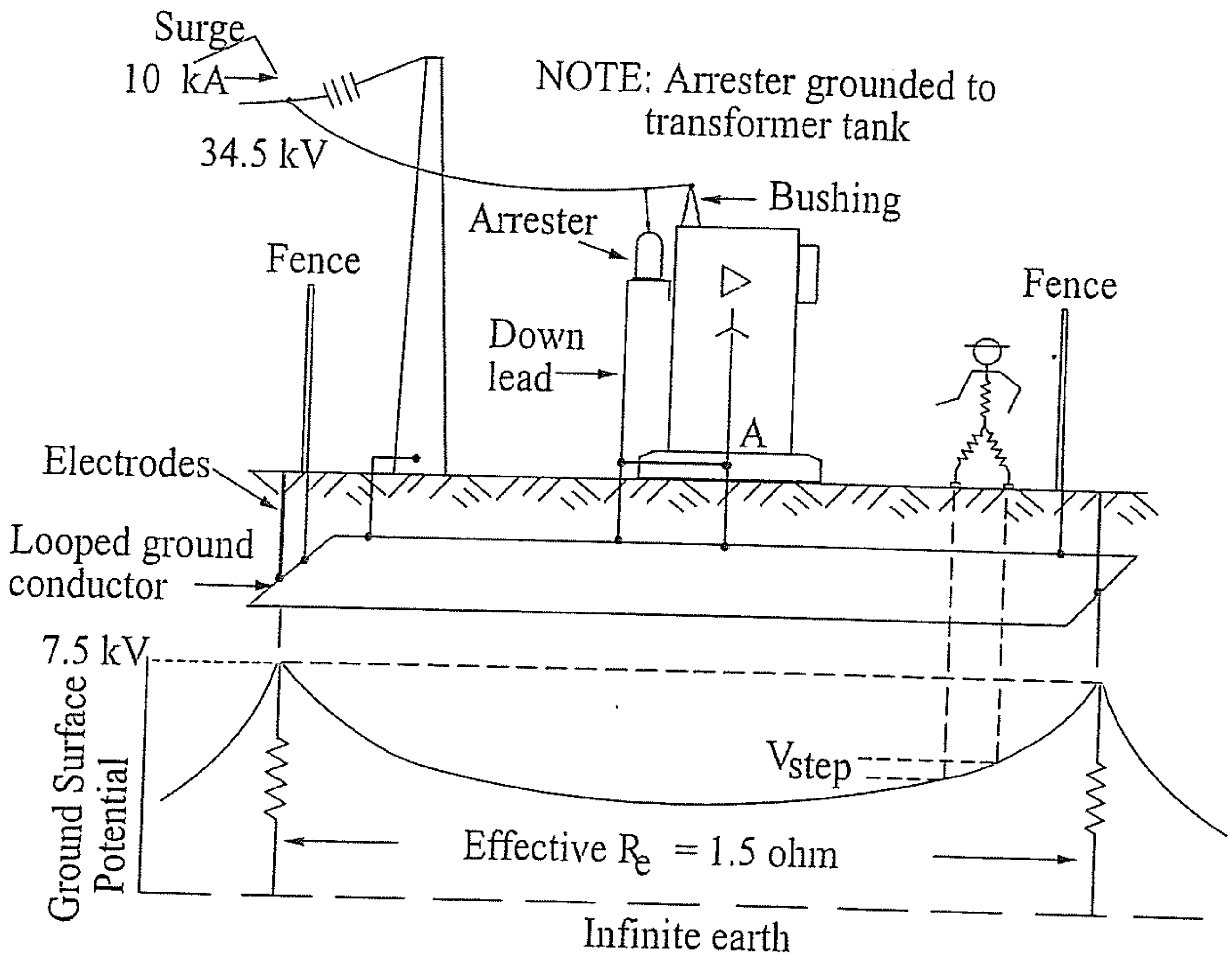
Ideal Ground Plane

- Moves all the transfer potential to the fence



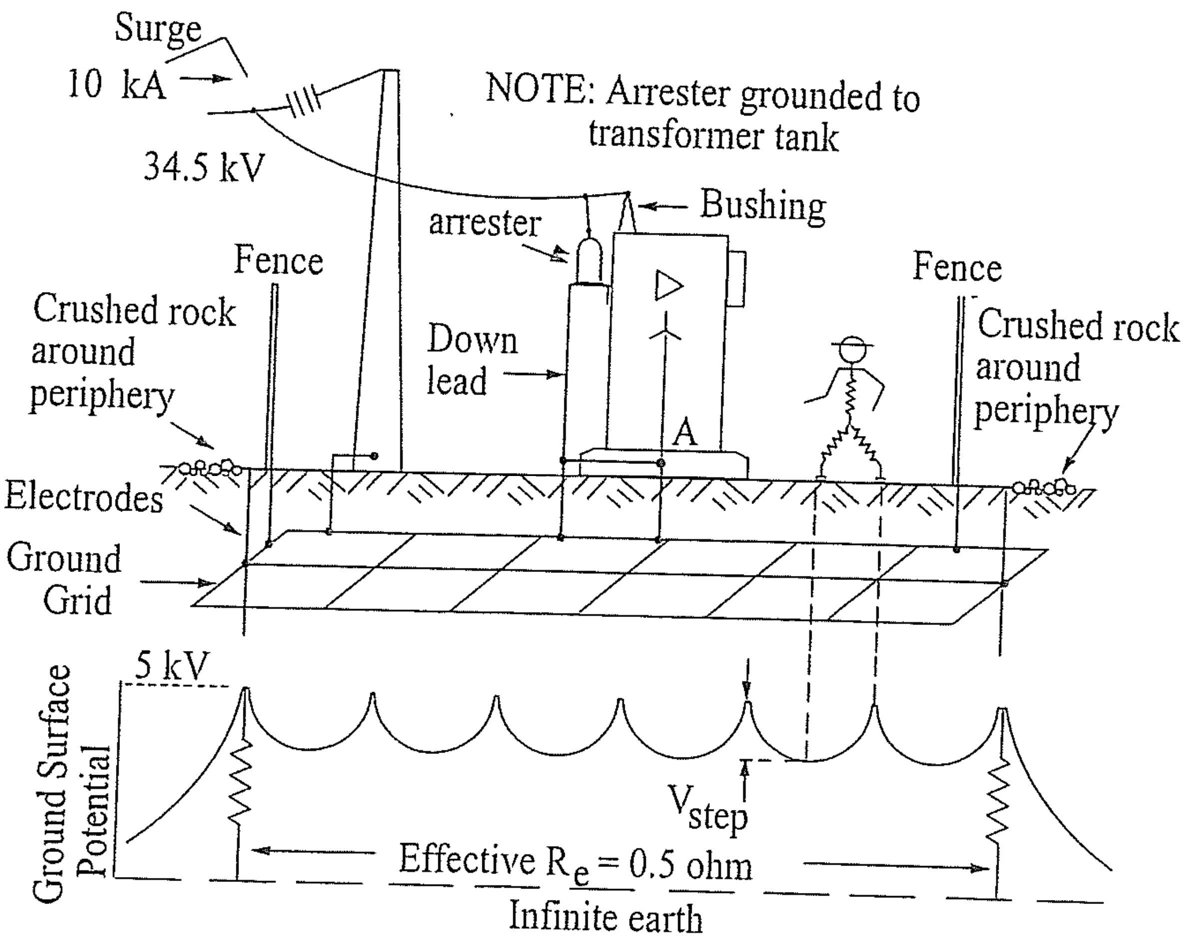
Single looped conductor - Step Potential in Yard

- Too Loose a ground mat
- Step potential increase



Typical Ground grid

- Minimize step and touch potential throughout



Information for Modeling

- **Soil Parameters**
- System Parameters
- Conductor Properties
- Ground System Arrangement (iterative)

Soil Parameters

- Soil Behaves as Resistance and Dielectric
  - Dielectric effect can be ignored except for high-frequency waves
  - Can be modeled as pure resistance
  - Conductivity is generally electrolytic
  - Resistivity affected by a number of factors, here is graph of a typical sandy loam soil:

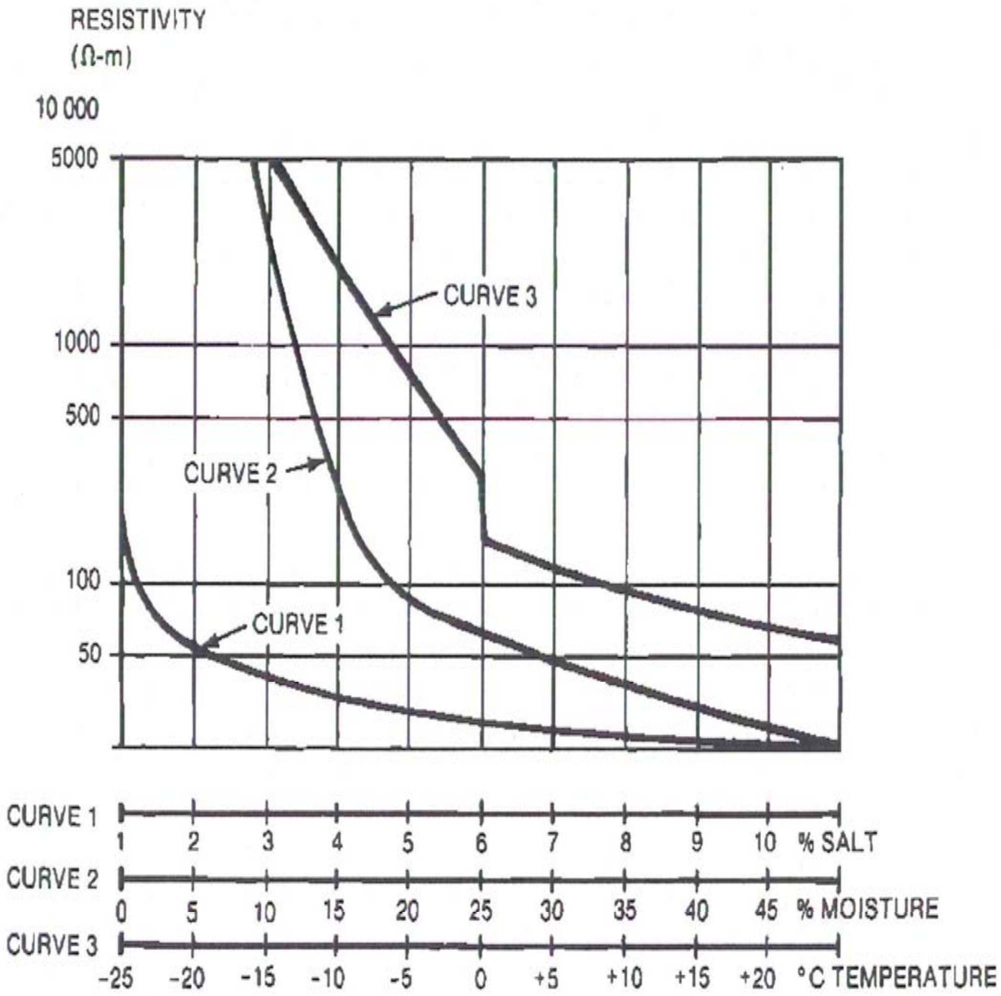
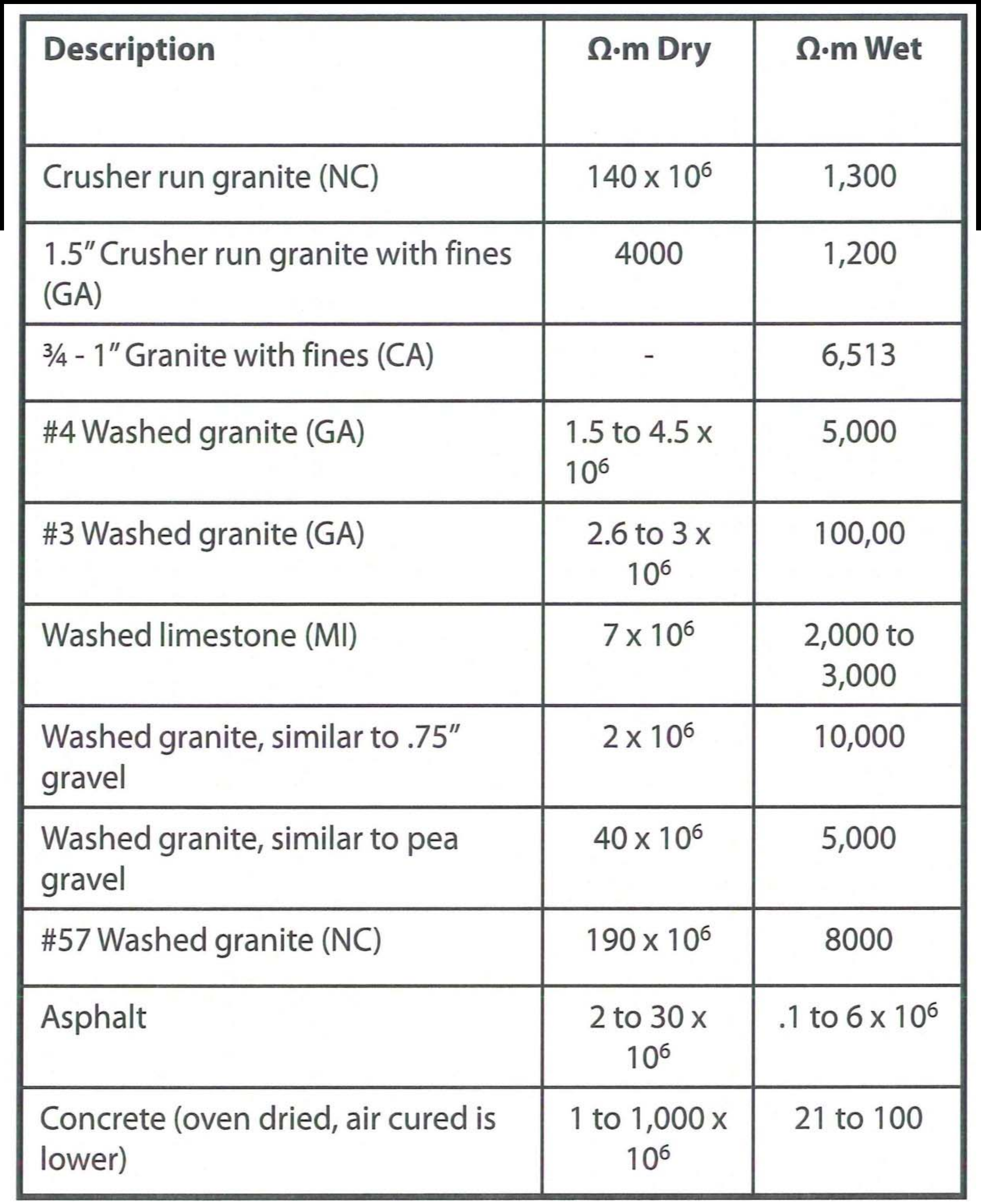


Figure 18—Effects of moisture, temperature, and salt upon soil resistivity

Surfacing

- Proper Surfacing is Extremely Valuable
  - Typically 3 to 6 inches thick
  - Helps eliminate soil dryout
  - Reduces shock current
    - ✓ Decreases ratio of body to short circuit current by 10 to 20 times, depending on surfacing resistivity
  - Resistivity is often provided by surfacing supplier or determined by tested
  - Typical values are indicated on next page

Surfacing



Description	Ω·m Dry	Ω·m Wet
Crusher run granite (NC)	140 x 10^6	1,300
1.5" Crusher run granite with fines (GA)	4000	1,200
¾ - 1" Granite with fines (CA)	-	6,513
#4 Washed granite (GA)	1.5 to 4.5 x 10^6	5,000
#3 Washed granite (GA)	2.6 to 3 x 10^6	100,00
Washed limestone (MI)	7 x 10^6	2,000 to 3,000
Washed granite, similar to .75" gravel	2 x 10^6	10,000
Washed granite, similar to pea gravel	40 x 10^6	5,000
#57 Washed granite (NC)	190 x 10^6	8000
Asphalt	2 to 30 x 10^6	.1 to 6 x 10^6
Concrete (oven dried, air cured is lower)	1 to 1,000 x 10^6	21 to 100

Modeling Soil

- **Three Methods Exist**
  - Uniform soil model
    - ✓ Calculations assume uniform soil
    - ✓ Requires homogeneous soil which is rare
    - ✓ Highly inaccurate for small grids where influence of top layer resistivity is more pronounced

  - Two-layer soil model
    - ✓ Uses upper soil layer of finite depth with specified resistivity
    - ✓ Includes lower soil with specified resistivity and infinite depth

  - Multilayer soil model
    - ✓ Uses more than two soil layers with different resistivities
    - ✓ Only required under circumstances not normally encountered

Bad Soil

- Some Solutions for High Resistivity Soil
  - Effectively increase the diameter of the conductors
    - ✓ The soil closest to the electrode comprises the bulk of the electrode ground resistance

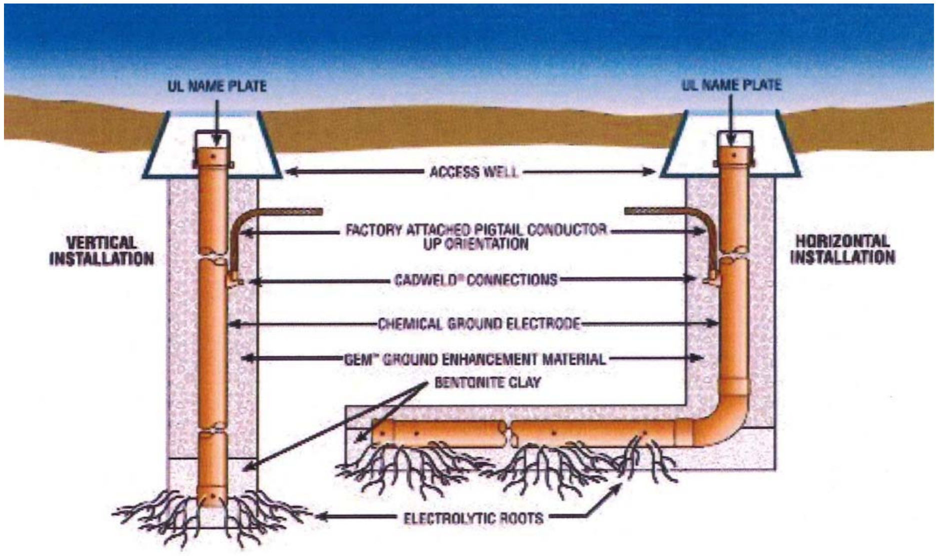
- Available methods
  - Use of salts such as sodium chloride, calcium chloride to treat soil around conductors
    - ✓ May need to be replenished
    - ✓ May be prohibited

  - Use of bentonite around conductors
    - ✓ Hygroscopic
    - ✓ Resistivity of 2.5 $\Omega \cdot m$ when wet

Bad Soil Continued

- Use of chemical electrodes
  - Porous copper tube filled with salt
  - Crammed in augured hole then back-filled

- Use of grounding enhancement material
  - Very low resistivity (5% of bentonite)
  - Contains aluminum silicates, carbon, quartz and cements
  - Claims of permanence and dry performance



Concrete and Steel

- Concrete-Encased (Ufer) Electrodes:
- Lower Resistance
  - Wire or rod in concrete has lower resistance than when directly buried

- Can corrode
  - Small DC currents can cause re-bar corrosion
  - Corroded re-bar can expand by 2.2X and damage footings
  - IEEE 80 gives a formula and a chart for predicting DC for various soil conditions

- Are required by NEC?
  - Yes, for any “building or structure served”
  - 2005 NEC didn’t really change anything
    - ✓ Replaced “if available on premises…” with “all that are present”
    - ✓ Language changed to clarify intent

Bad Soil Continued

- What About My Substation?
  - Ultimately it is up to the authority having jurisdiction.
  - The intent of the NEC passage is bonding of all present grounding to form a system
  - In my view, the intent of passage is indicated to right:

250.52(A)(1) Metal Underground Water Pipe

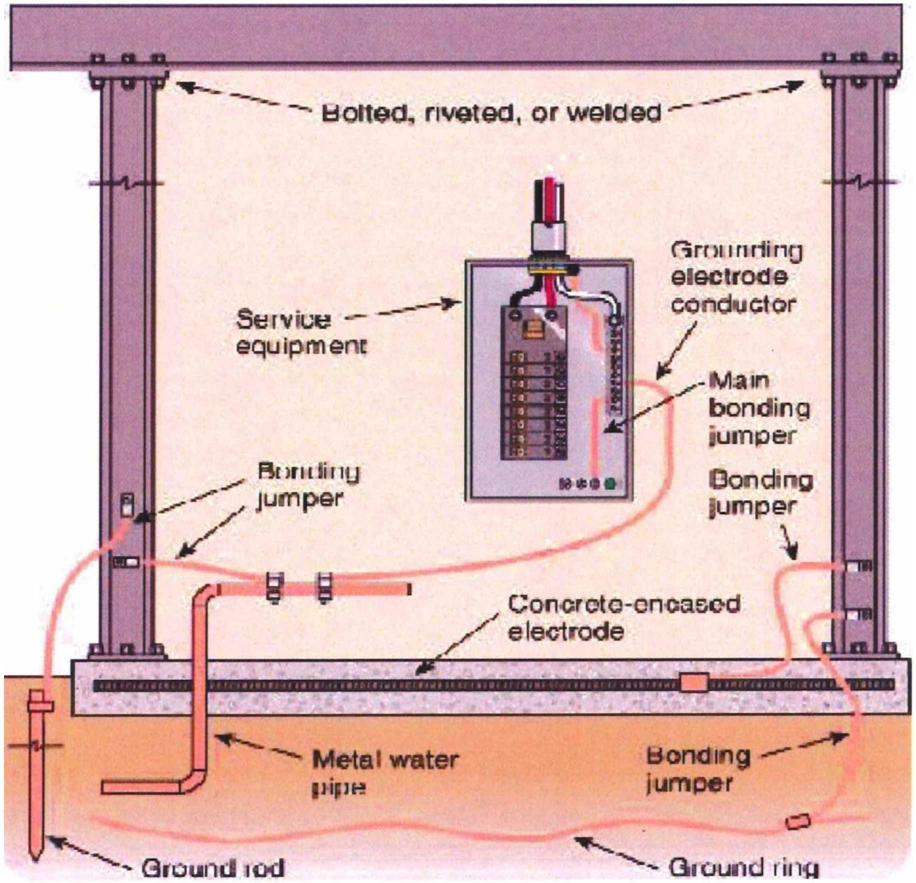
250.52(A)(2) Metal Frame of the Building or Structure

250.52(A)(3) Concrete-Encased Electrode

250.52(A)(4) Ground Ring

250.52(A)(5) Rod and Pipe Electrodes

250.52(A)(6) Plate Electrodes



Concrete and Steel

- **IEEE 80**
  - Gives equations and methodology for determining resistance of concrete encased electrode (typically a rod enclosed in a cylinder)
  - Recommends the following
    - ✓ Connect anchor bolt and angle stubs to the re-bar
    - ✓ Reduce current duty and dc leakage by making sure primary electrodes carry bulk of current
    - ✓ Use ground enhancement material in high resistivity soil around primary electrodes

Information for Modeling

- Soil Parameters
- **System Parameters**
- Conductor Properties
- Ground System Arrangement (iterative)

Determining Maximum Grid Current I_G

- Determine Type and Location of Worst-Case Fault
- Define Current Division Factor S_f
  - Define I_g
- Determine, for Each Fault, the Decrement Factor D_f
- Select the Largest Product of $D_f \, x \, I_g$

$$I_g = S_f \times I_f$$

$$S_f = \frac{I_g}{3I_0}$$

$$I_G = D_f \times I_g$$

- **Where:**

  S_f is the fault current division factor

  I_f is the rms symm. Ground fault current in A

  I_g is the rms symm. Grid current in A for a fault duration t_f

  I_0 is the zero-sequence system fault current in A

  I_G is the maximum grid current in A for a fault duration t_f

  D_f is the decrement factor in s

Assessing Type and Location of Fault

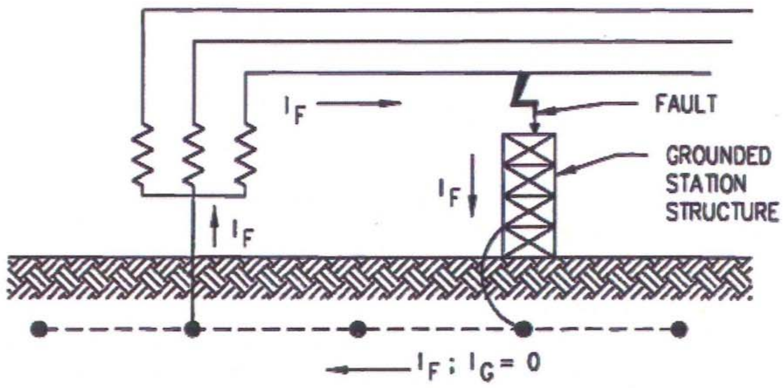


Figure 28—Fault within local substation; local neutral grounded

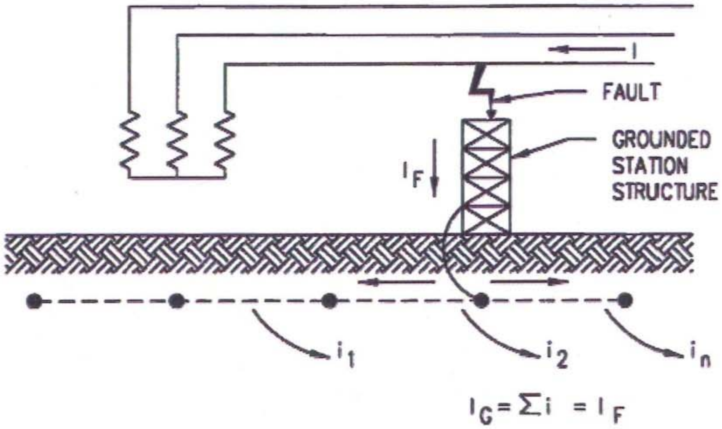


Figure 29—Fault within local substation; neutral grounded at remote location

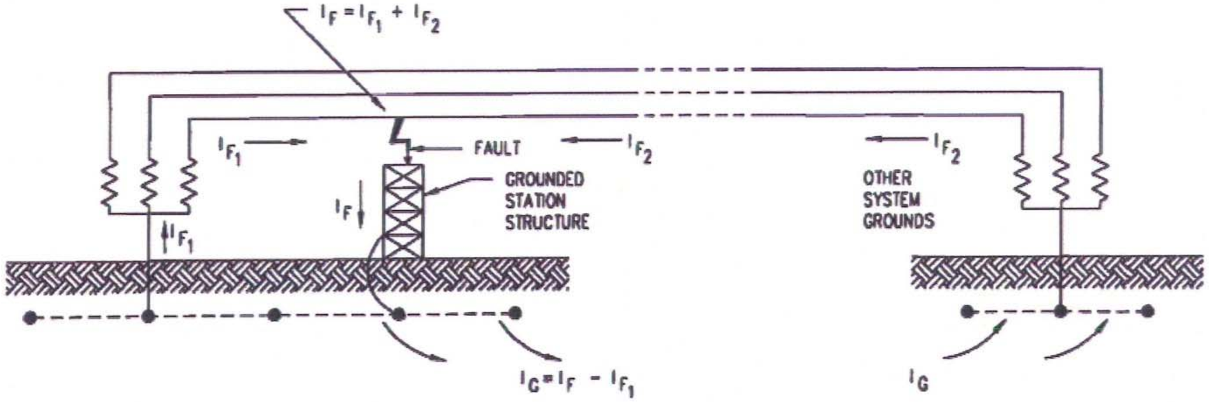


Figure 30—Fault in substation; system grounded at local substation and also at other points

Information for Modeling

- Soil Parameters
- System Parameters
- **Conductor Properties**
- Ground System Arrangement (iterative)

Selecting Grounding Components

- Grounding Materials Must:
  - Have sufficient conductivity -determined by grounding calculations
  - Resist fusing and mechanical deterioration during faults
  - Be mechanically reliable and rugged
  - Be able to maintain function when exposed to corrosion or abuse

Selecting Materials

- Typical Materials
  - Copper
    - ✓ Used for conductors and electrodes
    - ✓ Excellent conductivity
    - ✓ Resistant to underground corrosion; cathodic
    - ✓ Can contribute to corrosion of other buried objects, particularly steel (forms galvanic cell)
  - Copper-Clad Steel
    - ✓ Used for rods, typically
    - ✓ Strong, can be driven
    - ✓ Theft resistant
    - ✓ Similar cathodic properties to copper
  - Aluminum
    - ✓ Rarely used
    - ✓ Not corrosion resistant; anodic
    - ✓ Not suitable for underground application per ANSI C2
  - Steel
    - ✓ Infrequently used for conductors and electrodes
    - ✓ Should be galvanized
    - ✓ May need cathodic protection

More on Sizing

- IEEE 80 Containing Charts for the Variables Based On Conductor Type

  From these charts, it can be determined that:

$$A_{kcmil} = \mathrm{I} \cdot K_f \sqrt{t_c}$$

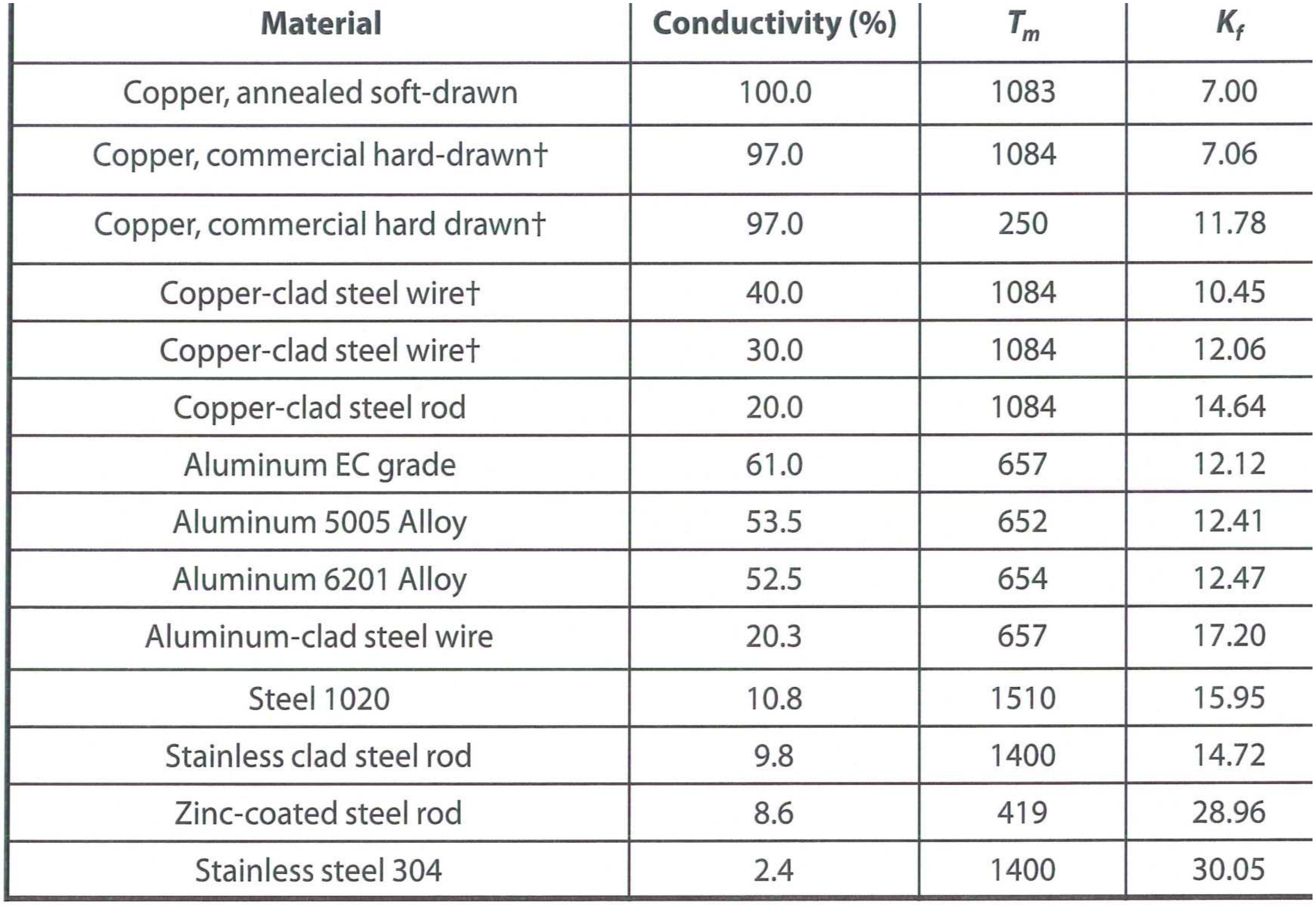
Where:

A_{kcmil} is the area of the conductor

t_c is the duration of the current

K_f is a constant from Table 2 in IEEE 80 at various values of T_m (see next)

Material Constants



Material	Conductivity (%)	T_m	K_f
Copper, annealed soft-drawn	100.0	1083	7.00
Copper, commercial hard-drawn†	97.0	1084	7.06
Copper, commercial hard drawn†	97.0	250	11.78
Copper-clad steel wire†	40.0	1084	10.45
Copper-clad steel wire†	30.0	1084	12.06
Copper-clad steel rod	20.0	1084	14.64
Aluminum EC grade	61.0	657	12.12
Aluminum 5005 Alloy	53.5	652	12.41
Aluminum 6201 Alloy	52.5	654	12.47
Aluminum-clad steel wire	20.3	657	17.20
Steel 1020	10.8	1510	15.95
Stainless clad steel rod	9.8	1400	14.72
Zinc-coated steel rod	8.6	419	28.96
Stainless steel 304	2.4	1400	30.05

†Different alloys as shown in Table 2 of IEEE 80

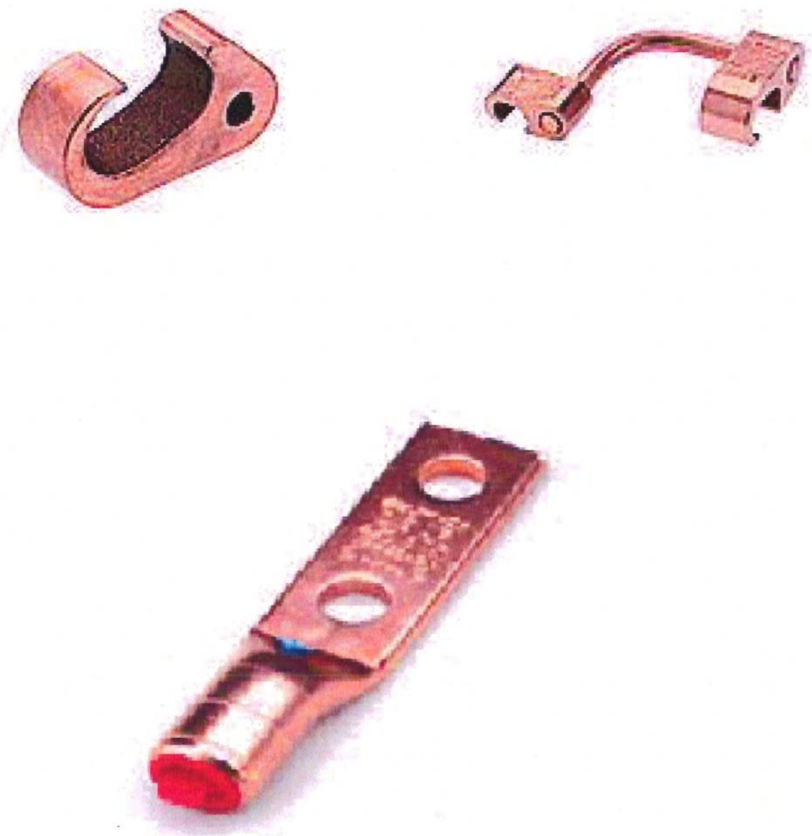
Types of Connectors

- Typical Connector Types
  - Compression
  - Exothermic
  - Mechanical

- Some Considerations
  - Will this need to be removed?
  - Does my connector need to be tested per IEEE 837?
  - Are special permits or precautions required at the site?
  - Where is the connection going to be located?

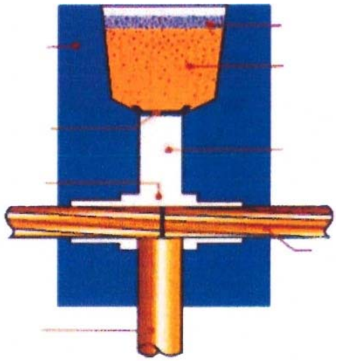
Connections

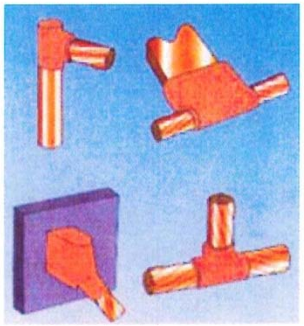
- **Compression**
  - Typically applied with portable hydraulic compression tool
  - Wide applicability, e.g.
    - ✓ Cable to cable
    - ✓ Cable to rod or re-bar
    - ✓ Cable to terminal
    - ✓ Can be used
      - Above grade
      - Below grade
      - In concrete
  - Irreversible
  - Manufacturer's tout
    - ✓ Safety versus exothermic
    - ✓ Strength
    - ✓ Conductivity
    - ✓ Irreversibility



Connections

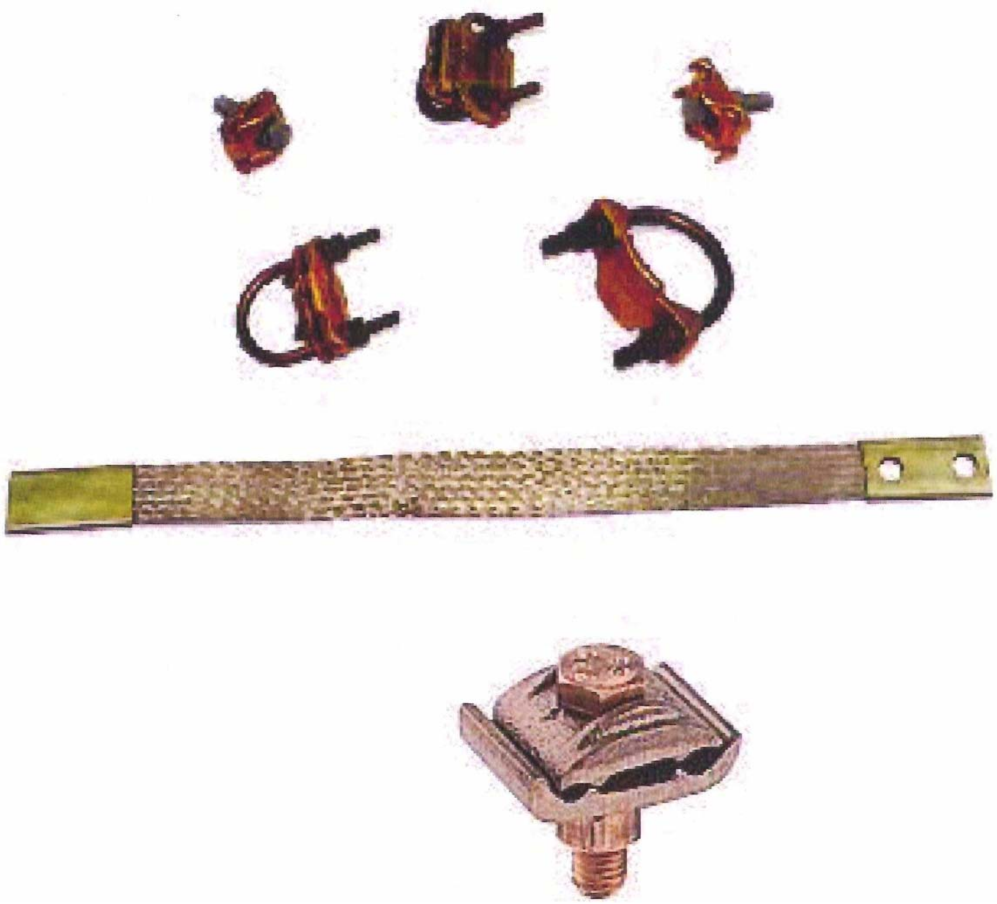
- **Exothermic**
  - Installed using mold (graphite for multi-use, ceramic for single use), weld powder (shot) and a flint igniter
  - Wide applicability, e.g.
    - ✓ Cable to cable
    - ✓ Cable to rod or re-bar
    - ✓ Cable to virtually anything
    - ✓ Locations
      - Above grade
      - Below grade
      - In concrete
    - ✓ Irreversible
    - ✓ Manufacturer's tout
      - Strength
      - Conductivity
      - Irreversibility
  - Some plants require hot work permit – releases energy





Connections

- **Mechanical**
  - Bolted, typically copper or bronze fittings, often tin plated
  - Varied applicability:
    - Cable to cable
    - Cable to rod or re-bar
    - Locations
      - Above grade
      - Below grade
      - In concrete
  - Reversible
  - Manufacturer's tout
    - Ease of installation
    - Conductivity
    - Irreversibility



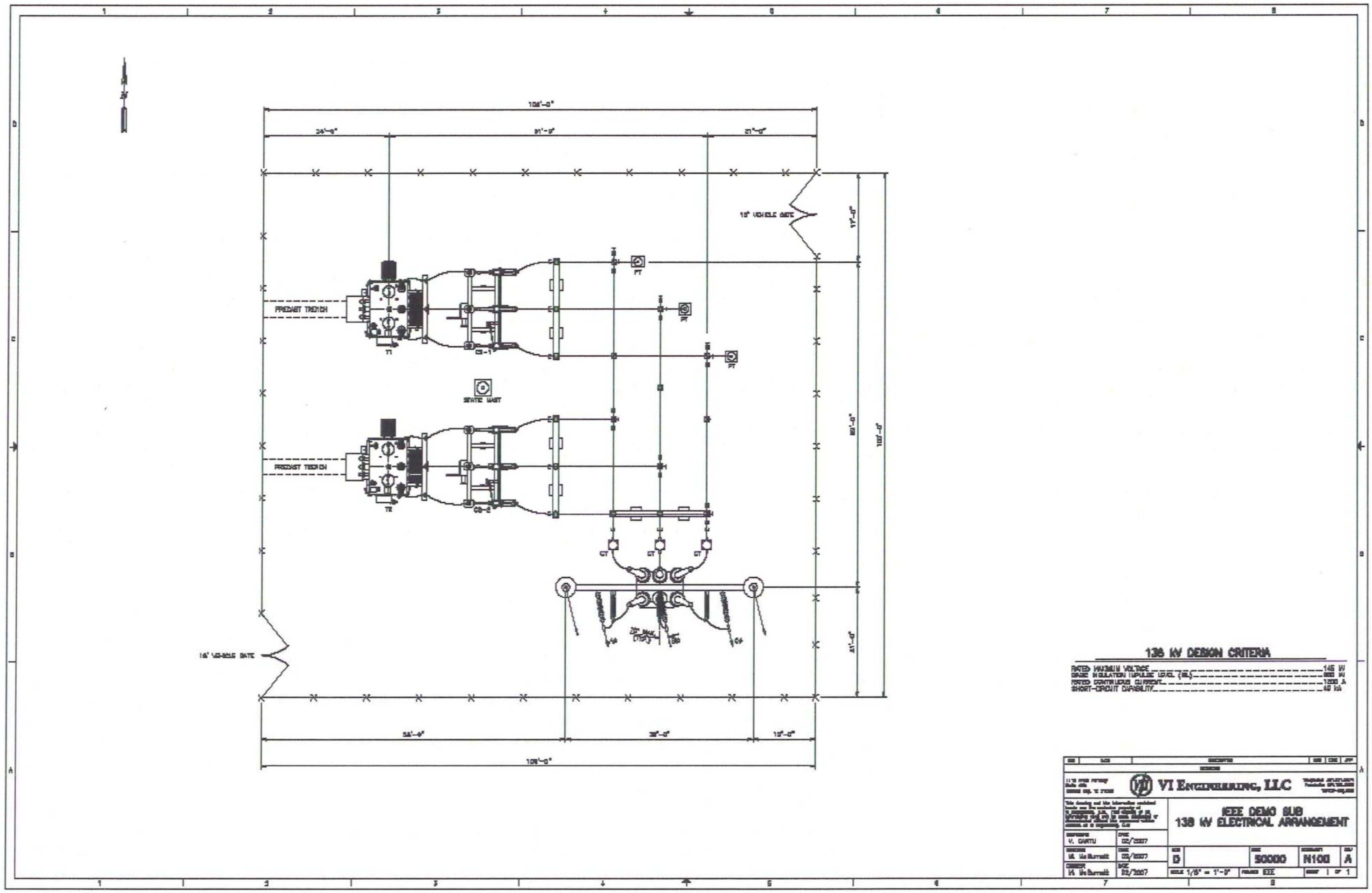
The IEEE 80 Twelve-Step Method

1. Determine Area From Layout, Determine Soil Resistivity
2. Determine Minimum Conductor Size
3. Calculate Tolerable Step and Touch Potential
4. Lay Out Preliminary Substation Grid, Loop Around Yard, Sufficient Equipment Taps
5. Determine Preliminary Resistance of Grounding System
6. Determine Grid Current
7. Determine GPR; If Less than Tolerable Touch Voltage, Done; Otherwise:
8. Calculate Mesh and Step Voltages.
9. If Mesh Voltage is Below Tolerable Touch Voltage, Done; Otherwise:
10. Check Step Voltage. If Below Tolerable Level, Done; Otherwise:
11. Revise Grid
12. Complete Detailed Design

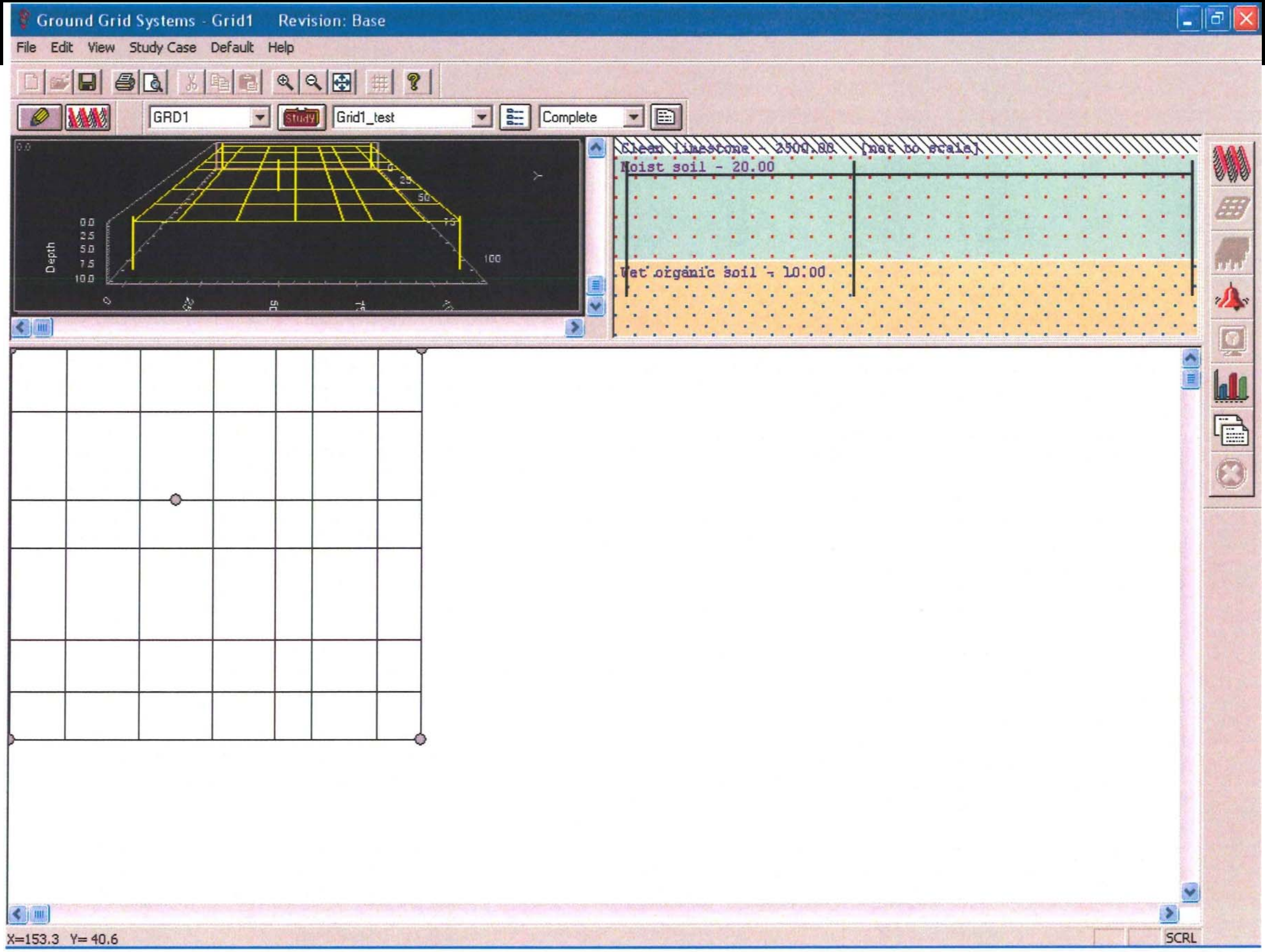
Information for Modeling

- Soil Parameters
- System Parameters
- Conductor Properties
- **Ground System Arrangement (iterative)**

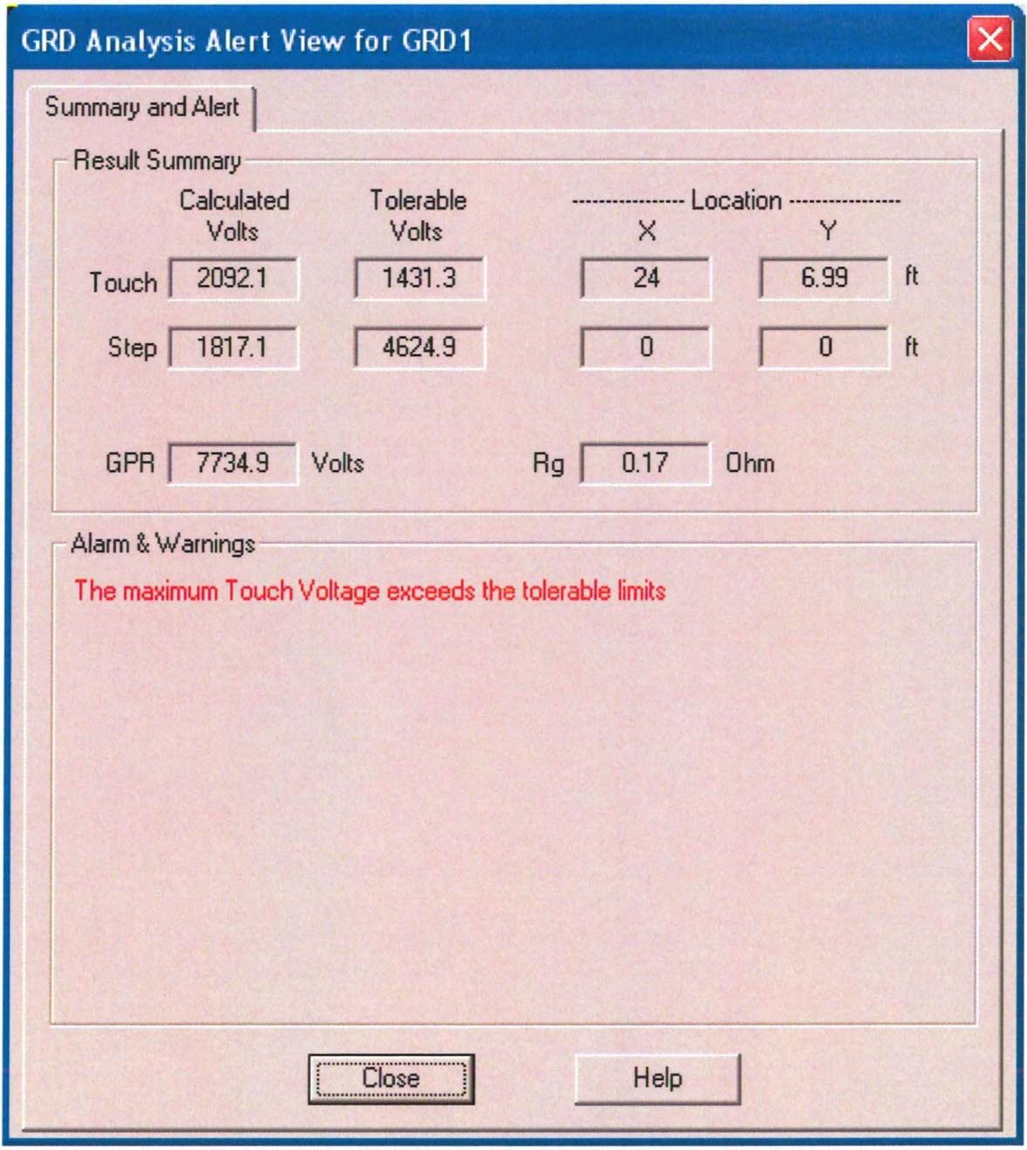
Sample Grid


108'-0"
24'-0"
21'-0"
16' VEHICLE GATE
PT
PT
PT
PRECAST TRENCH
T1
CS-1
STATIC MAST
PRECAST TRENCH
T2
CS-2
CT
CT
CT
16' VEHICLE GATE
17'-0"
100'-0"
41'-0"
38'-0"
13'-0"
108'-0"
138 kV DESIGN CRITERIA
RATED MAXIMUM VOLTAGE — 145 kV
BASIC INSULATION IMPULSE LEVEL (BIL)
RATED CONTINUOUS CURRENT — 1200 A
SHORT-CIRCUIT CAPABILITY — 40 kA
VI ENGINEERING, LLC
IEEE DEMO SUB
138 kV ELECTRICAL ARRANGEMENT
V. CARTU 02/2007
M. McBurnett 02/2007
M. McBurnett 02/2007
D
50000
N100
A
SCALE 1/8" = 1'-0"
IEEE
SHEET 1 OF 1

Initial Grid



It Didn't Work (As Expected)



Result Summary

	Calculated Volts	Tolerable Volts	Location X	Location Y	
Touch	2092.1	1431.3	24	6.99	ft
Step	1817.1	4624.9	0	0	ft

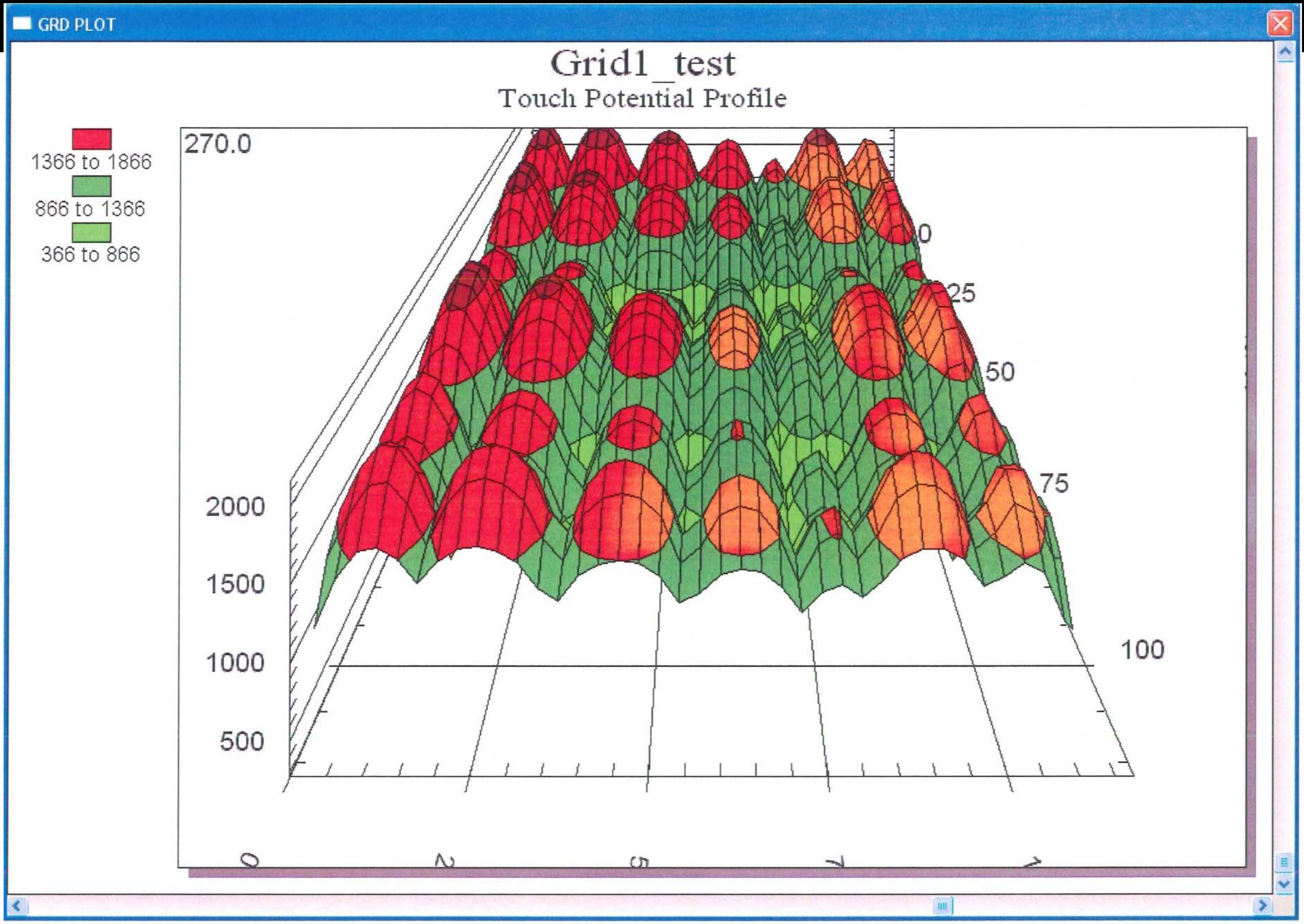
GPR 7734.9 Volts

Rg 0.17 Ohm

Alarm & Warnings

The maximum Touch Voltage exceeds the tolerable limits

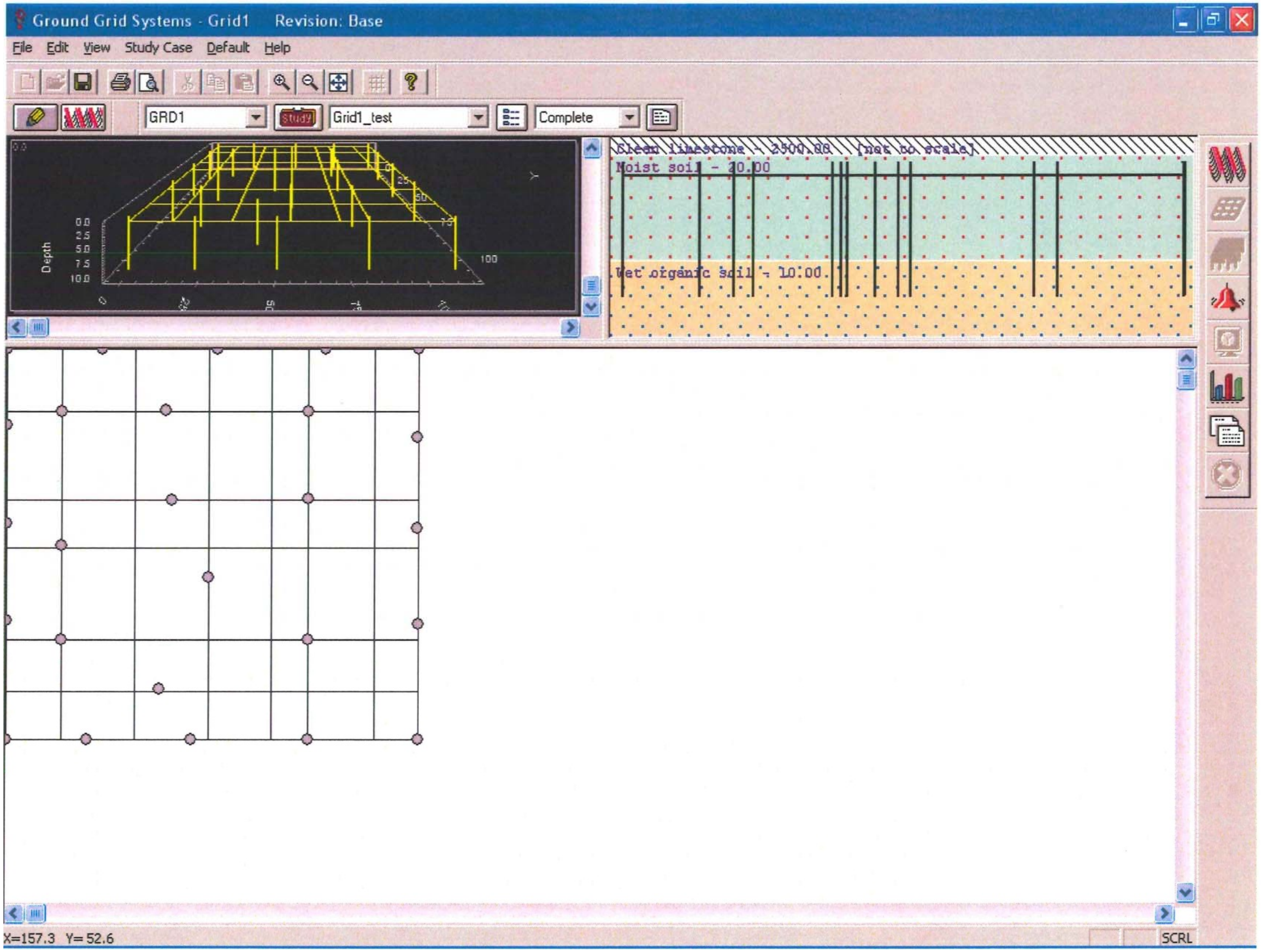
How Do I Fix It? – Examine Profile



Enhance Design

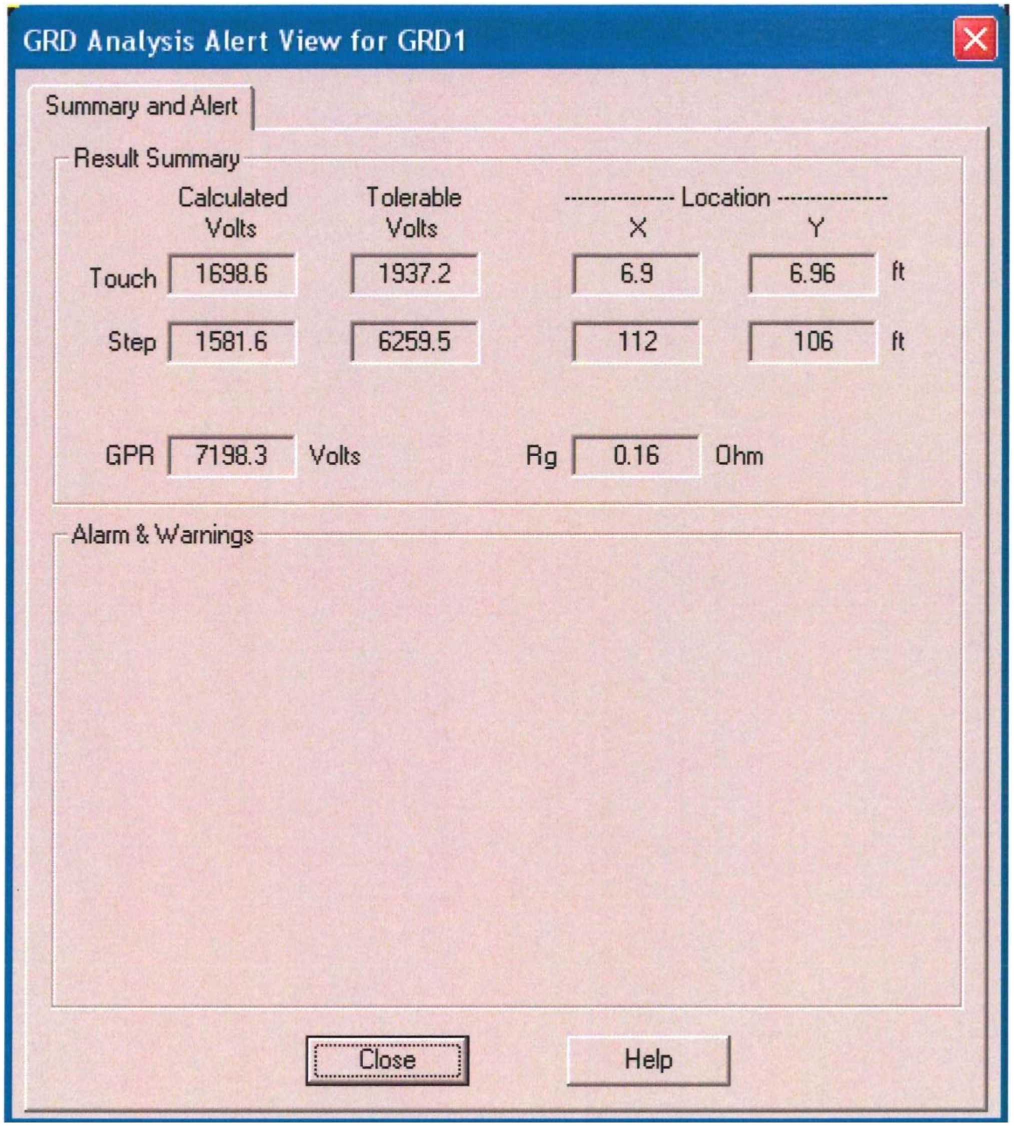
- Numerous Areas Over Touch Limit
- What Can Be Done?
  - Relaying can be modified to clear faults more quickly
  - A more accurate value for S_f can be determined
  - Rods can be added or lengthened
  - Conductor can be added
  - GEM can be added
  - Grid depth can be adjusted
- What Can Be Done for This Grid?
  - Solution based on experience and feel
  - The lower soil is less resistive in this case so let's add rods
  - The sub is small so it is understood that grid spacing will be tight so we could add copper
  - S_f can be adjusted. This sub is connected with two static wires. Transformers have delta primaries.

New Grid


Ground Grid Systems - Grid1 Revision: Base
File Edit View Study Case Default Help
GRD1
Study
Grid1_test
Complete
Depth
0.0
2.5
5.0
7.5
10.0
100
Clean limestone - 2500.00 [not to scale]
Moist soil - 20.00
Wet organic soil - 10.00
X=157.3 Y= 52.6
SCRL

Success! Imagine Doing it by Hand

(modified arrangement and use 70 kG criterion)



Result Summary

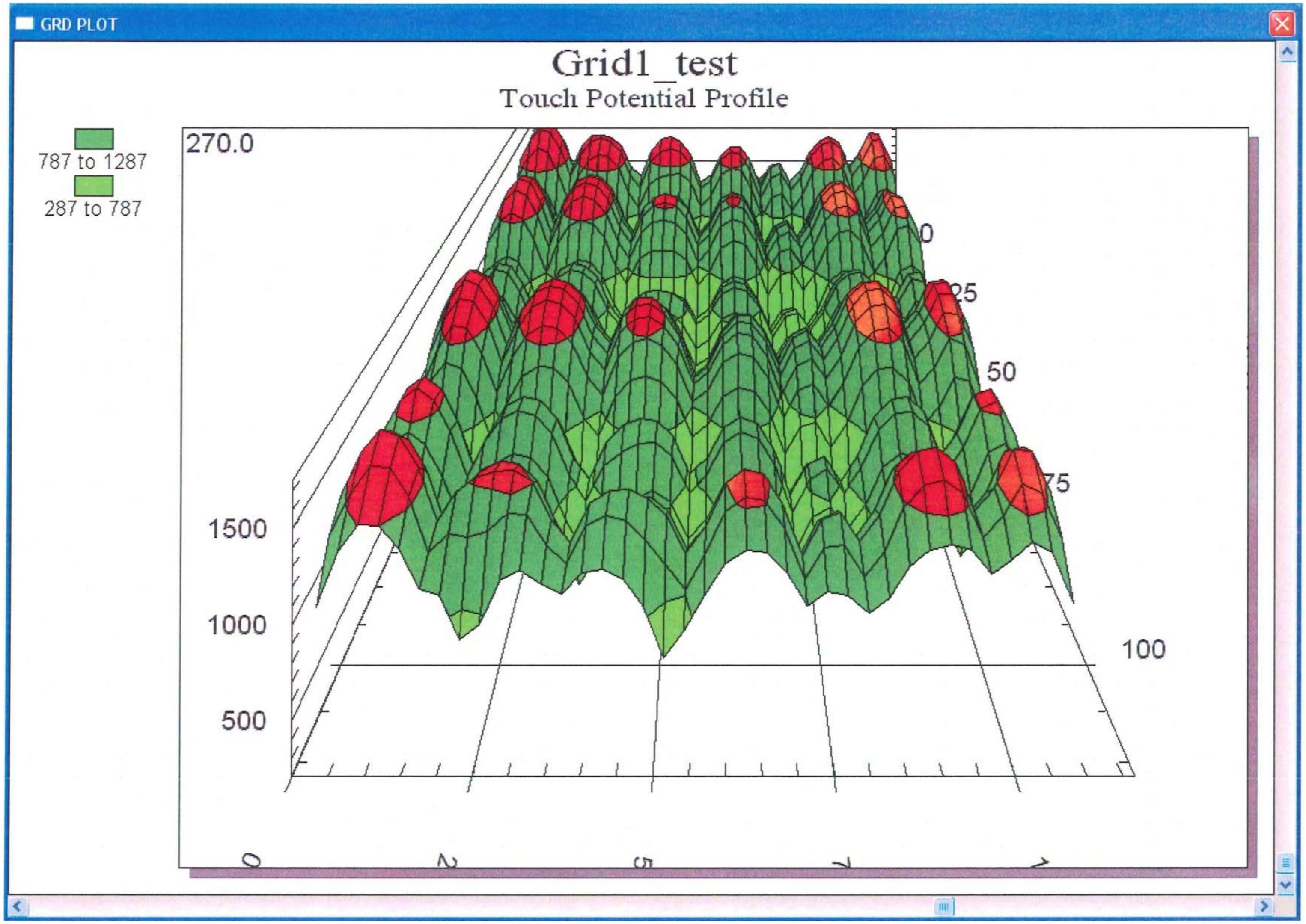
	Calculated Volts	Tolerable Volts	Location X	Location Y	
Touch	1698.6	1937.2	6.9	6.96	ft
Step	1581.6	6259.5	112	106	ft

GPR 7198.3 Volts

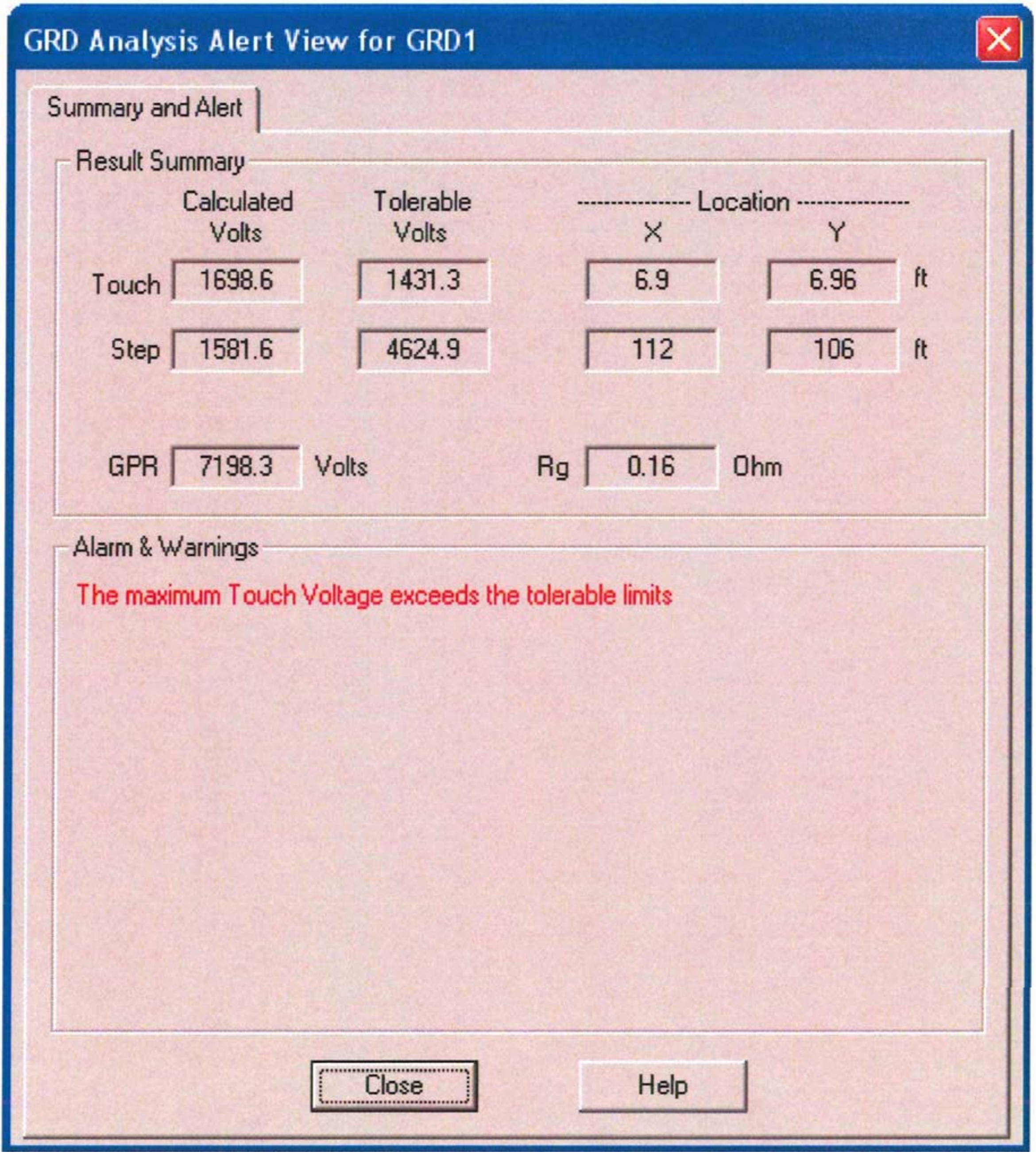
Rg 0.16 Ohm

Alarm & Warnings

Finished


GRD PLOT
Grid1_test
Touch Potential Profile
787 to 1287
287 to 787
270.0
0
25
50
75
100
1500
1000
500
0
2
5
7

Same Grid, 50 kG Criterion



Result Summary

	Calculated Volts	Tolerable Volts	Location X	Location Y	
Touch	1698.6	1431.3	6.9	6.96	ft
Step	1581.6	4624.9	112	106	ft

GPR 7198.3 Volts

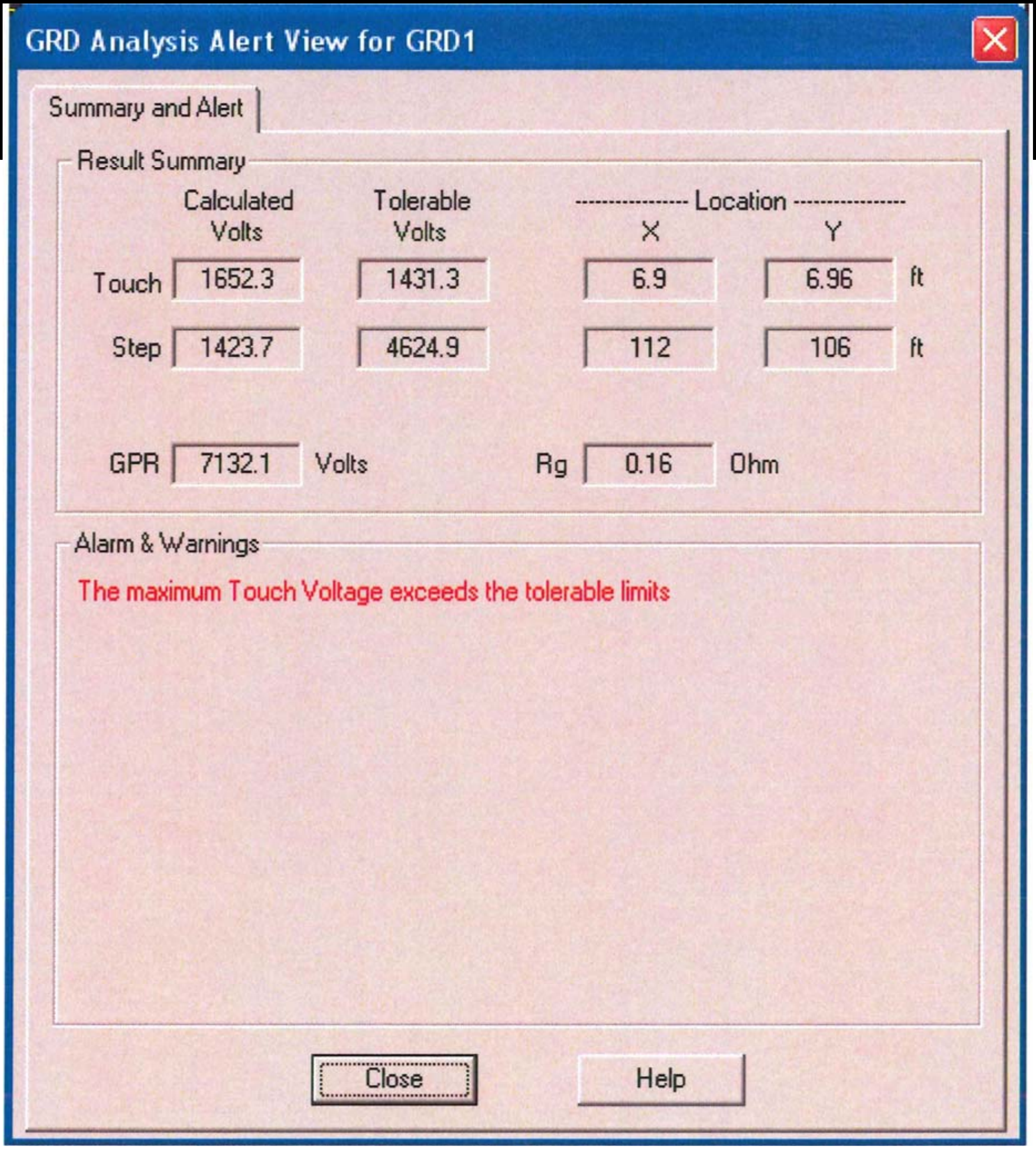
Rg 0.16 Ohm

Alarm & Warnings

The maximum Touch Voltage exceeds the tolerable limits

Same Grid

with 2' Surfacing



Result Summary

	Calculated Volts	Tolerable Volts	Location X	Location Y	
Touch	1652.3	1431.3	6.9	6.96	ft
Step	1423.7	4624.9	112	106	ft

GPR 7132.1 Volts

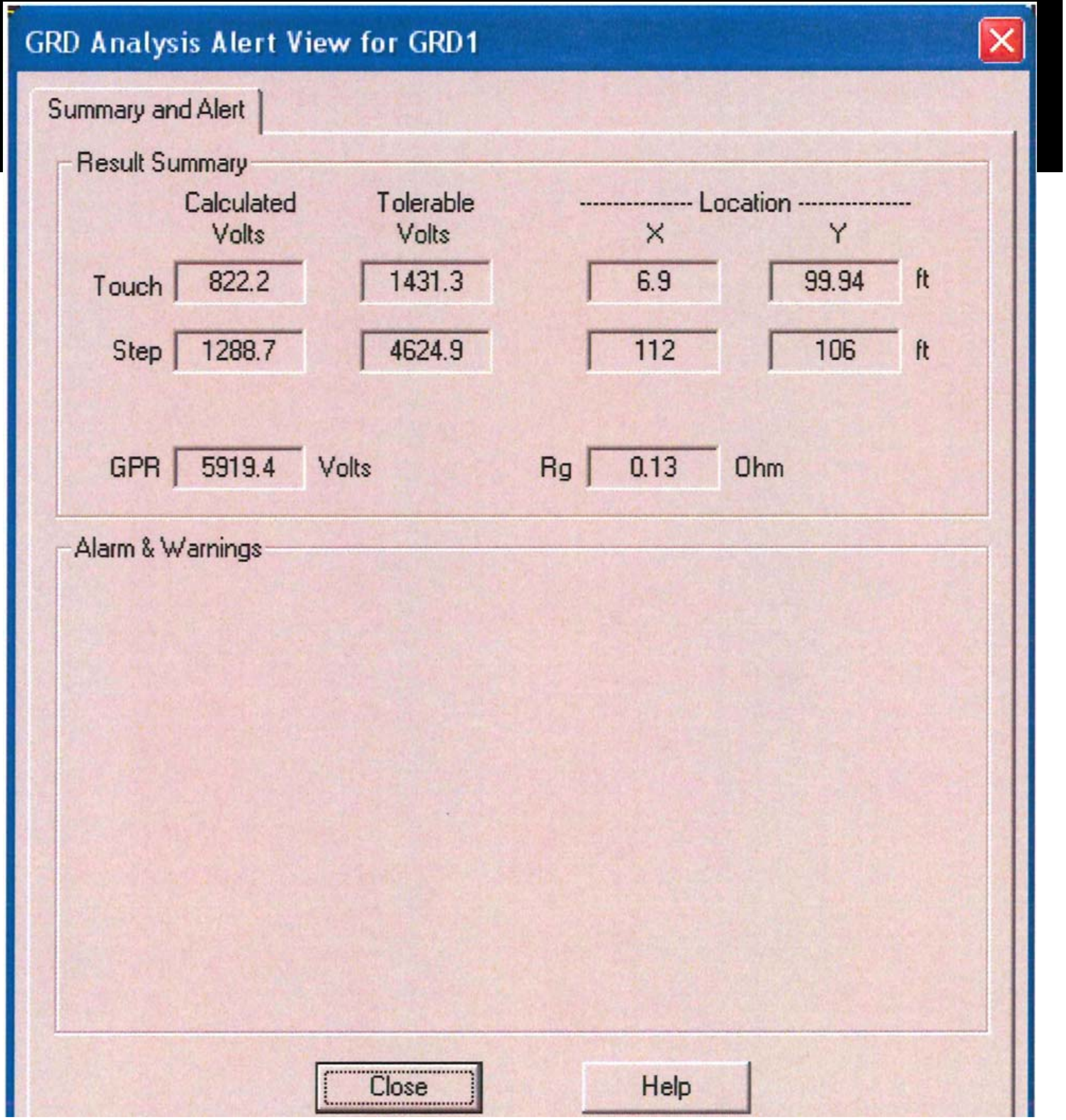
Rg 0.16 Ohm

Alarm & Warnings

The maximum Touch Voltage exceeds the tolerable limits

Same Grid

with 20' Ground Rods



GRD Analysis Alert View for GRD1

Summary and Alert

Result Summary

	Calculated Volts	Tolerable Volts	Location X	Location Y	
Touch	822.2	1431.3	6.9	99.94	ft
Step	1288.7	4624.9	112	106	ft

GPR 5919.4 Volts

Rg 0.13 Ohm

Alarm & Warnings

Possible Problems and Solutions

- Problems
  - Poor soil
  - Small area
  - High fault current
  - Oddly shaped grids
  - Long fault clearing time

- Solutions
  - More copper (grid, rods)
  - Ground enhancement material
  - Take close look at static connections
  - Faster relaying
  - Deeper grid
  - More surfacing
  - Different surfacing
  - Other methods (explosives with fill, deep well grounds)

Problems Areas

- Non “Substation” Stuff (e.g. storage areas) Within or Near Substation
  - Check step and touch voltages
  - Extend grid or isolate
- Disconnect Switch Handles
  - Problems
    - ✓ Ionized air will be present, facilitates potential fault
    - ✓ Touch voltage hazard routinely present
    - ✓ Insulator or mechanical failure
  - Possible solutions
    - ✓ Install operator platform
    - ✓ Bond platform to switch handle and grid
  - Transformer Oil Containment
    - ✓ Different surfacing (e.g. concrete)
    - ✓ Possible solutions
      - Asphalt
  - Control Building
    - ✓ Problems
      - Concrete instead of rock
      - Possibly difficult to route conductors underneath
  - Possible Solutions
    - ✓ Examine exposure –is touch voltage actually a problem?
    - ✓ Ground foundation and do calculations
    - ✓ Use frameless metal building on piers and extend grid under building

Fence Grounding

- Substation Fence
  - Problems
    - ✓ Serious touch voltage hazard
    - ✓ Frequently accessible to public
    - ✓ Various installation scenarios
      - Fence within grid area and connected to grid
      - Fence outside grid area and connected to grid
      - Fence outside the grid area but grounded separately
      - Fence outside grid area and grounded only through posts
- IEEE 80 Goes Into Great Detail About Fences – Here's the Skinny
  - Extend ground grid outside the fence (3' works well)
    - ✓ Greatly helps with touch potential
    - ✓ If touch potential is okay, step should work
  - Install isolating sections between substation fence and other fence
    - ✓ Substation fence must be isolated from plant perimeter fence
    - ✓ Multiple isolating sections work even better

GIS Continued

- IEEE 80 Gives a Cursory Glance at GIS
  - Definitions
  - Special problems
    - ✓ Small size
    - ✓ High-frequency transients

- Circulating Currents
  - Induced voltages from current flow in phase conductor
  - Continuous vs. non-continuous enclosures

- Foundations
  - General Rule –Include the slab

- Summary
  - Follow manufacturer's instructions

Testing Ground Systems

- Defined in IEEE 81
- Compare Results to Calculated Values
- Methods of Testing
  - Two-point method
    - ✓ Resistance of system and an auxiliary ground
    - ✓ Not particularly accurate
- Three-point method
  - Uses two test electrodes and one station ground
  - Inaccurate for large substations
- Staged-fault tests
  - High-current test –Inject current then measure voltage
- Fall-of-potential method
  - Measure resistance of system relative to remote electrode
  - Most widely used

The End