

Safety by Design- Neutral Grounding Methods to Reduce Risk of Arc Flash

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Equipment Grounding and Bonding - Introduction

- Electrical Code objectives- protection against electric shock and property damage
- Limiting circuit voltages
- Limiting 150 volts or less for interior wiring
- Limit ground voltages

Grounding and Bonding

- Ground: Provides a common electrical reference point.
- By connecting a point in the supply source to the ground it is ensured that any other point of the system stays at a certain potential with reference to the ground

Grounding and Bonding

- Equipment ground (bonding) must be a permanent, continuous, low-impedance bonding between ground and all enclosures and frames.
- Electrical system grounding: Electrical systems that are grounded shall be connected to earth in a manner that will limit the voltage imposed by lightning, line surges, or unintentional contact with higher voltage lines and that will stabilize the voltage to earth during normal operation.

Bonding

Static charge drains through ground bond

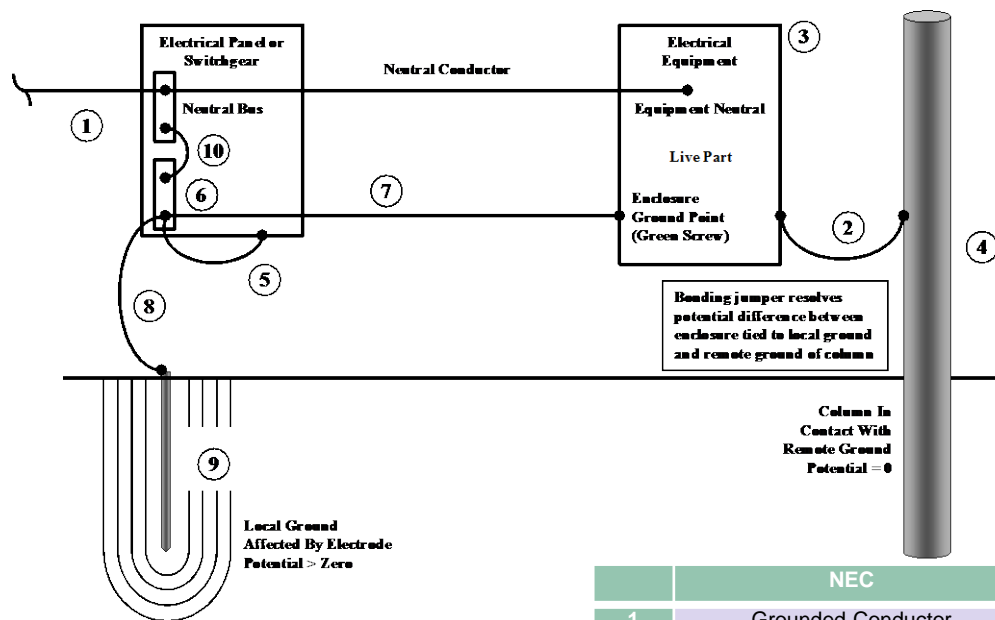
- **Absence of Bonding will cause potential difference to exist between different enclosures or local ground reference points causing problems for sensitive electronic equipment.**
- **The potential difference can break down insulation, cause sparks or become safety hazard from touch potential**
- It provides low impedance path for accumulated static charges and surges caused by lightening or electrical switching ensuring that no damage to equipment or personnel is caused by them

Bonding

- Bonding: Connecting metallic enclosures to ground ensures that the enclosures stays at ground potential thus remains safe to touch
- Ensure that metallic electrical equipment enclosures, metal/raceways, cable armour and sheaths are bonded to a common point and to ground. To avoid potential differences between exposed metal and grounded surfaces
- Bonding methods include conductors, metallic cable sheaths and metal raceways
- Minimizes the risk of current flow through the body on contact
- Ensures that sufficient current will flow to operate promptly protective devices to remove the electrical faults

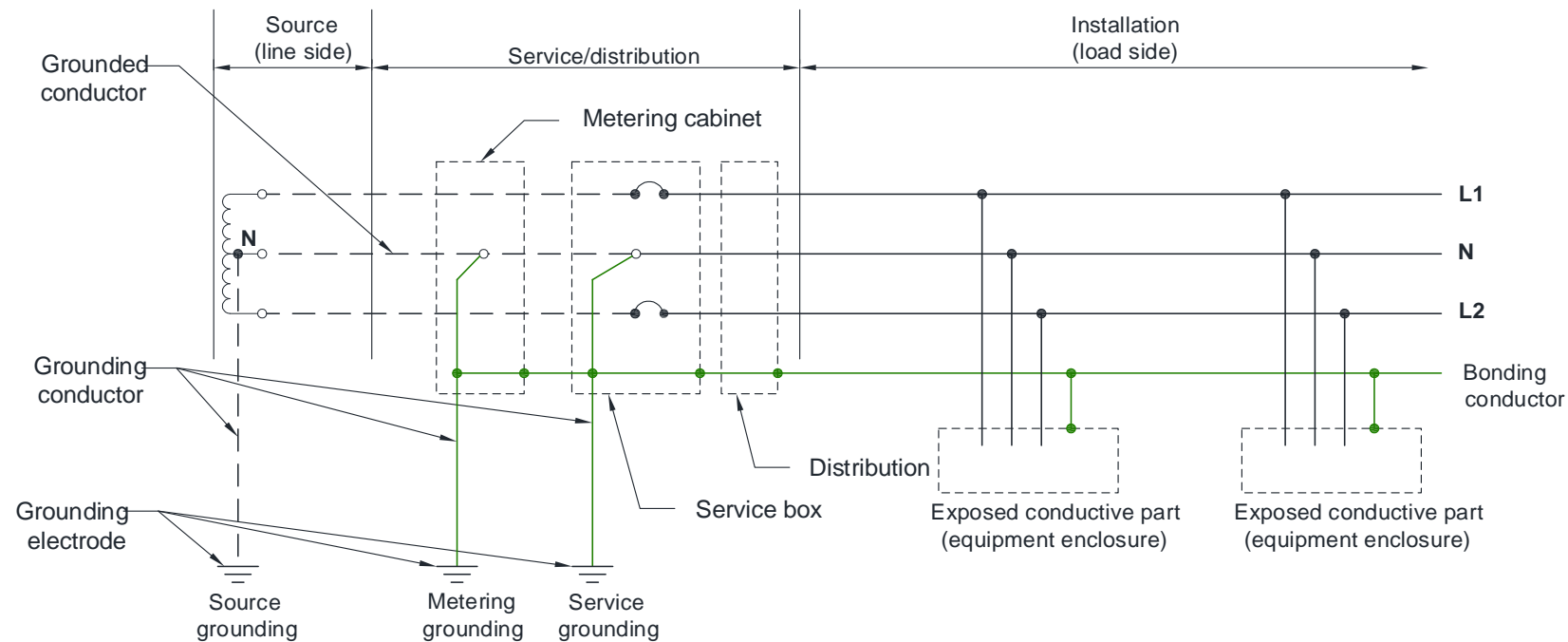
Definitions

- **Grounding and Bonding-** System Grounding and Equipment Grounding
- **Equipment Grounding Conductor-** Conductor used to connect the service equipment to the ground electrode
- **System Grounding Conductor-** Conductor used to connect the System to the ground electrode
- **Grounding electrode-** A buried metal object or water-piping system or device buried in or driven in to the ground so as to make intimate contact there with to which a grounding conductor is electrically and mechanically connected.
- **Bonding-** A low impedance path obtained by permanently joining all non current carrying parts to assure electrical continuity and having the capacity to conduct safely any current likely to be imposed on it.
- **Bonding Conductor-** A conductor that connects the non current carrying parts of electrical equipment, raceway or enclosure to the service equipment or system grounding conductor



	NEC	IEC	CEC
1	Grounded Conductor	Protective Earth Neutral (PEN)	Grounded Conductor
2	Bonding Conductor or Jumper	Bonding Jumper	Bonding Conductor
3	Conductive Electrical Equipment Enclosure	Exposed Conductive Parts	Non-Current carrying metal parts
4	Building Steel, Metal Fence, Metal Pipe	Extraneous Conductive Part	Building Steel, Metal Fence, Metal Pipe
5	Equipment Bonding Jumper	Equipment Bonding Jumper	Bonding Conductor
6	Ground Bus	Earthing Bus	Ground Bus
7	Equipment Grounding Conductor(EGC)	Protective Earth Conductor(PE)	Grounding Conductor
8	Grounding Electrode Conductor (GEC)	Earthing Electrode Conductor	Grounding Conductor
9	Grounding Electrode	Earth Electrode	Grounding Electrode
10	Main Bonding Jumper	Main Bonding Jumper	Grounding Conductor

North American Terminology

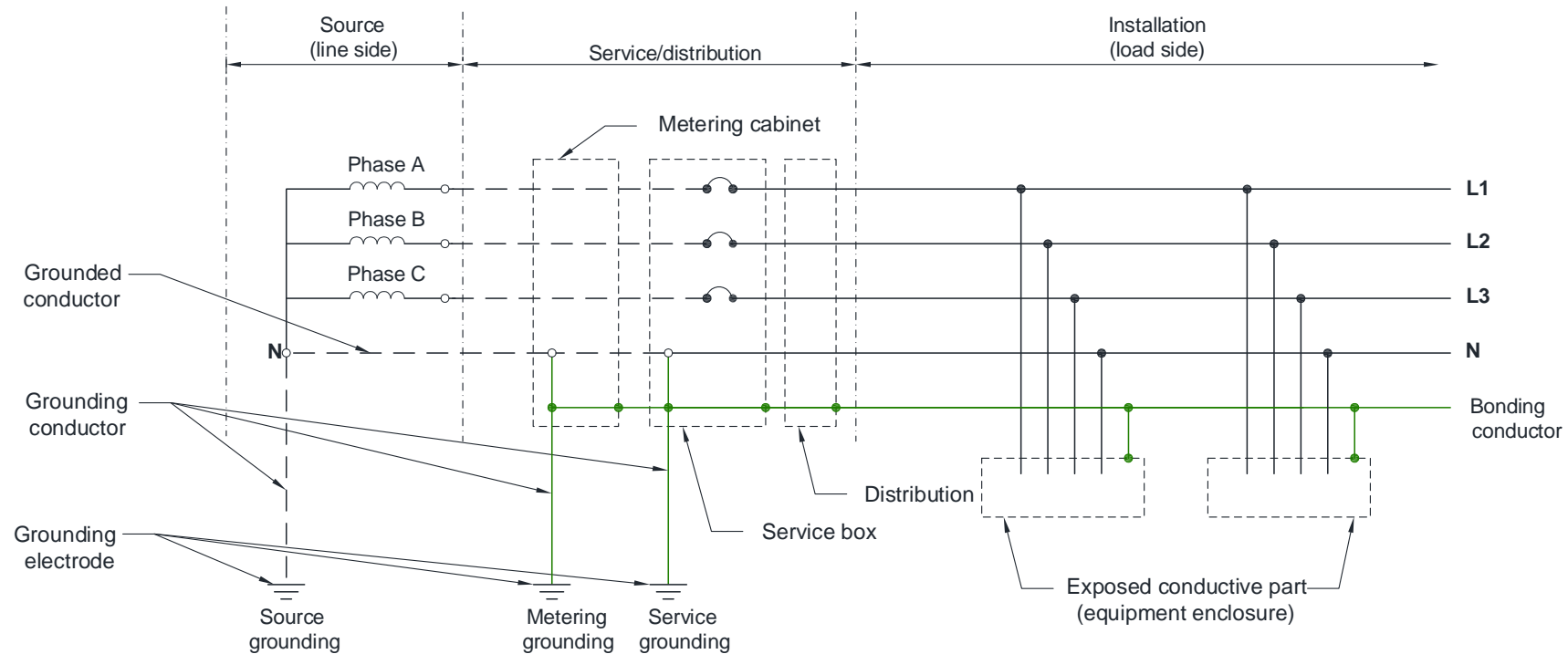


Notes:

- (1) Neutral and bonding conductor functions are combined in a single conductor (system grounded conductor) on the line side of the service
- (2) Neutral (grounded circuit conductor) and bonding conductor functions are separate on the load side of the service

Single-phase, 3-wire solidly grounded system (midpoint grounded)

North American Terminology

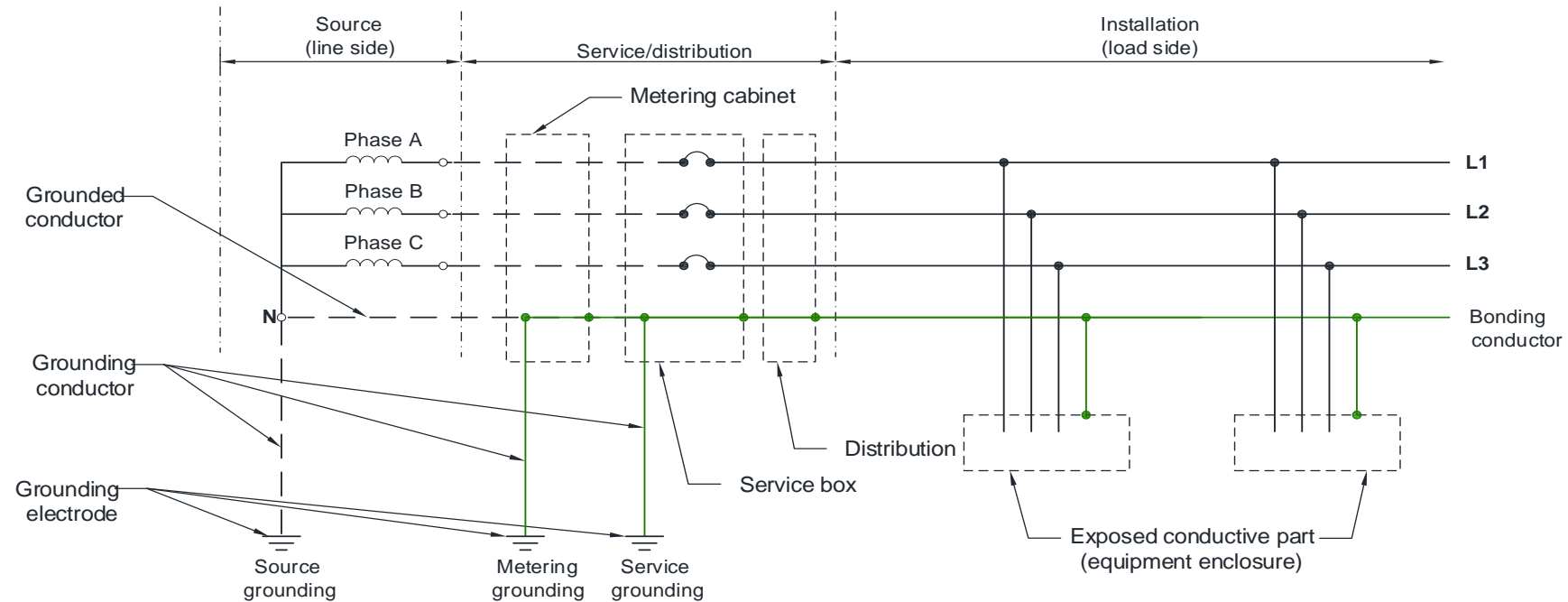


Notes:

- (1) Neutral and bonding conductor functions are combined in a single conductor (system grounded conductor) on the line side of the service.
- (2) Neutral (grounded circuit conductor) and bonding conductor functions are separate on the load side of the service.

Three-phase, 4-wire solidly grounded system

North American Terminology

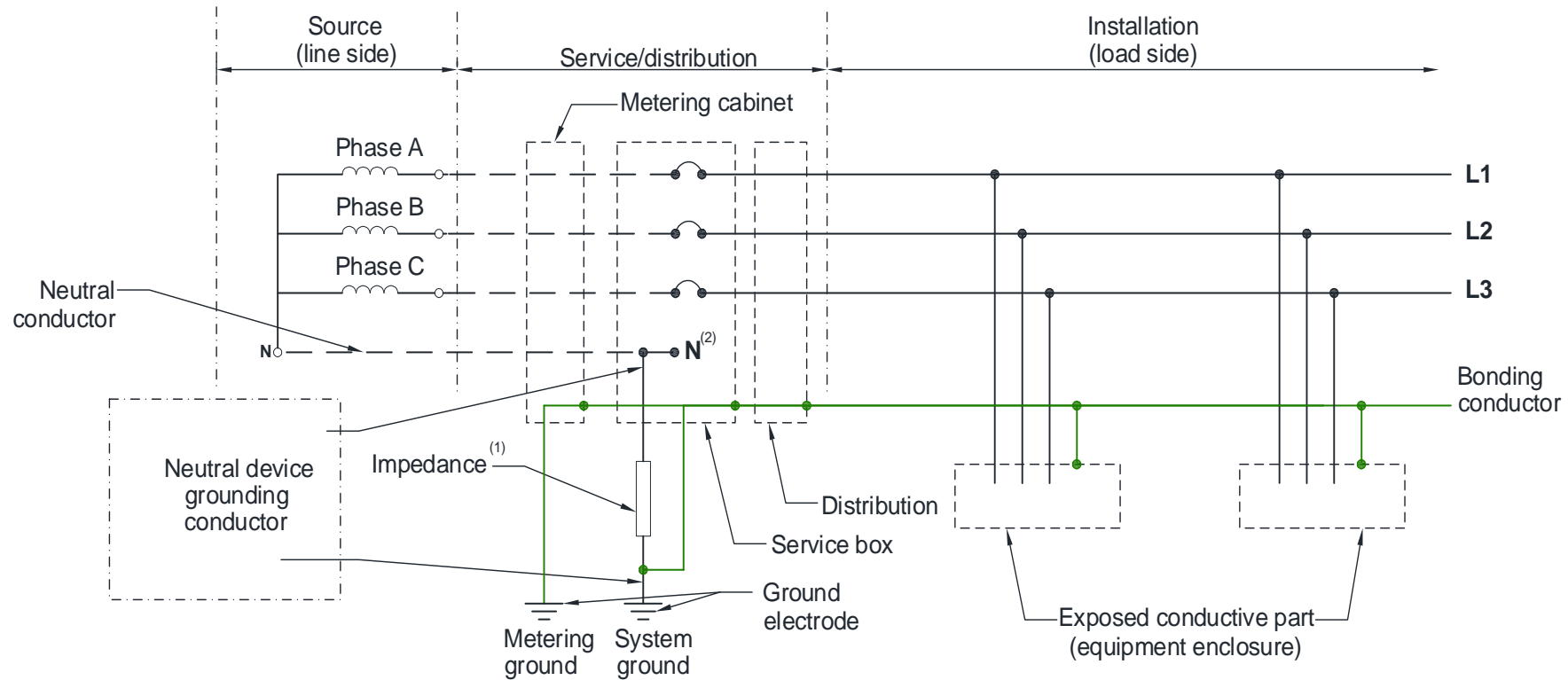


Notes:

- (1) The grounded conductor on the load side of the service functions as a bonding conductor with no distributed neutral throughout the system.
- (2) The grounded conductor on the line side of the service (system grounded conductor) with no neutral currents is sized as specified for bonding conductors

Three-phase, 4-wire solidly grounded system with no neutral load (3-wire on load side)

North American Terminology

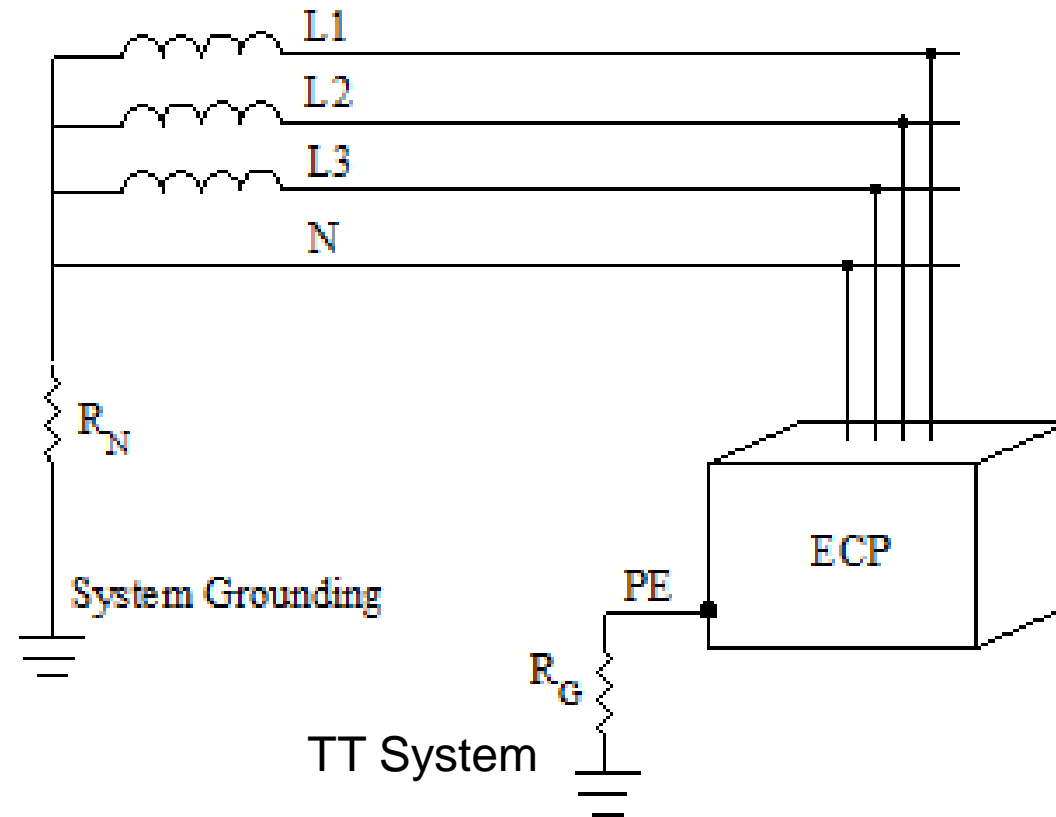


Notes:

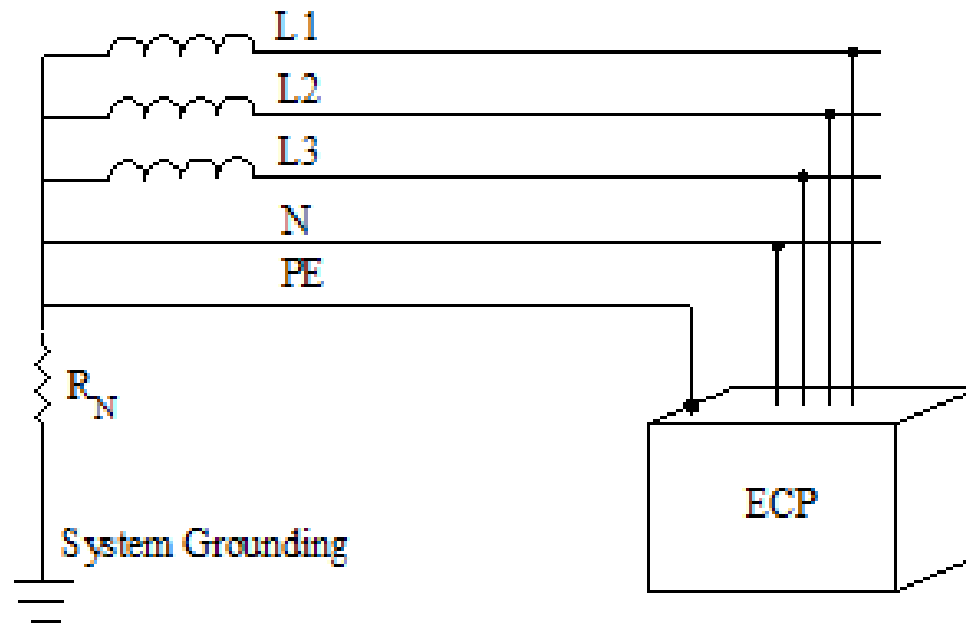
- (1) System connected to ground via sufficiently high impedance.
- (2) The neutral may or may not be distributed.
- (3) See Subsection "Installation of neutral grounding devices"

Three-phase, 4-wire impedance grounded system

IEC Terminology

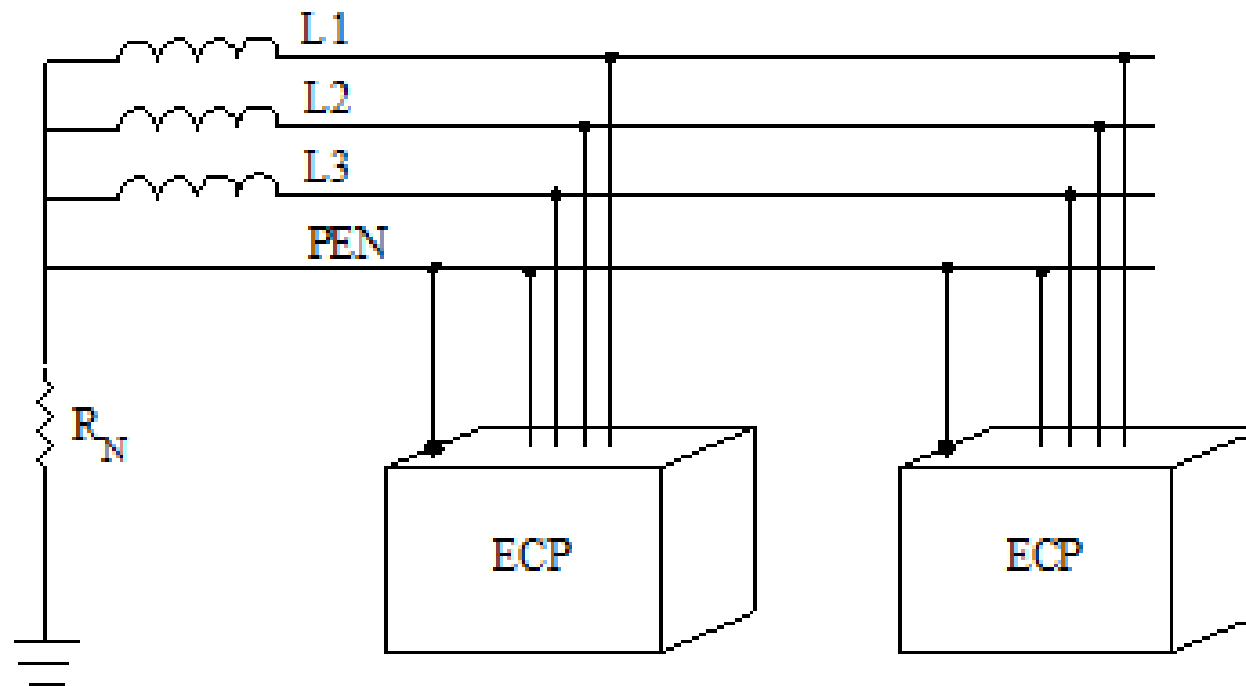


IEC Terminology



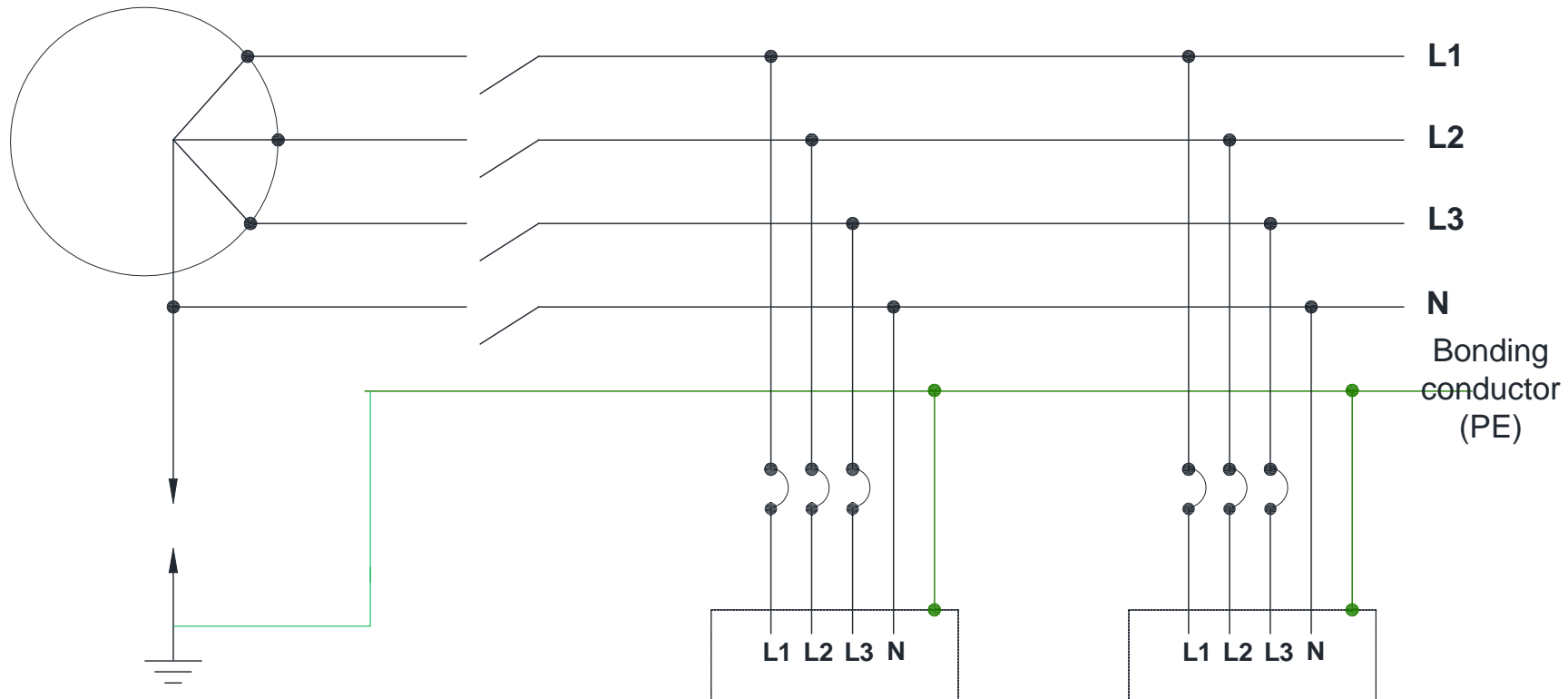
TN-S System

IEC Terminology



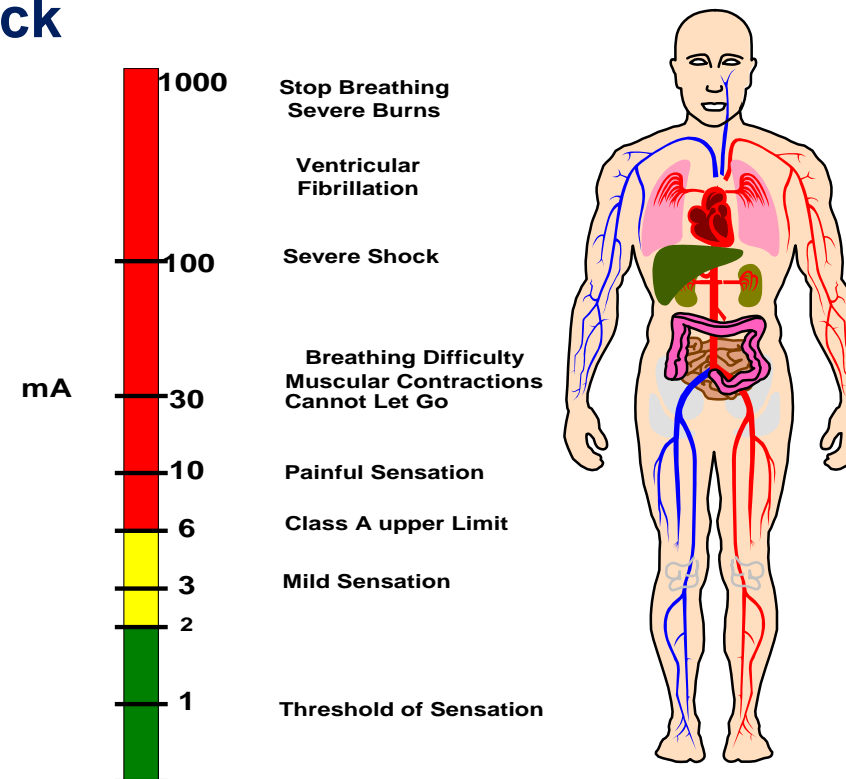
TN-C System

IEC Terminology



IT System

Effects of Electrical Shock



Range of Tolerable Current

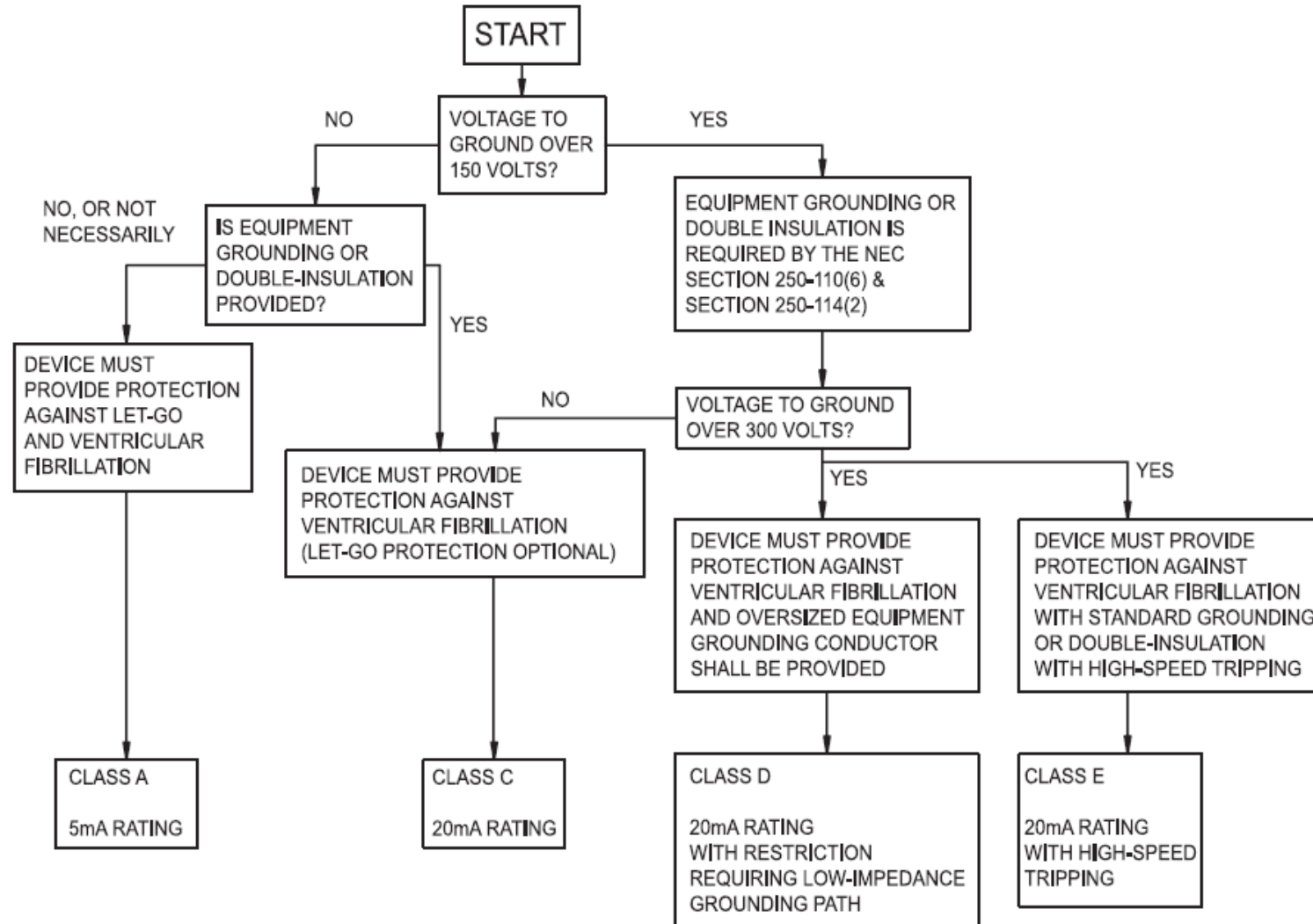
- Effect of Frequency: 50-60 Hz 0.1 A
DC 5X, @ 3000 – 10kHz > 5X
- Effect of Magnitude and duration
Tolerable current related to energy over duration 0.03 to 3.0 secs
$$I_b = .116 / \sqrt{ts} \quad \text{for 50 kg}$$
$$I_b = .157 / \sqrt{ts} \quad \text{for 70 kg}$$
- Can tolerate very high surges due to lightening
- Effect of Re-closing : energy effect cumulative

Ref IEEE 80 and IEC 60479

Body Resistance

- Internal resistance= 300 ohms
- Assumed to be 1000 ohms (500 – 3000)
- Touch potential: standing 1 m away
- Step potential: step 1 m wide
- Transfer potential

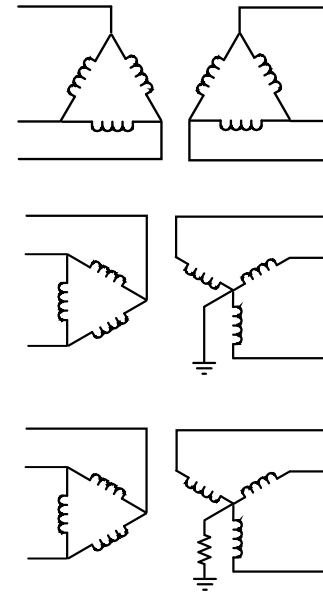
Protection from Electric Shock, UL 943C



su0628

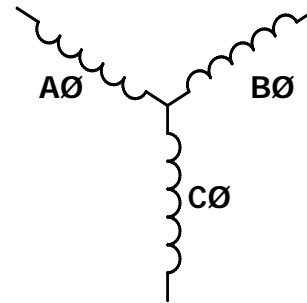
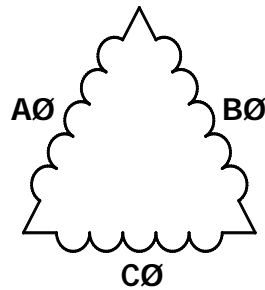
Power System Grounding Methods

- Ungrounded
- Solidly Grounded
 - Corner Delta Grounded System
 - Mid Phase Grounded System
- Resistance Grounded



Ungrounded Systems

- Ungrounded systems do not have an intentional connection from the source generator or transformer to ground
- Typically a three wire delta system.
- Can be a four wire system where the source neutral is not connected to ground.



What Causes the Hazards in Ungrounded Systems

System Capacitance

Unable to discharge leading to transient over-voltages

No direct return path for ground fault current

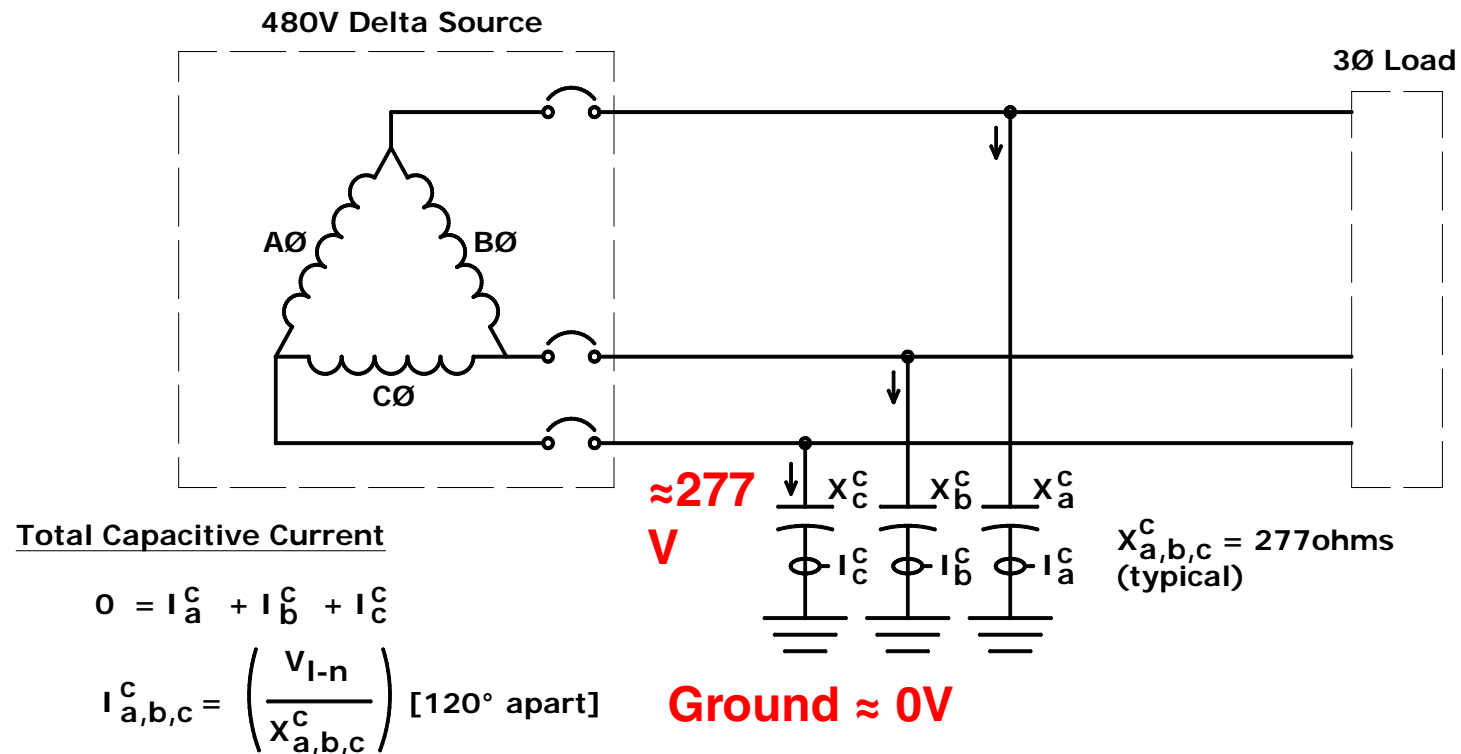
Prolonged fault conditions due to inability to quickly locate fault.

NEC 250.21(B) Ground Detectors. Ungrounded alternating current systems as permitted in 250.21(A)(1) through (A)(4) operating at not less than 120 volts and not exceeding 1000 volts shall have ground detectors installed on the system.

Ungrounded Systems

Unintentionally grounded through system capacitance

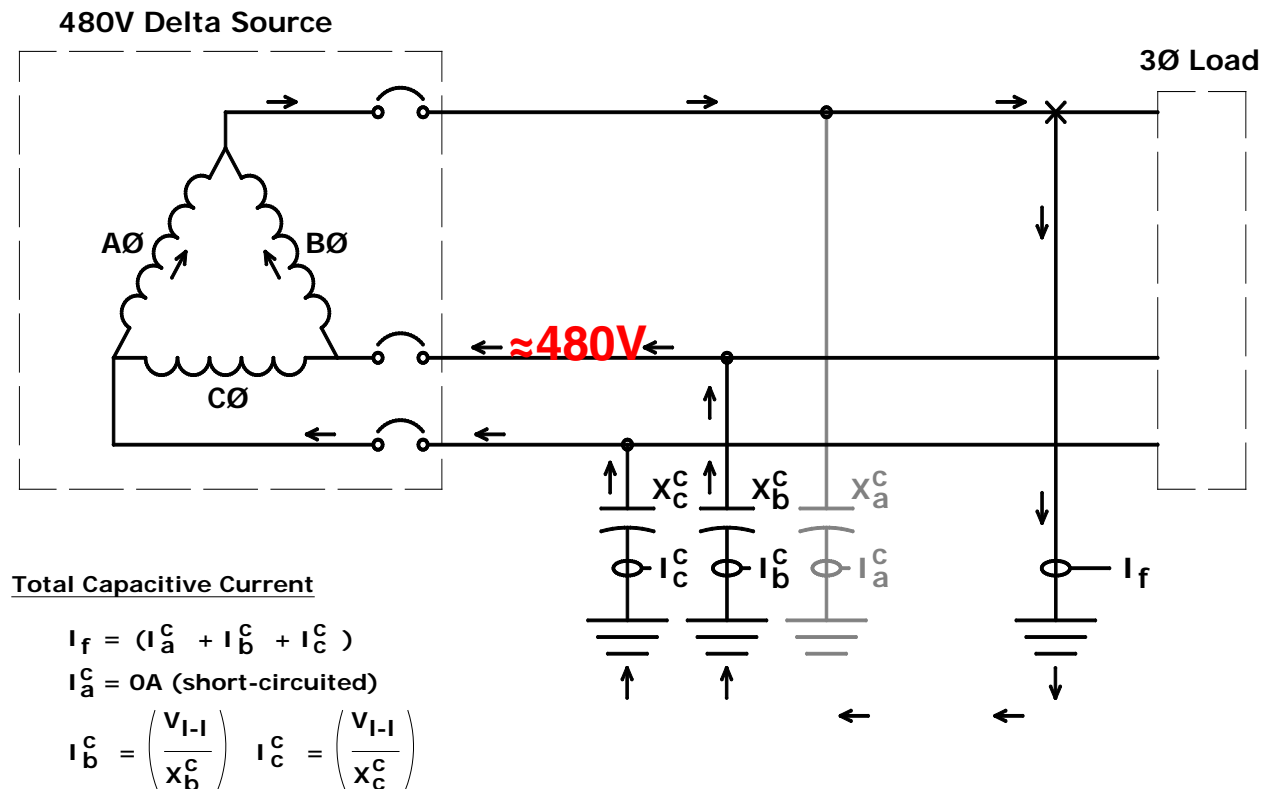
- Such as cables, transformers, motors, surge suppressors, etc.



Ground Faults

Unintentionally grounded through system capacitance

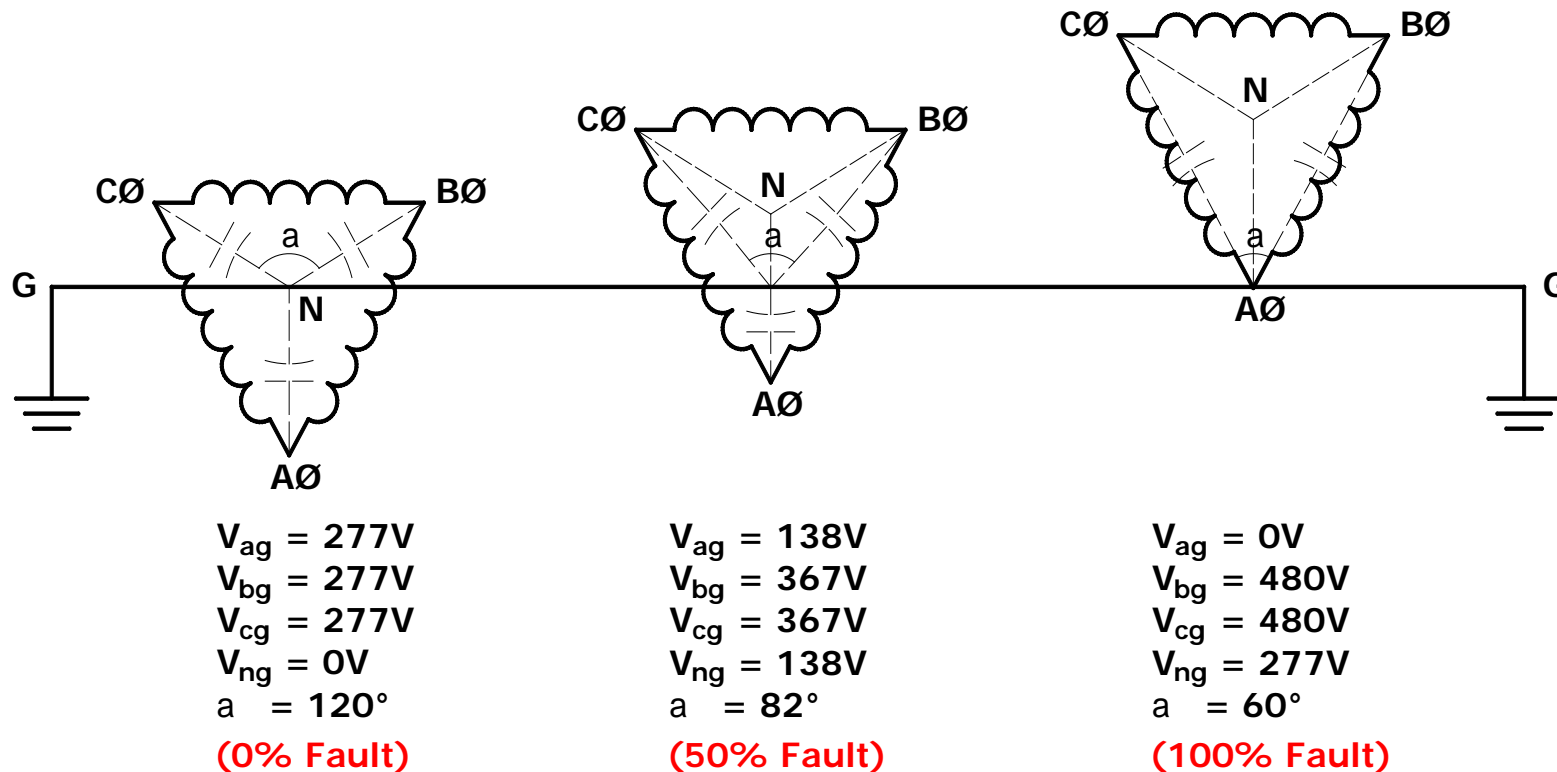
- Such as cables, transformers, motors, surge suppressors, etc.



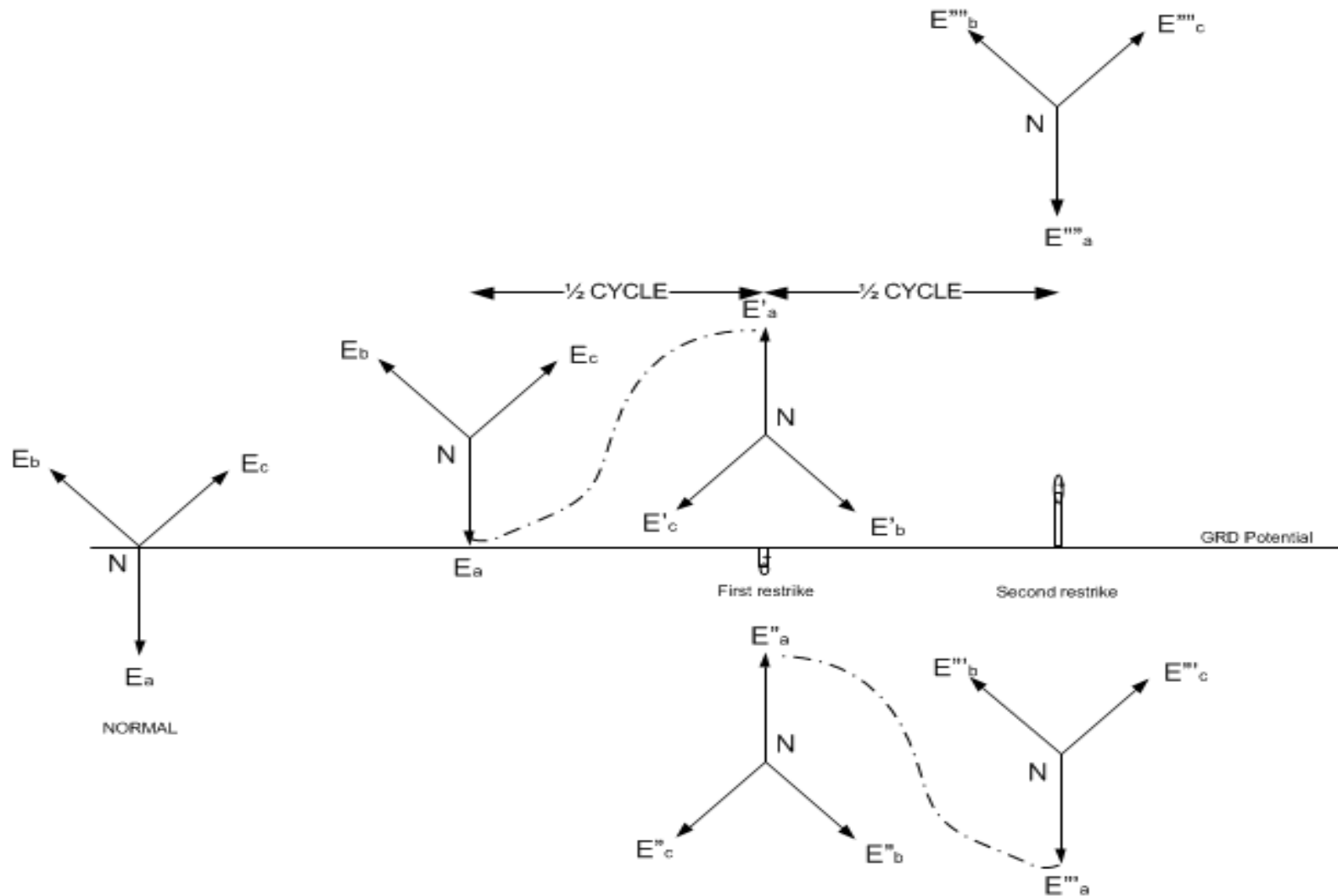
Ground $\approx AØ$

Ground Faults

Ground Fault Voltage Distribution (voltage rise)

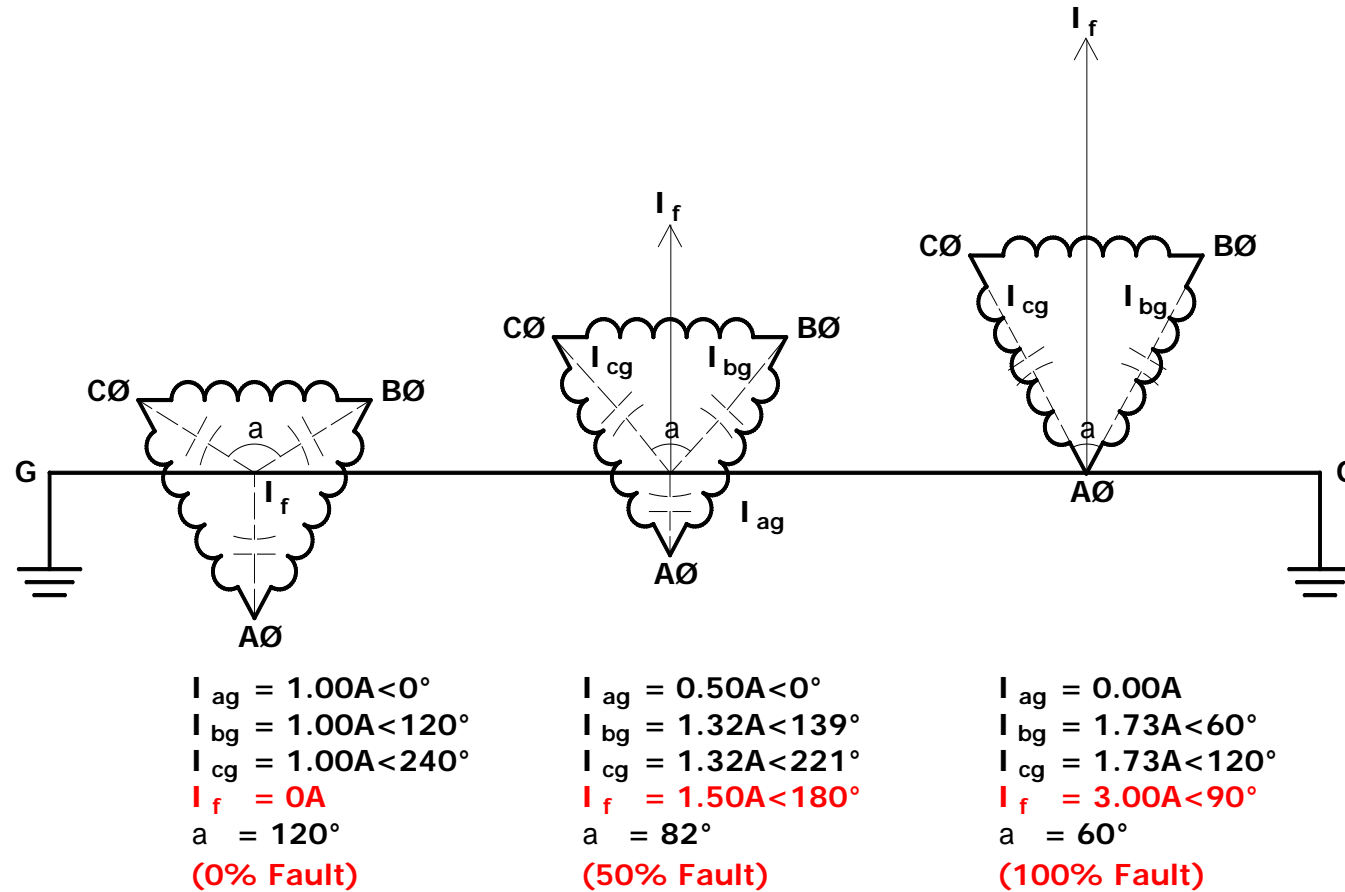


Ground Faults

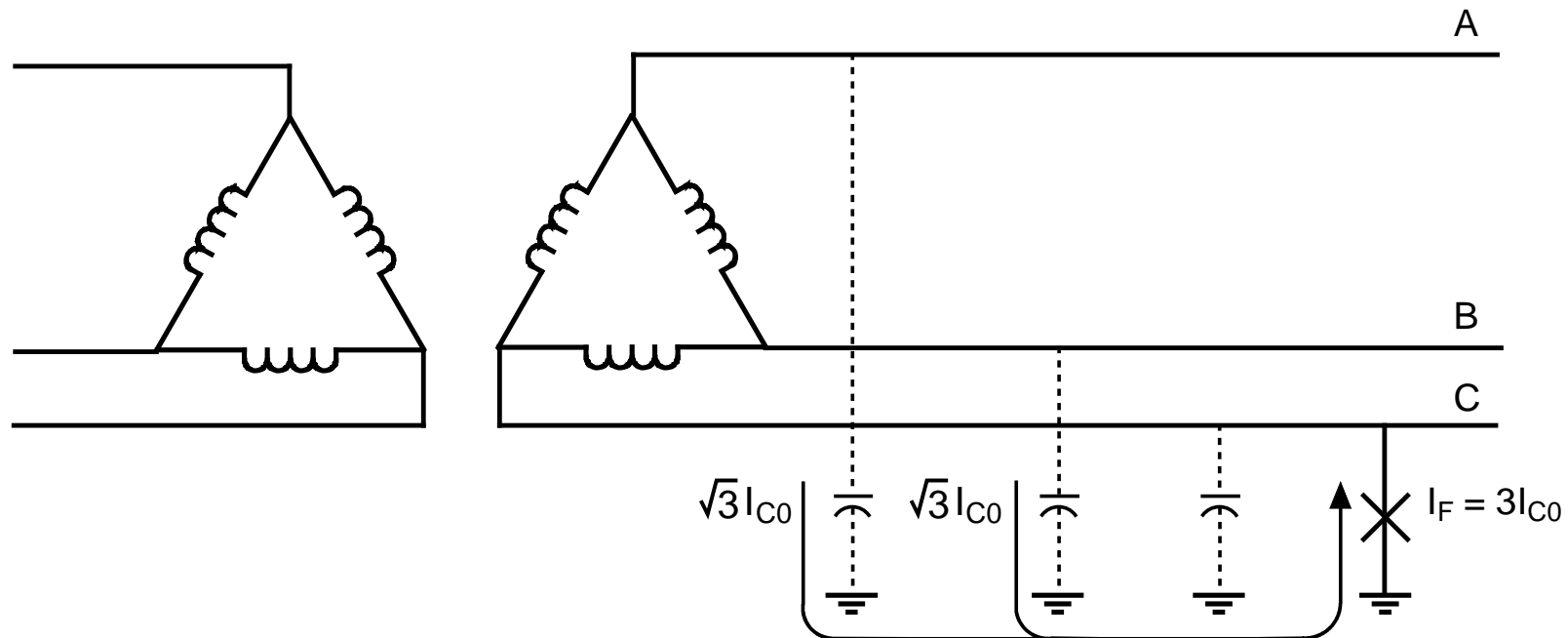


Ground Faults

Ground Fault Current Distribution (current rise)



System Charging Current $3I_{C0}$



Ungrounded Systems

- Negligible fault current and no tripping on first ground fault
- Difficult to locate ground faults
- 5-6 times transient voltage escalation on intermittent, sputtering arcing ground faults due to voltage buildup across the stray capacitance to ground

Distribution System Design Criteria

Ungrounded

- **Reliability** Prone to double faults and thus trip outs
- **Safety** Transient voltages can occur
- **Cost effectiveness** Locating faults is difficult
- **Scheduled Maintenance** Double faults can cause unscheduled shut downs
- **Prioritized load** Coordination lost in case of double faults

**Existing Ungrounded Systems
should be converted to
High Resistance Grounded systems**

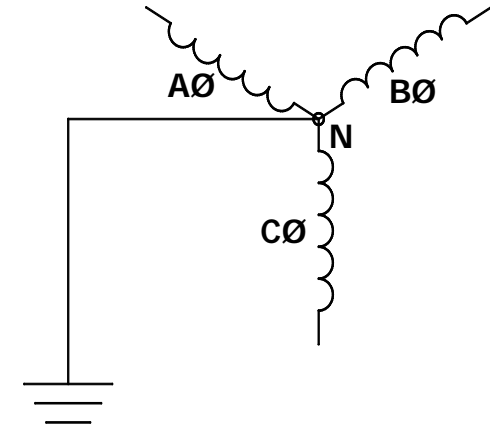
Why Ground?

250.4 (A)

(1) Electrical System Grounding. Electrical systems that are grounded shall be connected to earth in a manner that will limit the voltage imposed by lightning, line surges, or unintentional contact with higher-voltage lines and that will stabilize the voltage to earth during normal operation.

Solidly Grounded Systems

- Grounded systems have an intentional connection from the source generator or transformer to ground
- Typically a four wire star system
- Can be a three wire system where the source neutral is not connected to loads



Solidly Grounded Systems



High Ground
Fault Current



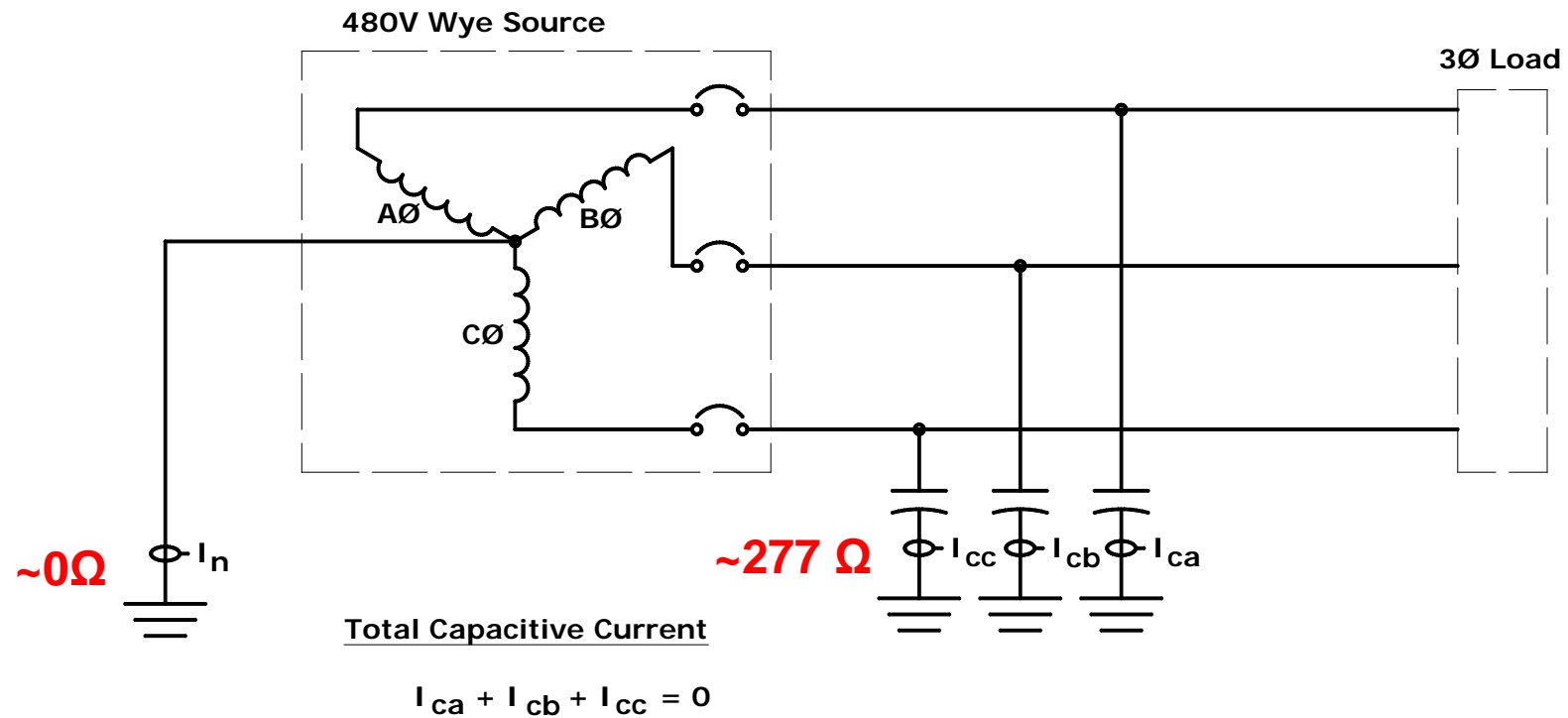
- Eliminates transient overvoltage problem
- Permits line-to-neutral loads (lighting, heating cables)
- Ground faults easy to locate, but cause unscheduled service interruption
- High fault currents need to trip breaker or open fuses quickly
- Sustained arcing faults can release intense heat and mechanical energy causing **severe damage and injury**
- Potential for severe damage at point of fault due to intense heat energy of the Arcing ground faults
- Higher risk of touch potential and step potential

What Causes the Hazards in Solidly Grounded Systems?

- Very low impedance in ground path
 - High fault current
 - High fault energy
- Ground Fault Coordination
 - Long time delays on upstream devices
 - High fault energy

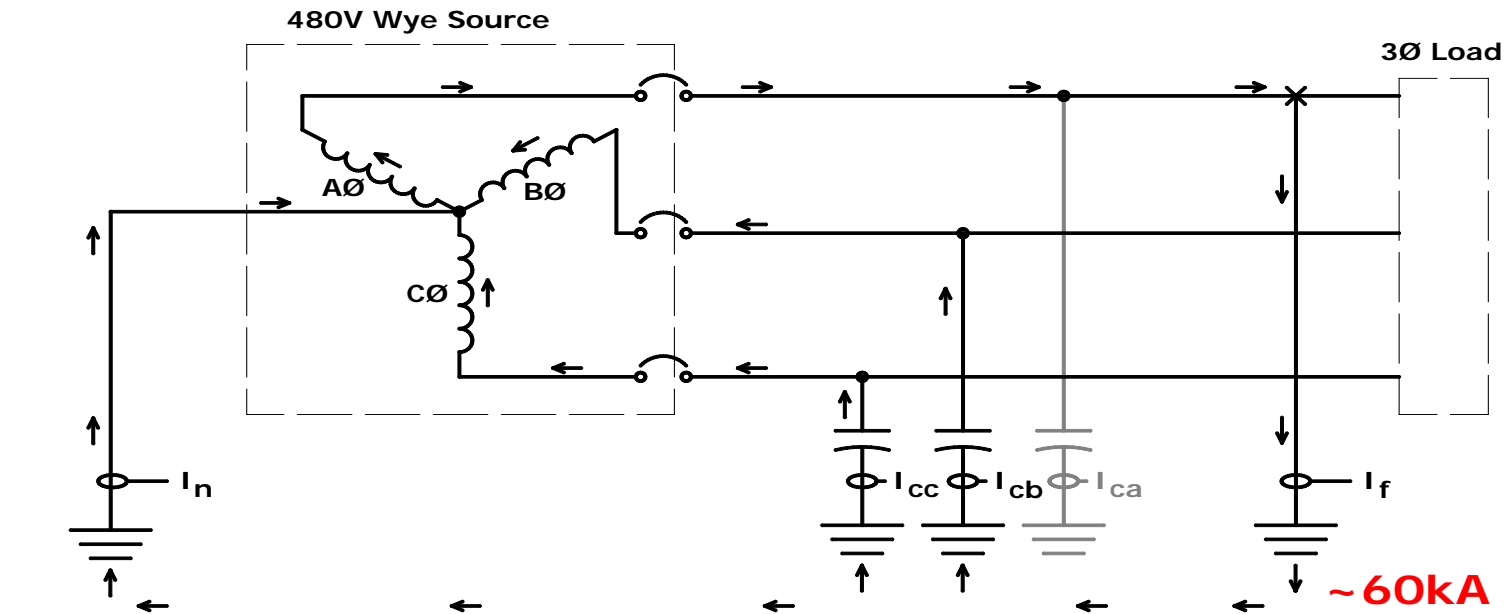
Solidly Grounded Systems

Intentionally grounded through ground wire



Bolted Grounded Systems

Ground fault current distribution on AΦ



Estimated Total Fault Current

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

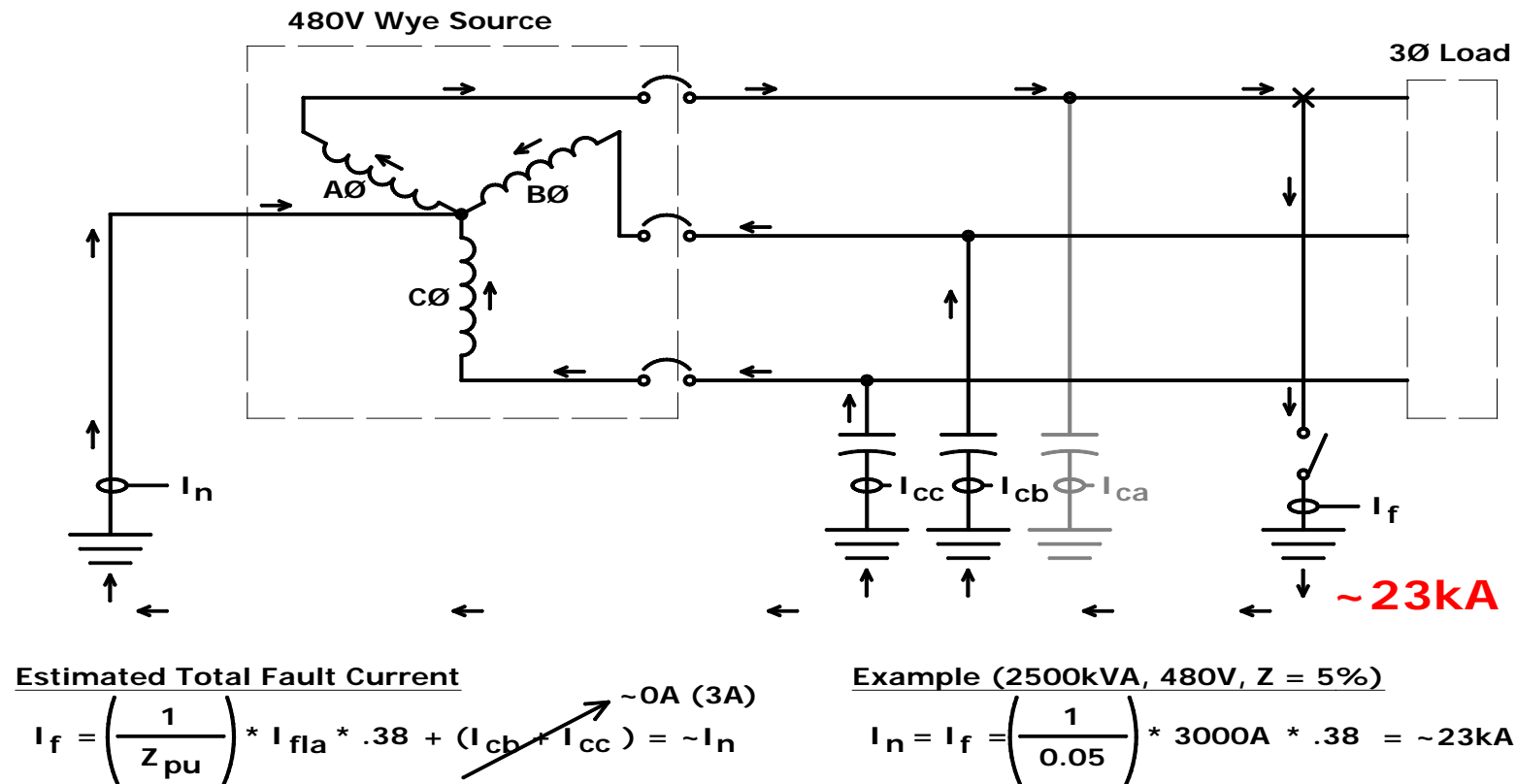
$\sim 0A$ (3A)

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

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

Arcing Faults in Solidly Grounded Systems

Ground fault current distribution on AΦ



Coordination Problems

- Discussed Over-Voltage and Over-Current Hazards ...
- Now discuss time factor:

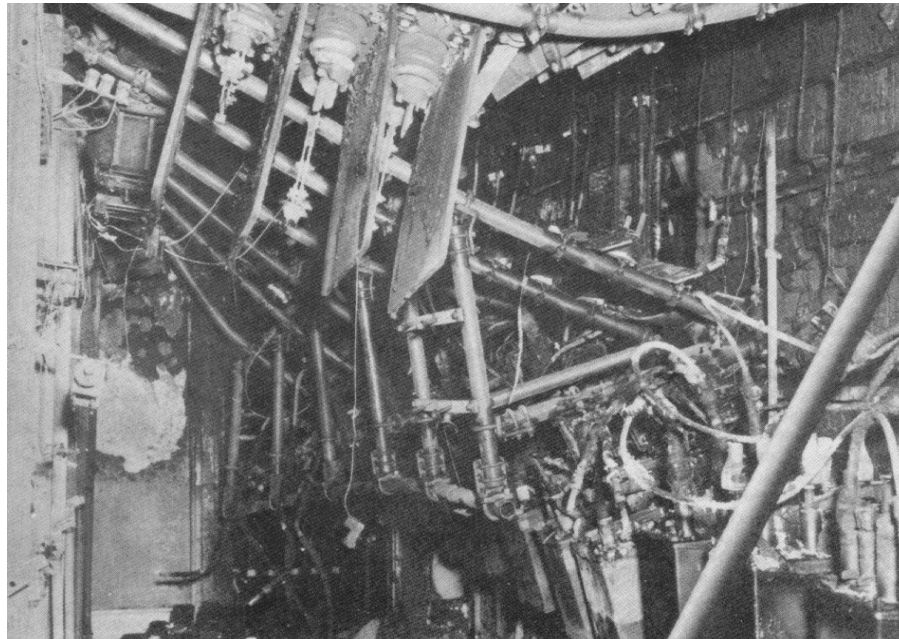
Energy is also a function of time

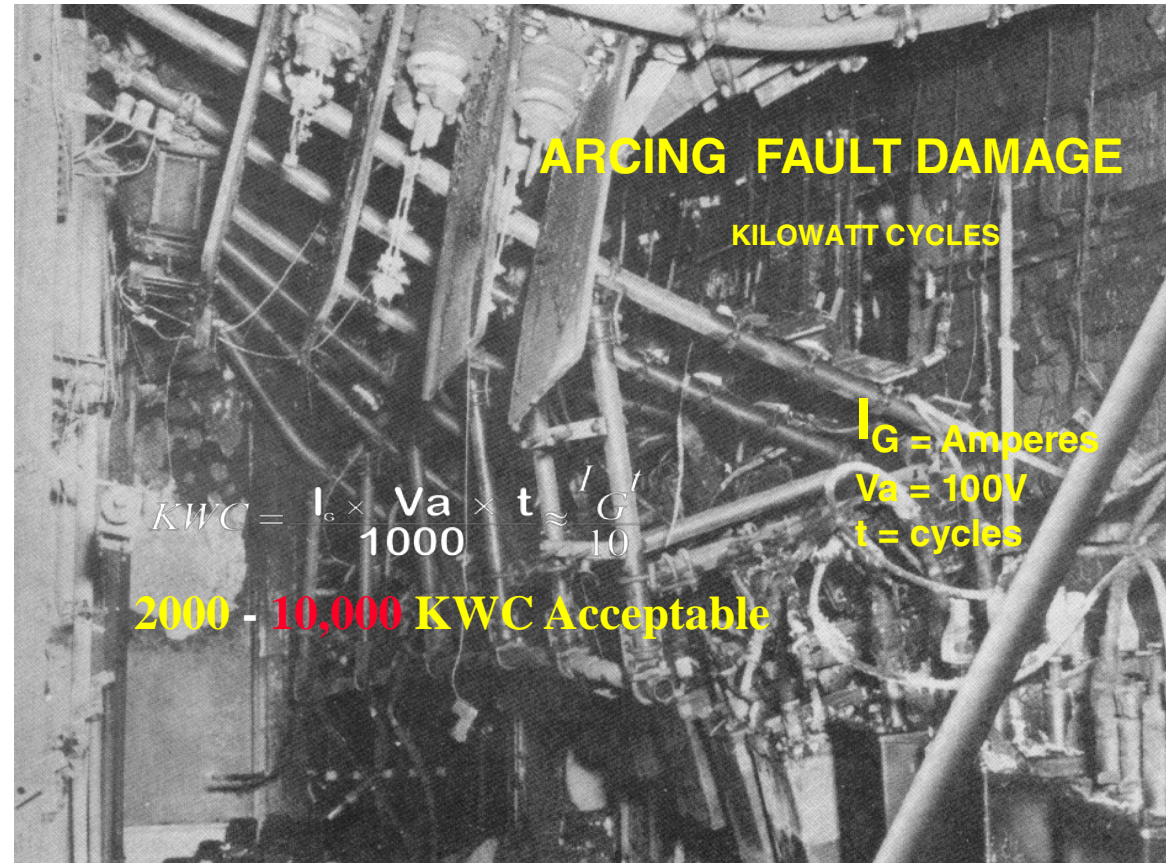
$$E = \text{volts} * \text{amps} * \text{time}$$

- Large radial systems have long time delays for coordination

Arcing Ground Faults

- Sustained arcing faults can release intense heat and mechanical energy causing **severe damage and injury**
- Fault current can be 50% of I_{sc} or substantially less





Arcing Ground Fault Damage

A) 100 Kilowatt Cycles

The location of the fault is identifiable by close inspection - there will be spit marks on the metal and some smoke marks.

B) 2000 Kilowatt Cycles

If there is no damage then the equipment can usually be restored by painting smoke marks and repairing punctures in the insulation.

C) 6000 Kilowatt Cycles

Minimal amount of damage results, but fault may more easily be located.

D) 10,000 Kilowatt Cycles

The fault will probably be contained by the metal enclosure.

E) 20,000 Kilowatt Cycles

The fault will probably burn through a single thickness enclosure and spread to other section of the equipment

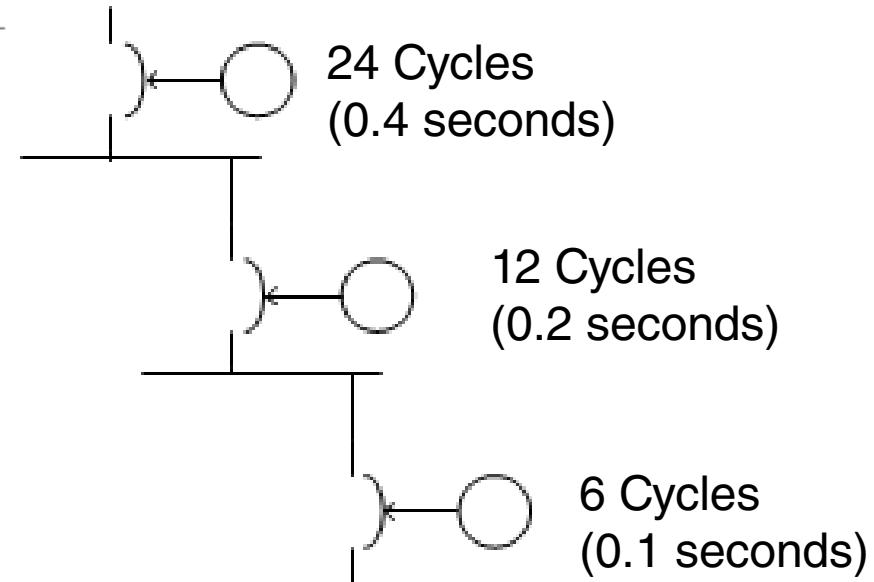
F) Over 20,000 Kilowatt Cycles

Considerable destruction in proportion to the let-through energy

Coordination Problems

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

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



Typical Transformer:

- 2500 kVA, 5% impedance
- Ground condition $I_g=23\text{kA}$
- **KWC = 55,200**

Not Acceptable???

Hazards with Ungrounded and Solidly Grounded

	Ungrounded	Solidly-Grounded
Transient Over-Voltage	High Risk	Low Risk
Transient Over-Current	Low Risk	High Risk
Fault Location	High Risk (Good Luck)	High Risk (Follow Smoke)
High Fault Energy	High Risk (2 nd Fault)	High Risk

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 141-1993**
Recommended Practice for Electric Power Distribution for Industrial Plants 7.2.4
In solidly grounded system Line to ground fault has the highest probability of occurrence and 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.

Testing done for IEEE 1584 demonstrates that migration of arc from Line to ground to line to line only takes 8-10 ms

Arc Mitigation- Total System Approach

Step 1
Reduce Hazard Frequency

Step 2
Pre- hazard warning - take
preventative action

Step 3
Impact Mitigation



Use Methods to Reduce Hazards

- NFPA 70E section 130.5(C) FPN No.4 states “Proven designs such as arc-resistant switchgear,...high-resistance grounding and current limitation....are techniques available to reduce the hazard of the System”
- CSA Z462 “Proven designs such as arc-resistant switchgear, remote racking (insertion or removal), remote opening and closing of switching devices, high-resistance grounding of low-voltage and 5 kV (nominal) systems, current limitation, and specification of a covered bus within equipment are techniques available to reduce the hazard of the system”

Safety Related Requirements in 70E- Informative Annex 0

- **0.2.2 Design Considerations**

Design should facilitate the ability to eliminate hazard or reduce risk by:

Reducing likely hood

Reducing Magnitude and Severity

Enabling achievement of an electrically safe work condition

- **0.2.4 Incident Energy Reduction Methods**

(2) Arc Flash Relay

(3) High resistance Grounding

Arc Flash Protection and Mitigation by Design

High Resistance Grounding

Line to ground faults are most likely faults and HRG limits the fault current so that no arc flash hazard exists

Arc Flash Protection tripping

For phase to phase faults where arcing is initiated fast detection and tripping will reduce the arc energy and thus reduce the hazard risk category

Arc Flash Protection

- Applied for Low and Medium Voltage systems
- Used in LV switchboards and LV switchgear as well as Metalclad and Metalenclosed circuit breaker switchgear
- Fast acting tripping system uses circuit breakers to trip and isolate. Total trip time needs to be 50 millisecs to minimize damage and provide protection from Arc Flash

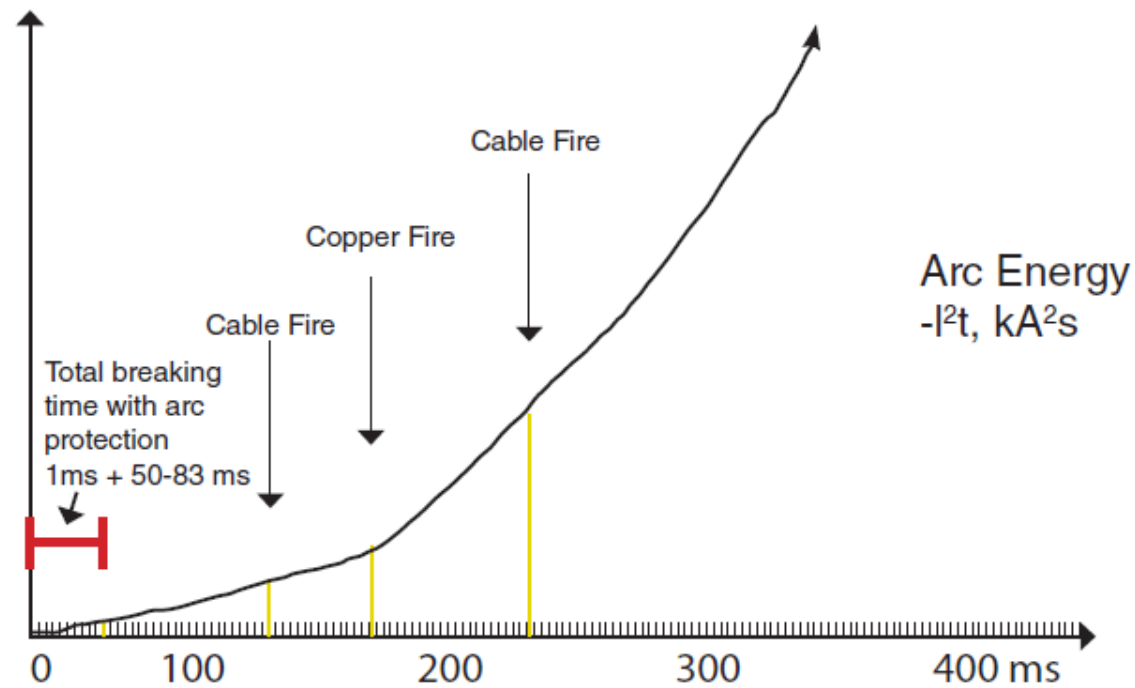
Arc Flash Protection

- Arc Flash Mitigation > detection in 1 millisecond
- Reduction of Arc Flash energy by fast detection and tripping. Minimizes total clearing time.
- Reliability— Ensures fastest possible reaction time with out nuisance tripping. Combine light sensing and overcurrent protection or pressure sensing

Typical Components

- **Main Module:** Provides control power, displays alarms, provides outputs and takes inputs
- **Arc Flash Module:** Detects Flash, adjustable sensitivity, optical sensors
- **Optical sensor:** Mounts in the switchgear compartment
- **Optical fibre:** Connects optical sensor directly to Arc Flash module < 100 m
- **Communication cable:** Twisted pair shielded (blue cable) identifies the sensor that detected the fault.

Fast Tripping Reduces Energy Exposure and Damage



Arc Detection and Mitigation

Protection Type	Clearance Time	Incident Energy
Over-Current	2.0 seconds	23.9 Cal / cm ²
Instantaneous	0.45 seconds	5.4 Cal / cm ²
Pressure sensor	0.058 seconds	1.3 Cal / cm ²
Optical Arc Detection	0.051 seconds	1.2 Cal / cm ²

Assumes circuit breaker interrupting time of 0.05 seconds

Arc Detection and Mitigation

Total Clearing Time is Critical

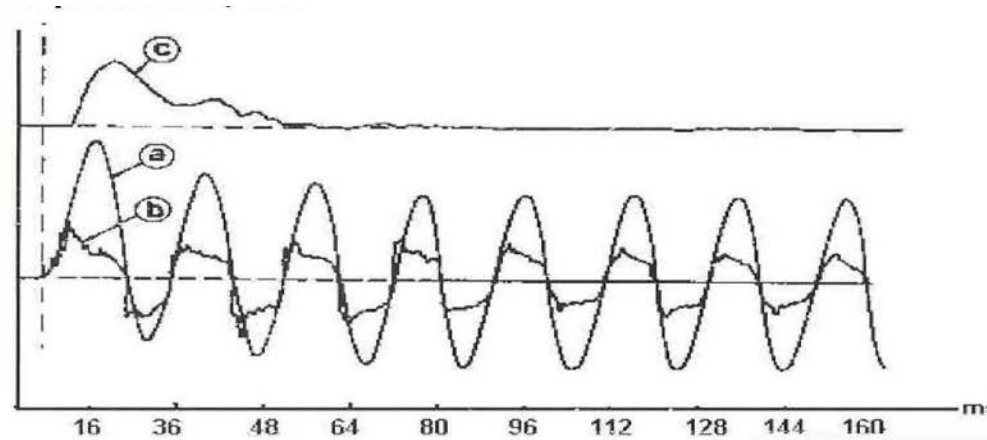
Reduce the Time,	Reduce the Damage,	Reduce the Incident Energy
-35 ms:	no significant damage to persons or Switchgear, which can often be returned to use after checking the insulation resistances	1.27 Cal /cm ²
- 100ms:	small damage, requires cleaning and possibly some minor repair likely	3.23 Cal/cm ²
- 500ms:	large damage both for persons and the switchgear, which must be partly replaced.	18.1 Cal/cm ²

The arc burning time is the sum of the time to detect the arc and the time to open the correct breaker.

**Based on 50kA maximum bolted fault current on a 480 volt solidly grounded system.*

Arc Detection and Mitigation

Arcing is accompanied by radiation in the form of light, sound, heat and electromagnetic waves as well as an associated pressure wave.



- ▶ **a: short circuit current (phase with max asymmetry)**
- ▶ **b: arc voltage**
- ▶ **c: internal pressure**

Arc Detection and Mitigation

Two Direct Detection Methods

Pressure Arc Detector

- Detecting the pressure wave generated by the arc
- Detection time 8ms

Light Arc Detector

- Detecting the arc flash through optical arc detection
- Detection time 1ms

NFPA 70E 0.2.3 Incident Energy Reduction Methods

- (6) High-resistance grounding. A great majority of electrical faults are of the phase-to-ground type. High-resistance grounding will insert an impedance in the ground return path and will typically limit the fault current to 10 amperes and below (at 5 kV nominal or below), leaving insufficient fault energy and thereby helping reduce the arc flash hazard level. High-resistance grounding will not affect arc flash energy for line-to-line or line-to-line-to-line arcs.

Resistance Grounding

- Used on LV and MV systems to limit ground fault current
- No arcing ground faults as with solid grounding
- No over voltages as with ungrounded systems
- Used in Process Industries, Water and Waste Water, Hospitals, Data processing Centers

Sizing the Resistor

1. The line-to-ground capacitance associated with system components determines the magnitude of zero-sequence charging current.
2. The resistor must be sized to ensure that the ground fault current limit is greater than the system's total capacitance-to-ground charging current. If not, then transient over-voltages can occur.
3. The charging current of a system can be calculated by summing the zero-sequence capacitance or determining capacitive reactance of all the cable and equipment connected to the system.

System Charging Current

Methods of Determining:

1. Calculation

- See Application Guide High Resistance Grounding

2. Experience

- < 2 A 480 V and 600 V
- 2 – 7 A 2.4 kV and 4.16 kV
- < 20 A 13.8 kV

3. Rule of Thumb (Conservative)

- 1 A / 2000 kVA 480 V and 600 V
- 1 A / 1500 kVA 2400 V
- 1 A / 1000 kVA 4160 V and higher

4. Measurement

Measuring Charging Current

3I_{C0} Current Measurement

It is preferable to measure the magnitude of the charging current on existing power systems for correct grounding equipment selection. The measured values must be adjusted, to obtain the maximum current, if not all system components were in operation during the tests.

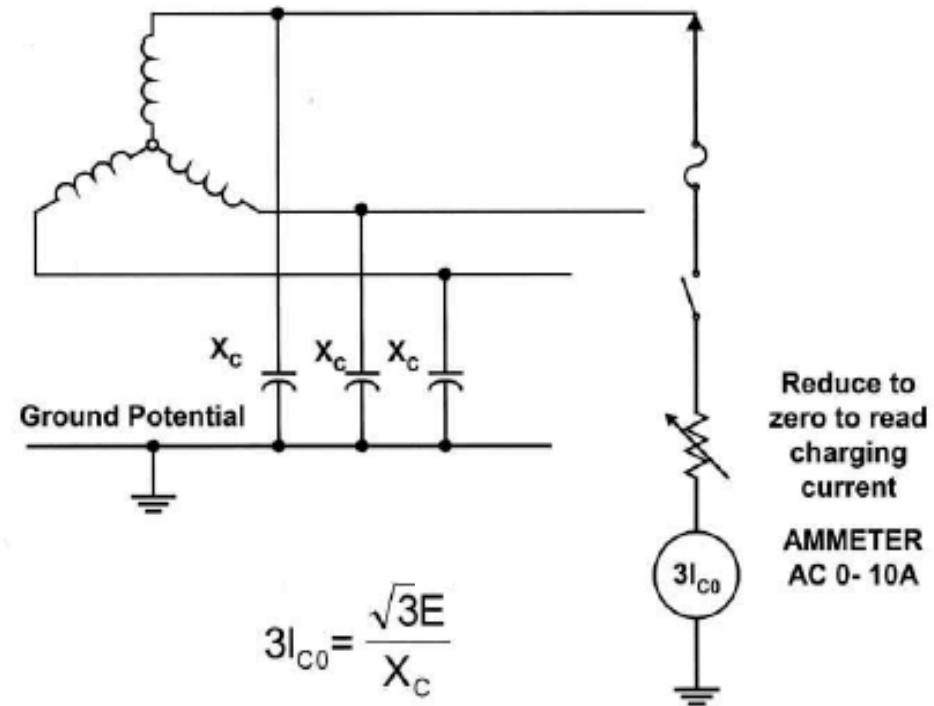


Figure A2.1: Measurement Of Charging Current.

Sources of System Charging Current

1. Surge Capacitors, TVSS, VFDs, UPS
2. Motors
3. Generators
4. Transformers (0.001 – 0.01 μ F, negligible)
5. Cables

System Charging Current Sources

DATA FOR ESTIMATING SYSTEM CHARGING CURRENT

SYSTEM VOLTAGE	COMPONENT TYPE		CHARGING CURRENT
UP TO 600V	Cables	600 - 1000 MCM in Conduit - 3 Conductor	0.15A/1000 Ft.
		250 - 500 MCM in Conduit – 3 Conductor	0.10A/1000 Ft.
		1/0- 4/0 in Conduit -3 Conductor	0.05A/1000 Ft.
		1/0- 4/0 on Trays – 3 Conductor	0.02A/1000 Ft.
	Transformers		0.02A/MVA
	Motors		0.01A/1000 HP
2400 V	Capacitors	Surge Suppression	0.78A Each Set
	Cables	Non Shielded in Conduit all sizes – 3 Conductor	0.05A/1000 Ft.
		Shielded all sizes – 3 Conductor	0.30A /1000 Ft.
	Transformers		0.05A/MVA
	Motors		0.10A/1000 HP
4160 V	Capacitors	Surge Suppression	1.35A Each Set
	Cables	X-Linked-Shielded 1/0 - 350 MCM – 3 Conductor	0.23A/1000 Ft.
		X-Linked-Shielded 500 - 1000 MCM - 3 Conductor	0.58A/1000 Ft.
		X-Linked Non-Shielded in Conduit all sizes - 3 Conductor	0.1A/1000 Ft.

System Charging Current Calculation

1. Estimate lengths of feeder cables for each cable size.
2. Obtain capacitance-to-ground per phase from cable manufacturer, in $\mu\text{F}/1000 \text{ ft.}$
From above data calculate capacitance for each feeder cable (C_0 , a per-phase value)

System Charging Current Sources

Single conductor cable or 3-conductor shielded cable:

$$C_o = \frac{0.00736\varepsilon}{\text{Log}_{10}\left(\frac{D}{d}\right)} \quad \mu\text{F}/1000\text{Ft}$$

For 3-conductor unshielded cable:

$$C_o = \frac{0.00834\varepsilon}{\text{Log}_{10}\left(\frac{D_1}{d}\right)} \quad \mu\text{F}/1000\text{Ft}$$

C_o = capacitance to ground in μF per 1000 feet.

ε = specific inductive capacitance of insulation.

D = diameter over insulation for single conductor cable.

D_1 = $d + 3c + b$ for three conductor cable.

d = diameter over conductor

c = thickness of insulation of conductor

b = thickness of belt insulation

System Charging Current Calculation

3. Sum the capacitance per phase of all feeder cables, surge protective devices, capacitors, VFDs and any other source of capacitance to ground , calculate system charging current:

$$3I_{C_0} = \frac{2\sqrt{3}\pi V_{LL} f C_0}{10^6} \text{ Amperes}$$

f = frequency, Hz

C_0 = capacitance-to-ground per phase, μF

V_{LL} = Volts

System Charging Current Calculation

4. Obtain generator charging currents from generator supplier.

System Charging Current Calculation

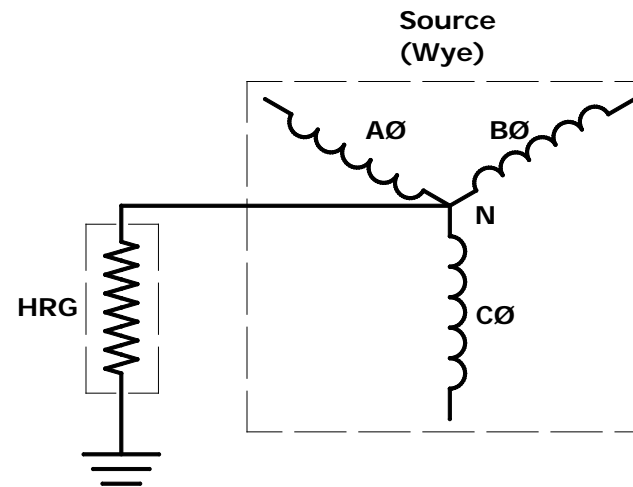
5. For motors use mfg. data or the following formula

$$3I_{c0} = 0.05 \frac{HP}{RPM} \text{ Amperes}$$

High Resistance Grounding

How does HRG solve these hazards?

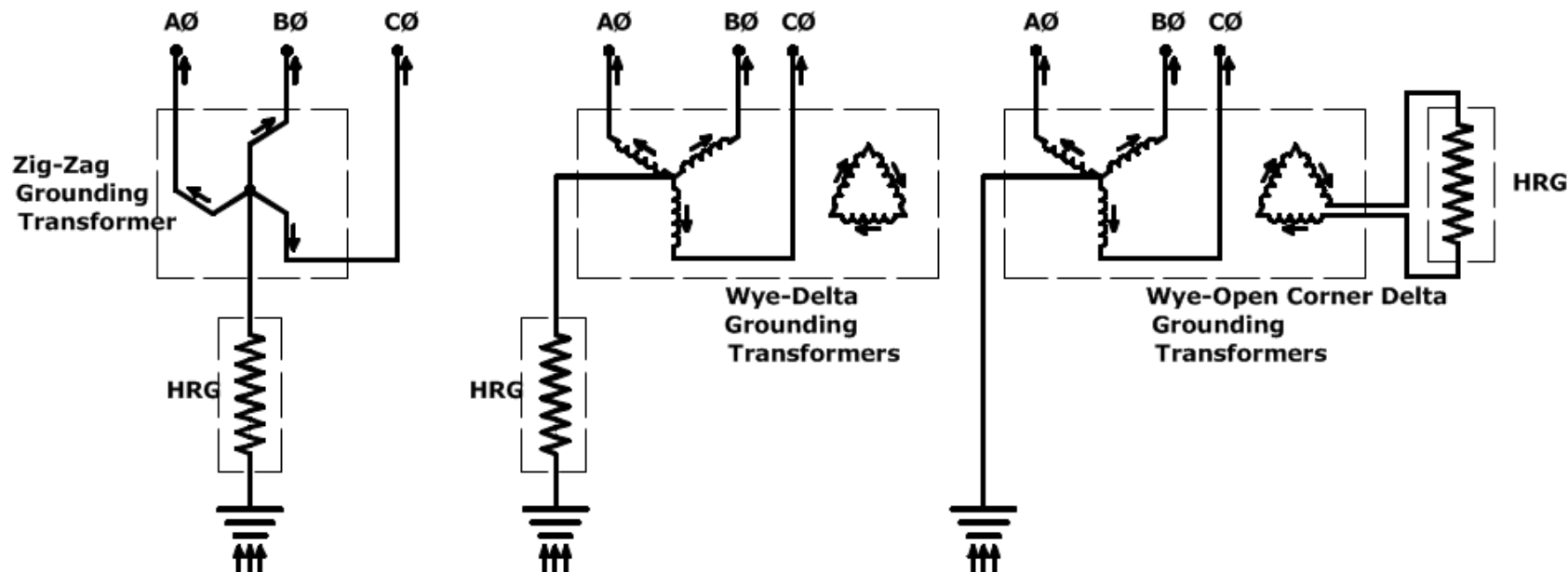
- Inserts a resistor between neutral and ground
- Eliminates 98% of Arc Flash / Blast Injuries



High Resistance Grounding

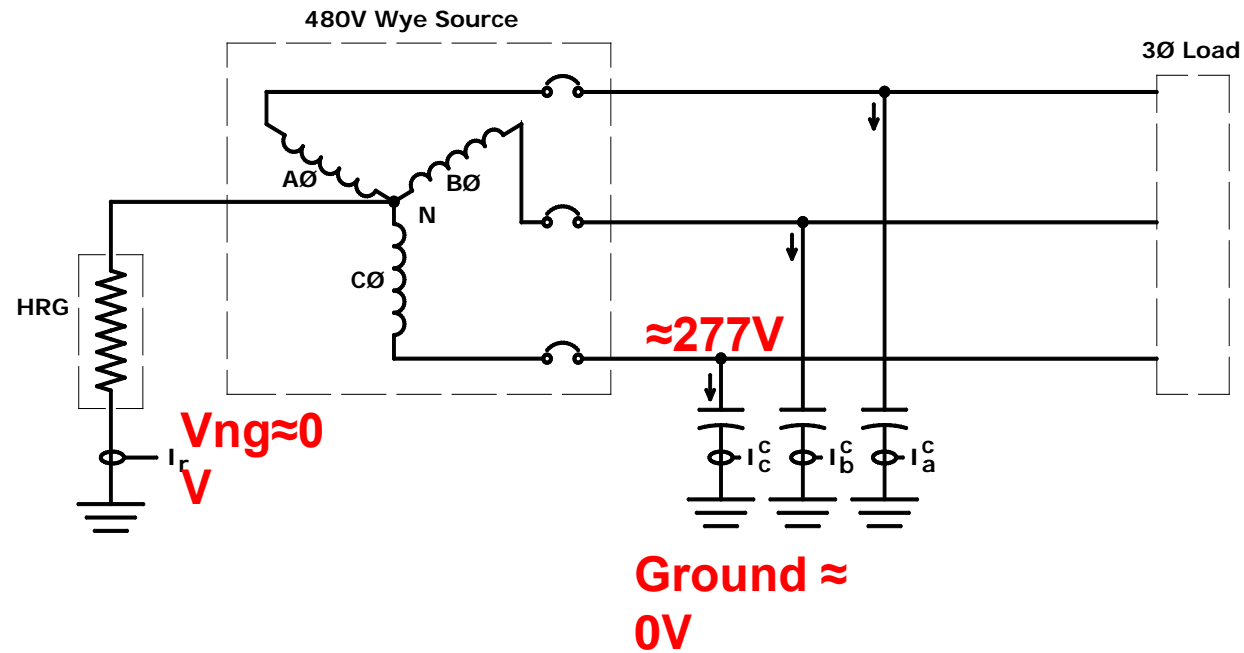
What if no neutral exists (i.e. delta systems)?

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.



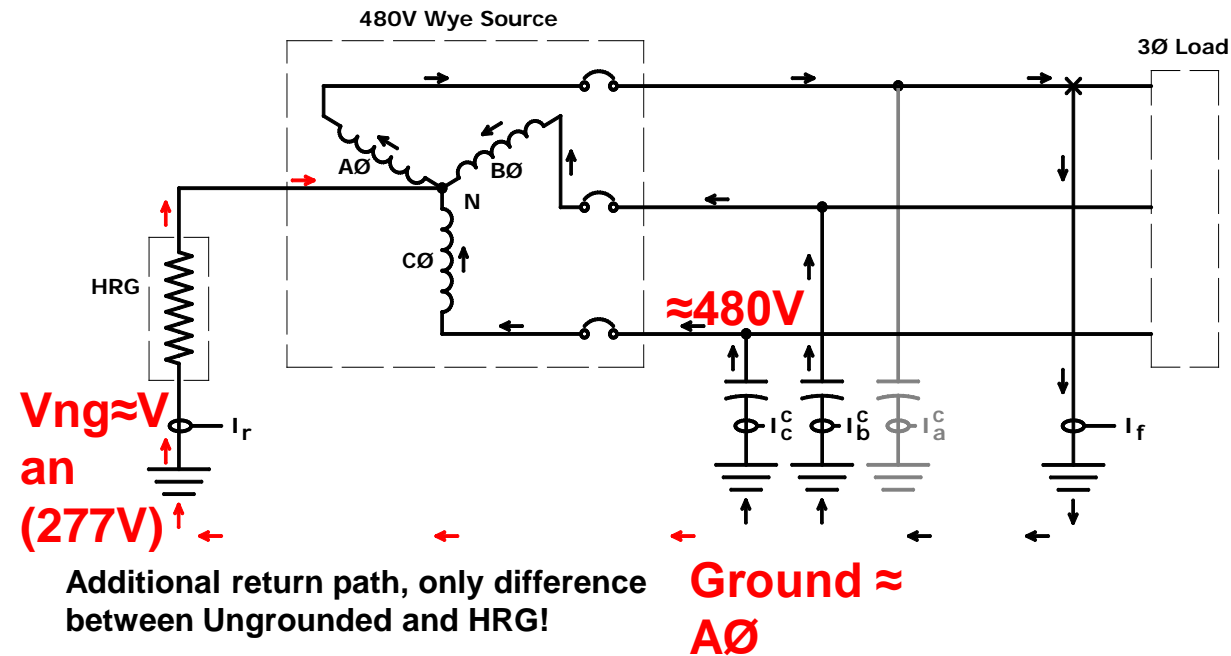
High Resistance Grounding

Intentionally grounded through neutral resistor

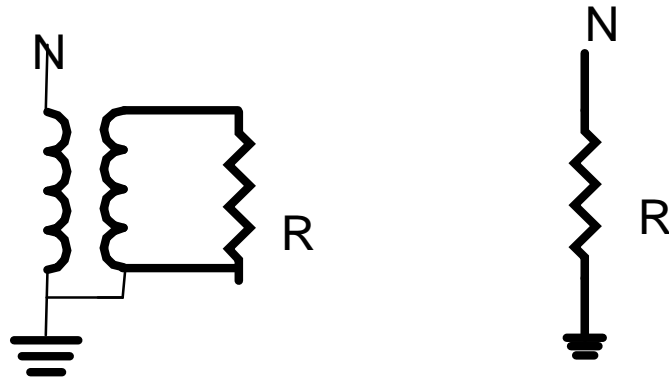


High Resistance Grounding

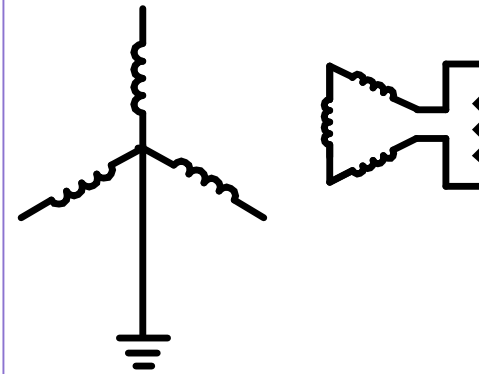
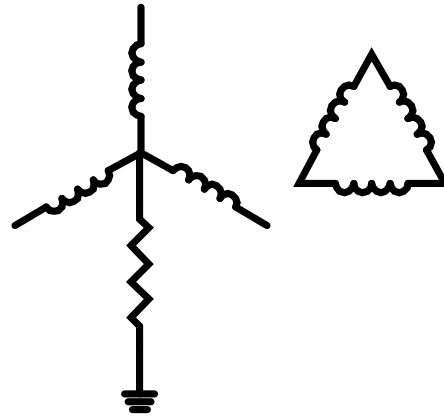
Compared to Ungrounded Systems (voltage rise)



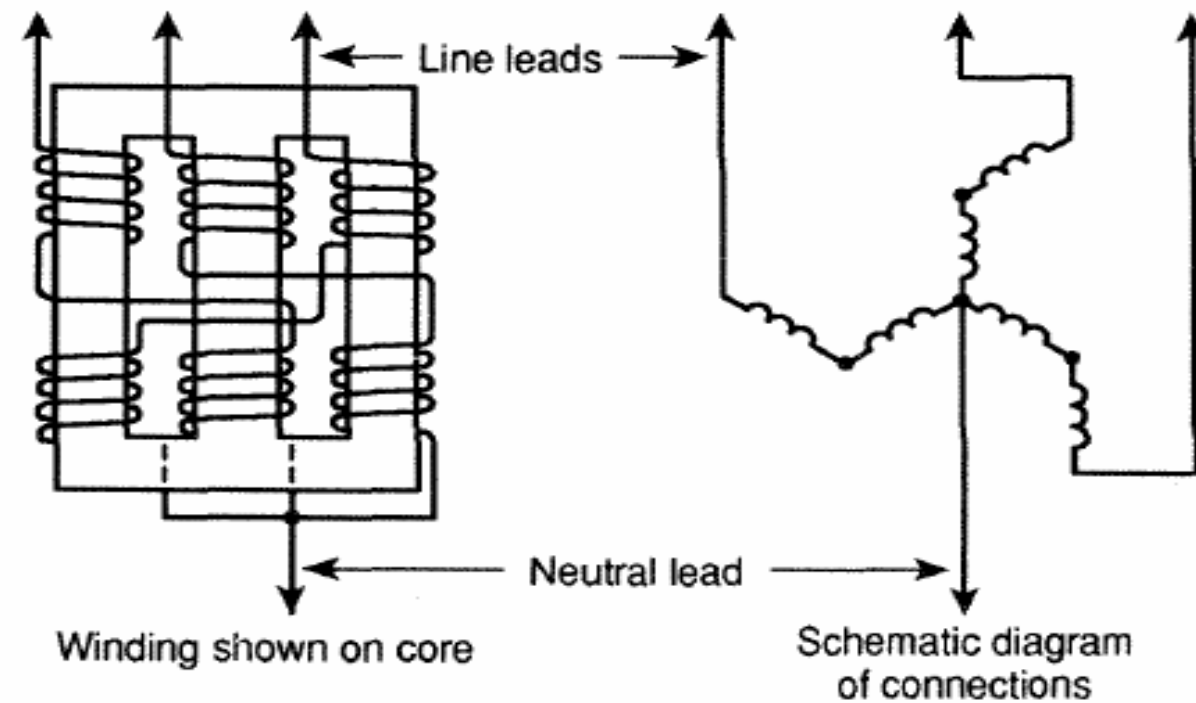
Methods of Grounding: Neutral Available



Methods of Grounding: Neutral Not Available or Not Convenient



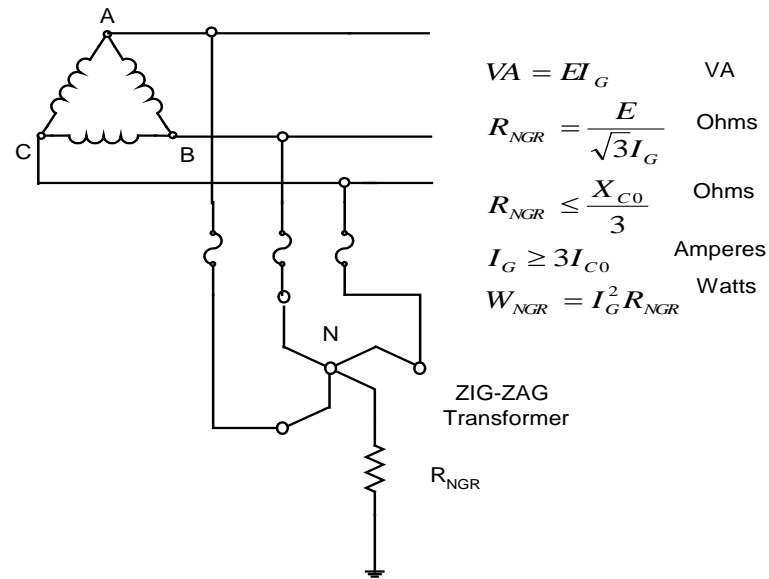
Zig-Zag Grounding Transformer



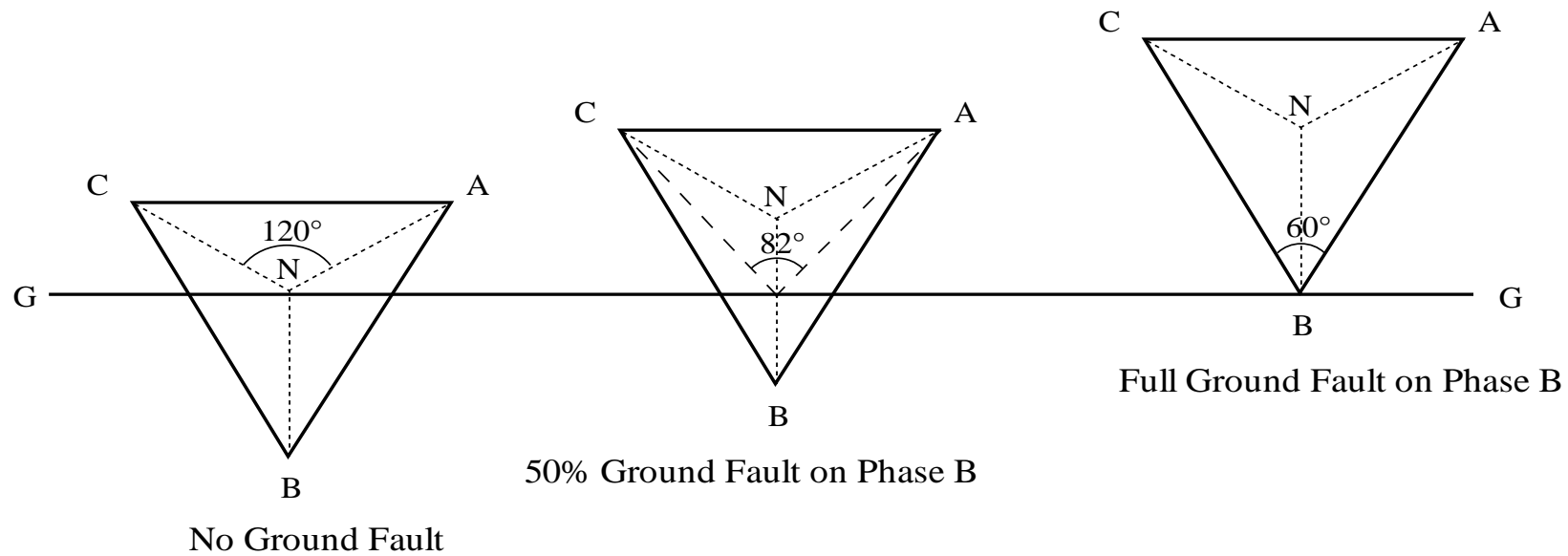
Locating the Resistor

Artificial Neutral

On a delta-connected system, an artificial neutral is required since no star point exists this can be achieved by use of a zig-zag transformer as shown.



Ground Fault on High Resistance Systems



High Resistance Grounding

Voltages:

- Normal Operation

$$V_{ag} = 277V$$

$$V_{bg} = 277V$$

$$V_{cg} = 277V$$

$$V_{ng} = 0V$$

- Fault Conditions

$V_{ag} = 0V$ (Faulted phase is at ground potential)

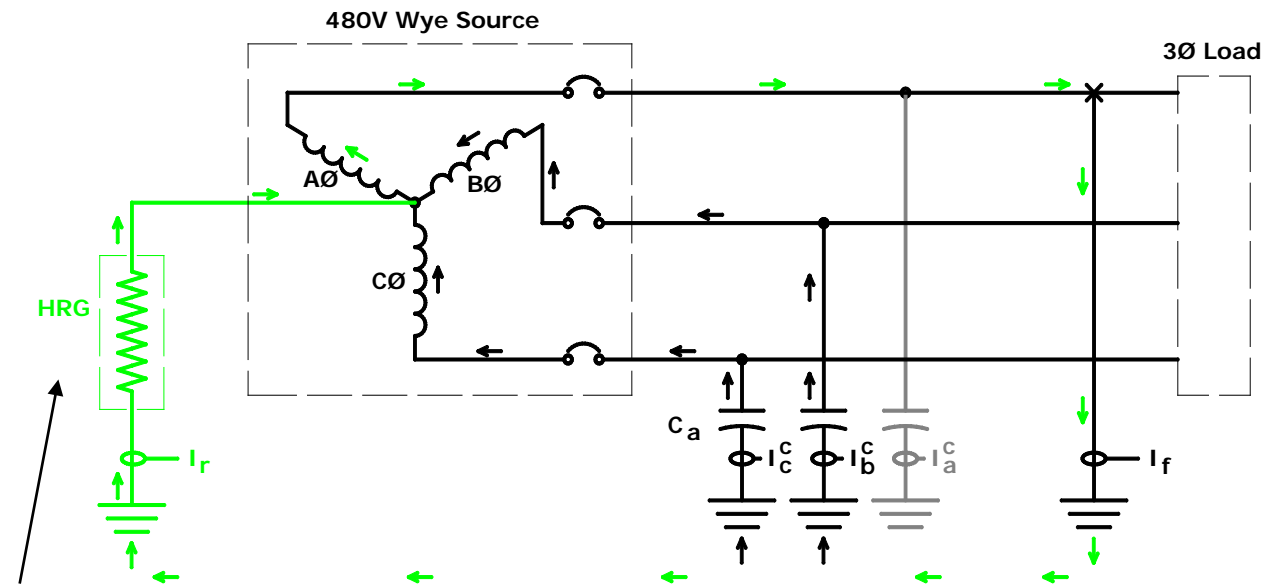
$$V_{bg} = 480V$$

$$V_{cg} = 480V$$

$$V_{ng} = 277V$$

High Resistance Grounding

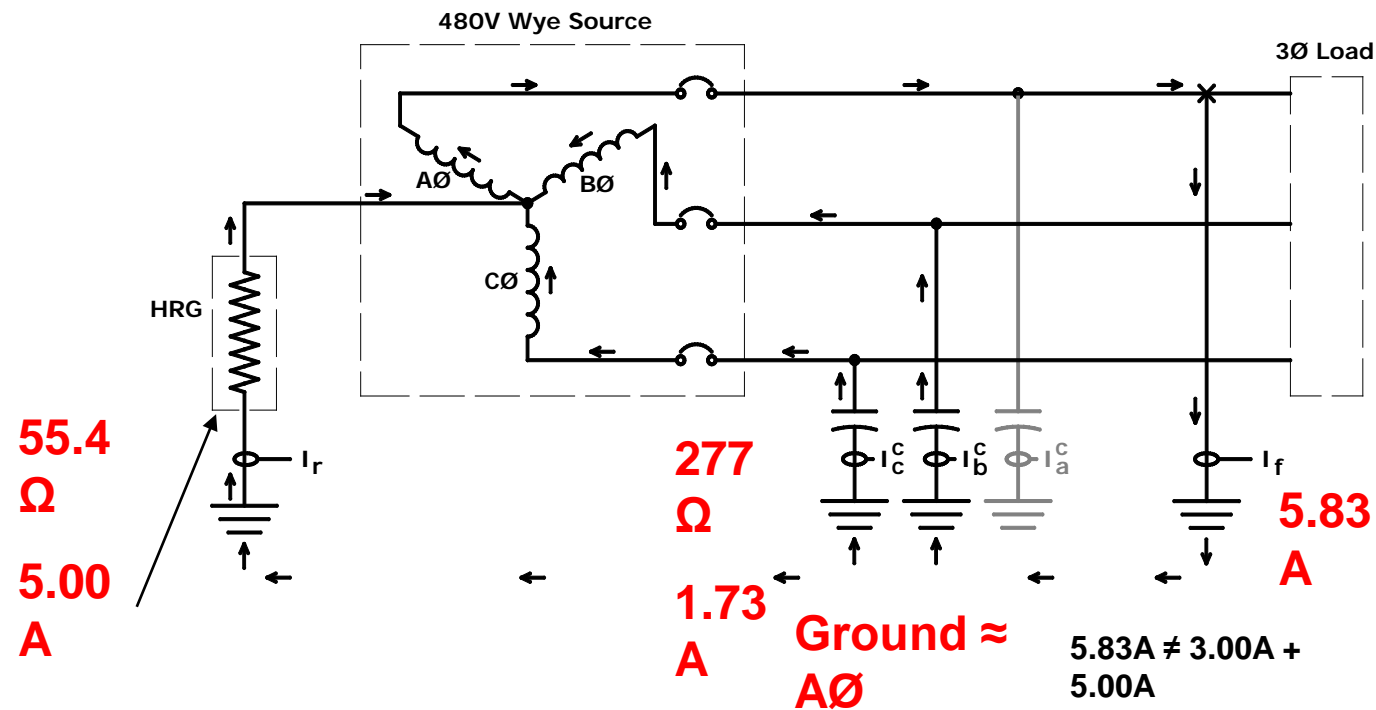
Importance of additional path versus Solidly Grounded



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!

High Resistance Grounding

Currents:

Normal Operation:

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

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

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

Fault conditions:

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

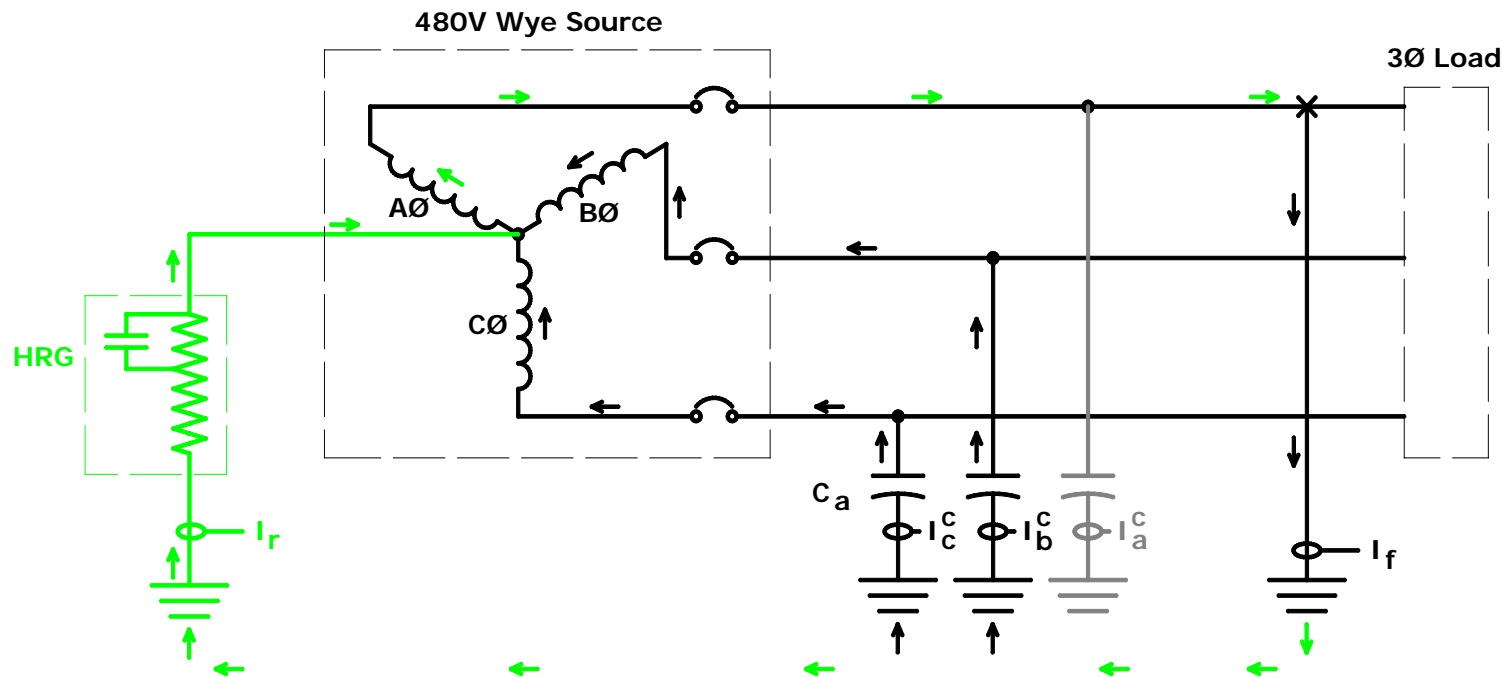
$$I_r = \frac{V_{ng}}{R_r} = \frac{277V}{55.4\Omega} = 5.00\angle 0^\circ A$$

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

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

High Resistance Grounding

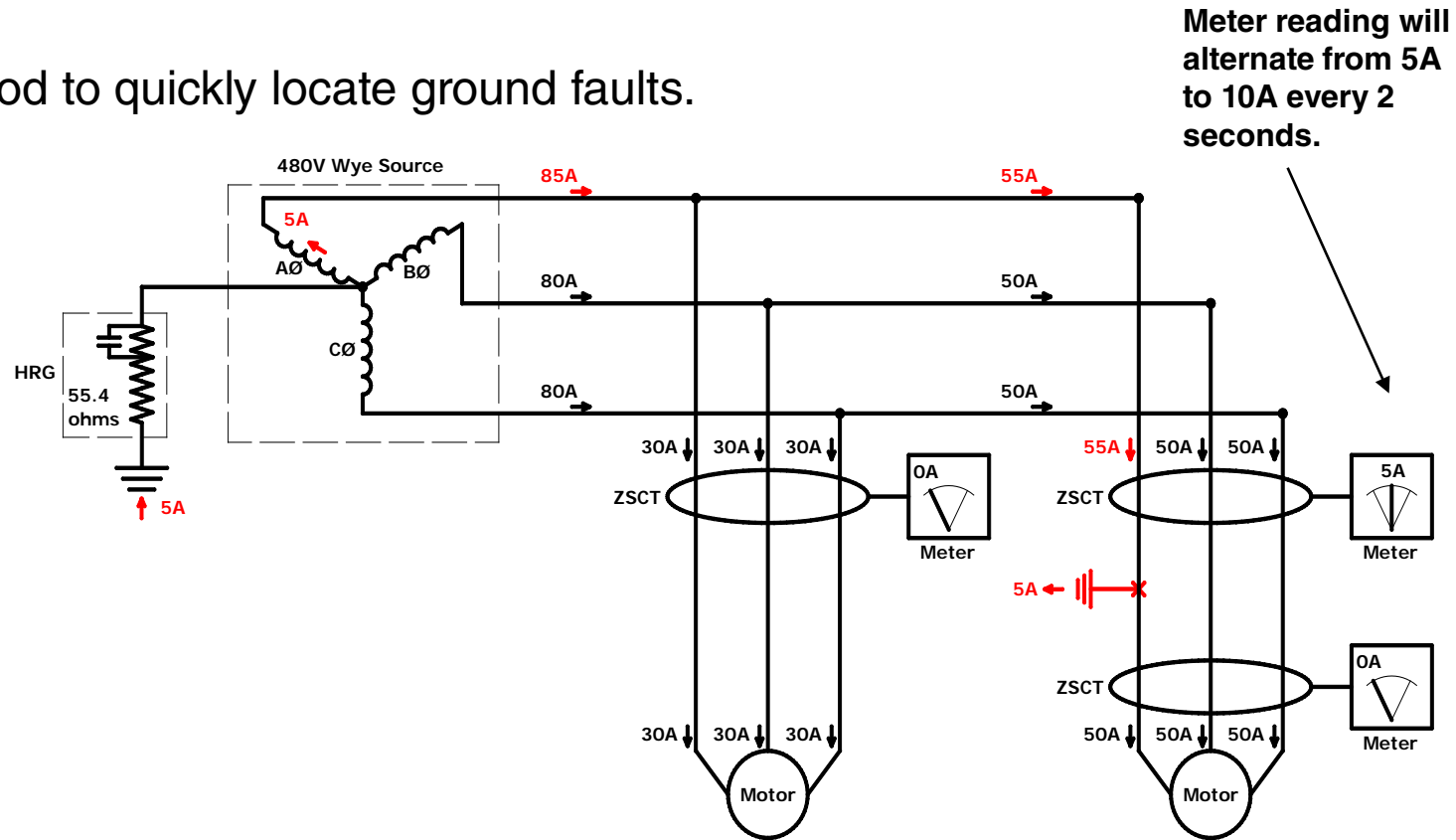
Another advantage of return path: ground fault location



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!

High Resistance Grounding

Method to quickly locate ground faults.



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

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

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

IEEE Application Guides Recommend HRG

IEEE Std 142-1991 (Green Book)

Recommended Practice for Grounding of Industrial and Commercial Power Systems

1.4.2 **Numerous advantages are attributed to grounded systems, including greater safety**, freedom from excessive system over-voltages that can occur on ungrounded systems during arcing, resonant or near-resonant ground faults, and easier detection and location of ground faults when they do occur.

1.4.3 **A system properly grounded by resistance is not subject to destructive transient over-voltages.**

IEEE Application Guides Recommend HRG

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.

- 1) **To reduce burning and melting effects** in faulted electric equipment, such as switchgear, transformers, cables, and rotating machines.
- 2) **To reduce mechanical stresses** in circuits and apparatus carrying fault currents.
- 3) **To reduce electric-shock hazards to personnel** caused by stray ground-fault currents in the ground return path.

IEEE Application Guides Recommend HRG

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.**

- 4) **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.
- 5) **To reduce the momentary line-voltage dip** occasioned by the clearing of a ground fault.
- 6) **To secure control of transient over-voltages while at the same time avoiding the shutdown of a faulty circuit** on the occurrence of the first ground fault (high resistance grounding).

IEEE Application Guides Recommend 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.

IEEE Application Guides Recommend HRG

IEEE Std 242-2001 (Buff Book)

Recommended Practice for Electric Power Distribution for Industrial Plants

8.2.5 Once the system is high-resistance grounded, over-voltages are reduced; and modern, highly sensitive ground-fault protective equipment can identify the faulted feeder on the first fault and open one or both feeders on the second fault before arcing burn down does serious damage.

High Resistance Grounding

- S**elective instantaneous feeder isolation- 2nd fault
- M**itigate 95-98% of arc flash incidents - on 1st phase to ground fault and simply alarm
- A**ssisted fault location
- R**esistor-integrity monitoring
- T**ime-selective feeder isolation

Unparalleled Protection

High Resistance Grounding

Canadian Electrical Code : 10-302

- Where a neutral grounding device is used on an electrical system operating at 5 kV or less, provision shall be made to automatically de-energize the system on the detection of a ground fault, unless:
 - The ground fault current is controlled at 10 A or less; and
 - A visual or audible alarm, or both, clearly identified to indicate the presence of a ground fault, is provided.

The Neutral to Ground path must be monitored and alarm indicated , the signaling should remain continuous until the condition has been corrected

Low Resistance Grounding

- Used on medium voltage (5 KV -36 KV) distribution systems where system charging current is too high for high resistance grounding
- Ground fault current limited to 15 – 100 A typically ($I_R > 3I_{C0}$)
- Trip on ground fault
- Prevents arc flash incident on ground fault

Distribution System Design Criteria

High Resistance Grounded

- **Reliability** Power continuity, no trips on ground fault
- **Safe** No Arc Blast or Flash Hazard on Ground Fault
- **Cost effective** 3 Wire Systems are cheaper than 4 wire
- **Scheduled Maintenance** Faulty equipment can continue to run,
scheduled shut downs and lower repair costs

- **Prioritized load** Overcurrent Coordination maintained
Selective second fault protection available

High Resistance Grounding

- Limit ground fault current to 10 A or less
- Provides service continuity on first ground fault
- Prevents arc flash incidents on first ground faults
- Allows faults to be located without de-energizing feeders (ground fault pulse locating)
- Used in 3 phase 3 wire circuits at 480 , 600 and 4160 V specially in continuous process industries, hospitals, data centers and station service in gen stations **where unscheduled downtime is costly or cannot be tolerated.**

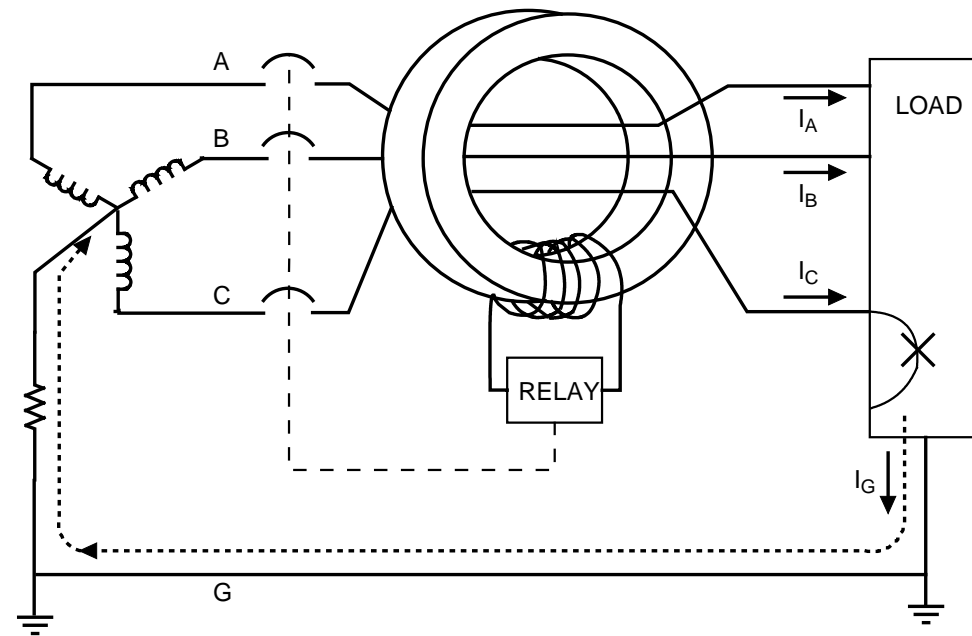
Alarming and Relaying

- Resistance grounding is not enough
- Must sense ground faults
- Take action
- Either alarm only, and locate the fault
- Or trip on fault

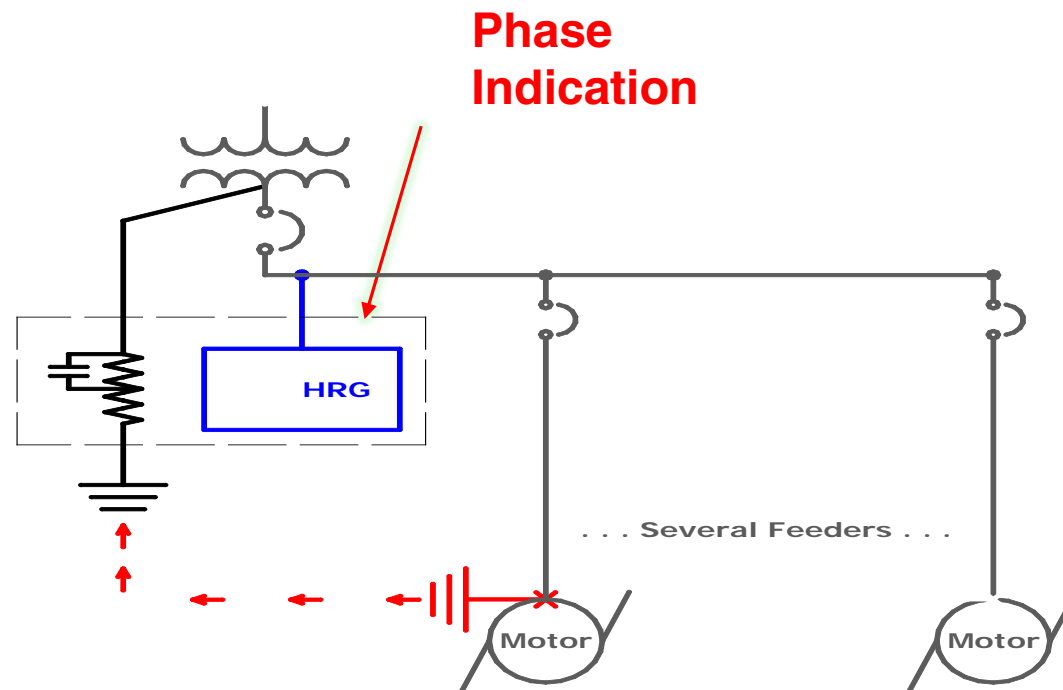
Approaches for Ground Detection

- Voltage Sensing GF Relay
- Current Sensing GF Relay
- Swbd Multi-Feeder GF Alarm Relay
- Swbd GF Relay with 2nd Fault Protection
- GF Relay for MCC's
- Combination wall-mounted NGR and GF Relay for Retrofits

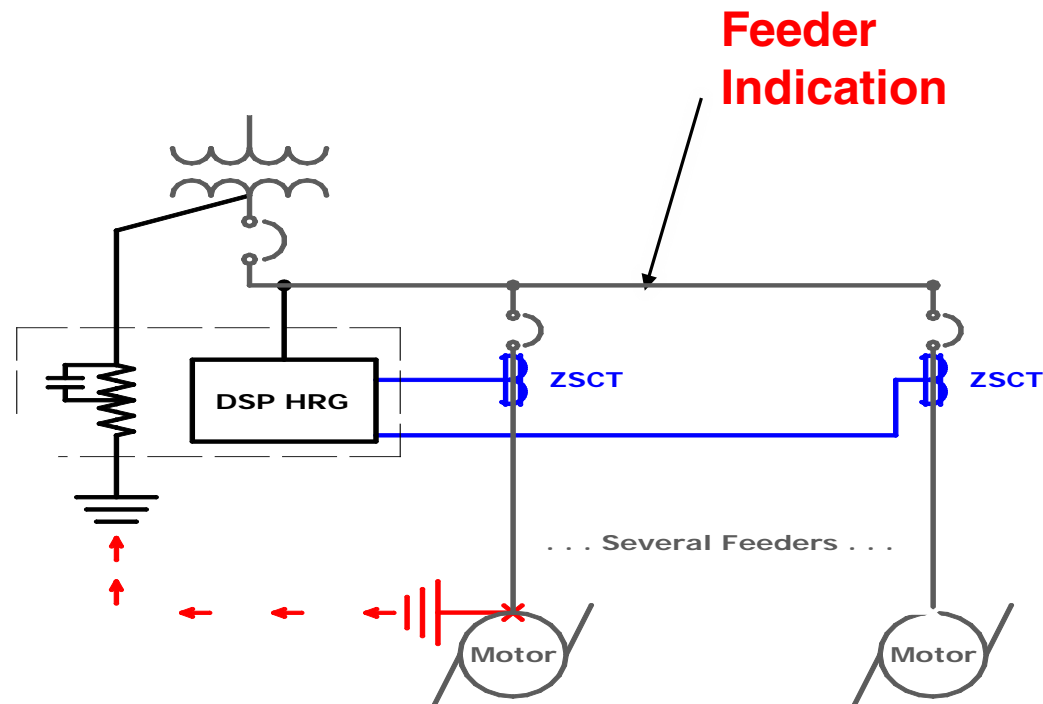
Sensing Ground Faults Using a Zero Sequence Sensor



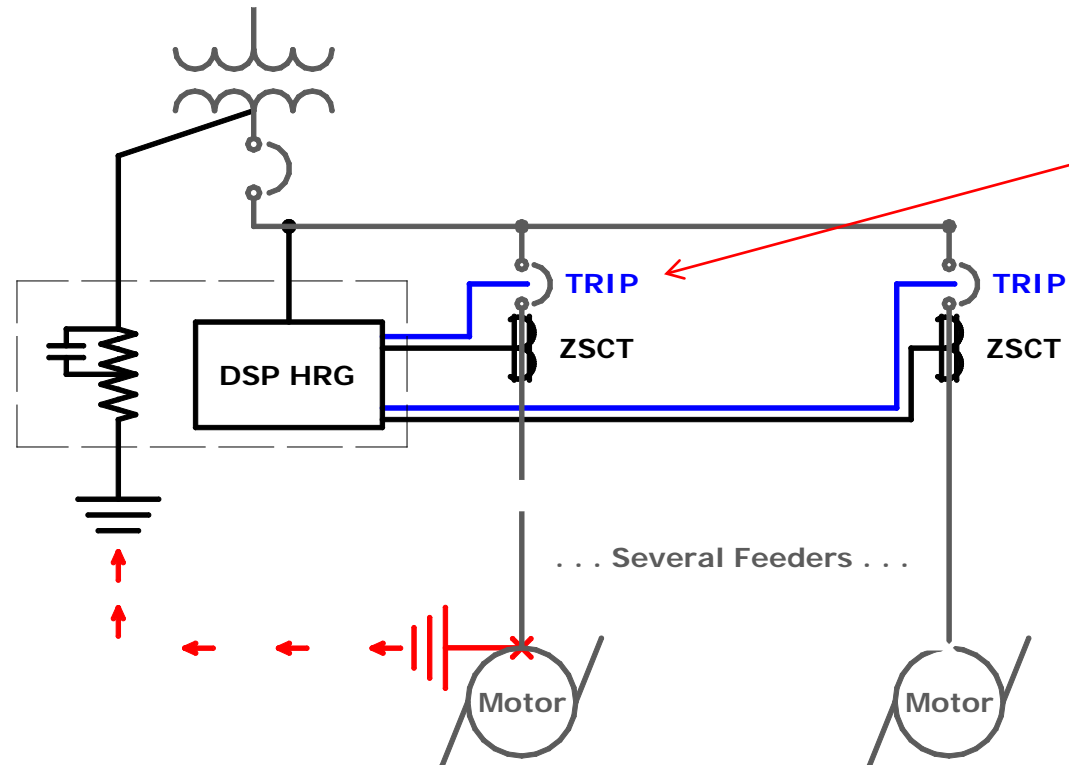
High Resistance Grounding Arcing Fault Location



High Resistance Grounding Arcing Fault Location



High Resistance Grounding Avoiding 2nd Ground Fault



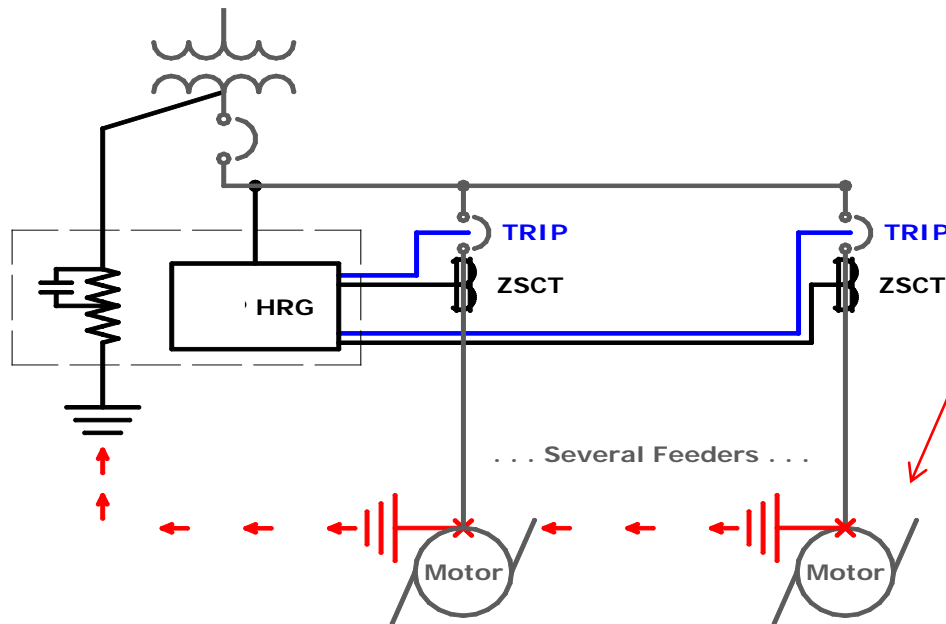
Options for Faulted Feeder:

1) Alarm Only (No Trip)

OR

2) Trip with Time Delay

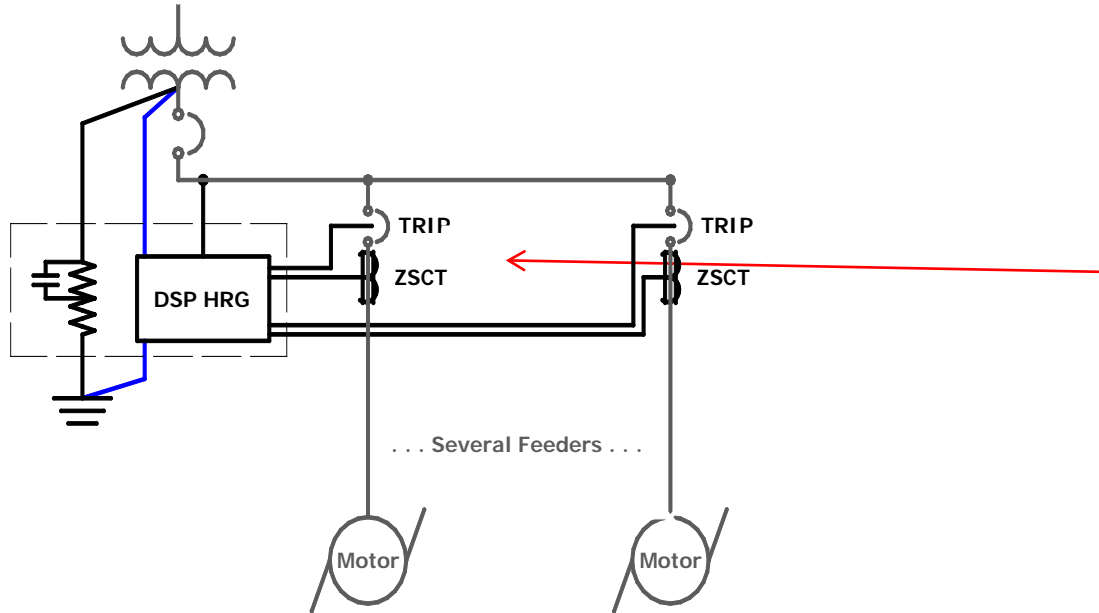
High Resistance Grounding Avoiding 2nd Ground Fault



2nd Ground Fault:

- **Prioritize Feeders**
- **Trips least important, maintaining operation on most important**
- **Up to 50 Feeders**

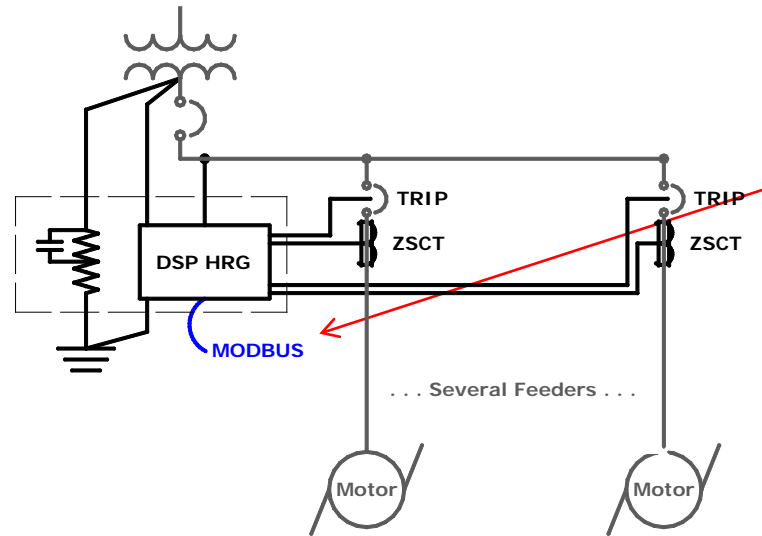
High Resistance Grounding Neutral Path



System Ground Monitor:

- **Continually monitors circuit from Neutral to Ground**
- **Alarms if OPEN circuit**
- **Alarms if SHORT circuit**

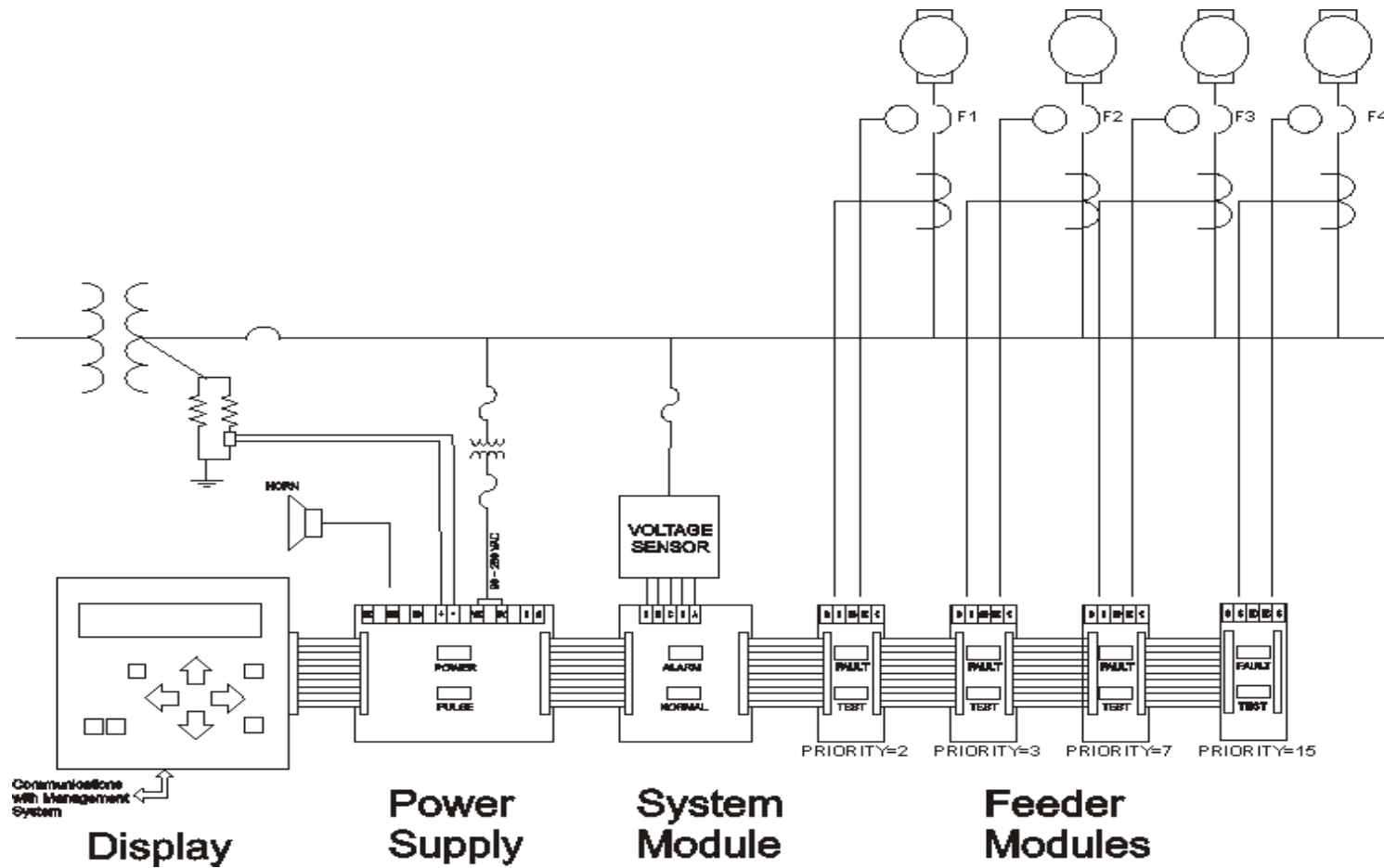
High Resistance Grounding Neutral Path



Remote Monitoring:

- Tie into Internet
- Monitor plant anywhere in world
- Notify maintenance or local qualified electrical contractor to locate ground fault

Minimizing 2nd Simultaneous Ground Fault



Design Considerations when applying HRG Systems

HRG is the best Grounding **Method** available today

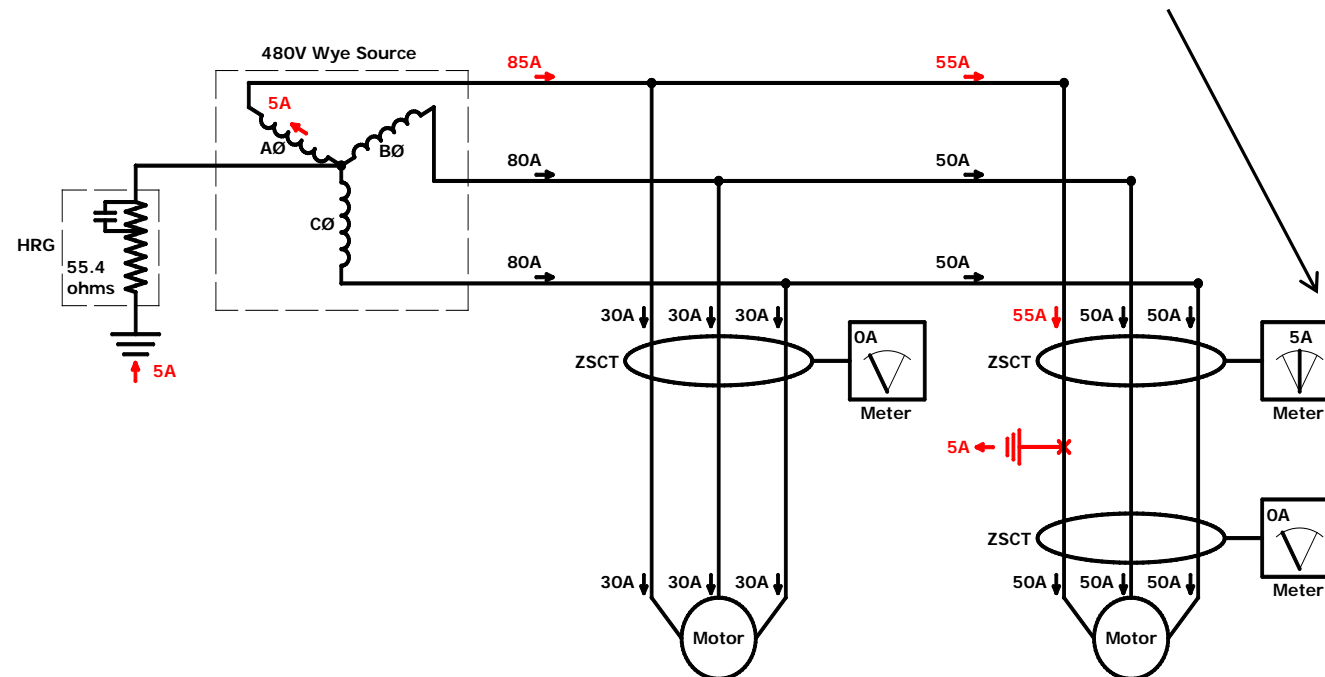
- First developed with resistor and pulsing contactor (Analog)
- Least Hazards of all grounding methods, but some still exist
 - Elevated Voltages
 - ✓ Trained Personnel
 - ✓ Cables, TVSSs, VFDs Insulation
 - Line-to-Neutral Loads
 - Phase-to-ground-to-phase Faults
 - ✓ Bypasses neutral grounding resistor
 - ✓ Single-pole break rating of circuit breakers

HRG **Systems** Resolve these Hazards

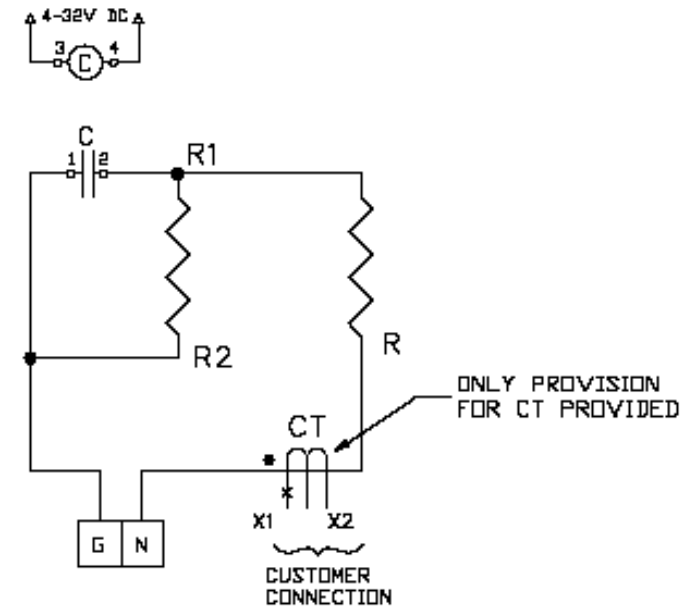
High Resistance Grounding

Method to quickly locate ground faults.

Meter reading will alternate showing high low pattern every 2 seconds.



Portable Current Sensor for Fault Tracing



Pulsing NGR

Ground Fault Pulse Locating

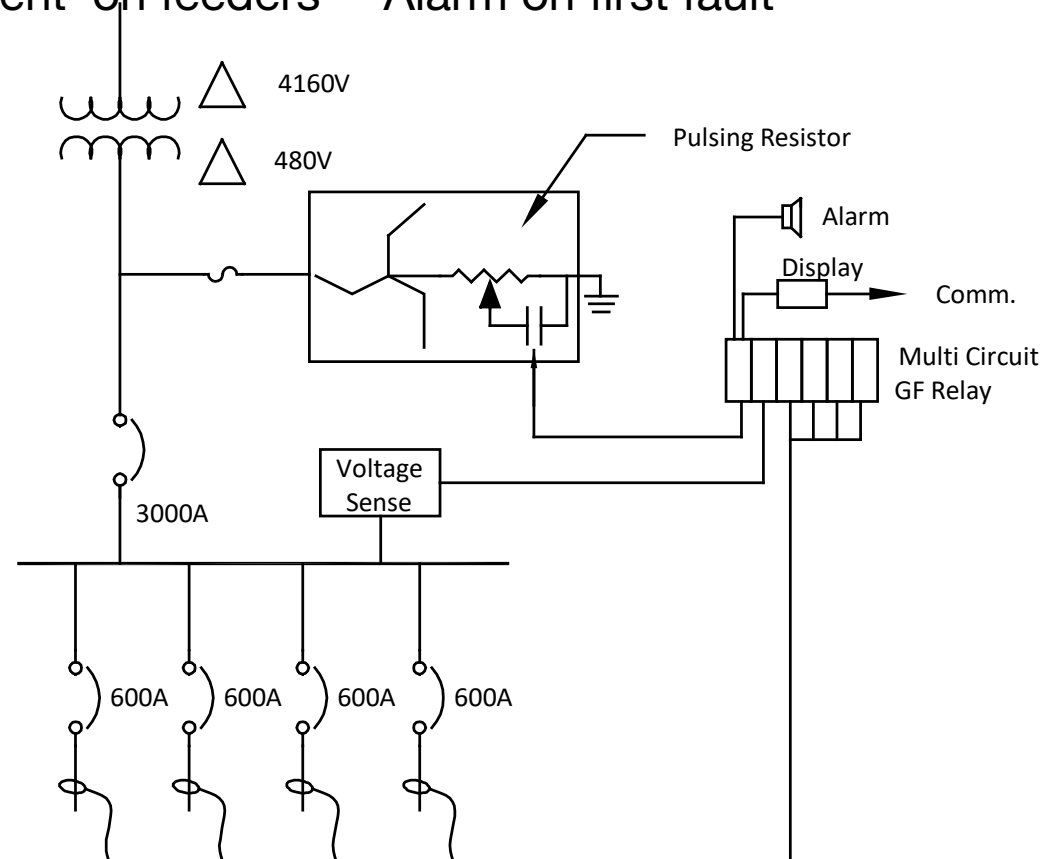


Application Considerations

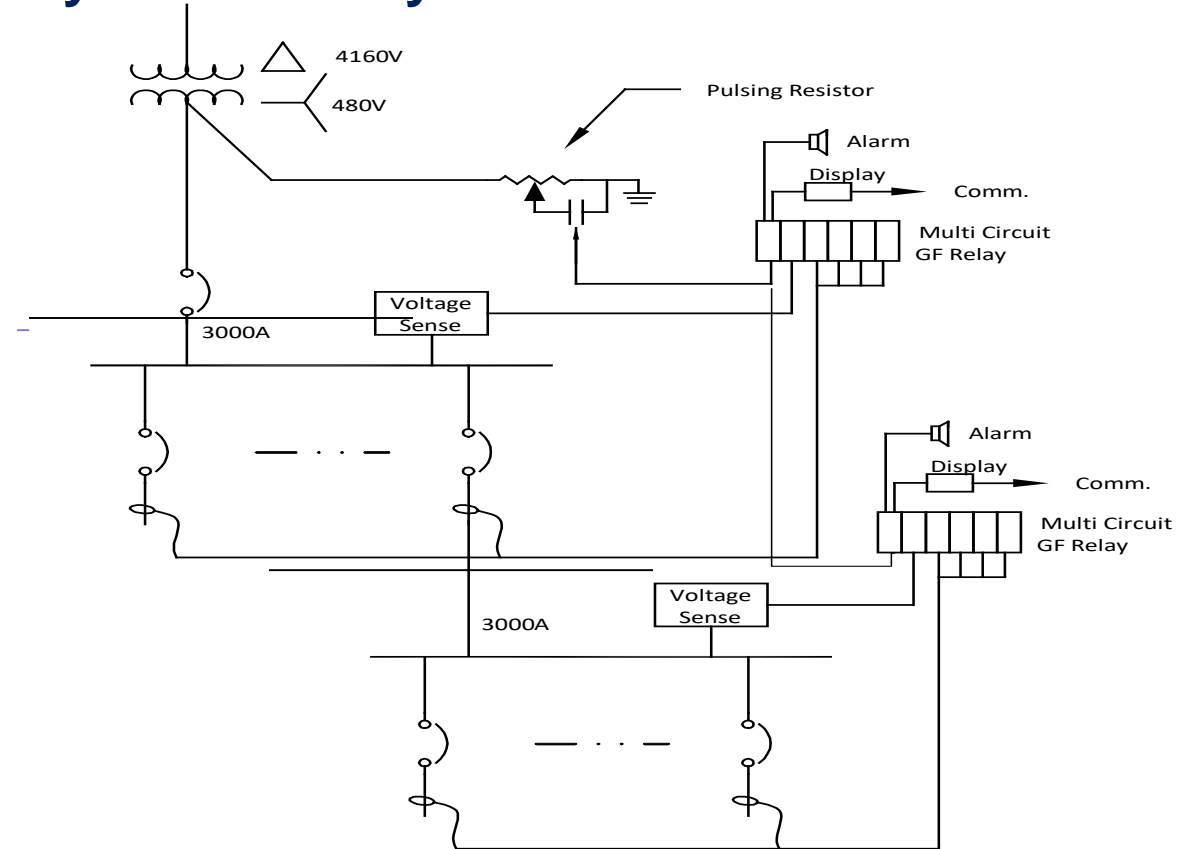
1. Where to apply the Grounding Resistor
 - At the transformer or
 - At the main bus
2. When to apply first fault alarm only
3. When to add 2nd fault trip function
 - Selective Instantaneous feeder tripping
 - Coordination with down stream Over current in 2nd fault trip
4. When to use 1st fault trip

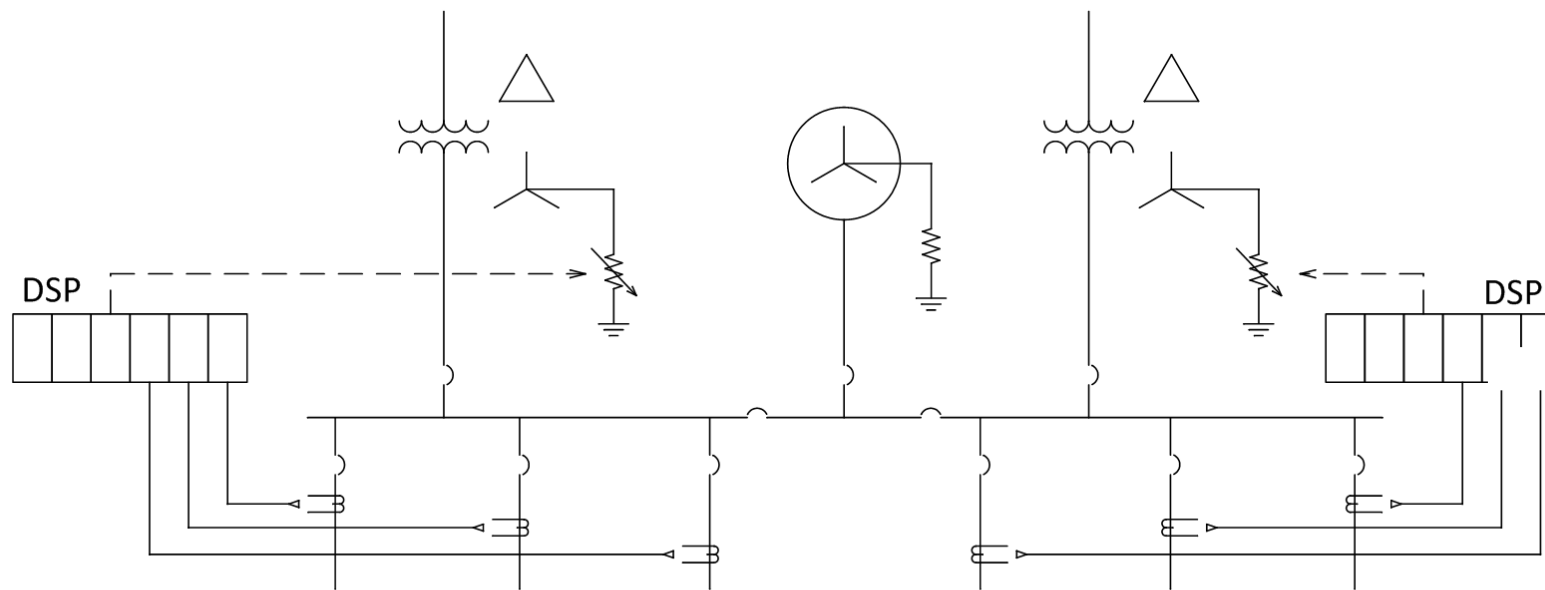
Single Source Systems

- Apply Ground fault detection with voltage to ground and zero sequence current measurement on feeders – Alarm on first fault



Single Source Fully Selective System





Main-Tie-Main DSP System

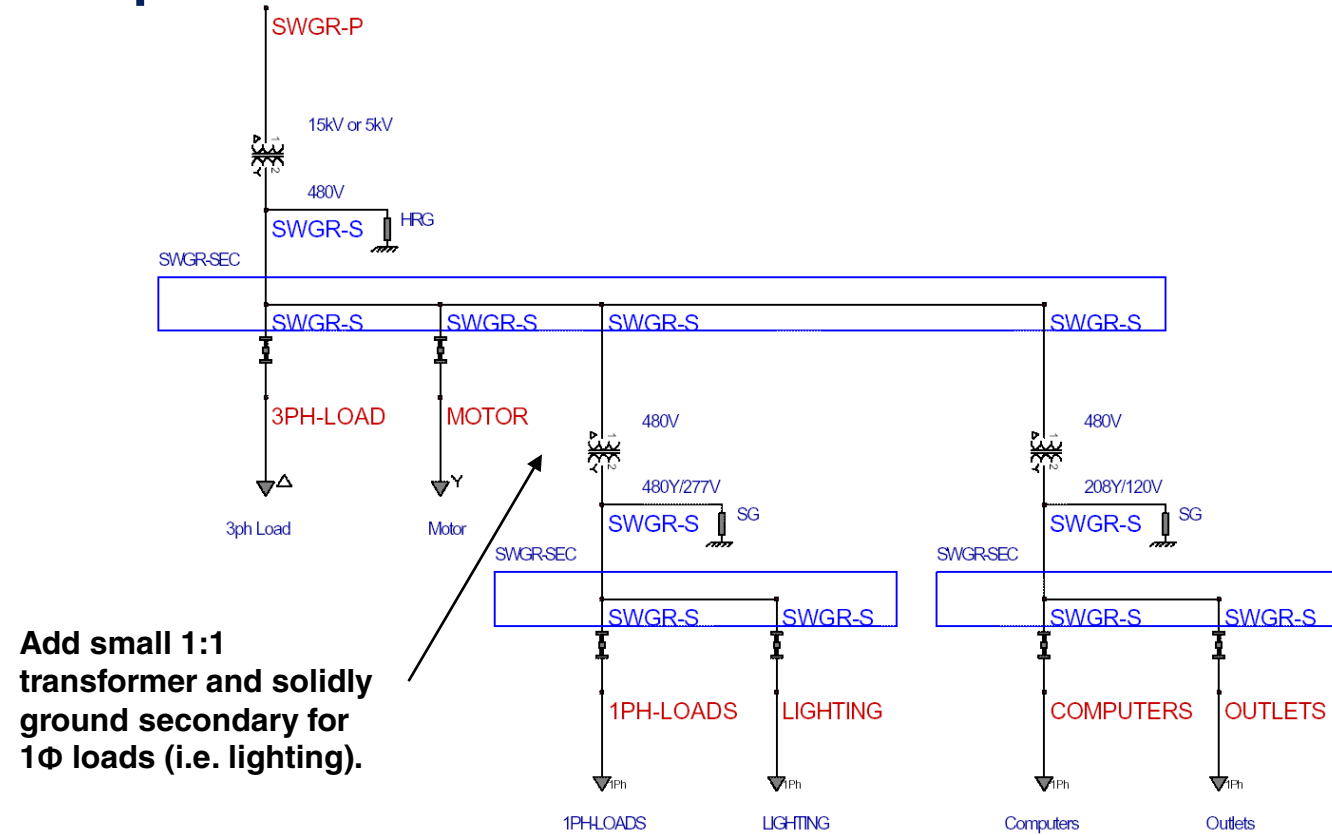
Design Considerations when Applying HRG Systems

NFPA 70: National Electrical Code (2018)

250.36/187 High-impedance grounded neutral systems in which a grounding impedance, usually a resistor, limits the ground-fault current to a low value shall be permitted for 3-phase ac systems of 480 volts to 1000 volts where all the following conditions are met:

- 1) The conditions of maintenance and supervision ensure that only qualified persons service the installation.
- 2) Ground detectors are installed on the system.
- 3) Line-to-neutral loads are not served.

Resolve NEC Requirement

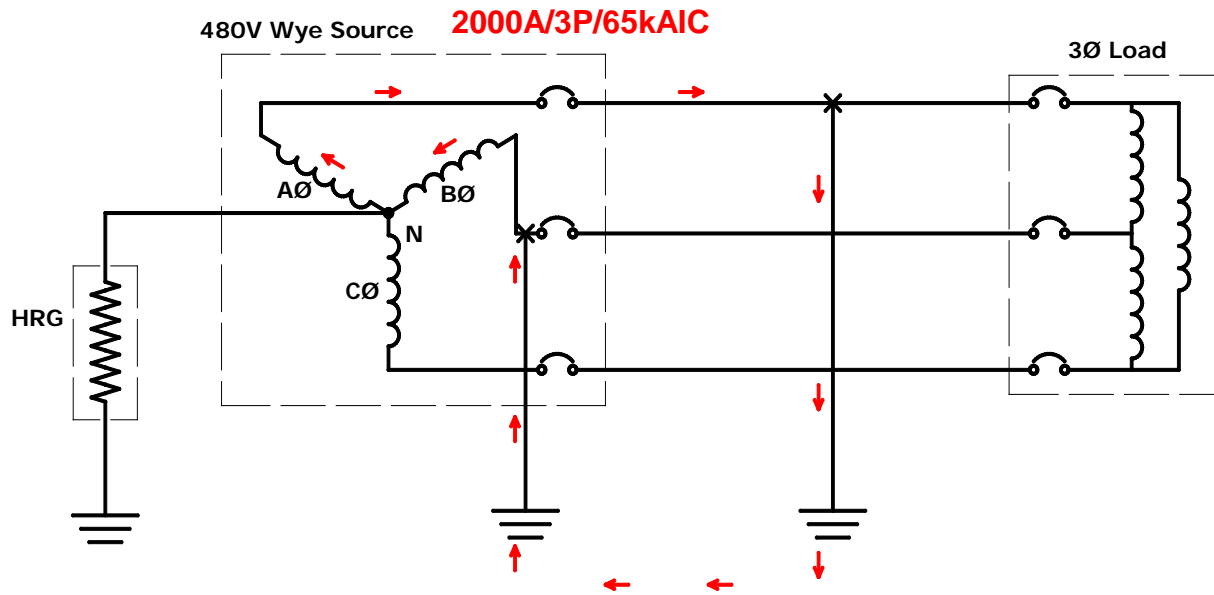


Resolve NEC Requirement

Advantages of 1:1 transformer

- Ability to retrofit HRG Systems
- Only ~20% of facility / plant load is 1 Φ
 - No neutral required from main source and main switchgear (cost savings,)
- Significantly reduced risk of Arc Blast / Flash Hazard
 - Only small portion of power system is solidly grounded
 - Lighting Ballasts

Single-poling circuit breaker



During phase-ground-phase fault, single-pole of MCB has to clear the 480V fault at 65kA. However, per UL 489, single-pole interrupting rating is only at 20kAIC. **HAZARDOUS?**

Phase-to-Ground-to-Phase Fault

For condition to occur, all of the following must be true:

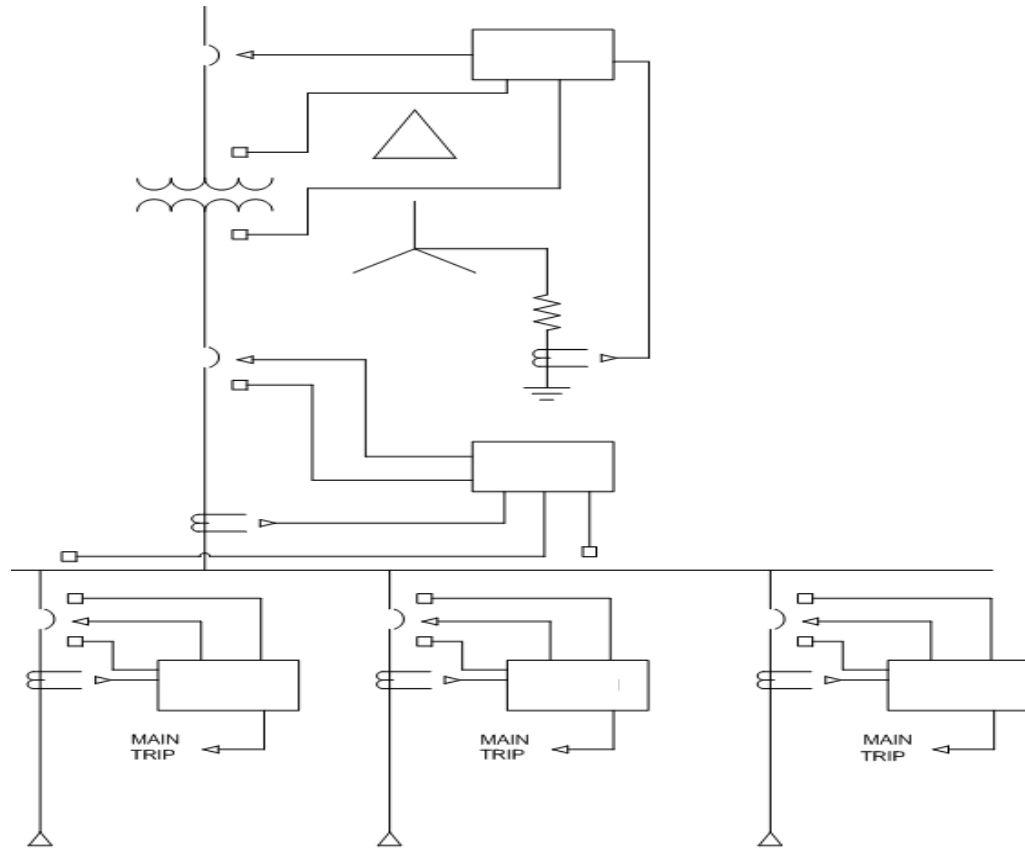
- 1) One fault must be on line side of MCB
 - Very uncommon
- 2) Low impedance per ground fault
 - Very uncommon
 - Ground faults are usually arcing faults (high impedance faults per IEEE Std 241, 9.2.5)
- 3) Faults on different phases
- 4) No other over-current protective devices in fault path
 - Very uncommon
 - If so, they will open: eliminating the single-pole interruption

Although remote, HAZARD may still exist:

- Should be considered during coordination study
- Detect ground faults per NEC 250-36

Reducing Arc Flash Energy Exposure On the Line Side of LV Main Breaker

- Use arc flash sensing relay and trip the primary side MV device. It has to be a fast breaker Load break switches even if they are trippable are too slow .
 - V AC breaker has to be used



HRG and Arc Flash Protection

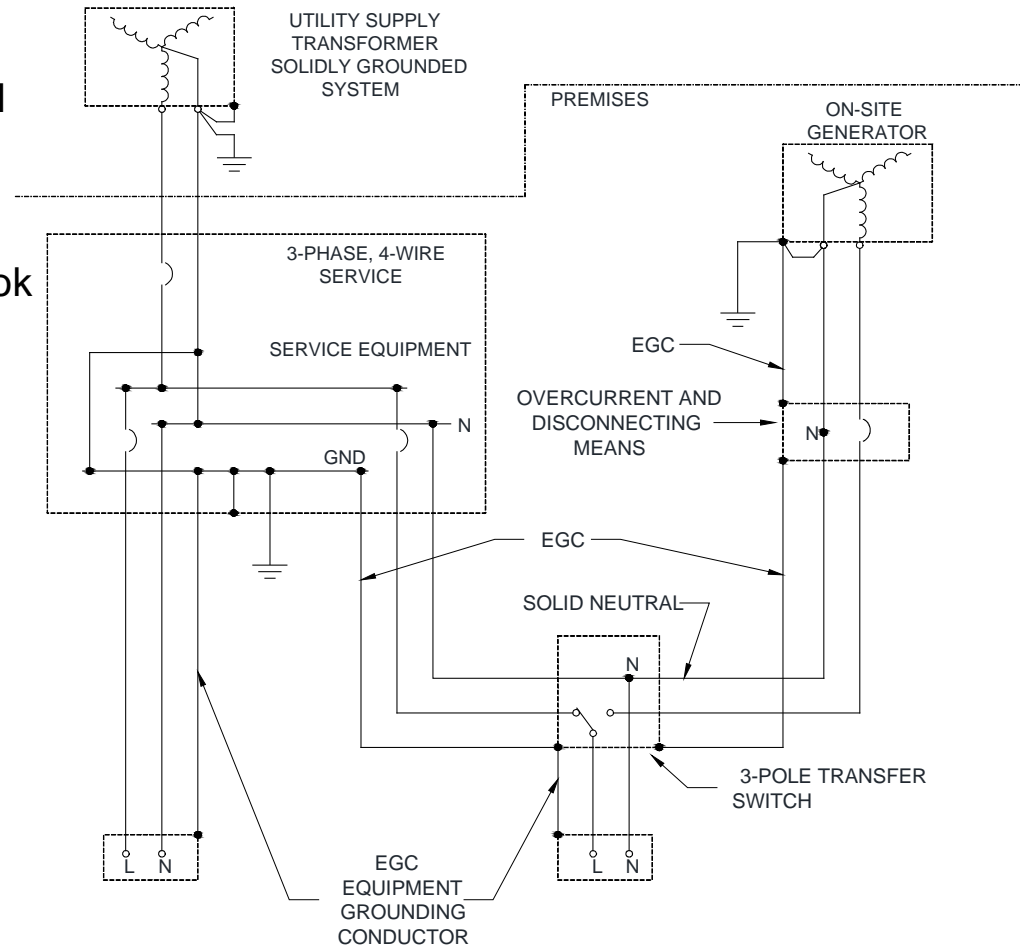
Issues in Solid Grounding of Generators and use of Automatic Transfer Switches

- Stray neutral current in bonding conductors (objectionable current) with multiple grounds
 - Nuisance trip of ground fault relays
 - Poor security
- Ground fault current in the neutral conductor
 - Ground fault relays fail to pick up
 - Poor reliability

Incorrect Grounding of 3-Pole ATS with Solid Neutral

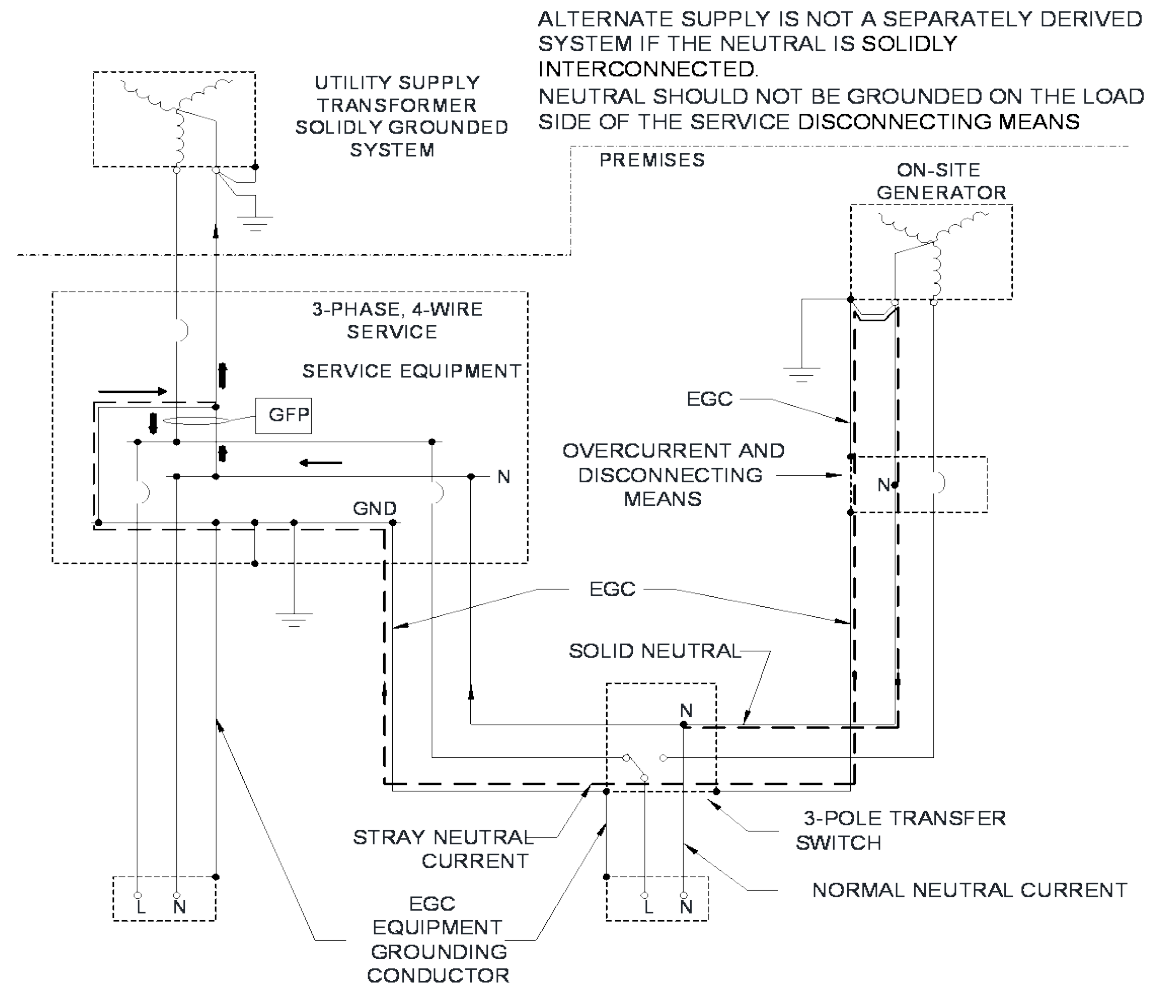
Multiple neutral grounds!

Figure 7-7
IEEE **Orange** Book
Std. 446-1995



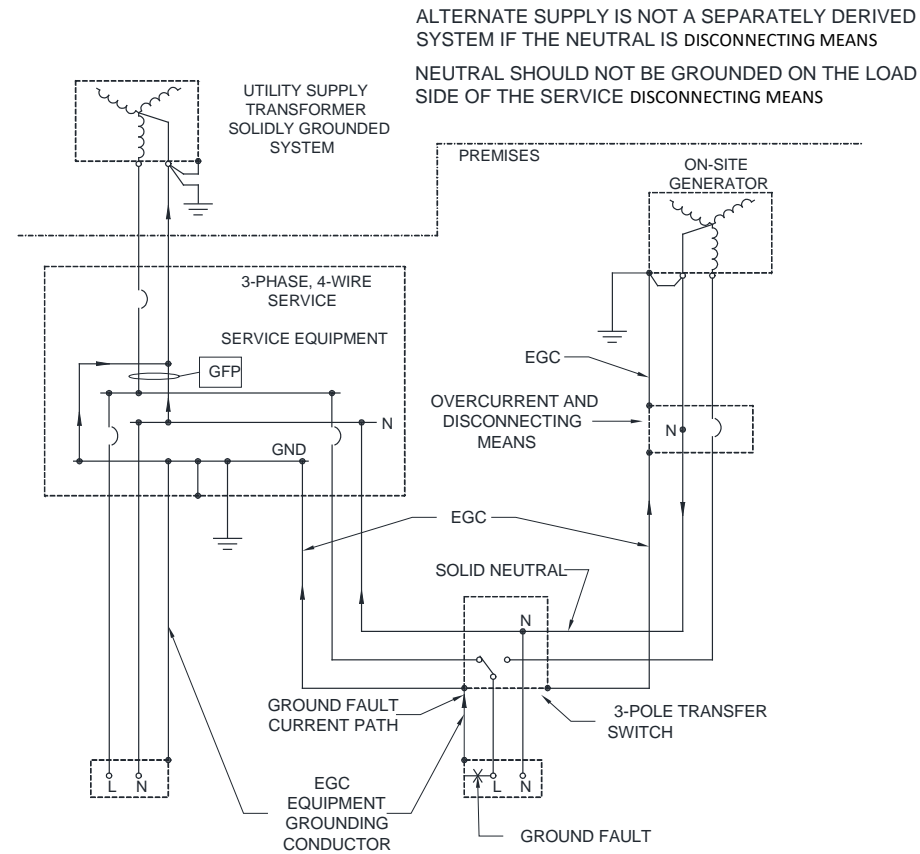
Multiple Neutral Grounds- Stray Neutral Current & Nuisance Ground Fault Trip

Figure 7-8
IEEE **Orange** Book



Multiple Neutral Grounds- Ground Fault Relay Fails to Trip

Figure 7-9
IEEE **Orange** Book
Std. 446-1995



ATS with Solid Neutral

LV generator with 4-wire loads can use a 3-pole ATS with solid neutral to ground the generator at the transformer when:

- single ATS only
- generator neutral grounded at transformer only
- no ground fault protection on generator (transformer only)
- generator not remotely located

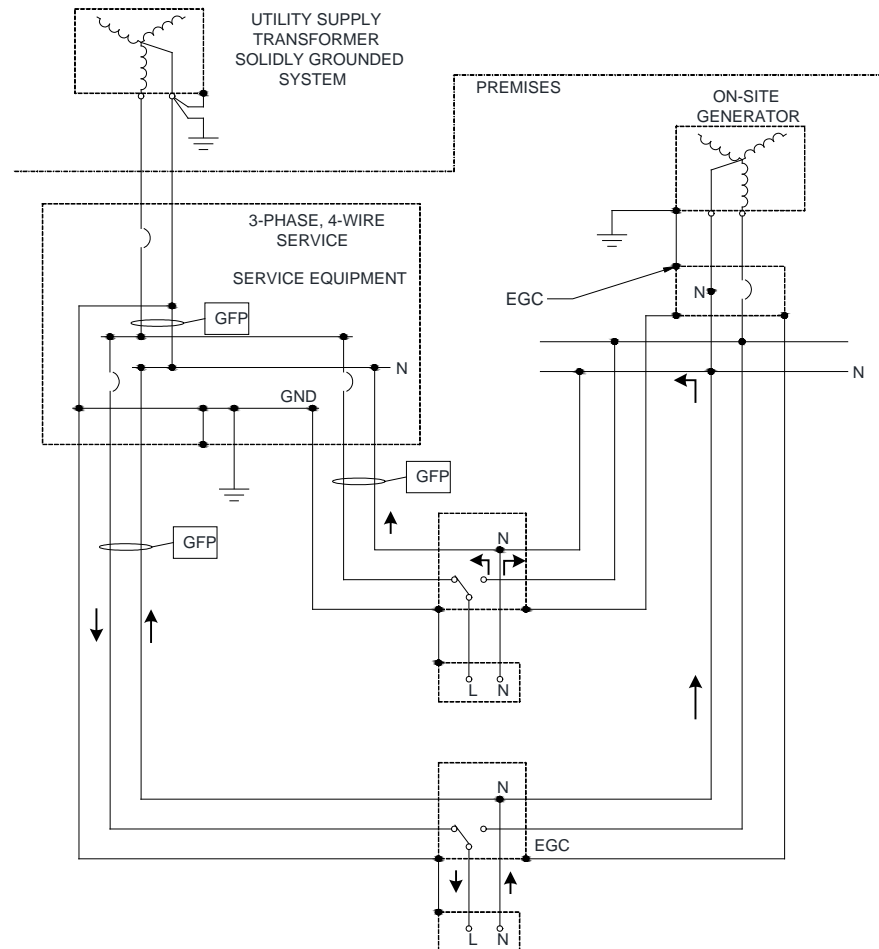
Otherwise:

Stray neutral currents from unbalanced loads and ground faults.

- nuisance trips of ground fault relays
- failure-to-trip of ground fault relays
- different ground potential at transformer and remote generator

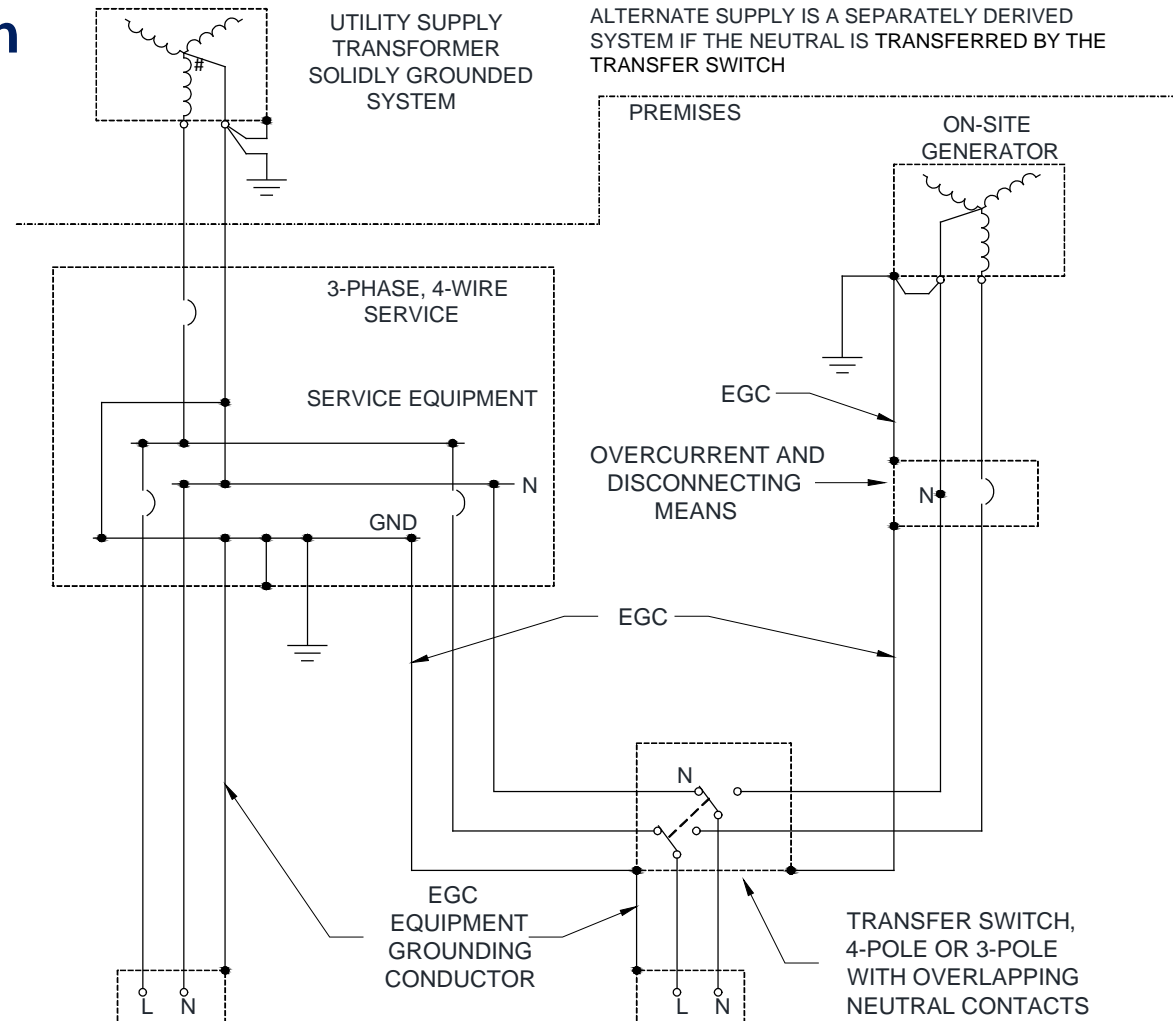
Multiple Transfer Switches- Nuisance Ground Fault Trips

Figure 7-17 (a)
IEEE **Orange** Book
Std. 446-1995



4-Pole Transfer Switch

Figure 7-13
IEEE **Orange** Book
Std. 446-1995



ATS with Switched Neutral

Required for all other LV generators serving 4-wire loads.

Switched neutral – two types:

- simultaneously switched neutral (4-pole transfer switch)
- make-before-break overlapping neutral contacts

Permits grounding at the generator.

Benefits:

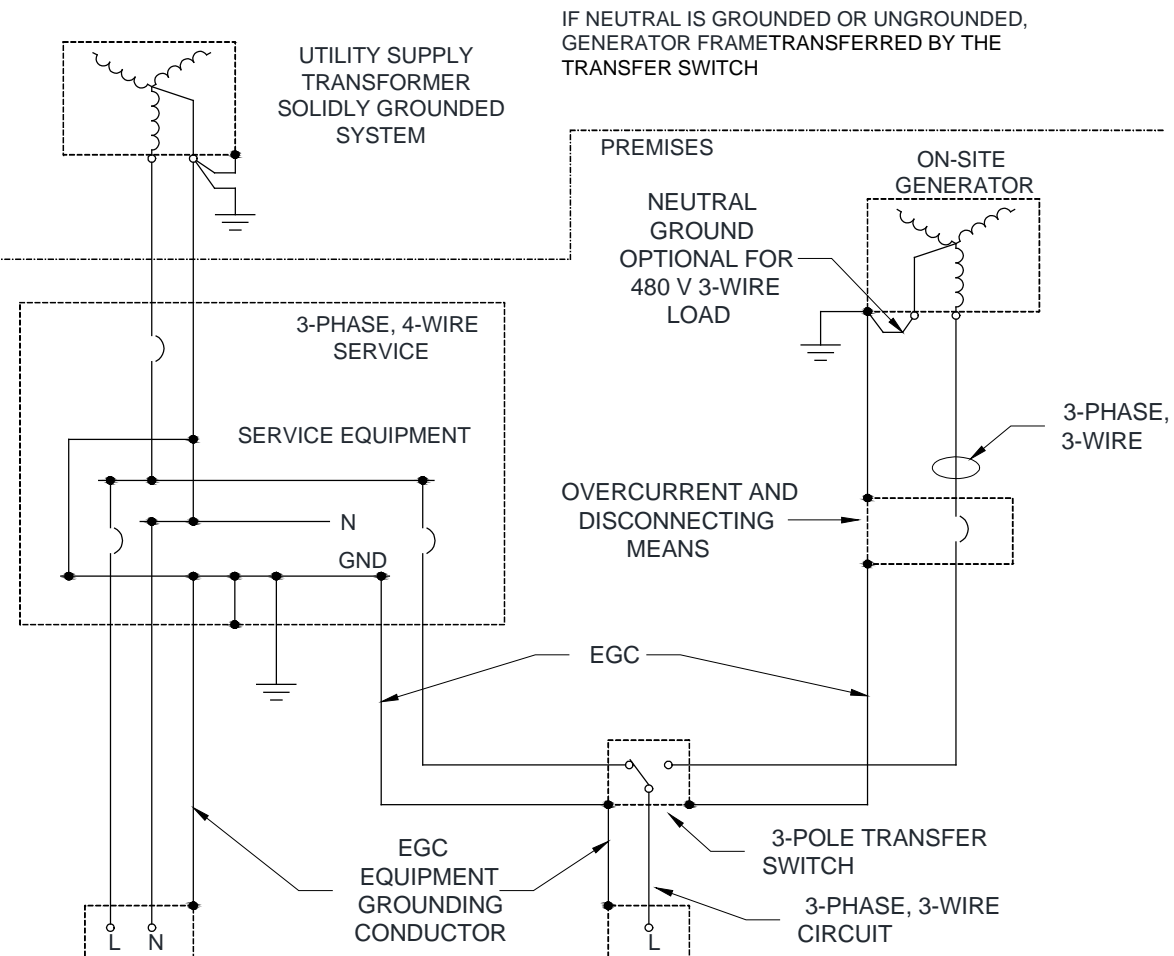
- generator can be remotely located
- allows ground fault protection for generator
- stray neutral currents eliminated
- proper operation of ground fault relays (security and reliability)

IEEE Orange Book says (7.9.1):

For most emergency and standby power systems with ground-fault switches, switching of the grounded circuit conductor by the transfer switch is the recommended practice.

3-Wire Emergency Load- 3-Pole Transfer Switch No Stray Neutral Currents

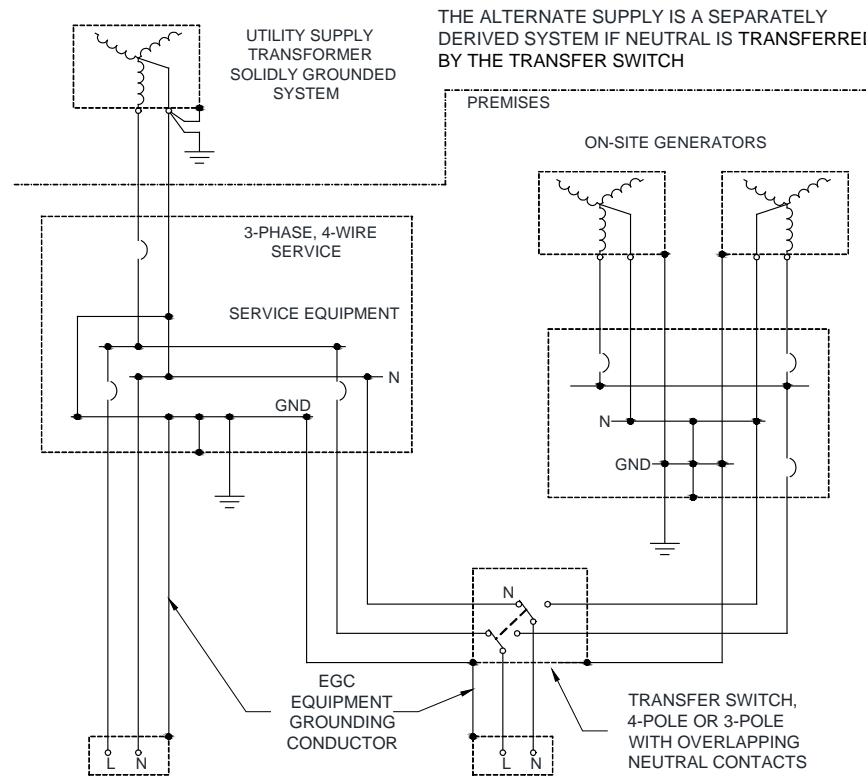
Figure 7-18
IEEE **Orange** Book
Std. 446-1995



4-Wire Emergency Loads: Parallel Generators

- If 4-wire parallel generators are a must, then a switched neutral ATS is recommended
- Must have one, single system ground for generators, located close to the generators
- Triplen harmonic circulating currents in the common neutral between generators may or may not be excessive

4-Wire Emergency Loads: Parallel Generators



Source: IEEE Std 446-1995, Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications, Figure 7-13, p. 236.

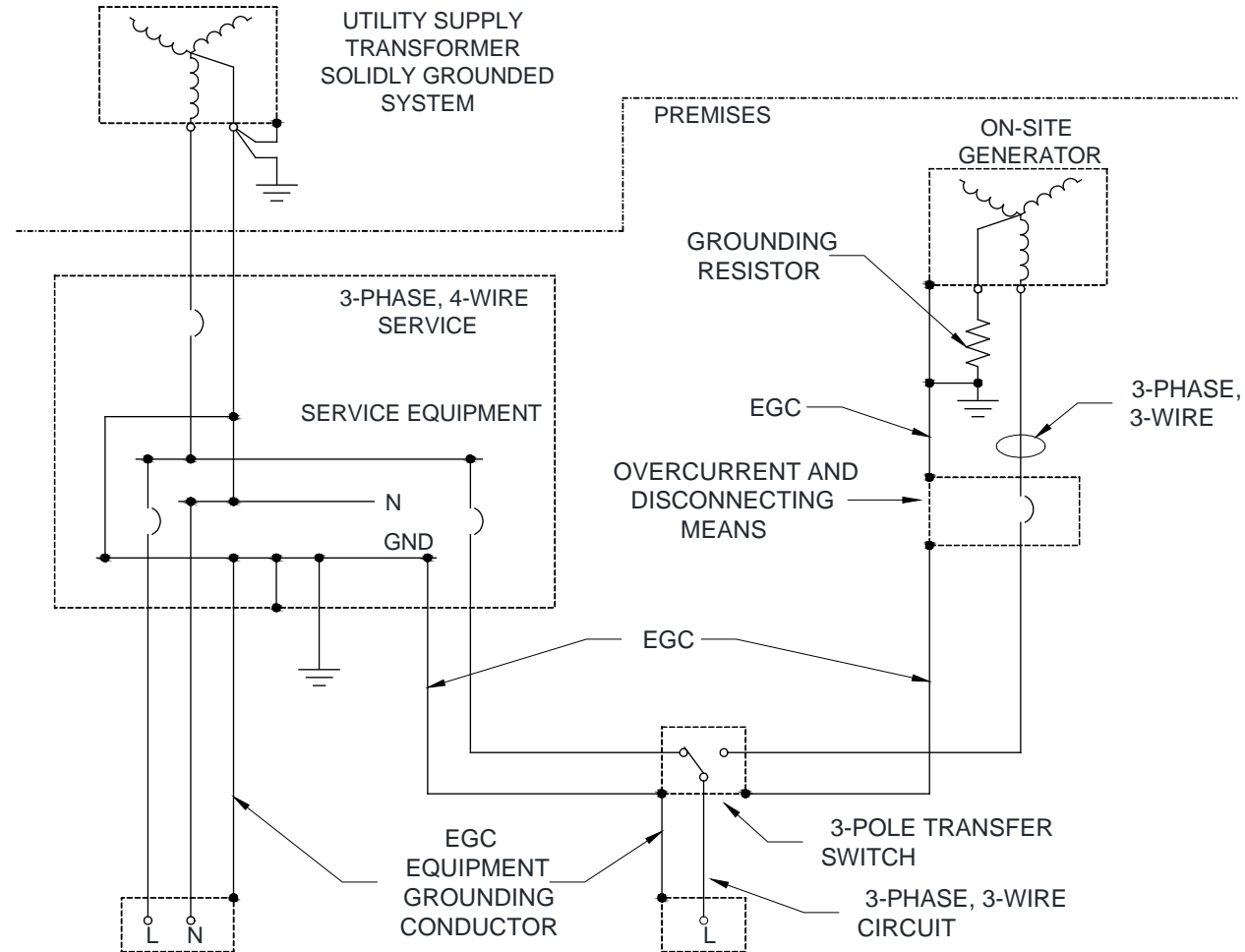
3-Wire Emergency Loads: Parallel Generators

- Individual solid grounding of a 3-wire generator system will produce excessive triplen harmonic circulating currents in the ground circuit
- Instead, each generator neutral should be connected to a common neutral bus in the paralleling switchgear and grounded at one point.
- Triplen harmonics will then circulate in the common neutral instead of ground circuit
- **IEEE Orange Book says (7.9.3):**
For a 3-wire system, it is generally recommended that the neutral of the generator not be solidly grounded so as to reduce circulating neutral currents within the ground system.

3-Wire Emergency Loads:

- Require 3-pole ATS only
- Generator neutral grounded at generator
- No nuisance tripping of ground fault relays

Alternative 3-Wire Distribution: High Resistance Grounding



Source: IEEE Std 446-1995, Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications, Figure 7-13, p. 246.

Additional Advancements in HRG Systems

Communications

- RS232 (Serial) / RS485 (Modbus, Profibus) / TCP/IP (Ethernet)
- Control and monitor relay remotely via existing SCADA system

Data Logging & Trending

- Most ground faults are intermittent, so when you go to locate via pulse, fault may have cleared
- Data log can link ground faults with equipment starting or running

To Summarize

Hazards with Ungrounded Systems

- Severe transient over-voltages
- Cannot efficiently locate ground faults

Hazards with Solidly-Grounded Systems

- Very high fault currents and time delays
 - Causing severe arc blast / flash conditions
- Ground fault coordination problems

To Summarize

High-Resistance Grounded Systems

Best Grounding Method today

- Resolves Ungrounded hazards
- Resolves Solidly-Grounded hazards

Technology continues to make HRG Systems safer than any other grounding method, but need help

- Continue to educate and train personnel (enr and maint.)
 - NETA
- Update standards and guideline that hinder HRG
 - NEC
 - NFPA 70E and IEEE 1584

Generator Grounding

- Generators are not braced for ground fault currents – only for three-phase bolted faults. The phase to ground fault current can be higher than the three phase bolted fault current
- Generators should be resistance grounded according to IEEE and NEMA to limit ground fault current

Why Excessive Ground Fault Current in Solidly Grounded Generators?

- *Generators have low zero-sequence impedance*
- Example: typical standby generator rated 600 V, 1500 kW, 1800 rpm
- Per unit sequence impedances:
 - $X_1'' = 0.235$
 - $X_2 = 0.263$
 - $X_0 = 0.068$
- Solid grounding and low zero sequence impedance cause excessive triplen harmonic current flow in neutral or ground, and excessive ground fault current.

Formulas for Generator Fault Current (per unit)

- Bolted three-phase fault current:
 - $I_F = V_S / X_1''$
 - $= 1.05 / 0.235$
 - $= 4.5 \text{ per unit}$
- Bolted single phase-to-ground fault current (solidly grounded):
 - $I_F = 3V_S / (X_1'' + X_2 + X_0)$
 - $= 3(1.05) / (0.235 + 0.263 + 0.0681)$
 - $= 5.6 \text{ per unit}$
- *Ground fault current 24% higher than 3-phase fault current!*

ANSI/NEMA Std. MG 1-2003 Motors and Generators

32.13 Short Circuit Requirements

A synchronous generator shall be capable of withstanding, without damage, a 30-second, *three-phase short circuit* at its terminals. The generator shall also be capable of withstanding, without damage, at its terminals any other short circuit of 30 seconds or less provided...

- b. *The maximum phase current is limited by external means to a value which does not exceed the maximum phase current obtained from the three-phase fault.*

ANSI/NEMA Std. MG 1-2003 Motors and 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 of a generator should not be solidly grounded unless the generator has been specifically designed for such operation. With the neutral solidly grounded, the maximum line-to-ground fault current may be excessive, and in parallel systems excessive circulating harmonic currents may be present in the neutrals.*

IEEE Green Book

IEEE Std. 142-1991, *Recommended Practice for Grounding of Industrial and Commercial Power Systems*:

1.8.1 Discussion of Generator Characteristics

Unlike a transformer...a generator will usually have higher initial ground-fault current than three-phase fault current if the generator has a solidly grounded neutral. According to NEMA, the generator is required to withstand only the three-phase current level unless it is otherwise specified...

If the winding is designed with a two-thirds pitch...third-harmonic voltage will be suppressed but the zero-sequence impedance will be lowered, increasing the ground fault current...

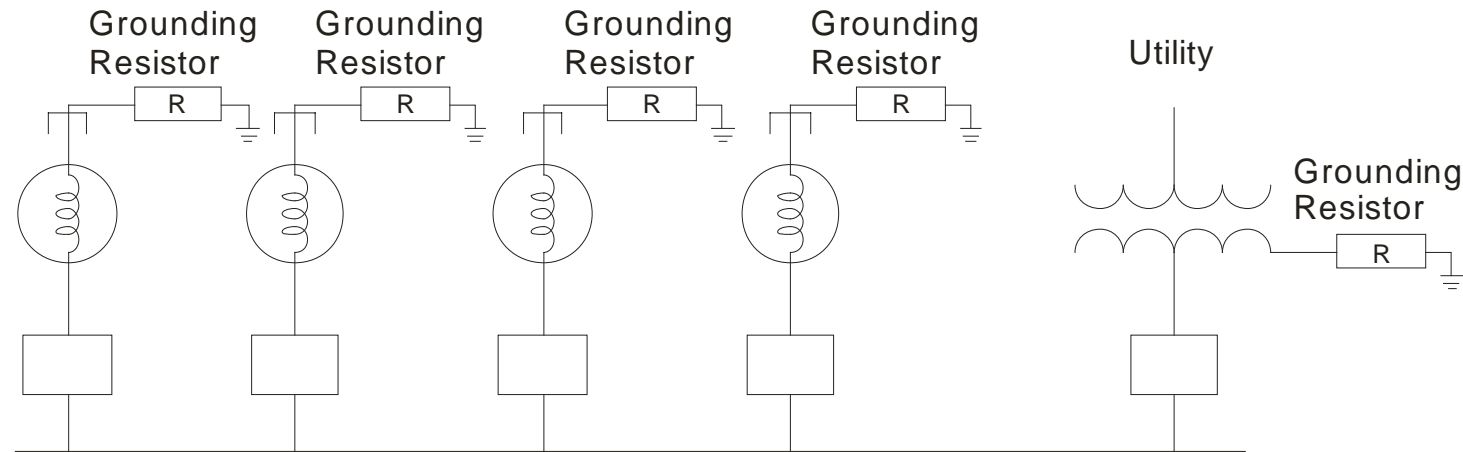
Internal ground faults in solidly grounded generators can produce large fault currents...Both the magnitude and duration of these currents should be limited whenever possible.

1.8.3 Paralleled Generators in Isolated System

High resistance grounding of the generators will adequately limit harmonic currents. Thus, it is attractive to use high-resistance grounding on the generators even if there are load feeders directly connected to the generator bus, and to use low-resistance grounding to provide selective relaying on the load feeders.

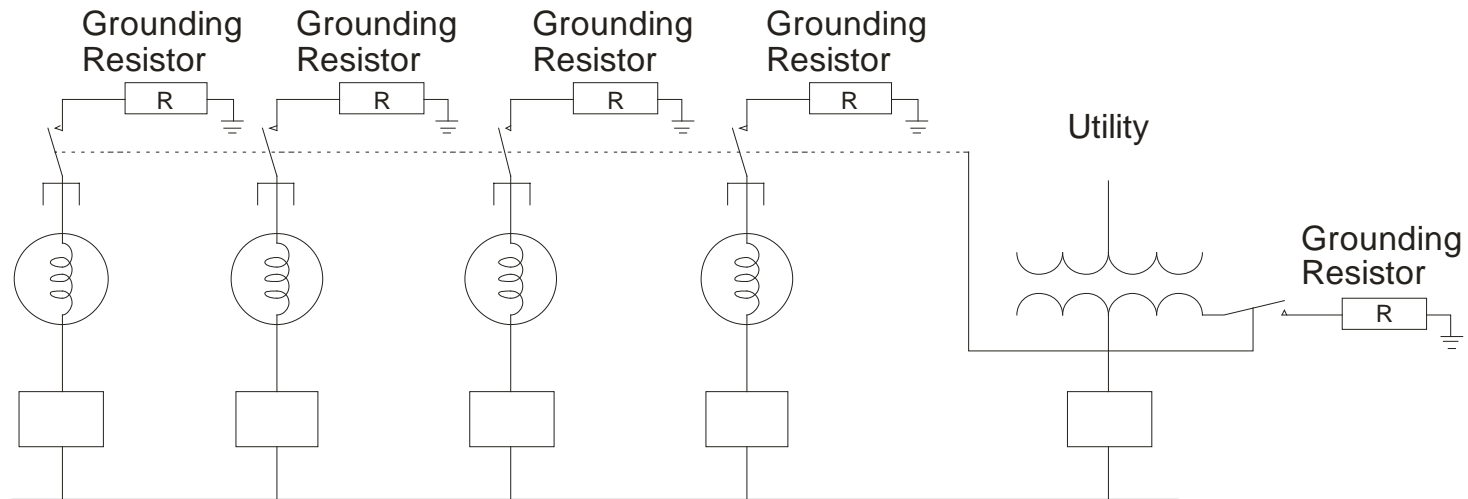
Multiple Generators Low Resistance Grounded

- Fault current is variable depending upon number of connected sources and damage can be very high if LRG 200 A – 800 A
- NOT Recommended



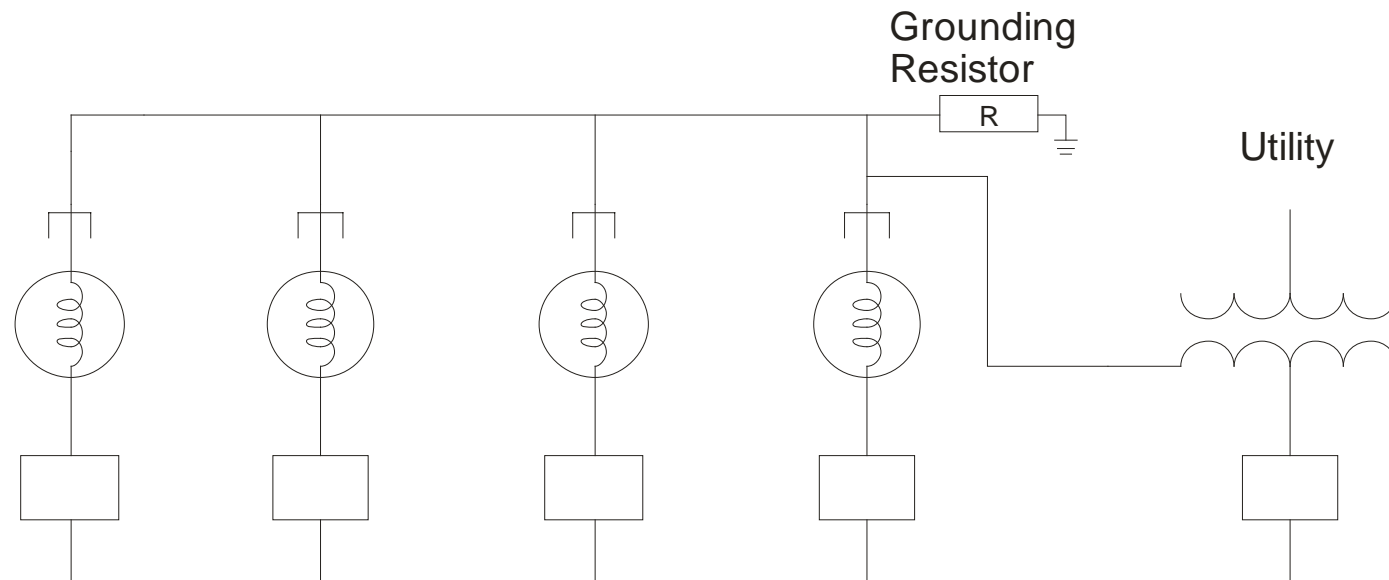
Single Point Ground Switched

- Very complex, switching required, danger of system becoming ungrounded if supply main breaker trips
- NOT Recommended



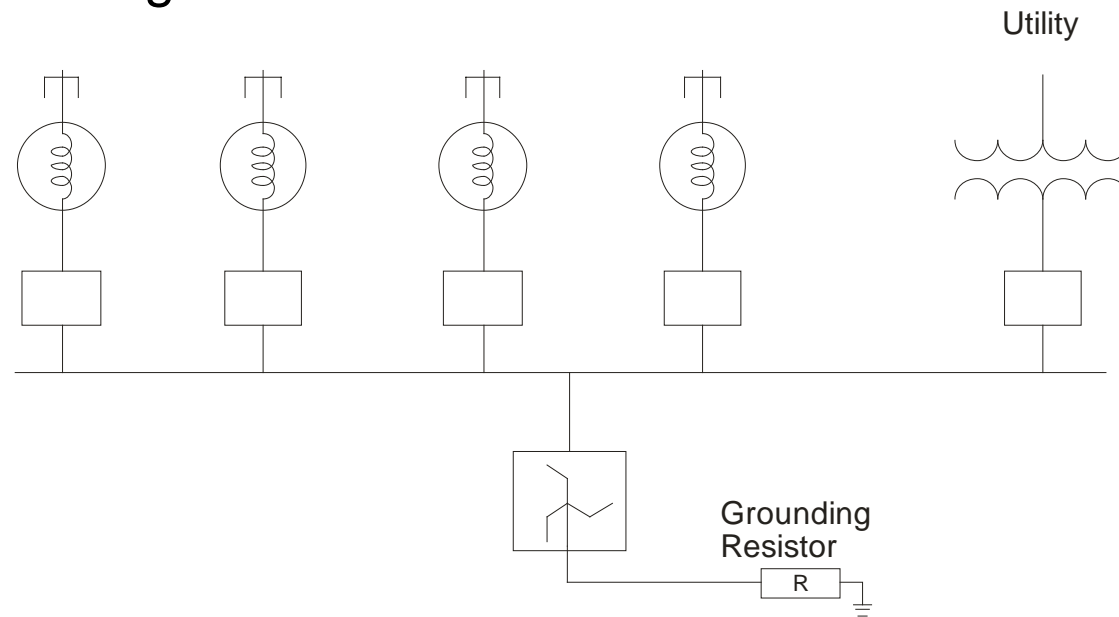
Common Neutral Low Resistance Grounded

- Circulating currents will flow causing generator de-rating



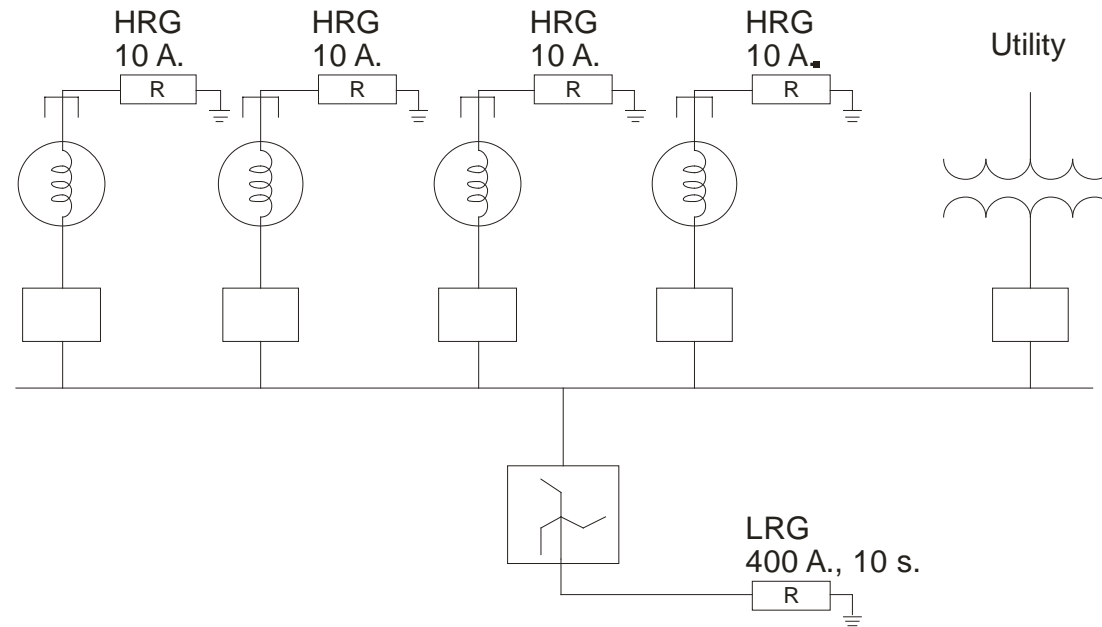
Single Point Ground at the Main Bus

- Known fault current for L-G faults, independent of number of generators in circuit



Hybrid Grounding of Multiple Generators

- Reduces generator damage. Sufficient current to overcome $3I_{CO}$, selective relaying easy to apply
- HRG can be 5A and LRG can be reduced to suit



Single 480 and 600V Generators

- All medium and large generators should be resistance grounded to ensure that the phase to ground fault currents are less than the bolted 3-phase short circuit current
- For 3-phase 3-wire service gen up to 5 MW can be high resistance grounded at less than 10 A, $I_r > 3I_{co}$

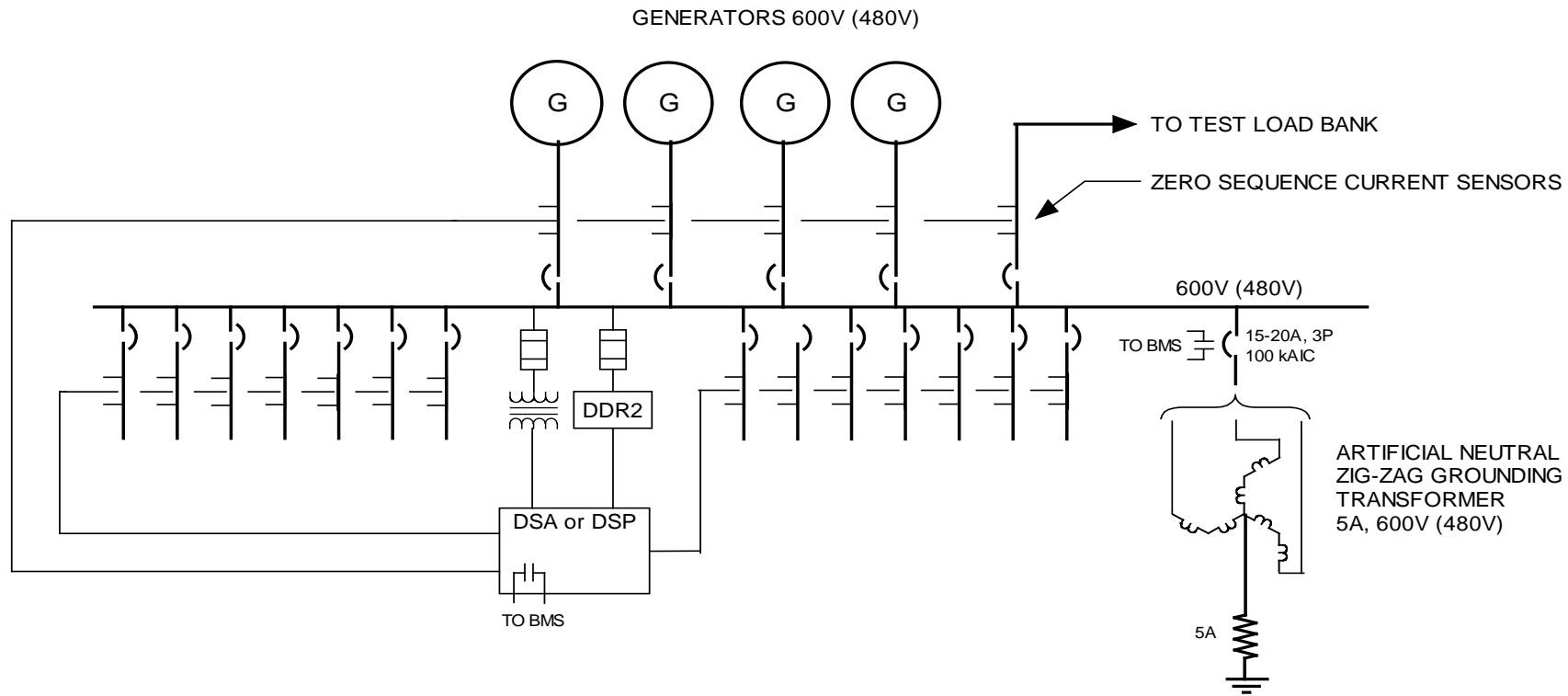
Single 5kV Generators

- Up To 10 MW - Can be HRG up to 10 A provided $I_r > 3I_{co}$ –
- Large generators should be Hybrid Grounded (LRG + HRG) to minimize stator damage

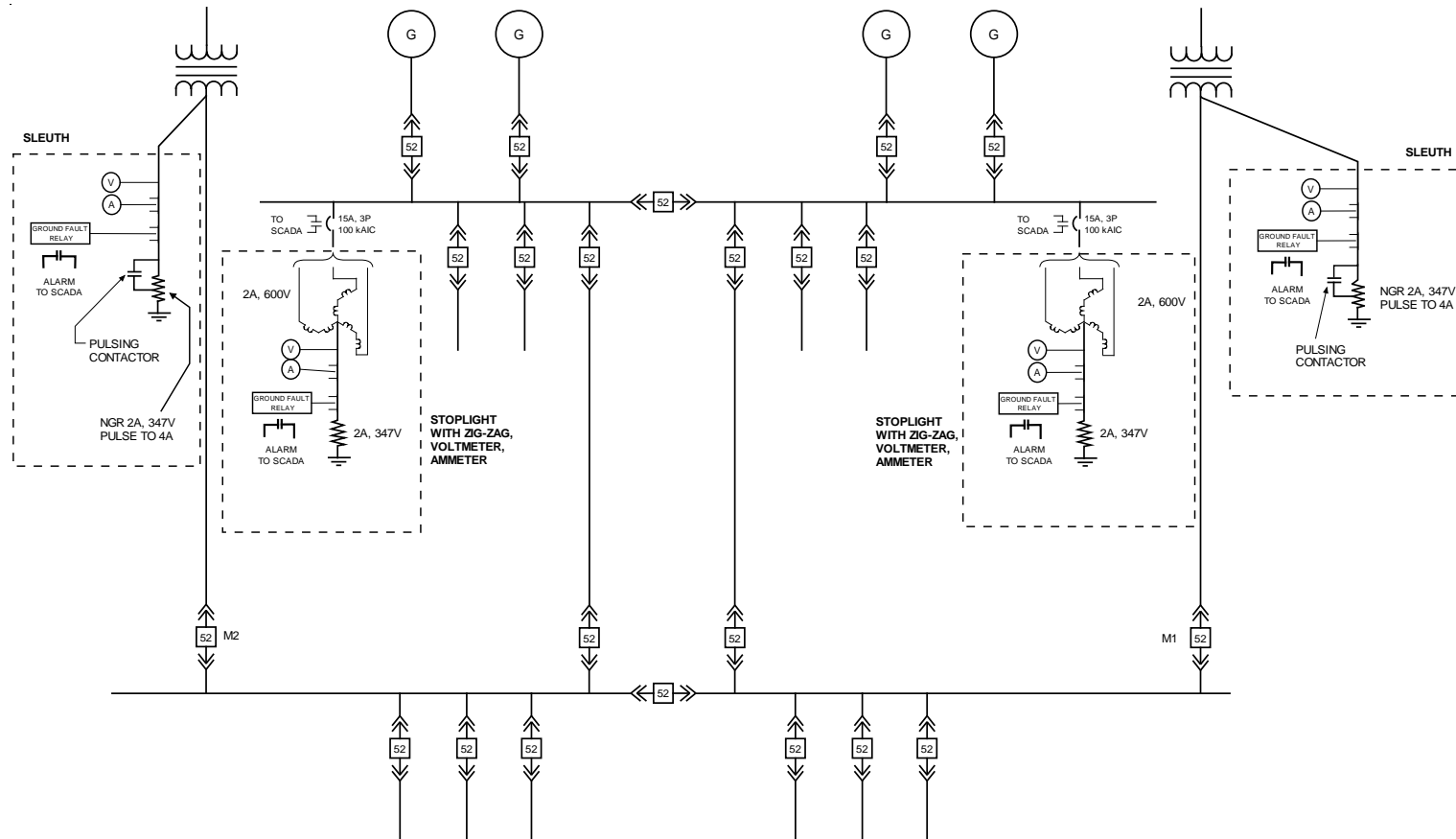
Multiple Generators In Parallel

- For LV generators grounding by Zig Zag + NGR at the main bus
- For MV generators apply HRG for each generator and apply additional LR grounding on the main bus so the net $I_r > 3I_{co}$ -

High Resistance Grounding of Parallel Generators

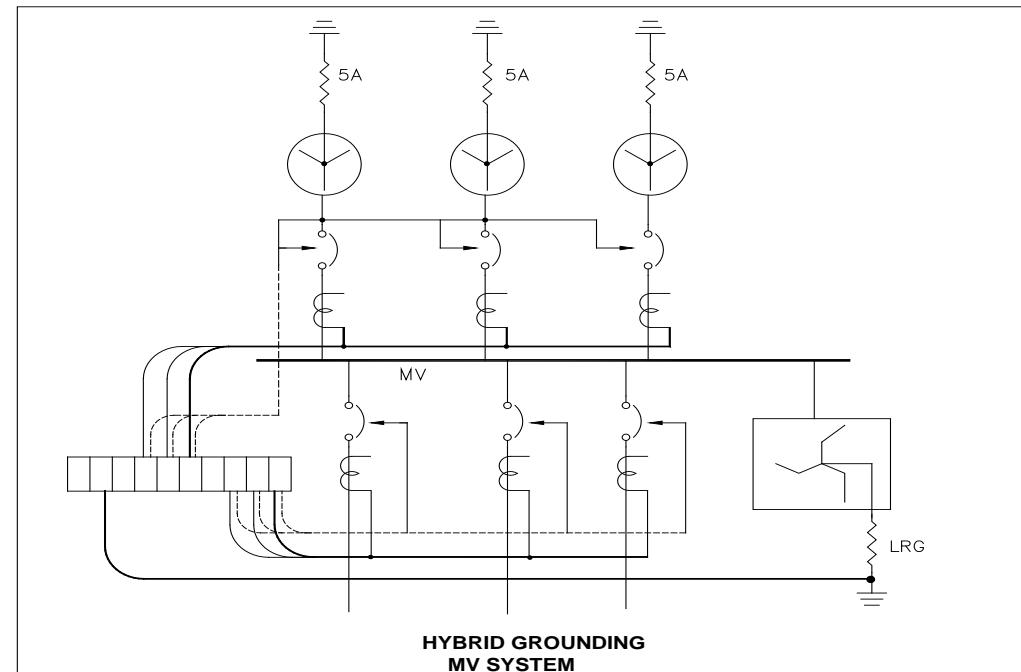


HRG Retrofit of Parallel LV Generators



Hybrid Grounding of Generators

Applied when $3I_{co}$ is larger than the current contributed by the generator NGRs



IEEE Guide for Generator Ground (AC) Protection

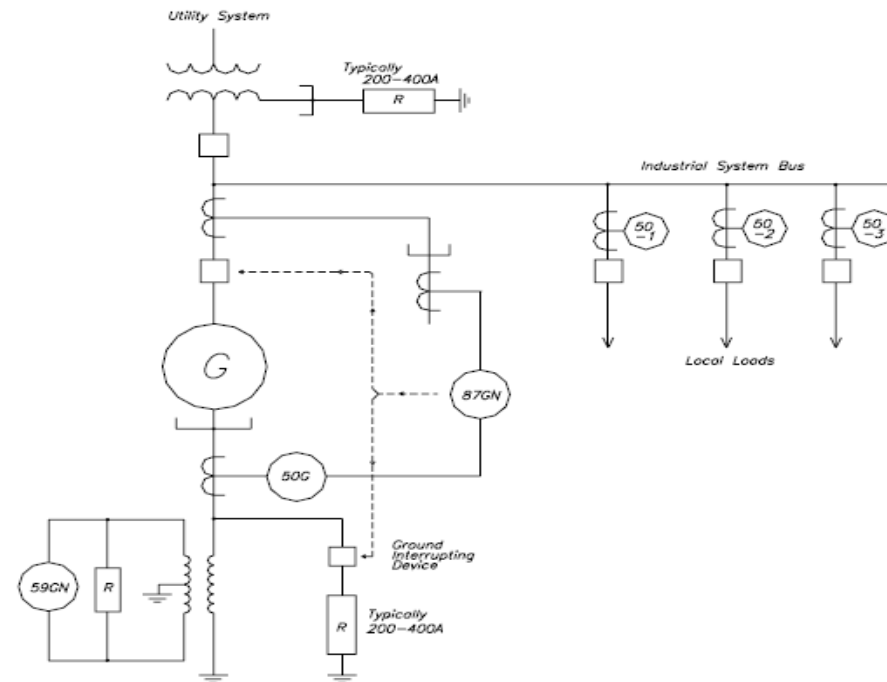
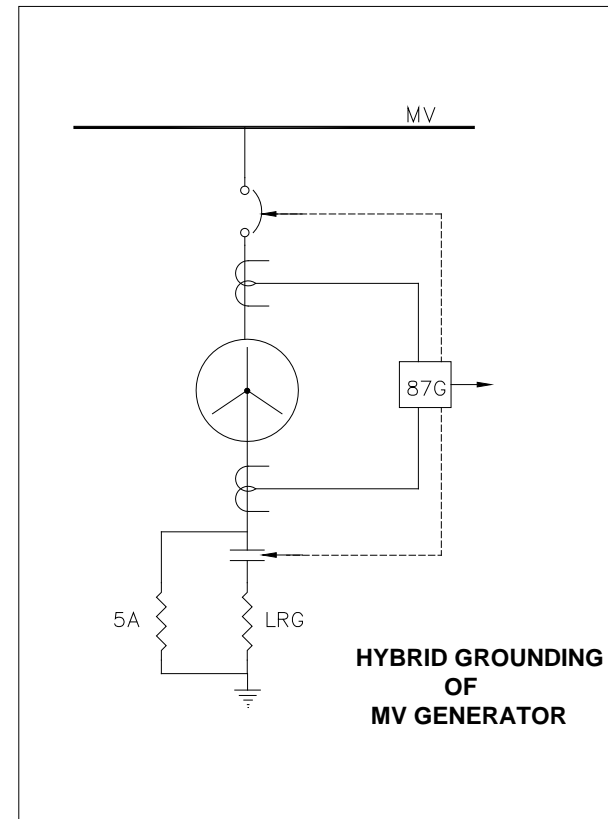


Figure 32—Hybrid grounding scheme

Hybrid Grounding MV Bus Connected Generator

Applied to limit
damage due to
stator winding fault
when LRG is 100A
or more

MV
Generators
ANSI
C37.101
ANSI
C37.102



Specifying Resistor Elements

- Commonly used materials:
 - Aluminum Chrome Steel 1JR (Ohm alloy)
 - Stainless Steel 18SR
 - 304 Nickel Chrome
- For low resistance grounding, 10-sec resistors have temp rise of 760°C
- For high resistance grounding, continuous duty resistors have temp rise of 375°C
- 304 increases resistance 43% for 760°C rise
- 1JR and 18SR increase resistance less than 20% for 760°C rise

Specifying Resistor Elements

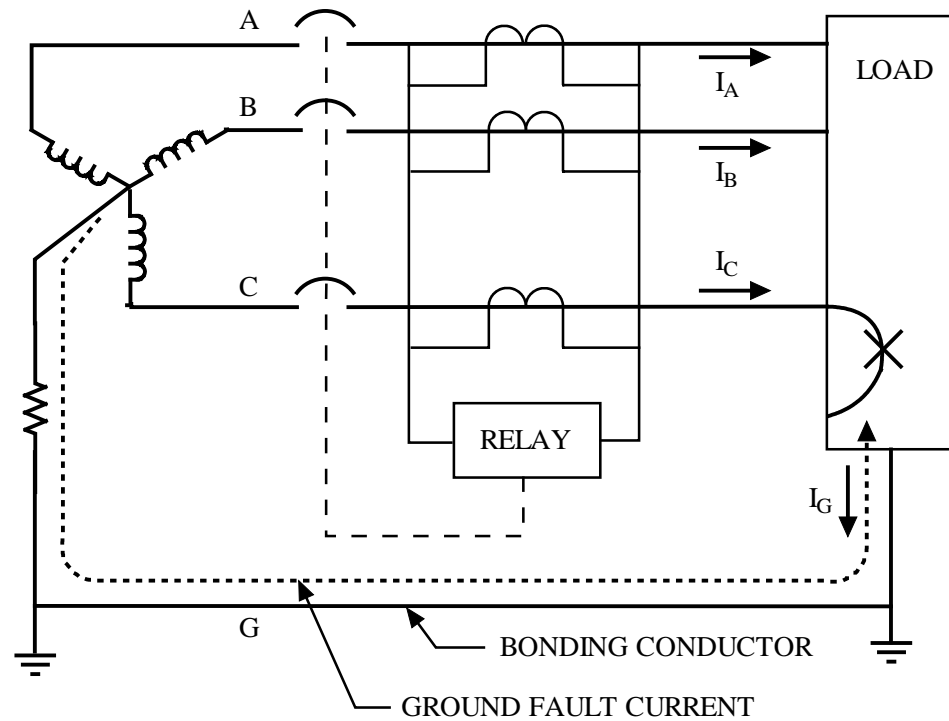
- No longer sufficient to specify:
 - Element material should be made from electrical alloy with low temperature coefficient of resistance.
- Should specify instead:
 - Element material should not have a temperature coefficient greater than 0.0002 ohms/°C
 - The resistor let-thru current shall not decrease by greater than 20% from ambient to full operating temperature.

Any Questions?



Thank you for your time

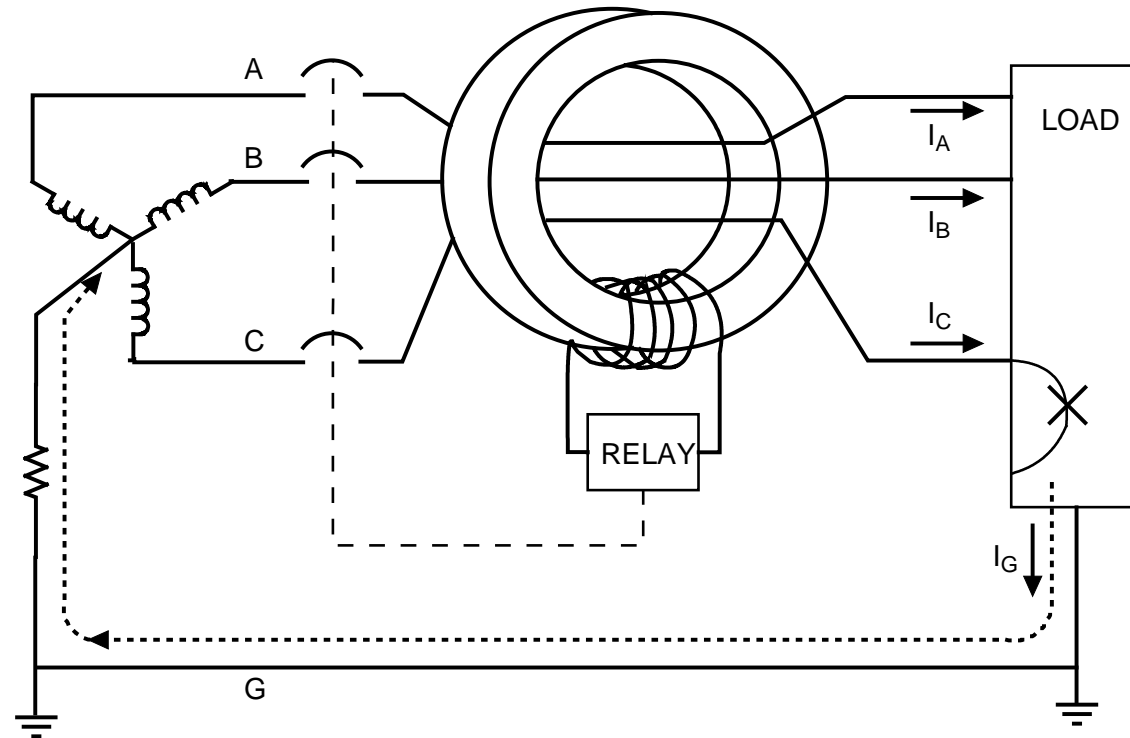
Ground Fault Sensing Residual CT Method



Zero Sequence CTS

- For ground fault pickup settings below 0.1 x feeder rating
- Usually cannot use residually-connected CTs for ground fault sensing
- Must use zero sequence (core balance) CT

Zero Sequence Core Balance CTS



What's Wrong with a 50:5 Amp?

- Turns ratio of 10 *is too low*
- Magnetizing inductance drops as the square of the turns ratio
- Magnetizing inductance *too low*
- Too much CT secondary current diverted to excite the magnetic field of the core
- CT inaccurate

Core Balance Sensor

IEEE Buff Book – Std. 242-2001 (8.4.2)

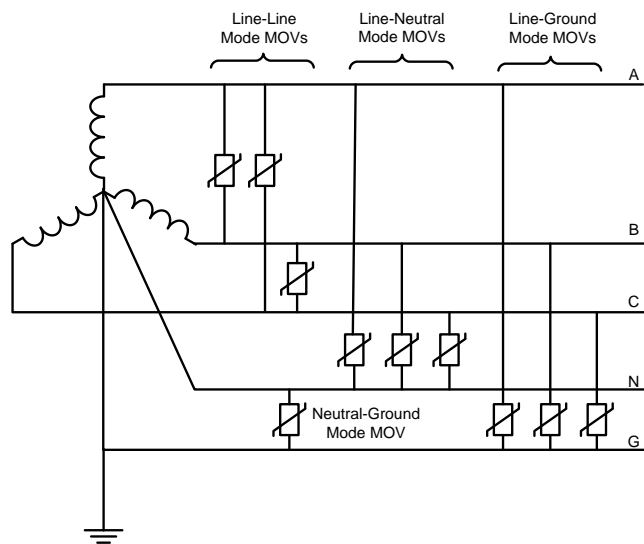
By properly matching the CT and relay, ground-fault detection can be made as sensitive as the application requires. Many ground protective systems now have solid-state relays specially designed to operate with core-balance CTs.

Care is necessary to prevent false opening from high unbalanced inrush currents that may saturate the CT core, or through faults not involving ground.

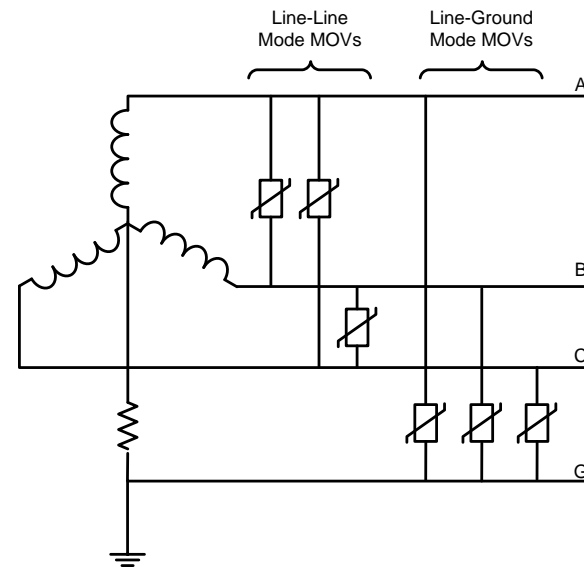
Application of TVSS/SPD on HRG Systems

- During a phase to ground fault. Phase to ground voltages on unfaulted phases rises to Phase to phase value so MCOV rating of the TVSS should be higher than V_{L-L}
- NEC 285.3 Requires that the MCOV of TVSS must exceed max continuous operating voltage and that they be approved for use on HRG systems (UL1449)

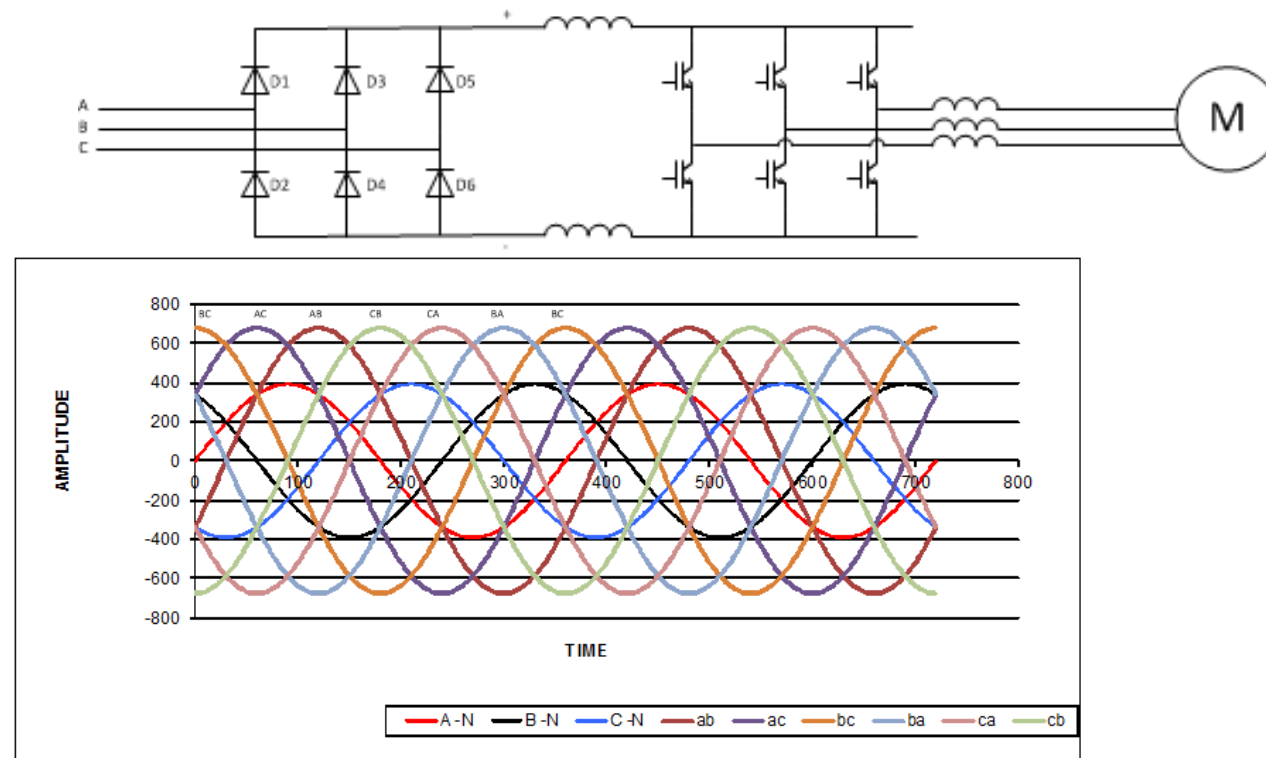
TVSS in Solidly Grounded System



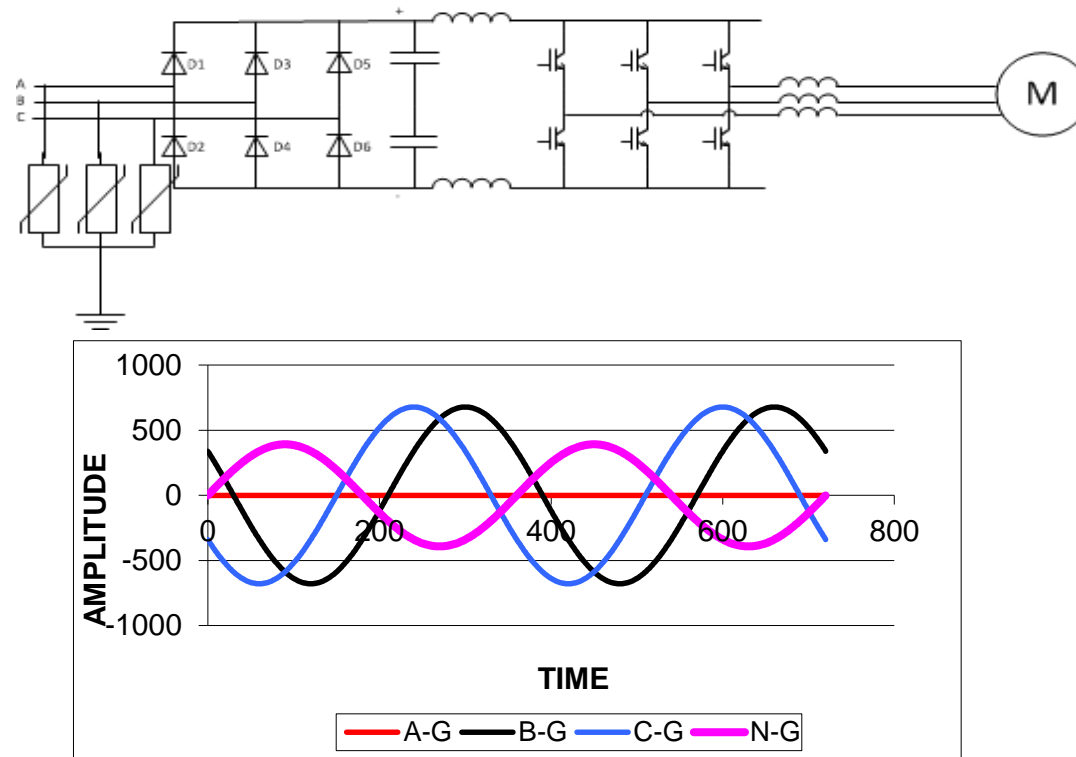
TVSS in HRG System



ASD, UPS



ASD, UPS



ASD, UPS

