

Vignettes in Grounding

IEEE San Francisco

3/26/2010



Agenda

- ▶ Comparison of grounding techniques
- ▶ Conversion of existing systems to HRG
- ▶ Neutral deriving transformers (and GTR/resistor pairs)
- ▶ HRG and VFD's
- ▶ Generator grounding

Comparison of Grounding Techniques

System Failures on Industrial Power Systems

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

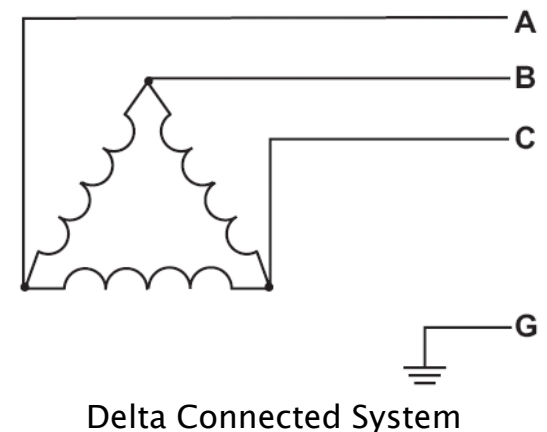
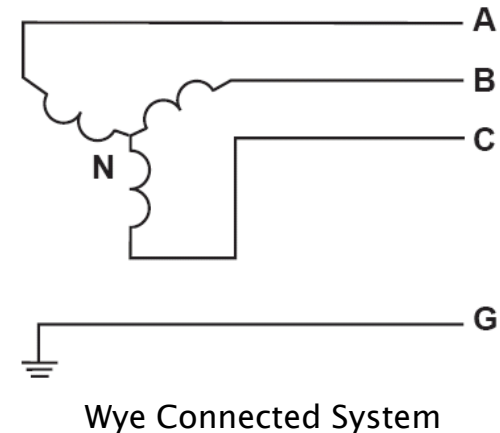
**Most three phase faults are man-made:
i.e. accidents caused by improper operating
procedure.*

System Grounding Methods

- ▶ Ungrounded
- ▶ Solidly Grounded
- ▶ Resistance Grounded
 - Low Resistance Grounding
 - High Resistance Grounding (HRG)

Ungrounded Power Systems

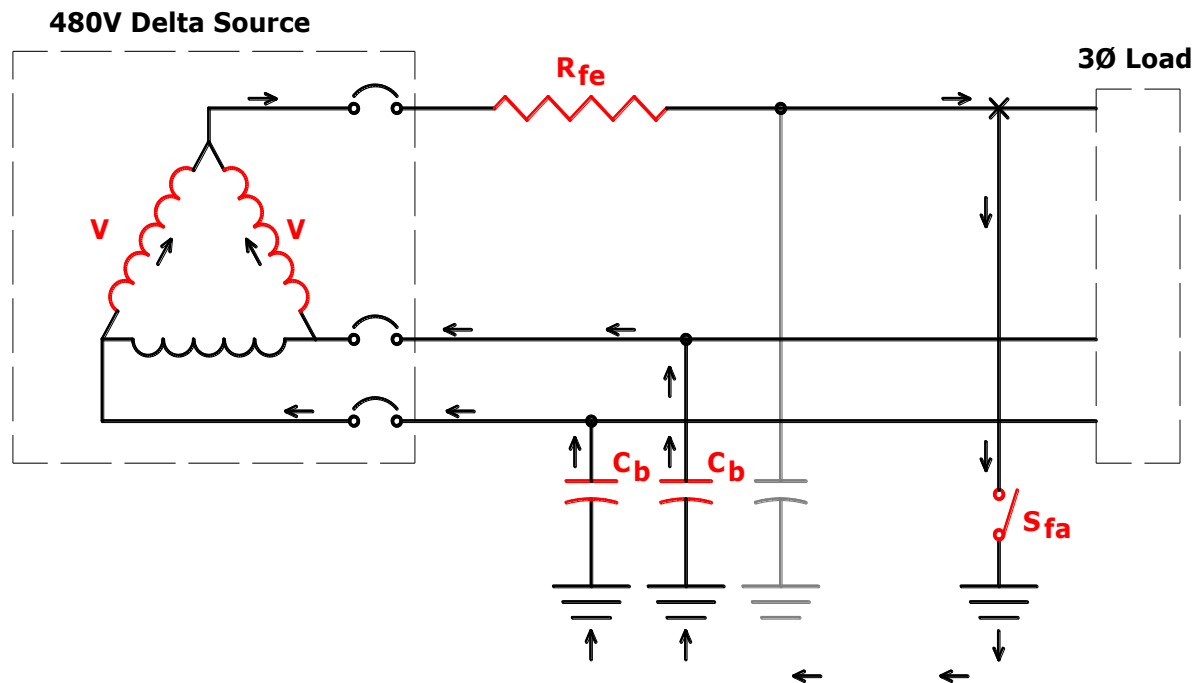
- ▶ 3-wire only
 - Line-to-neutral loads cannot be used
- ▶ Ground detection system is required
- ▶ Faults difficult to find
- ▶ Allows continuity of power in the event of a line-to-ground fault
 - Fault only grounds the system
 - Very low current would flow
 - Circuit breakers and fuses will not open
- ▶ Line-to-ground voltage could exceed line-to-line voltage by several times due to transients or other abnormal conditions
- ▶ Typically seen at 600V or less



Arcing Ground Faults

Intermittent or Re-strike

- 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 .



Industry Recommendations

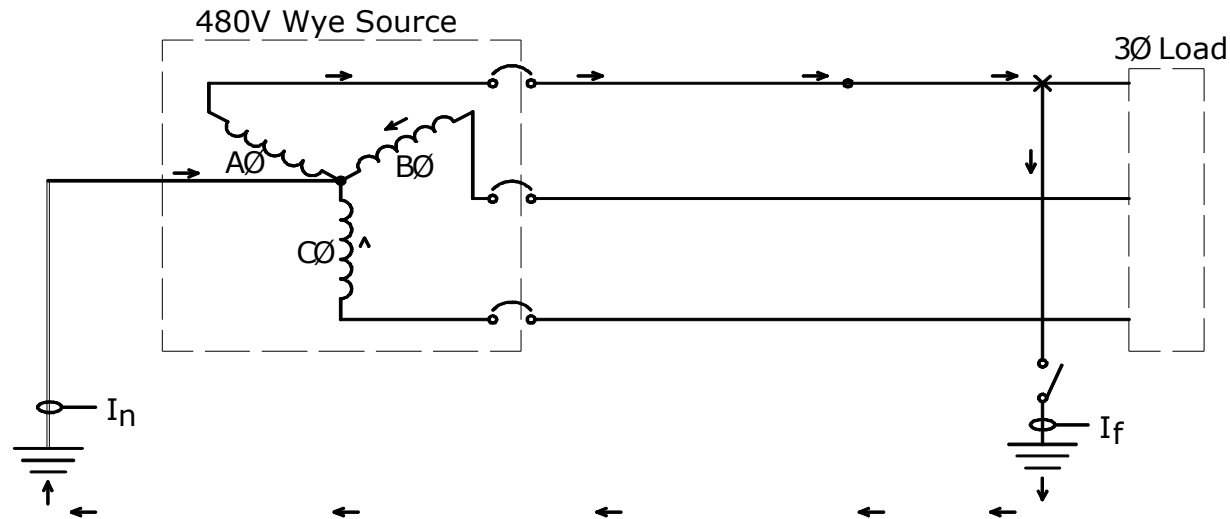
IEEE Std 242–2001 (Buff Book)

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.

Solidly Grounded Systems



Advantages

- Fixed line to ground voltage
- Direct path for common mode noise
- Permit line-to-neutral loads

Disadvantages

- Unscheduled service interruption
- Danger from low-level-arcing faults
- Strong shock hazard to personnel



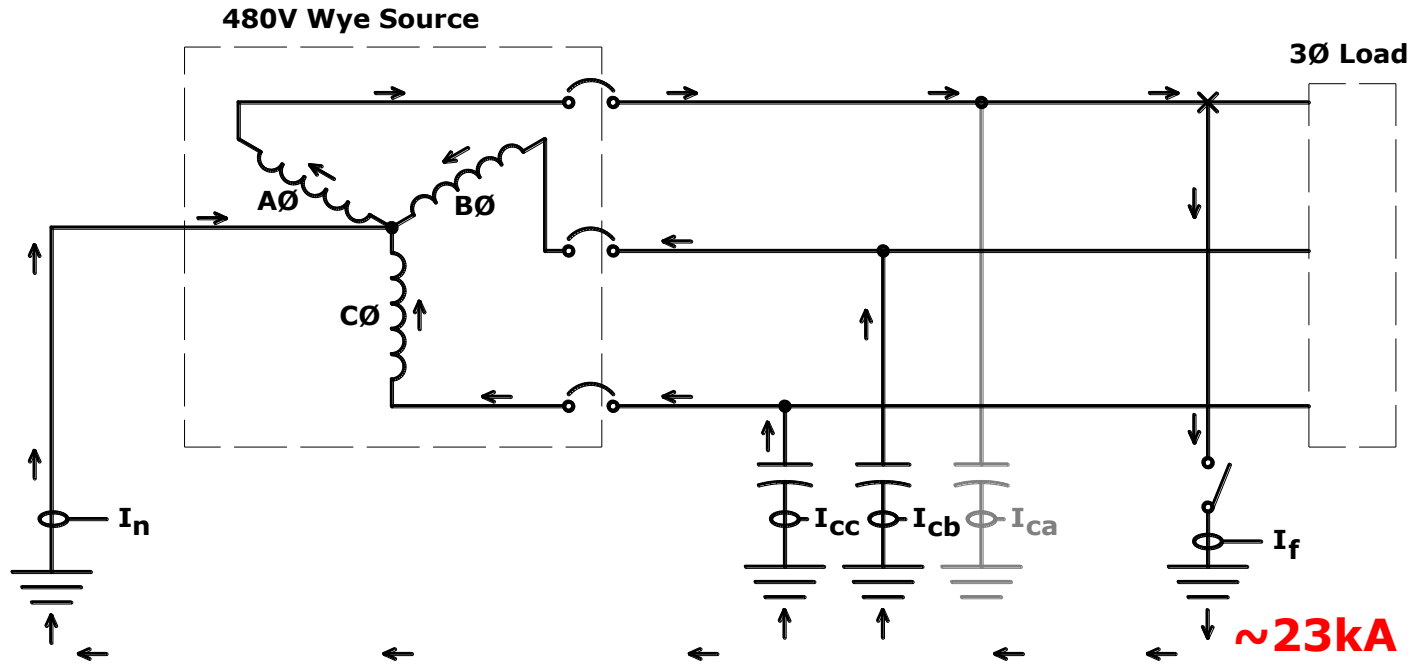
Post Glover

"The Resistor Specialists"



Arcing Ground Faults

Ground fault current distribution on AΦ



Estimated Total Fault Current

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

~0A (3A)

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

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

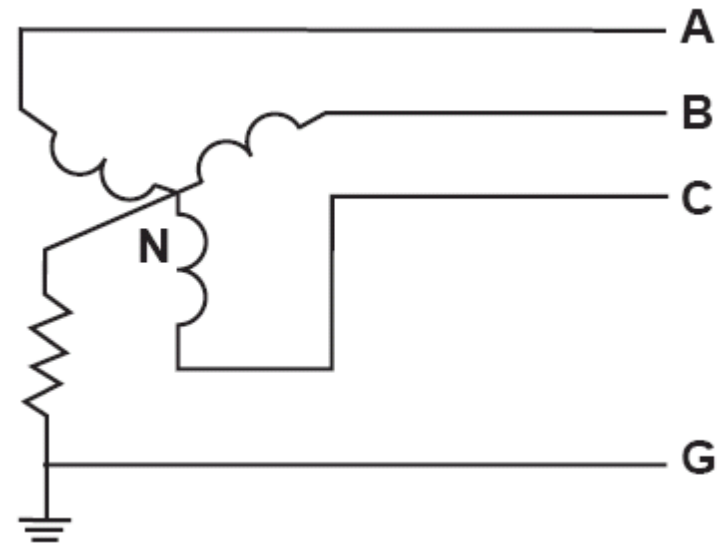
IEEE – Arcing Faults

- ▶ **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
- ▶ 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.**

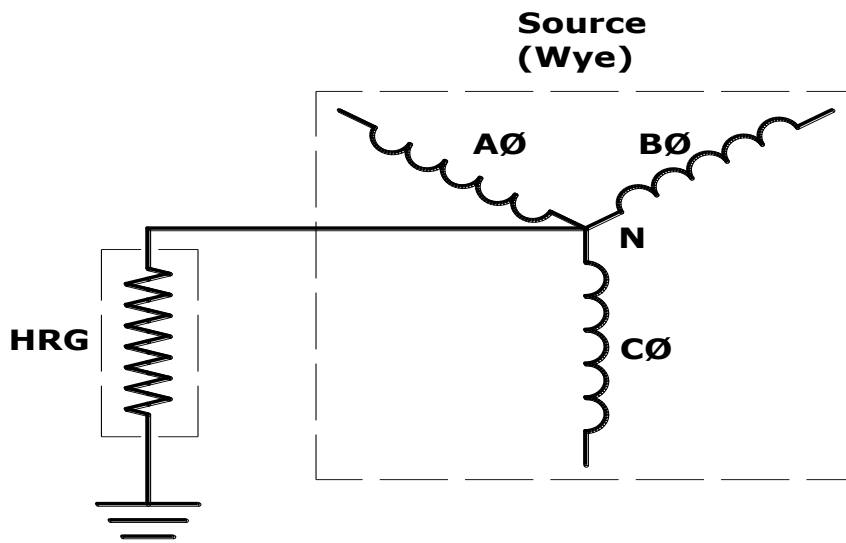
Wye Connected Power System

Impedance Grounded Neutral

- ▶ 3-wire only
 - Line-to-neutral loads cannot be used
- ▶ Ground detection system required
- ▶ Fewer coordination issues
- ▶ No transient overvoltages
- ▶ Impedance selected to limit line-to-ground fault current
 - Typically 10 A or less
 - Reduces incident energy for line-to-ground arcing faults
- ▶ Becoming a more popular system where continuity of power is critical
 - Low level of line-to-ground fault current will typically not cause circuit breakers or fuses to open



High Resistance Grounding



- ▶ Advantages
 - Limits Ground Fault current to 10 Amps or less
 - Allows faulted circuit to continue operation
 - Controlled path for common mode noise
- ▶ Disadvantages
 - Potential for nuisance alarming
 - Maintenance personnel may ignore first fault

Duty Ratings for NGR's

IEEE Std 32

Time Rating and Permissible Temperature Rise for Neutral Grounding Resistors

Time Rating (On Time)	Temp Rise (deg C)
Ten Seconds (Short Time)	760°C
One Minute (Short Time)	760°C
Ten Minutes (Short Time)	610°C
Extended Time	610°C
Continuous	385°C

Duration Must Be Coordinated With Protective Relay Scheme

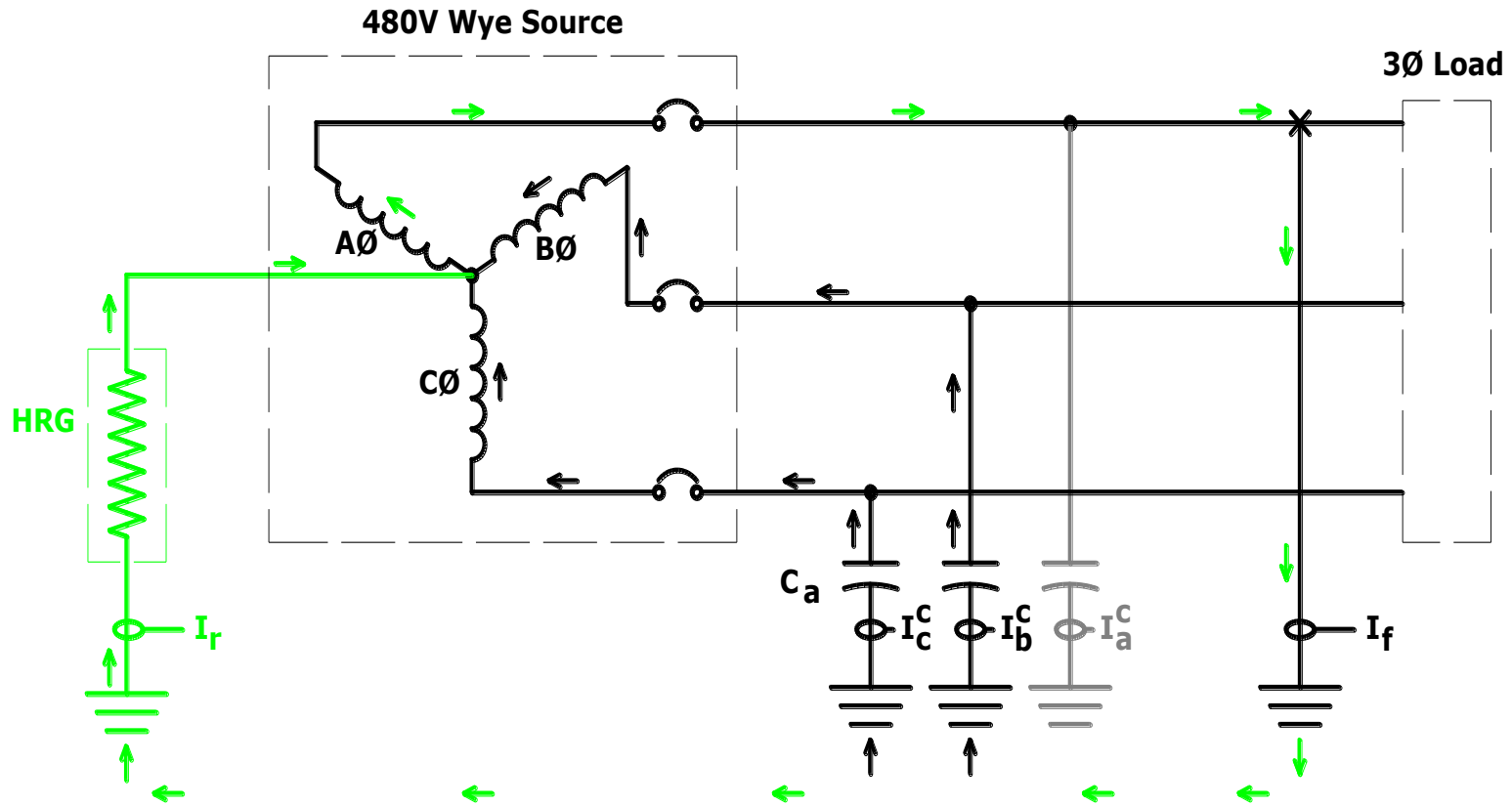
How to Make Money Selling Resistors

- ▶ Resistor mass proportional to rated current, duty and specific heat of material used
- ▶ Shorter duration or higher temperature rise equates to lower cost

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

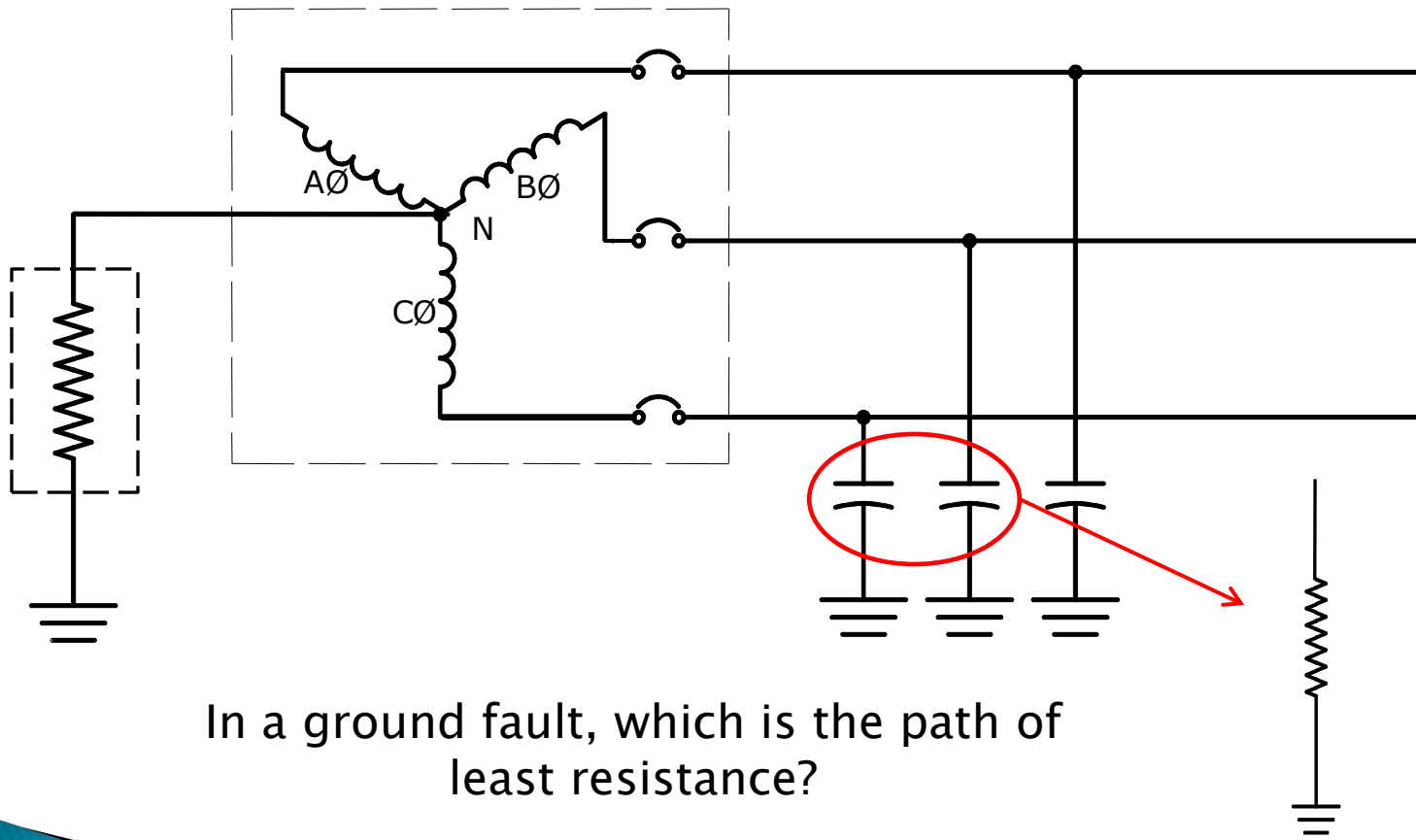
Conversion of Existing Systems

Proper Resistor Rating



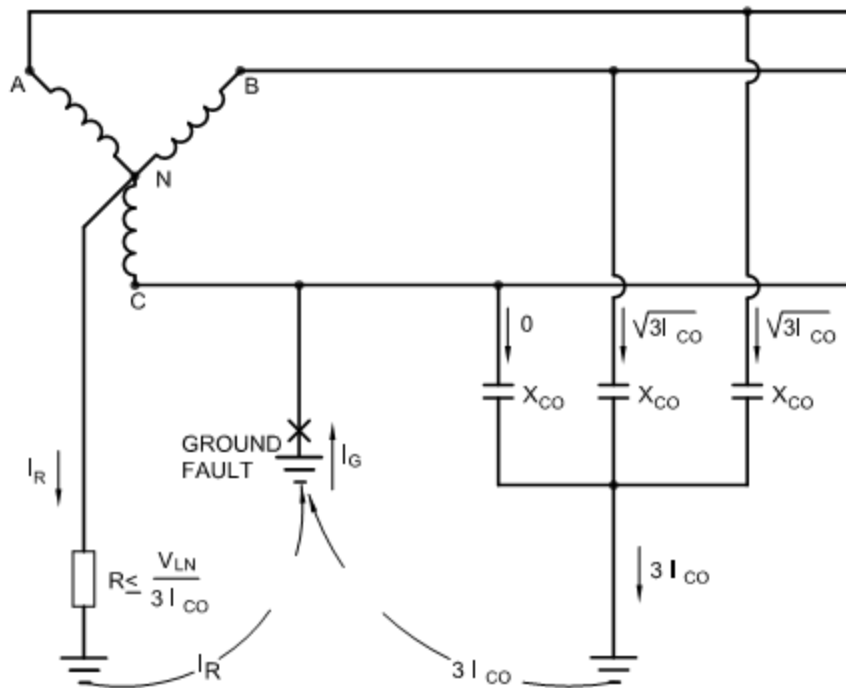
Grounding resistor must be path of least resistance

System Capacitance



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

Importance of Charging Current



In ungrounded systems, a voltage is held on the system capacitance after a fault. In an arcing or intermittent fault, this can lead to a significant voltage build-up.

In a high resistance grounded system, the resistance must be low enough to allow the system capacitance to discharge relatively quickly.

System Charging Current

Only discharges if $R_o < X_{co}$, so $I_r > I_{xco}$
(per IEEE142-1991 1.4.3)

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

Transformer (kVA)

1000

1500

2000

2500

Charging Current (A)

0.2 – 0.6

0.3 – 0.9

0.4 – 1.2

0.5 – 1.5

Estimating Charging Current

TABLE II
I_c DATA FOR ESTIMATING SYSTEM CHARGING CURRENT

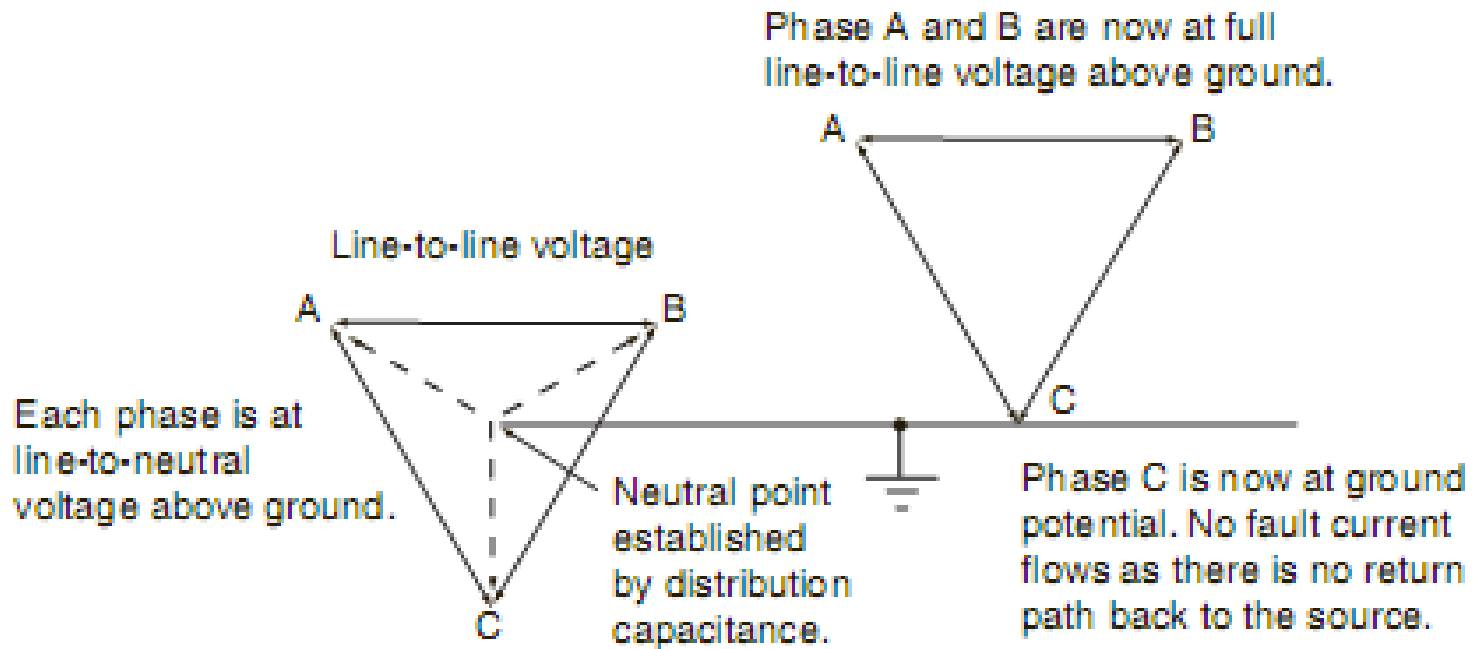
	I _c
13.8kV	
Surge Capacitors	2.25 A Each Set
Cable 1000 MCM Shielded	1.15 A/1000 ft. of 3c
750 MCM Shielded	.93 A/1000 ft. of 3c
350 MCM Shielded	.71 A/1000 ft. of 3c
4/0 MCM Shielded	.65 A/1000 ft. of 3c
2/0 MCM Shielded	.55 A/1000 ft. of 3c
Transformer - negligible	-
Motors	.15 A/1000 HP
4.16kV	
Surge 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

Choosing resistor setting

- ▶ Chose fault current higher than capacitive charging current
- ▶ Ex. If charging current is determined to be 1.9 A, chose at least 3 A of fault current

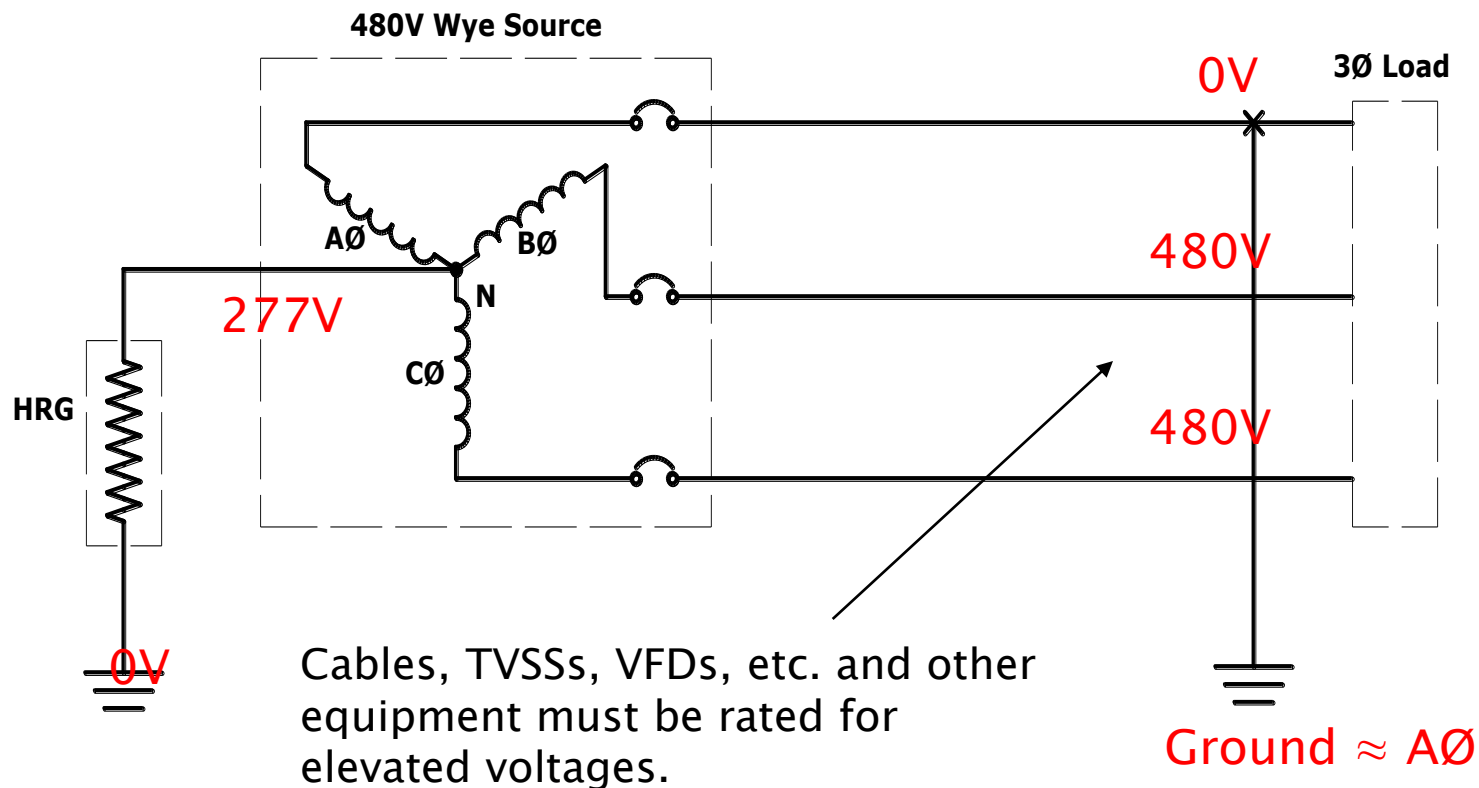


Elevated Neutral with Fault



Elevated Voltage Hazard

- ▶ Properly rated equipment prevents Hazards.

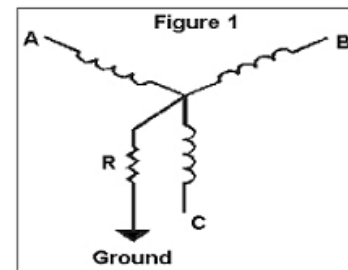


Choice of SPD

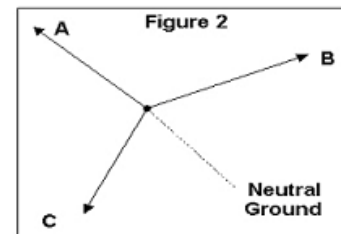
- ▶ Use a Delta connected surge protection device for any type of impedance grounded system

HIGH RESISTANCE GROUNDING AND WYE OR DELTA SPDS

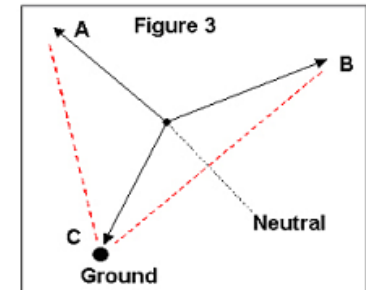
In today's manufacturing facilities ground faults can wreak havoc on production and process equipment. These manufacturing facilities may have a high resistance grounding (HRG) system. In a HRG system, a resistance, which is connected between the neutral of the transformer secondary and earth ground, is used that effectively limits the fault current to a low value current under ground fault conditions. Usually, the current is limited to 10A or less. As a result, the system will continue to operate normally even under the ground fault condition. Figure 1 depicts a system that has a resistance grounding scheme. In the case where surge suppression is required for a 3 phase, 4 wire, wye system with a neutral ground resistance (NGR), a 3 phase, 3 wire, delta SPD will want to be specified and used.



In a wye system, the neutral and ground are both located at the center, as shown in Figure 2. If the neutral is bonded to the ground, the system will remain unchanged under fault conditions.



In the case where the neutral is not bonded to ground and a fault condition is present, the ground will 'move' towards the phase that has the fault. Figure 3 shows a fault condition on phase C. The result is phase A to ground and phase B to ground are now at line to line voltage instead of line to neutral voltage. If a 3 phase, 4 wire, wye SPD was installed in an application where the neutral was not bonded to ground and a fault condition occurred on one of the phases, the result would be SPD failure.



In today's electrical systems, with many different grounding systems and various voltages, determining which SPD voltage configuration to specify can be confusing. Following are several helpful guidelines to follow when specifying SPD's:

- Only apply a wye (3 phase, 4 wire) configured SPD if the neutral is physically connected to the SPD and if the neutral is directly and solidly bonded to ground.
- Use a delta (3 phase, 3 wire) configured SPD for any type of impedance (resistive, inductive) grounded system.
- Use a delta (3 phase, 3 wire) configured SPD for a solidly grounded wye system where the neutral wire is not pulled through to the SPD location.
- Use a delta (3 phase, 3 wire) configured SPD if the presence of a neutral wire is not known.

Reminder: Resistors Get Hot

Table A-1
CONVERSION OF NEMA ENCLOSURE TYPE RATINGS

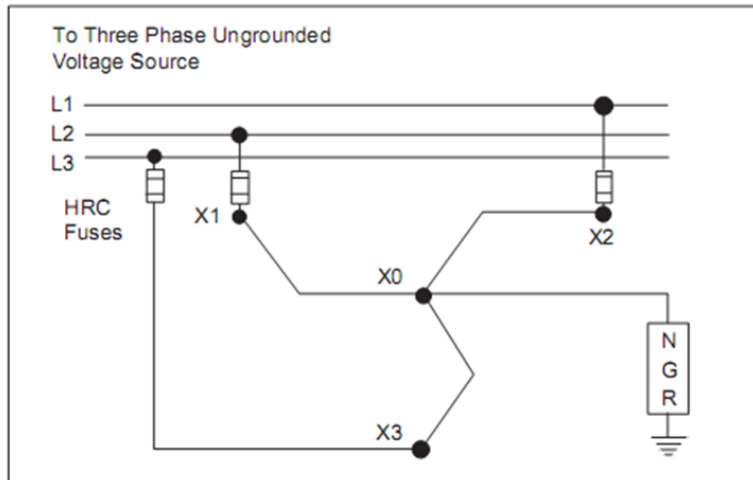
IP First Character	IP Second Character
	13
IP0_	IP_0
IP1_	IP_1
IP2_	IP_2
IP3_	IP_3
IP4_	IP_4
IP5_	IP_5
IP6_	IP_6
	IP_7
	IP_8

A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
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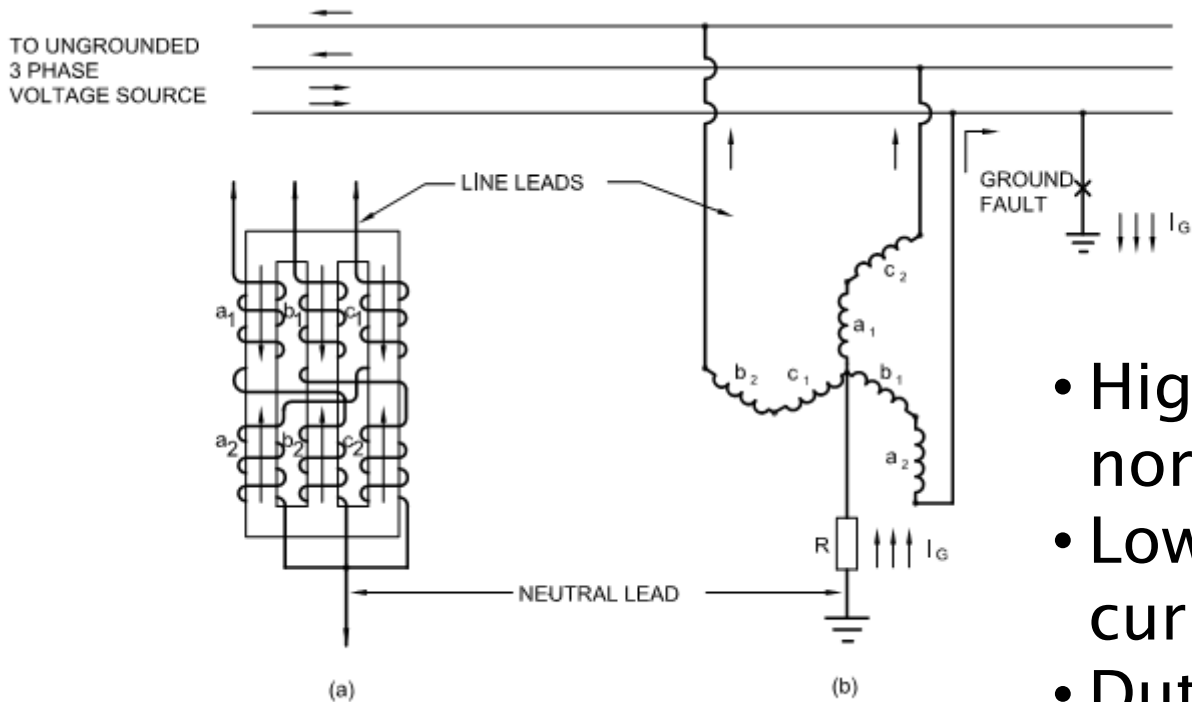
Neutral Deriving and GTR's

Neutral Deriving Transformer



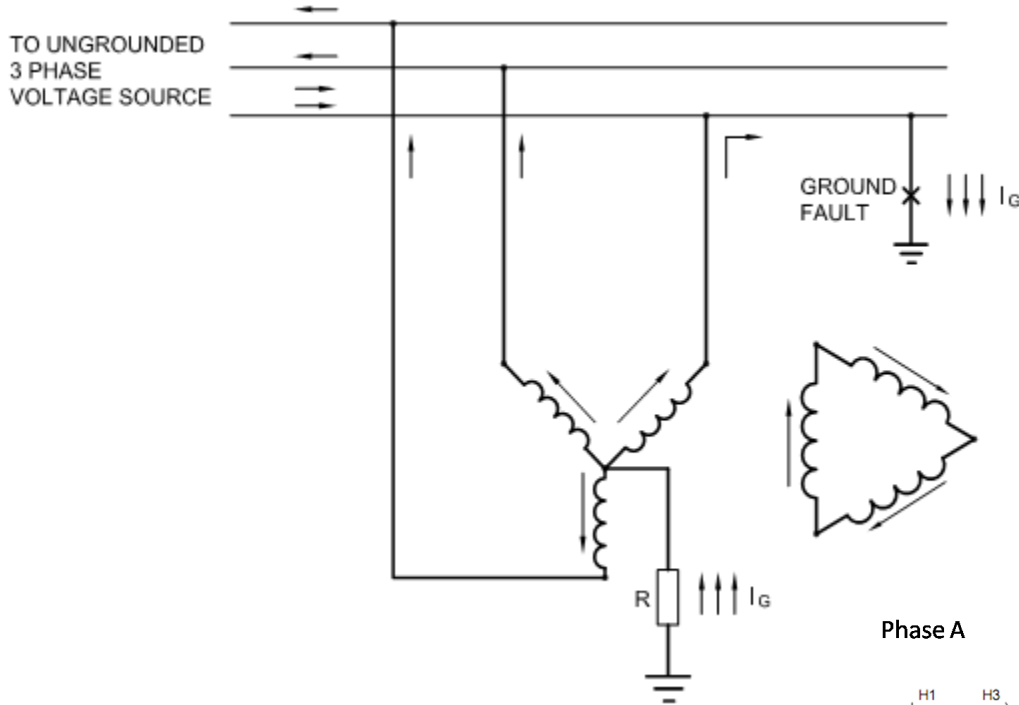
- Creates a neutral point in a 3 wire system
- Rated for system voltage, expected current and duty cycle
- Two methods to establish a neutral

Zig-Zag Transformer

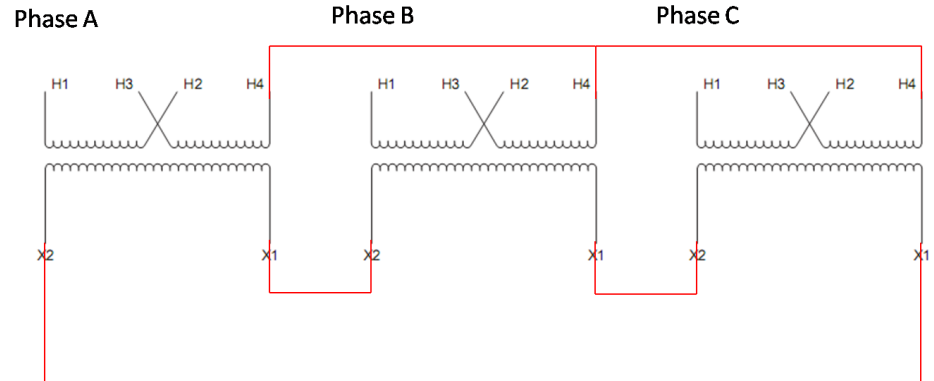


- High impedance to normal phase currents
- Low impedance to fault current
- Duty cycle same as resistor

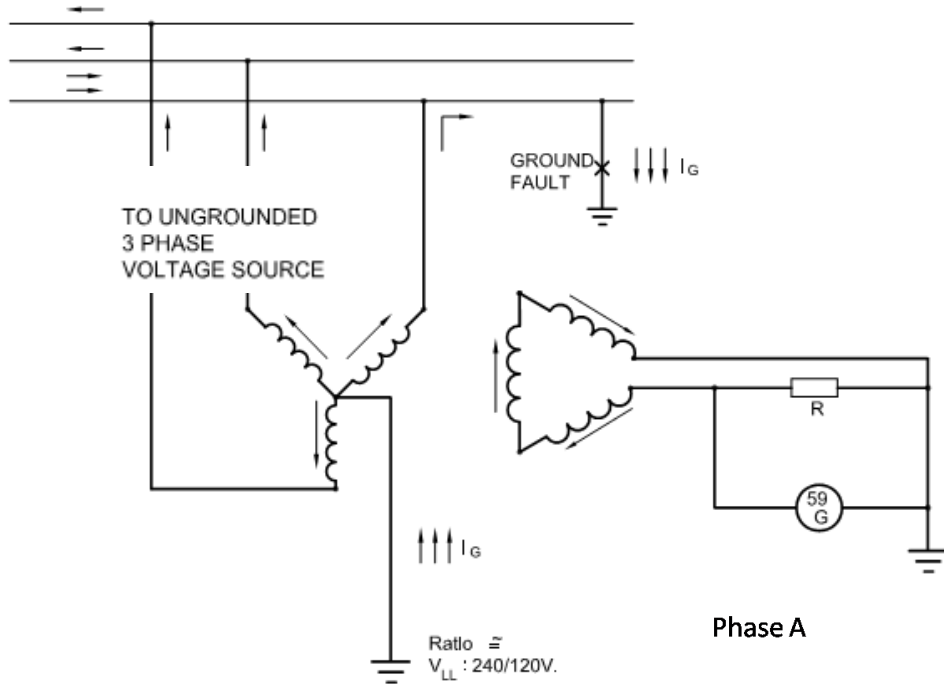
Wye Delta Transformer



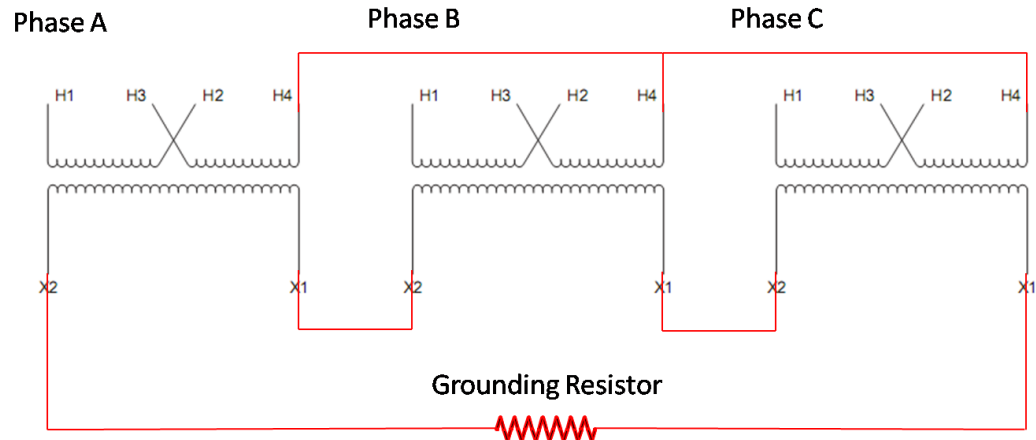
- Built from 3 industrial control transformers
- Connect to create neutral
- Fully insulated resistor



Broken Delta

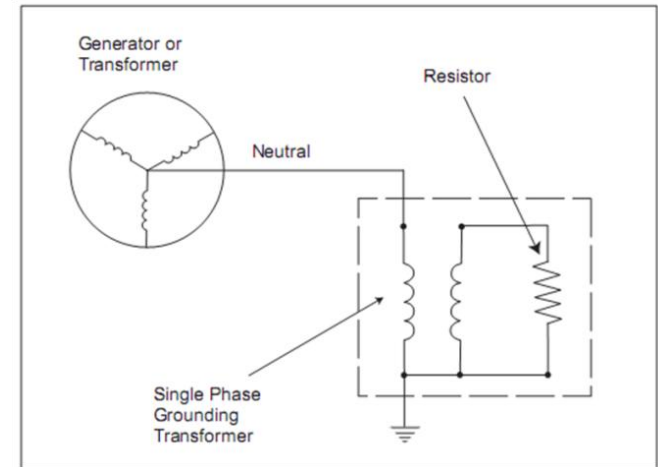


- Same 3 industrial control transformers
- Connect to create neutral
- Low voltage resistor

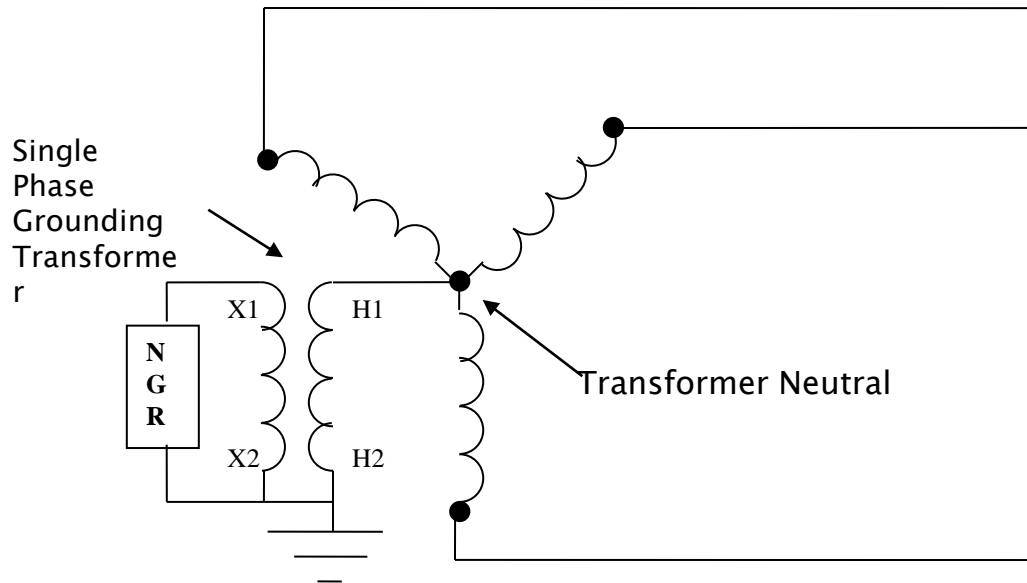


Single Phase GTR

- ▶ Usually paired with resistor to give HRG at MV
- ▶ Using line to neutral rated resistor not size/cost efficient
- ▶ Current normally less than 15A
- ▶ Voltage equal to system line to neutral voltage
- ▶ Secondary typically 240 V



MV HRG Schematics

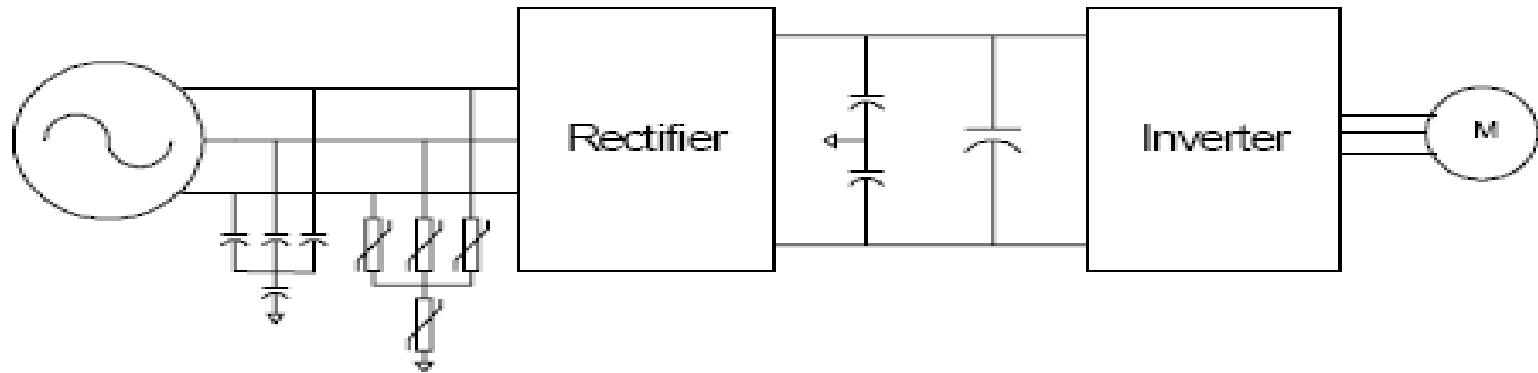


Medium Voltage Wye (Four-Wire) Connected Neutral Grounding Resistor



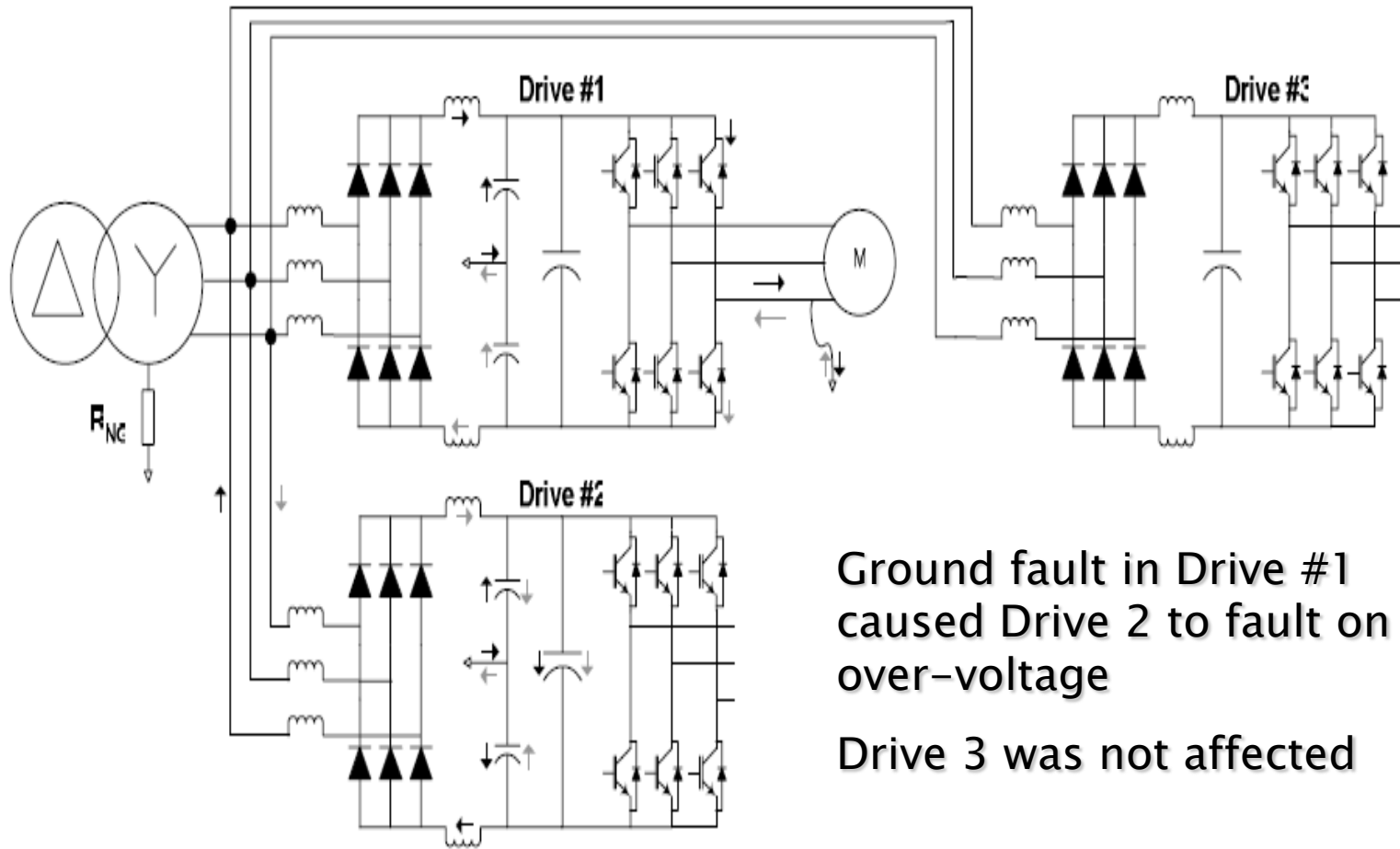
HRG & VFD's

CM Capacitors and MOVs



- ▶ CM Capacitors provide path for Common-mode currents in output motor leads
- ▶ MOVs protect against Transients

CM Capacitors and HRG



Ground fault in Drive #1
caused Drive 2 to fault on
over-voltage

Drive 3 was not affected

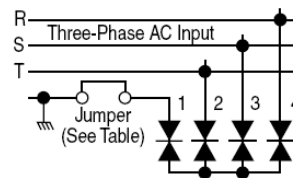
Jumper Removal

Option code
14PSUG will do this
for MCC mounted
drive units



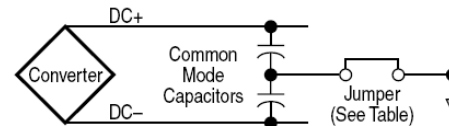
ATTENTION: When installing a drive on an ungrounded, high-resistance or B phase grounded distribution system, disconnect the phase-to-ground MOV circuit and the common mode capacitors from ground.

Phase to Ground MOV Removal



Frame	Jumper	Removes
A, B, C and D	JP3 – JP2	MOV to Ground
E	JP2 – JP1	MOV and Line to Line Capacitors to Ground

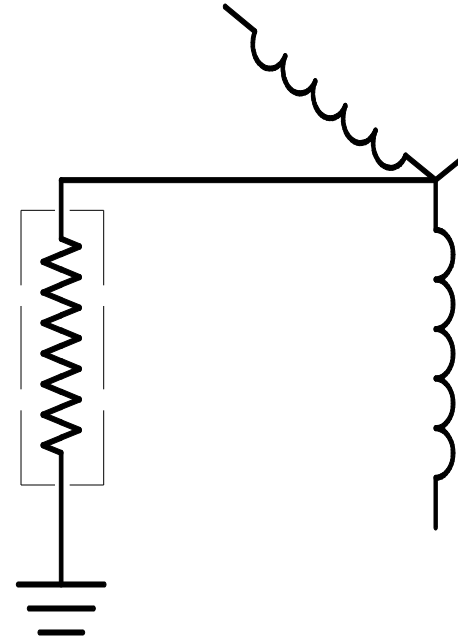
Common Mode Capacitors to Ground Removal



Frame	Jumper	Removes
A	N/A	
B	JP6 – JP5	Common Mode Capacitors to Ground
C and D	JP3B – JP3A	Common Mode Capacitors to Ground
E	JP3 – JP4	Common Mode Capacitors to Ground

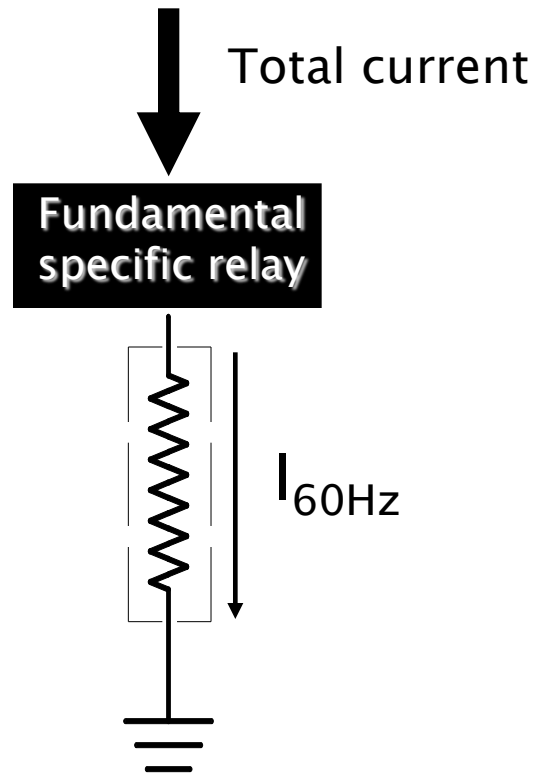
Excessive Neutral Current

- ▶ Neutral current includes ground fault current and harmonics/noise
- ▶ Cumulative current may be sufficient to alarm/trip
- ▶ Faults can be ignored or system disabled



$$I_{\text{total}} = I_{\text{fault}} + I_{3\text{rd}} + I_{5\text{th}} + I_{7\text{th}} \dots$$

Filter or Better Relay



- ▶ System must be able to monitor fundamental current only
- ▶ Use a filter before the relay
- ▶ Use a relay insensitive to harmonics

How to Make Money Selling Resistors – Part Deux

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

Material	Resistance change per °C	Resistance change at 400°C
Nickel chromium	0.01%	4%
18SR/1JR SS	0.02 – 0.04%	8 – 16%
304SS	0.22%	88%

Generator Grounding

Objective

- ▶ Account for harmonic content
- ▶ 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

Guidelines

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.

Guidelines

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 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.

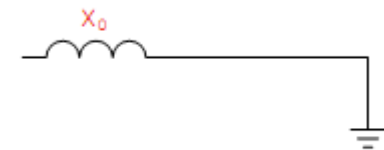
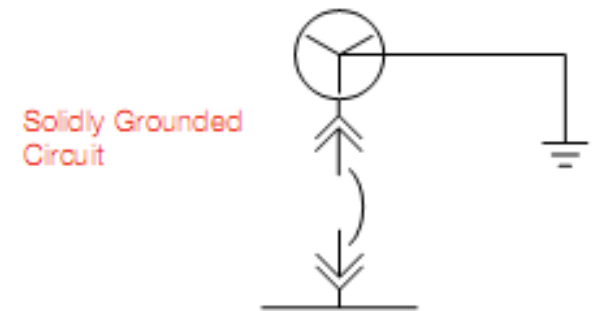
Summary of the “Experts”

- ▶ No ungrounded
- ▶ Only solidly ground if the generator is specifically rated
- ▶ Beware the third harmonic
- ▶ Account for internal and external faults



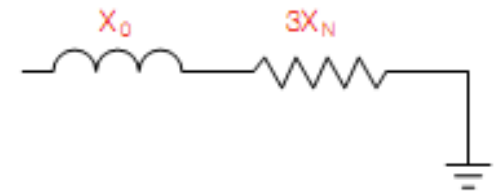
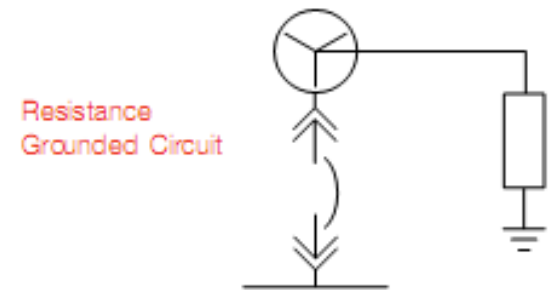
Solidly Grounded Systems

- ▶ 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 3 ϕ , 3W systems
- ▶ Capacitive charging current important
- ▶ Improved overall protection
- ▶ Reduced maintenance time and expense
- ▶ Greater personnel safety
- ▶ Reduced frequency of unplanned shutdowns



Resistance Grounding

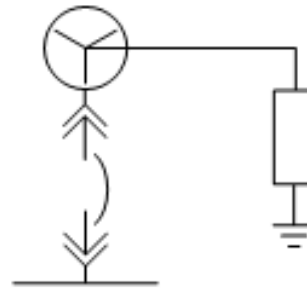
Low Resistance

- ▶ More often at MV than LV
- ▶ Less than 1000 amps for ten seconds
- ▶ Safely shutdown
- ▶ Less damage than solidly grounded

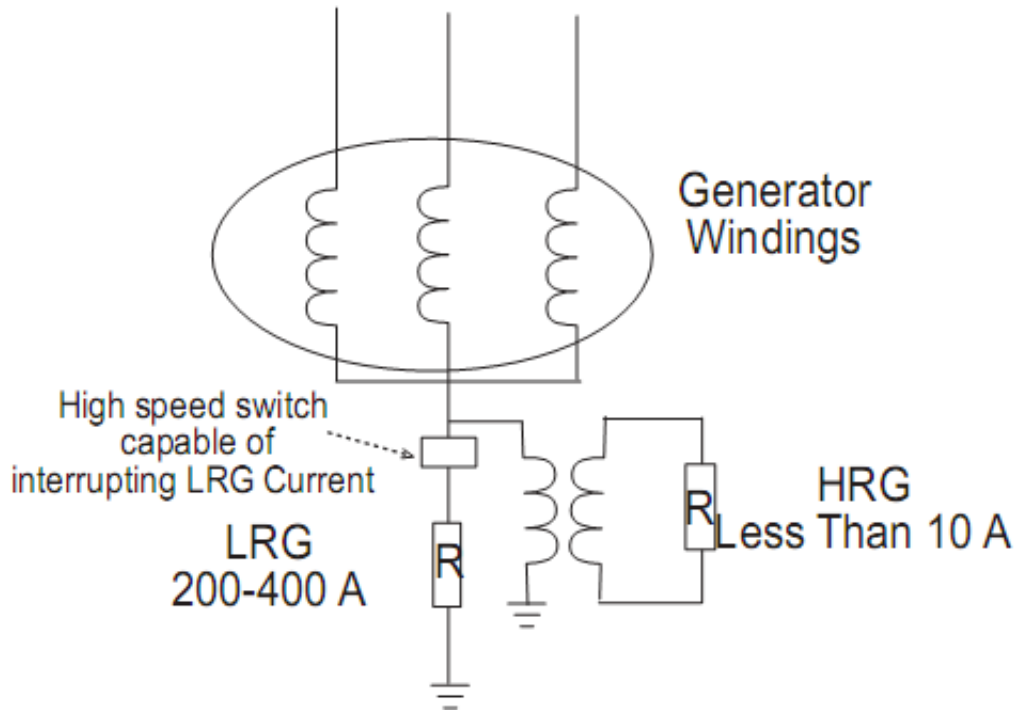
High Resistance

- More often at LV than MV
- Less than 10 amps continuously
- Avoid shutdowns
- Least damage

Resistance
Grounded Circuit



Hybrid Grounding



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

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

IEEE Std. 142-1991 (Green Book)

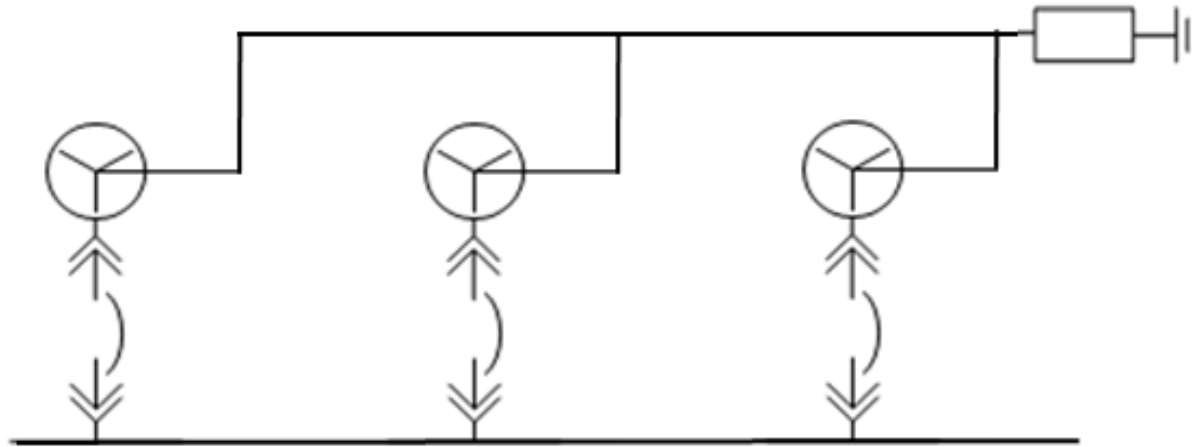
1.7.3 Paralleled Generators in an Isolated System

Generator Impedance Example

		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							
ckW		900	1000	1100	1250	1400	1500
kVA		1125	1250	1375	1563	1750	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
	75%	94.8	94.9	95.4	95.7	96.0	96.1
	50%	94.7	94.9	95.2	95.5	95.8	96.0

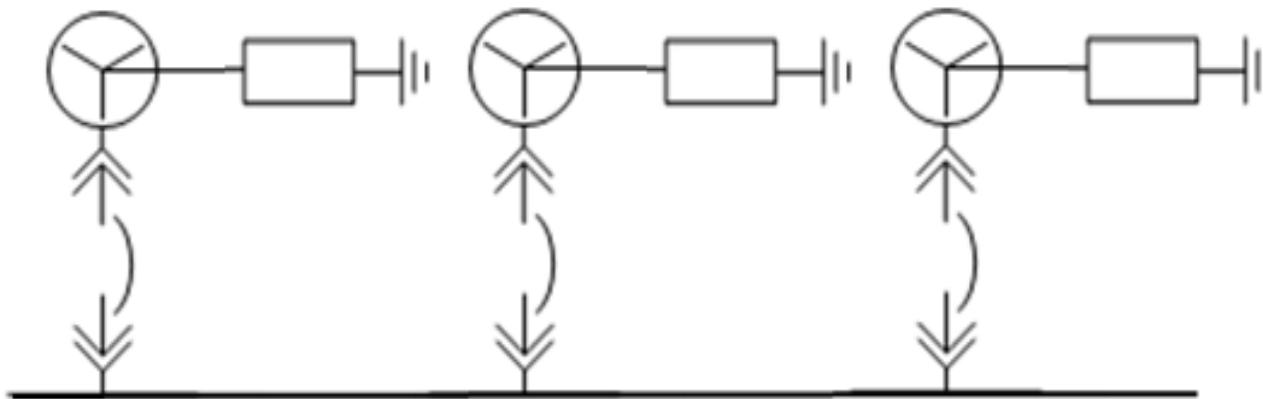
Reactances (per unit)							
Subtransient-Direct Axis							
X''d		0.1723	0.1988	0.179	0.1662	0.1783	0.2346
Subtransient Quadrature Axis							
X''q		0.2027	0.233	0.2174	0.2027	0.2209	0.292
Transient Saturated							
X'd		0.2492	0.2833	0.2583	0.2405	0.2529	0.3273
Synchronous Direct Axis							
Xd		3.522	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

Common Grounding Path



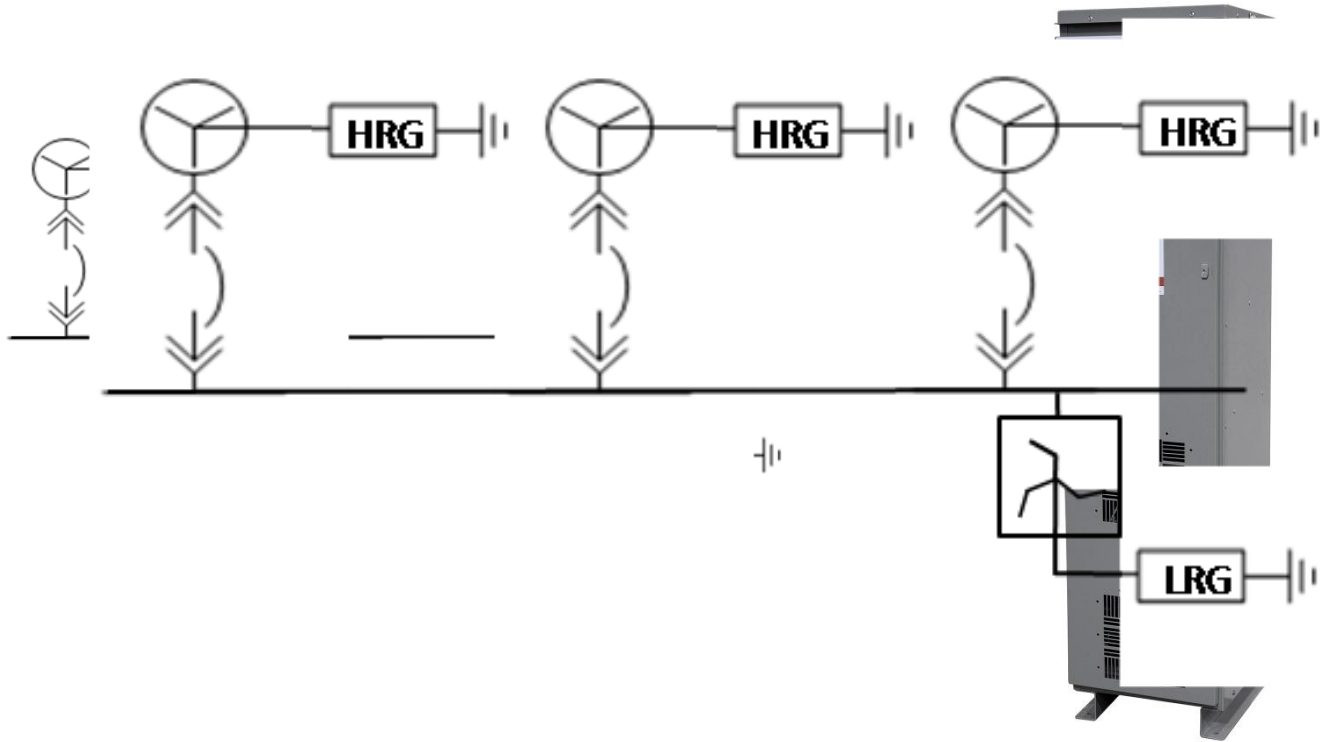
- Collecting neutrals and solidly grounding them collectively creates a path for excessive 3rd harmonic current
- Collecting neutrals through a single grounding resistor may exceed the continuous duty of the resistor

Separate Grounding Paths



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

Distributed Hybrid Grounding



- A neutral deriving transformer holds the fault current on the main bus to a consistent current rating
- Each generator is protected against internal faults by HRG

Recommendation

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