IEEE P.E.S. MEETING
APRIL 14, 2005

POWER SYSTEM GROUNDING AND RESISTANCE GROUNDING

Topics

1. Grounding Overview
2. Resistance Grounding
3. Ground Fault Pulse Locating
4. Alarming and Relaying of resistance grounded systems.
5. Application Examples

Power System Grounding

- Grounding: the intentional and permanent connection between neutral and ground
- Ground Fault: unintentional connection between an energized conductor and ground
- 90% electrical faults are ground faults

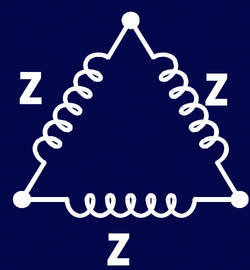
Grounding & Bonding

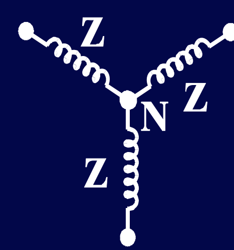
- Bonding: connection of all non-current carrying conductive parts of a distribution system together to form a bonding system
- Bonding System is connected to the Grounding Electrode by a Grounding Conductor.
- Bonding is not affected by the choice of power system grounding

THE POWER TO PROTECT

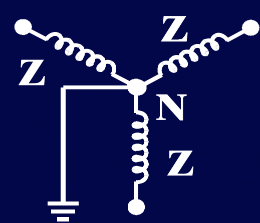
Types of Power System Grounding

Ungrounded Systems
3 Phase , 3 wire



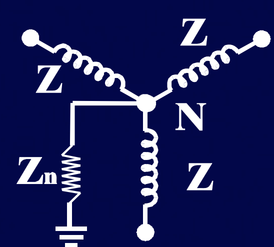


Solidly Grounded



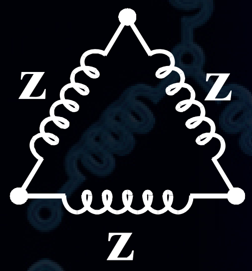
3 Phase, 3 Wire or 4 Wire

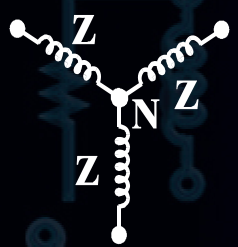
Resistance Grounded



3 Phase, 3 Wire

Ungrounded Systems

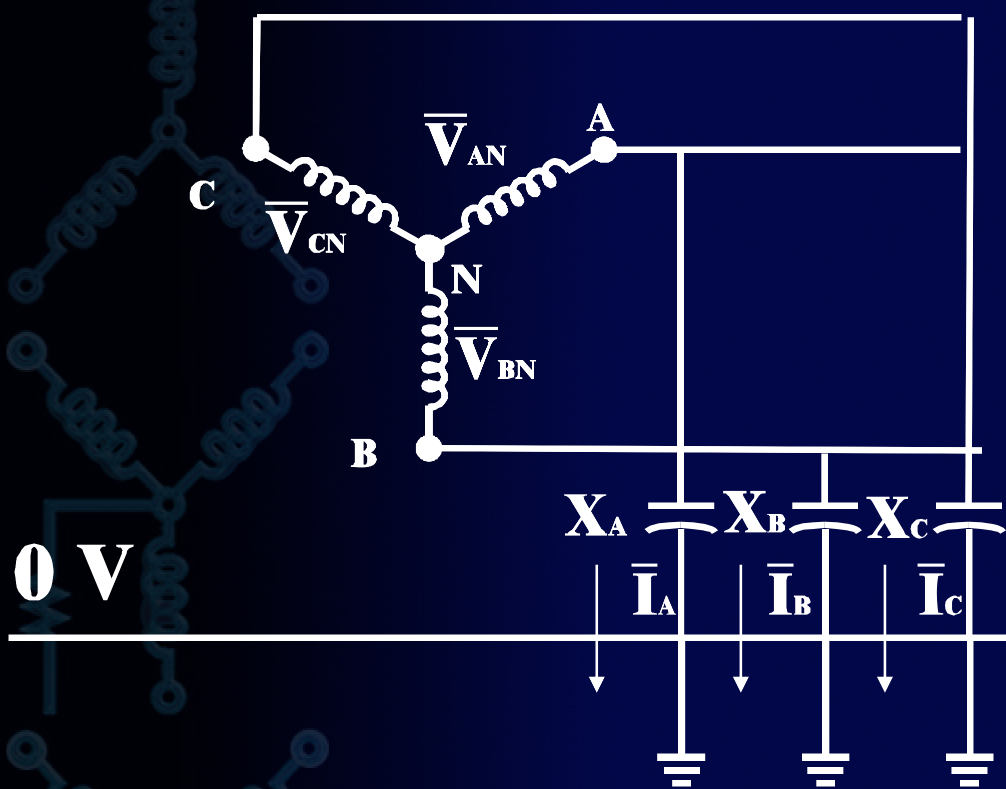


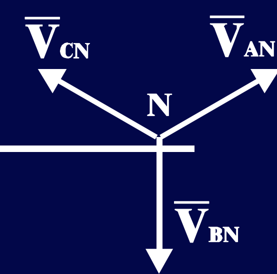


- No intentional connection to ground.
- Used in industrial plants.
- Popular on 3-wire LV systems up to 1950’s.
- Operational Benefit – Load continues operating under a ground fault
- Economic Benefit – no neutral conductor

Ungrounded Systems

Normal System



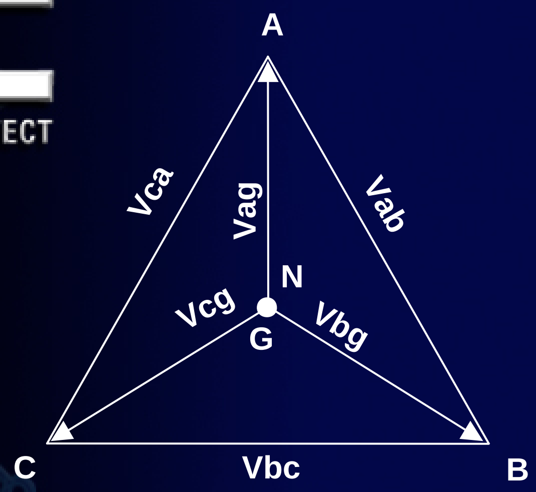


$\bar{I}_A + \bar{I}_B + \bar{I}_C = 0$

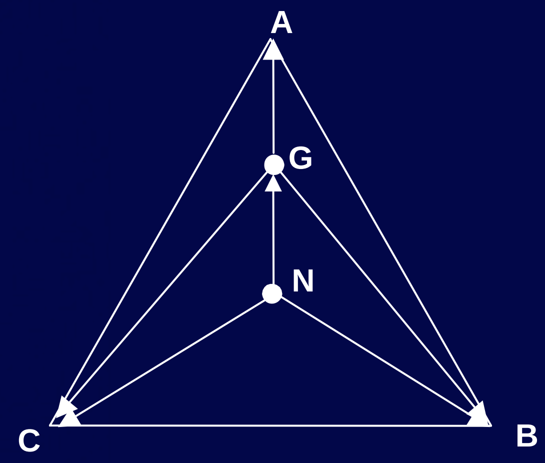
$I_A = I_B = I_C = I_{C0}$

System Charging Current = 3 x I_{C0}

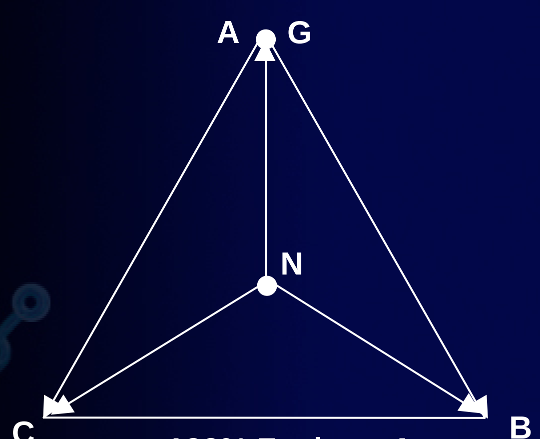
Voltage Shift on Ungrounded & Resistance Grounded Systems with Ground Fault



Normal Balanced
Stray Capacitance Current



Partial Fault on
A Phase

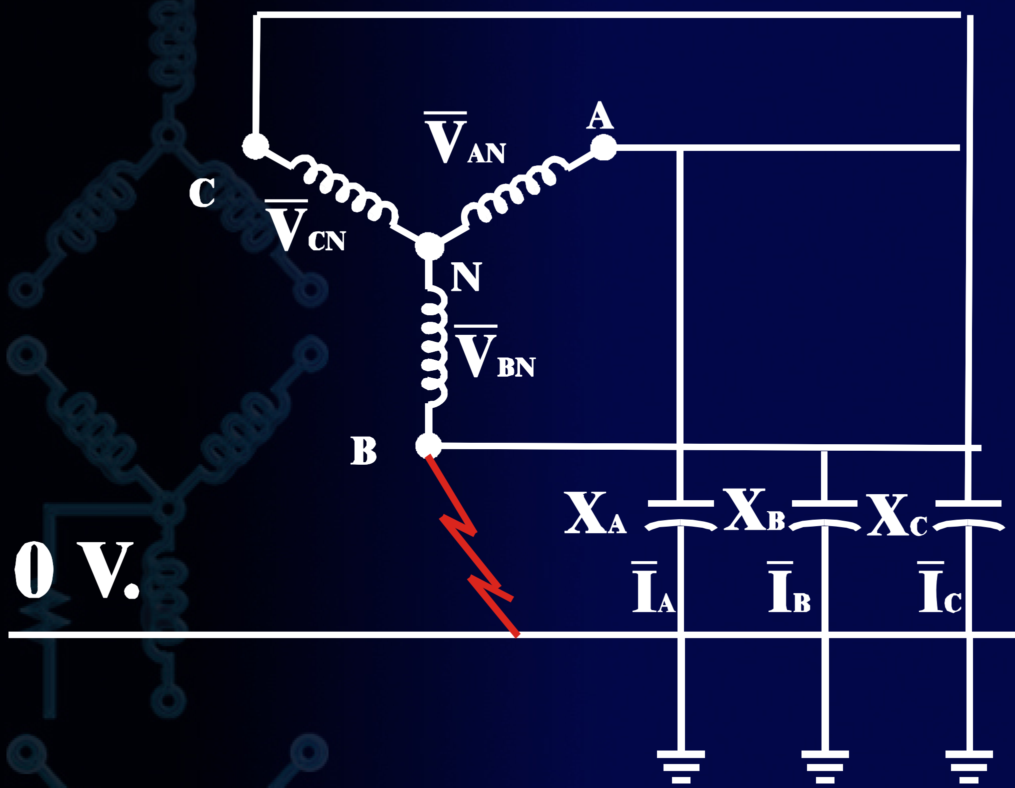


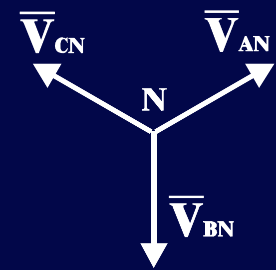
100% Fault on A
Phase

Ungrounded Systems

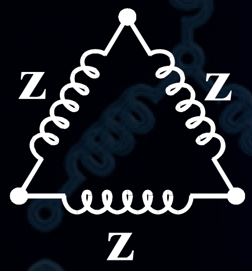
Faulted System

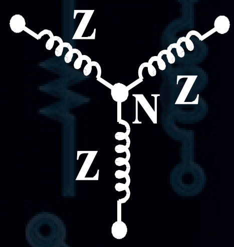
Arcing (intermittent)





Ungrounded Systems - Disadvantages





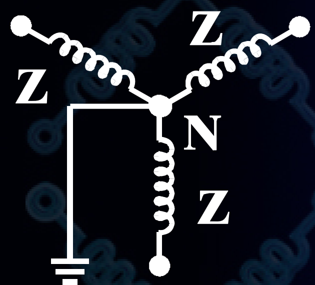
- Susceptible to build-up of >6 times rated voltage on intermittent arcing faults.
- Ground faults difficult to locate

Ungrounded Systems – What Does IEEE Say?

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

8.2.5
Ungrounded systems offer no advantage over high-resistance grounded systems in terms of continuity of service, and have the disadvantages of transient over-voltages, locating the first ground fault and burn downs from a second ground fault. For these reasons, they are being used less frequently today than high-resistance grounded systems.

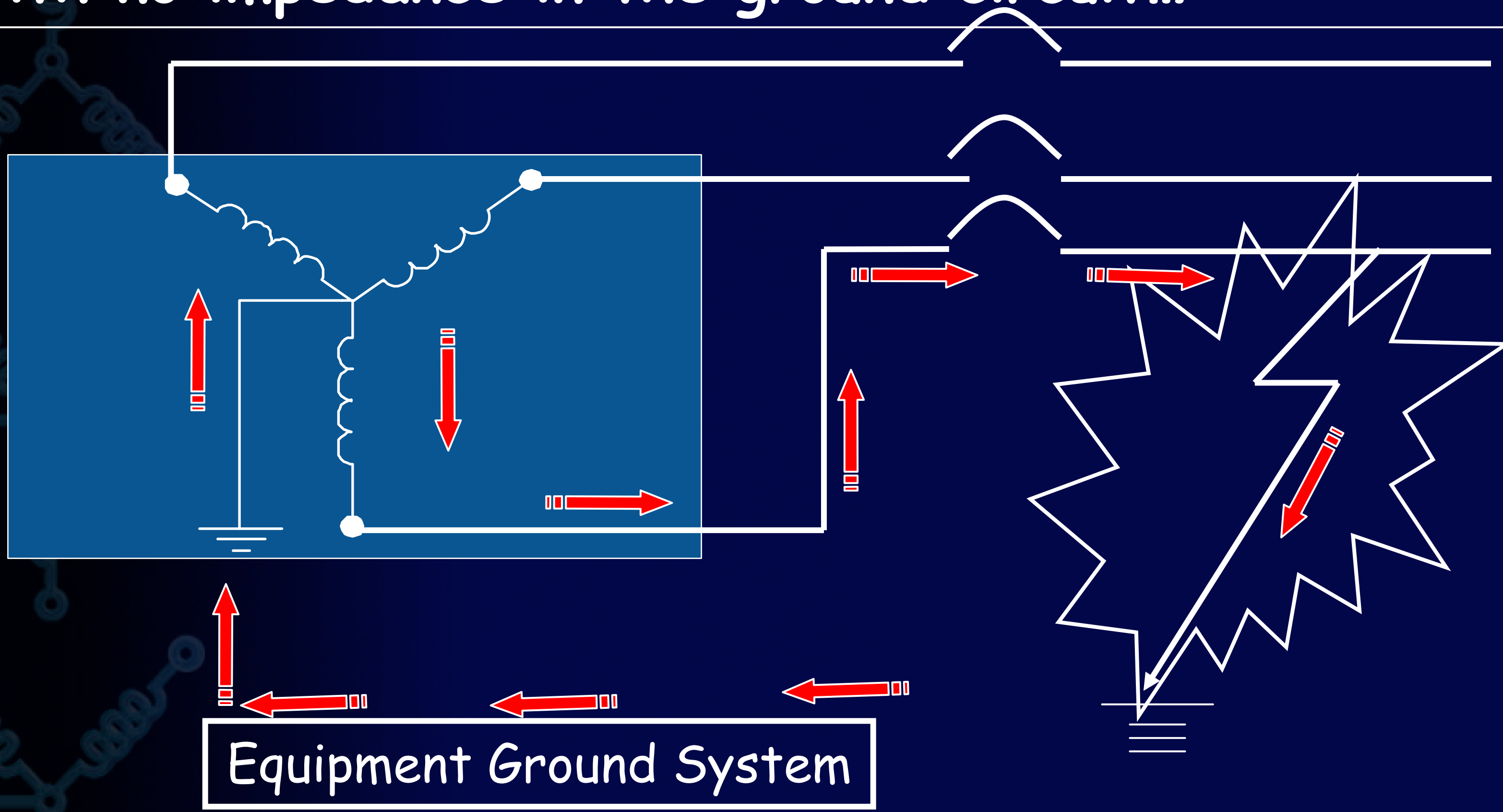
Solidly Grounded Systems



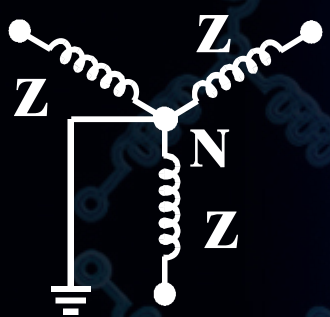
- Intentional connection of neutral to ground.
- Popular for 3-wire 480V and 600V systems since 1950's.
- Solved system overvoltage problem of ungrounded systems
- Inadvertently created new problem – arcing ground faults

Solidly Grounded Systems

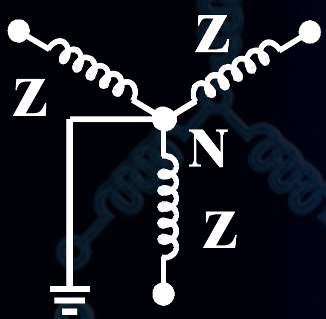
With no impedance in the ground circuit…



Solidly Grounded Systems



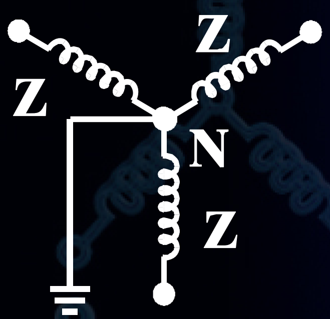
- Fault path has two parts:
  1. Impedance of the fault, between the live conductor and bonding system (unpredictable)
  2. Impedance of the bonding system (low)
- BOLTED FAULTS have low impedance, which quickly de-energize and isolate the faulted circuit
- ARCING FAULTS have high impedance, despite the bonding system, hence do not quickly trip the breaker



Solidly Grounded Systems

- Arcing faults can cause severe damage at point of fault due to intense heat and mechanical energy released
- Fault energy limited only by impedance of fault circuit, which is unpredictable
- Arcing faults more frequent and more damaging at 480V and 600V than 208V.

THE POWER TO PROTECT



Arcing Faults

- Self-extinguishing arcs limited to ½ cycle
- Sustained arcs are dangerous, continue to restrike every ½ cycle until circuit is interrupted.
- Most arcing faults are started by a line-to-ground fault of more than ½ cycle duration
- Arcing faults should be cleared between 6-30 cycles, ideally in less than 12 cycles (200 ms).

IPC
THE POWER TO PROTECT

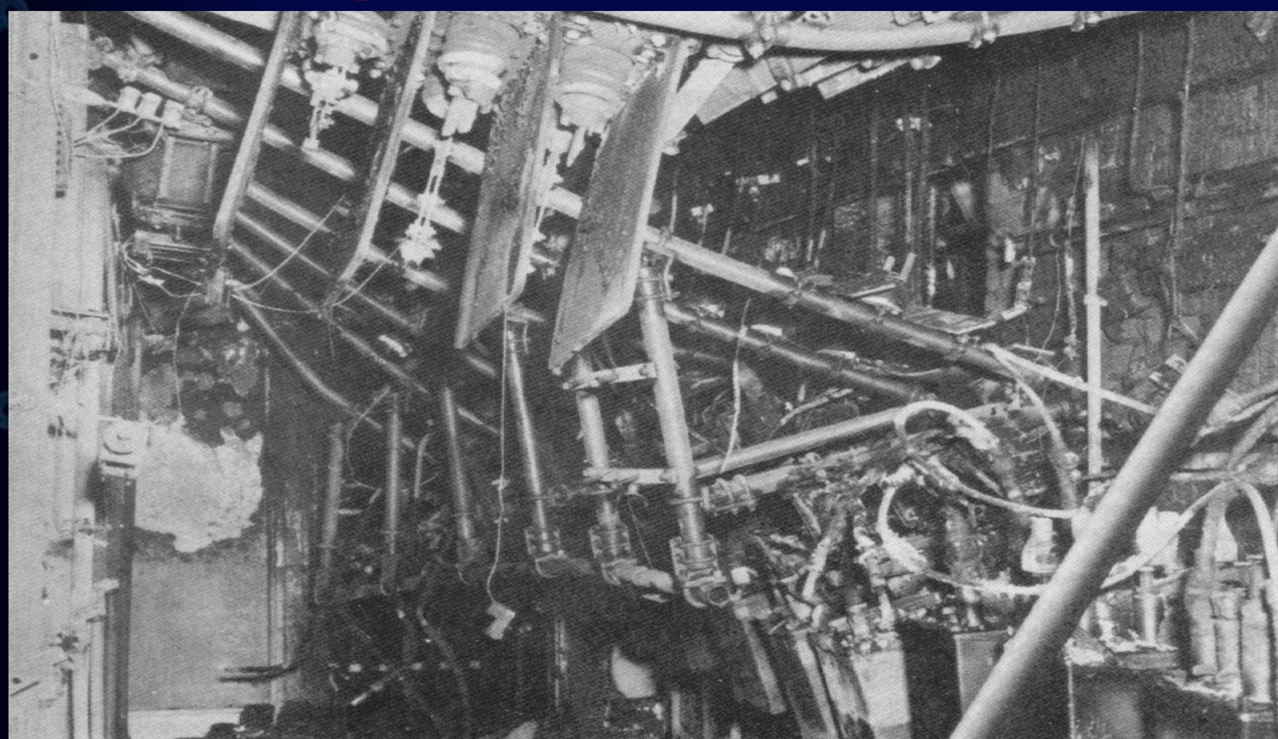
Arcing Fault Damage

KILOWATT CYCLES

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

I_G = Amperes
V_a = 100V
t cycles

2000 – 10,000 KWC Acceptable



Arcing Ground Fault Damage

A) **100 Kilowatt Cycles**
Fault location identifiable at close inspection - spit marks on metal and some smoke marks.

B) **2000 Kilowatt Cycles**
Equipment can usually be restored by painting smoke marks and repairing punctures in insulation.

C) **6000 Kilowatt Cycles**
Minimal amount of damage, but fault more easily located.

D) **10,000 Kilowatt Cycles**
Fault probably contained by the metal enclosure.

E) **20,000 Kilowatt Cycles**
Fault probably burns through single thickness enclosure and spreads to other sections.

F) **Over 20,000 Kilowatt Cycles**
Considerable destruction.

Why the CEC Requires Ground Fault Protection

From CEC Handbook
Rationale for Rule 14-102:

Arcing *ground* faults in solidly *grounded* electrical *systems* or components can cause very severe damage to *electrical equipment* and premises. Because of the resistance of the arc, the fault current may be small enough that the regular *overcurrent device* does not sense its existence, and arcing may persist for a long time. This is particularly true of *systems* operating at more than 150 *volts-to-ground* and rated at more than 1000 A, where there is adequate *voltage* and power to sustain the arc.

Solidly Grounded Systems – What Does IEEE Say?

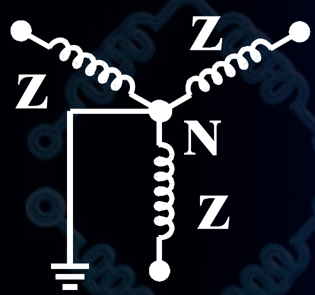
IEEE Std 242-2001 (Buff Book)

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

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

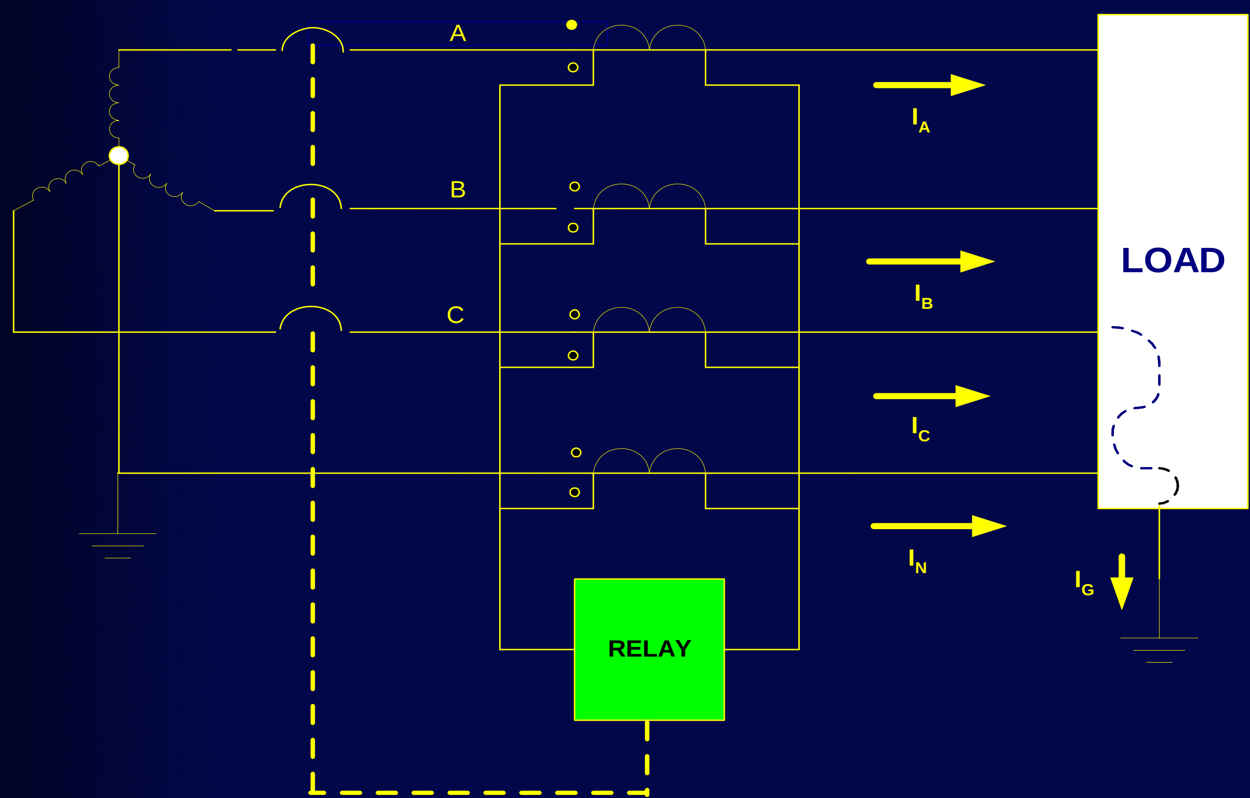
7.2.4
The solidly grounded system has the highest probability of escalating into a phase-to-phase or three-phase arcing fault, particularly for the 480 and 600 V systems. The danger of sustained arcing for phase-to-ground fault…is also high for the 480 and 600 V systems, and low or near zero for the 208 V system.

Solidly Grounded Systems – Coordination



- Ground Fault Coordination is difficult to achieve down to the branch breaker level, unless all branch breakers have ground fault relays

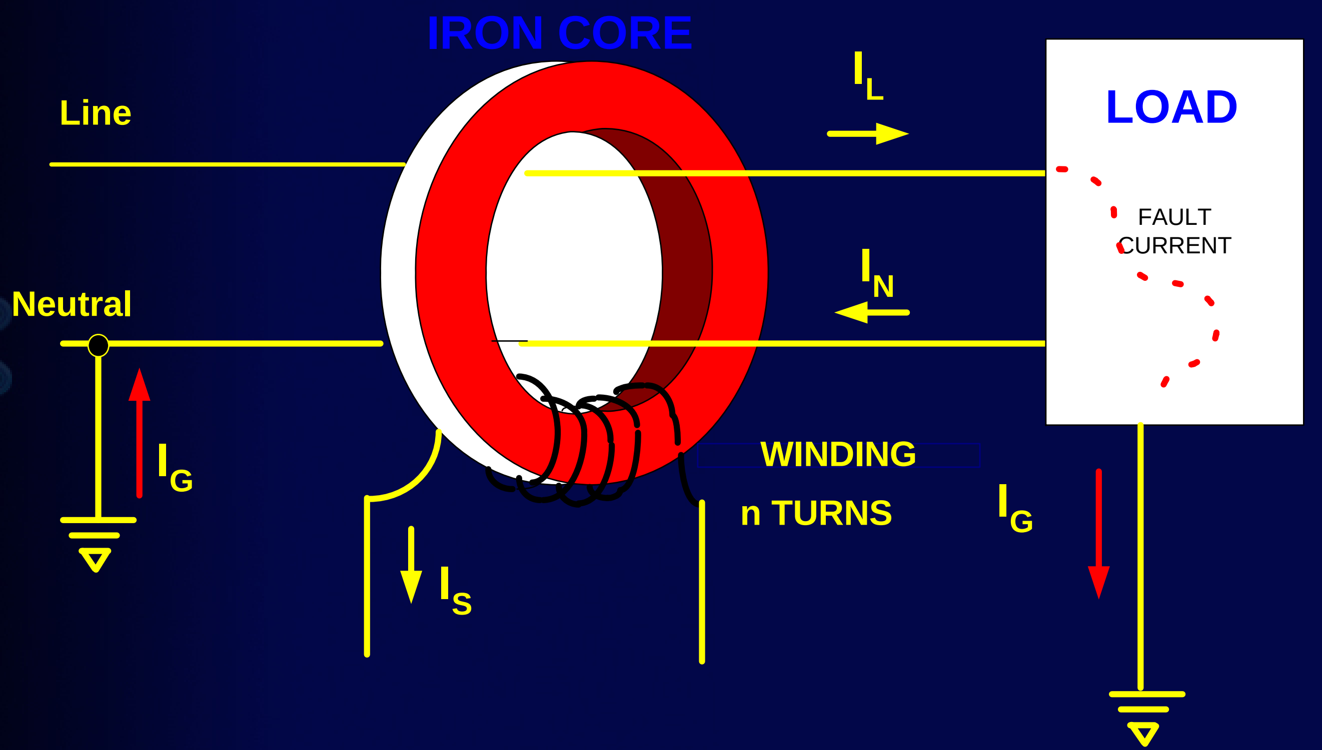
Ground Fault Sensing
Method 1 – Residual Sensing



$$I_G = I_A + I_B + I_C + I_N$$

- **50A to 1200A pickup**
- **Application: Solidly grounded LV & MV systems**

Method 2 –
Zero Sequence Current Sensing

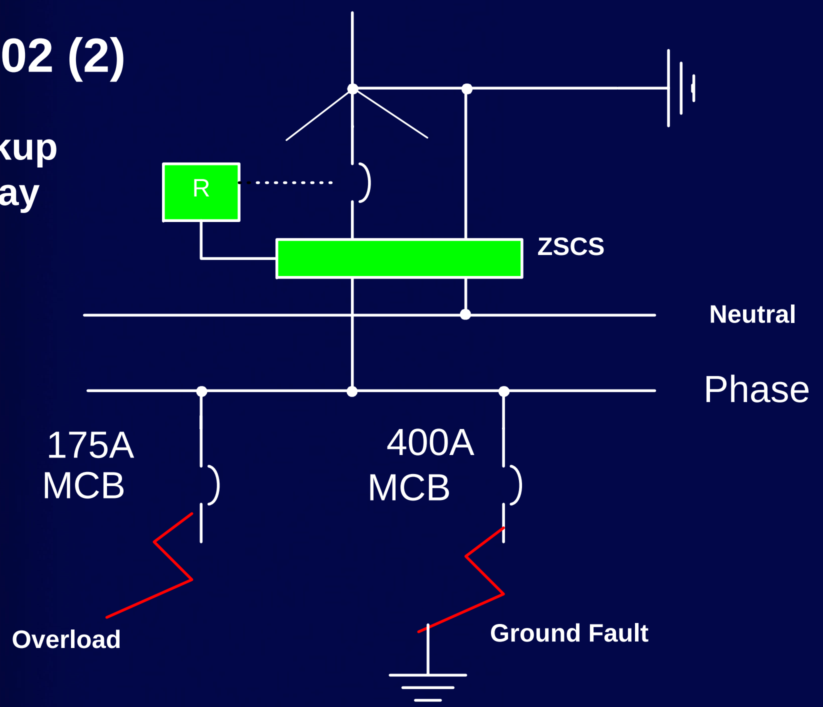


- 5 mA to 1200A
- More sensitive than residual sensing
- Used on high resistance and solidly grounded systems

Lack of Coordination on Solidly Grounded Systems

CEC Rule 14-102 (2)

1200 A Pickup
1 Second Delay



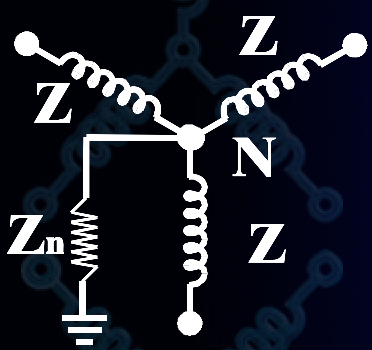
Feeder Trips on Overload

Main Breaker may Trip on Ground Fault!

Topics

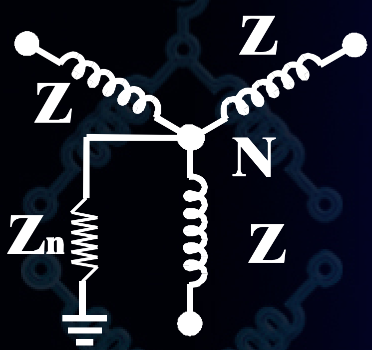
1. Grounding Overview
2. Resistance Grounding
3. Ground Fault Pulse Locating
4. Alarming and Relaying of resistance grounded systems.
5. Application Examples

Resistance Grounded Systems



- Resistance inserted between neutral and ground.
- Popular for 3-wire 480V and 600V systems since 1970s
- Limits fault current, prevents arcing ground faults.
- Still limits transient overvoltages.

Resistance Grounded Systems

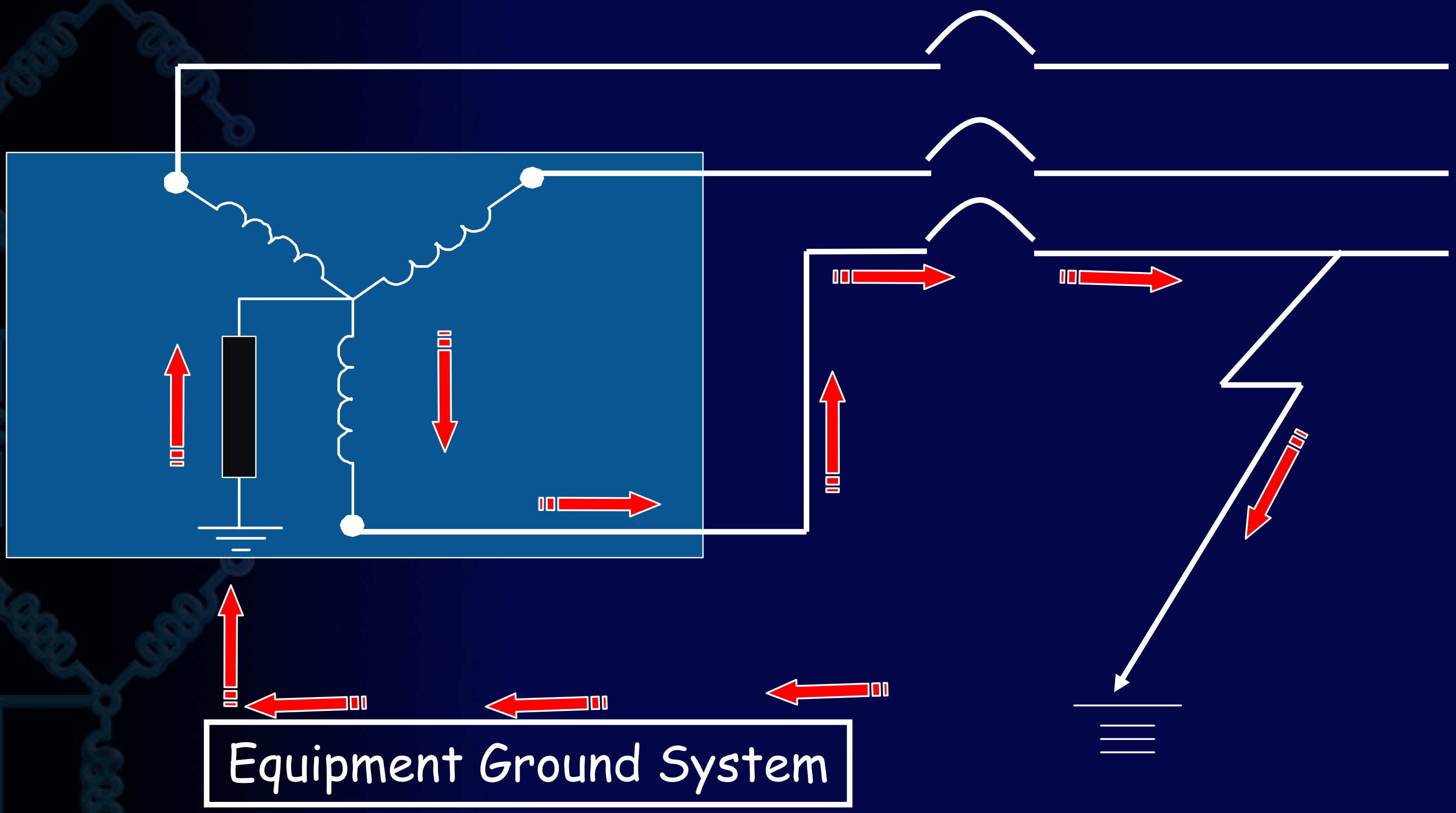


Where Used:

- Continuous Process Plants
- Generators
- Hospitals
- Data Centres

Resistance Grounded Systems

With impedance in the ground circuit….



Neutral Grounding Device – Definition

CSA Standard M421-00, Use of Electricity in Mines

2.1
Neutral Grounding Device – an impedance device used to connect the neutral of an electrical system to ground for the purpose of controlling ground current and voltage-to-ground.

Contrast with Power Systems not using a Neutral Grounding Device

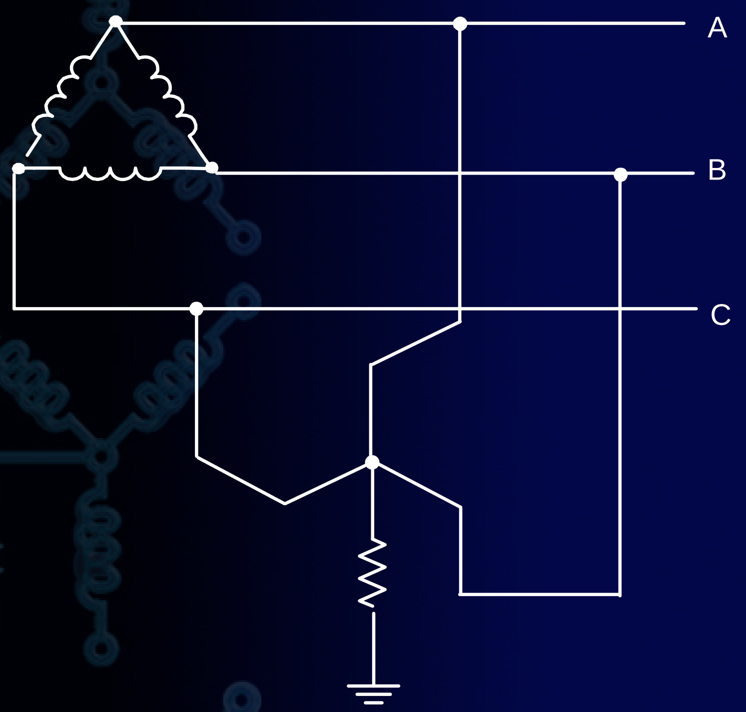
Ungrounded Systems:

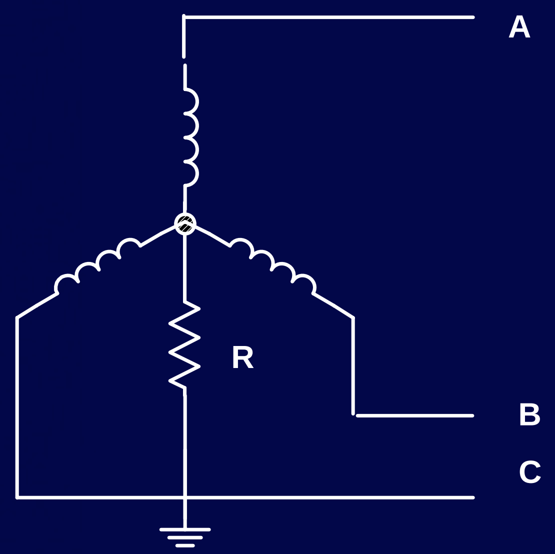
- Control of ground current
- No control of voltage-to-ground

Solidly Grounded Systems:

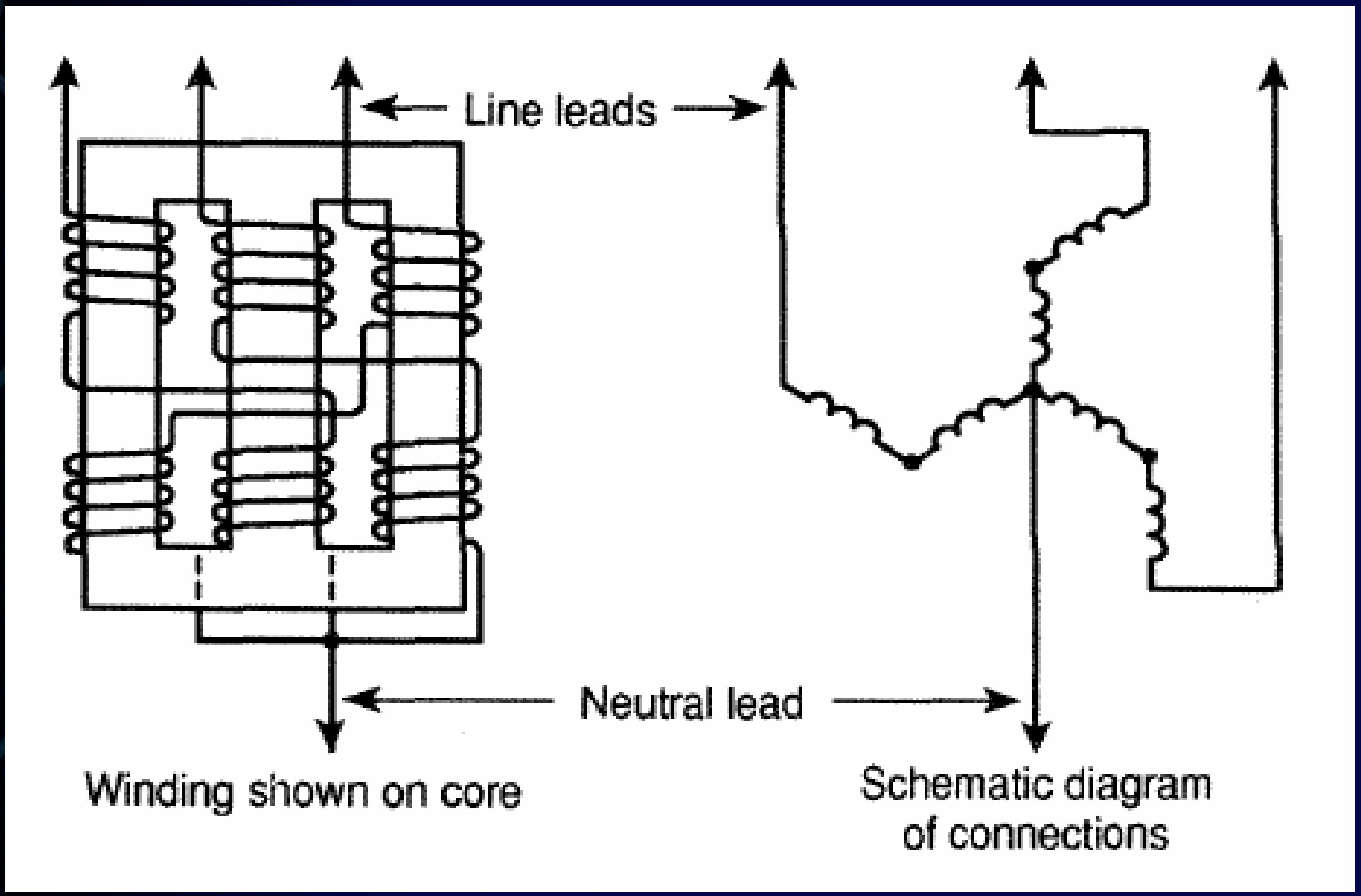
- Control of voltage-to-ground
- No control of ground current

Resistance Grounding





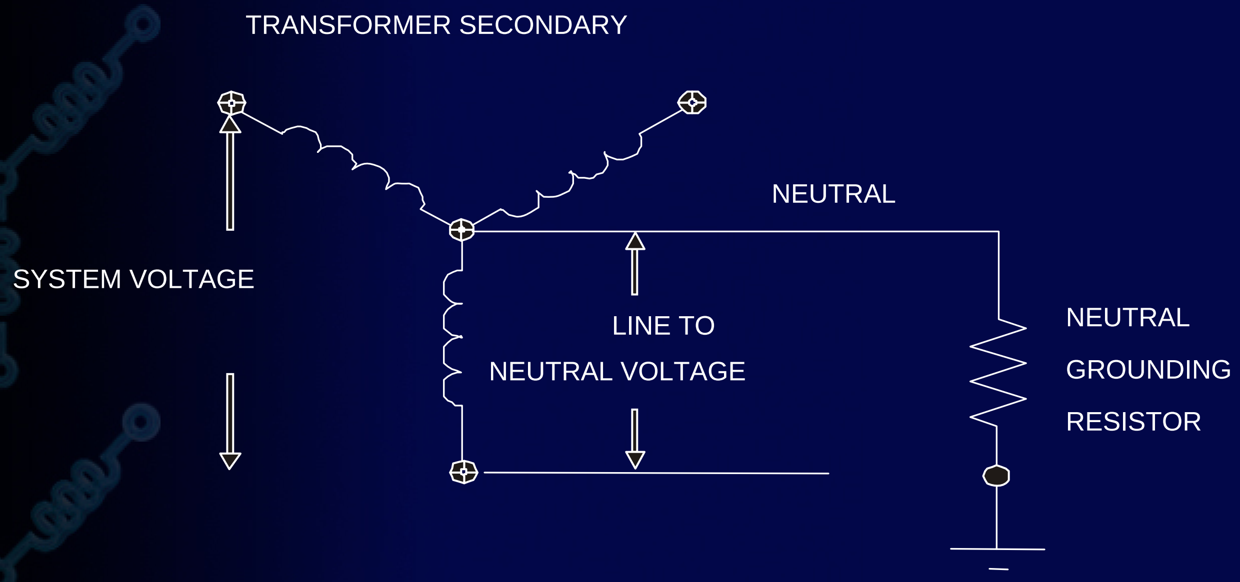
Zig-Zag Grounding Transformer



Resistance Grounded Systems

Two categories :

- high resistance
- low resistance



LINE TO NEUTRAL VOLTAGE EQUALS

SYSTEM VOLTAGE DIVIDED BY 1.732

IPC
THE POWER TO PROTECT

Low Resistance Grounding

Limit ground fault current to a high level (25-400A) in order to operate protective fault clearing relays.

- Limits damage to equipment
- Prevents additional faults
- Provides safety for personnel
- Localizes the fault

Resistors typically rated for 10 seconds and commonly used on medium voltage systems (2.4 kV to 15 kV)

Ground fault relay typically set to trip at 20% of resistor let-thru current

IPC
THE POWER TO PROTECT

High Resistance Grounding

- Limits ground fault current to a low level ($\leq$ 10 A).
- Used mainly on 480V and 600V systems.
- Safe on 2.4 kV and 5 kV systems where the system charging current is $\leq$ 5.5 A
- System charging currents:
  - 480V and 600V: 0.5 A per 1000 kVA
  - 2400V: 0.7 A per 1000 kVA
  - 4160V: 1.0 A per 1000 kVA

High Resistance Grounding

- System continues operating with ground fault, since fault current is very low.
- Ground Fault Coordination on first fault is no problem.
- Ground fault pulsing allows for ground faults to be quickly located while the plant is running.
- Fault Current:

$$I_F = \sqrt{I_R^2 + I_C^2}$$

High Resistance Grounding – What Does IEEE Say?

IEEE Std 242-2001 (Buff Book)

8.2.4
High-resistance grounding helps ensure a ground-fault current of known magnitude, helpful for relaying purposes. This makes it possible to identify the faulted feeder with sensitive ground-fault relays.

IEEE Std 141-1993 (Red Book)

7.2.2
High-resistance grounding provides the same advantages as ungrounded systems yet limits the steady state and severe transient over-voltages associated with ungrounded systems. There is no arc flash hazard *[for a ground fault on 480V and 600V systems]*, as there is with a solidly grounded system, since the fault current is limited to approximately 5A.

High Resistance Grounding – What Else Does IEEE Say?

IEEE Std. 142-1991 (Green Book)

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
4. to reduce arc blast or flash hazard to personnel who may have accidentally caused or who happen to be in close proximity to the fault current
5. to reduce the momentary line-voltage dip occasioned by the occurrence and clearing of a ground fault

Resistor Sizing

The resistor must be sized to ensure that the ground fault current limit is greater than the system charging current. If not, then transient over-voltages can occur.

Resistor Let-Through Current > System charging current

Determine system charging current by:

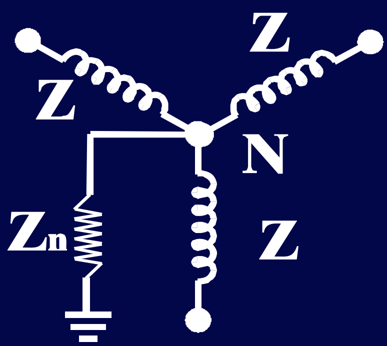
- Calculation
- Rule of thumb
- Measurement

Resistor for 480V and 600V systems – 5A.

Resistor for 2400V and 4160V systems – 10A.

Codes and Neutral Grounding Devices

1. Engineered and manufactured to IEEE Standard 32
2. CSA approved at IPC Resistors
3. Installed in Canada to CEC Rules 10-1100 thru 10-1108
4. Installed in USA to NEC 250.186 and 450.5(B)
5. Electrically Rated for:
   - line-to-neutral volts
   - let-thru current
   - allowable “on” time



Note on CEC Rule 10-1102 for Neutral Grounding Devices

- The CEC requires the supply authority's ground grid system to be interconnected to the consumer's ground grid system as outlined in Rule 10-204(2) for solidly grounded systems
- In Rule 10-204(2), the grounded conductor (neutral) interconnects the two grids .
- Appendix B on Rule 10-1102 requires the ground grid systems to be interconnected in high resistance systems, similar to Rule 10-204(2), yet there is no grounded conductor.
- Hence a separate conductor should be run to interconnect the two ground grid systems, sized to Table 17.

Another Note on Code Rule 10-1102

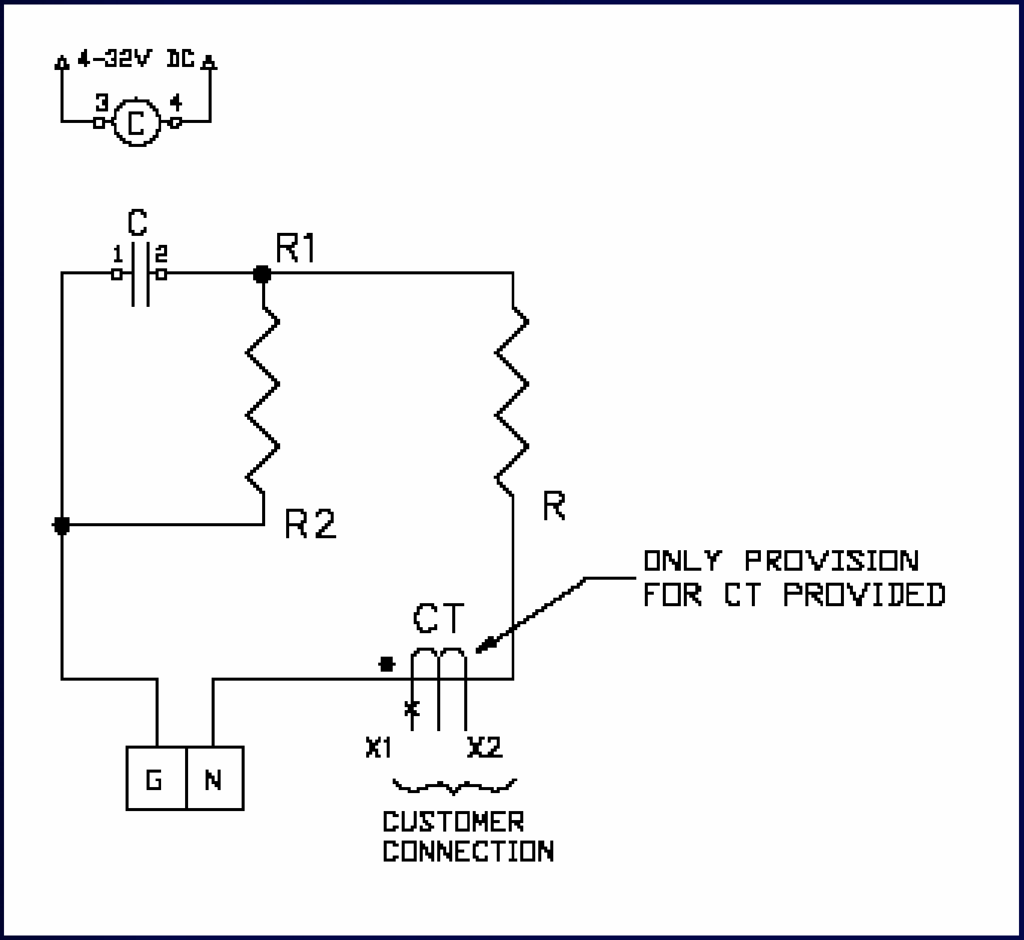
Supply Authority Metering:

- Figure 10-1100 in the CEC Handbook shows a separate conductor run from the transformer star point to the service entrance switchboard for use by the supply authority metering equipment
- For each application, where supply authority metering is required on the load side of a neutral grounding resistor, check whether this separate conductor is required for supply authority metering.

Topics

1. Grounding Overview
2. Resistance Grounding
3. Ground Fault Pulse Locating
4. Alarming and Relaying of Resistance Grounded Systems
5. Application Examples

Ground Fault Pulsing



Flexible CT Sensor

Ground Fault Pulse Locating

Topics

1. Grounding Overview
2. Resistance Grounding
3. Ground Fault Pulse Locating
4. Alarming and Relaying of resistance grounded systems.
5. Application Examples

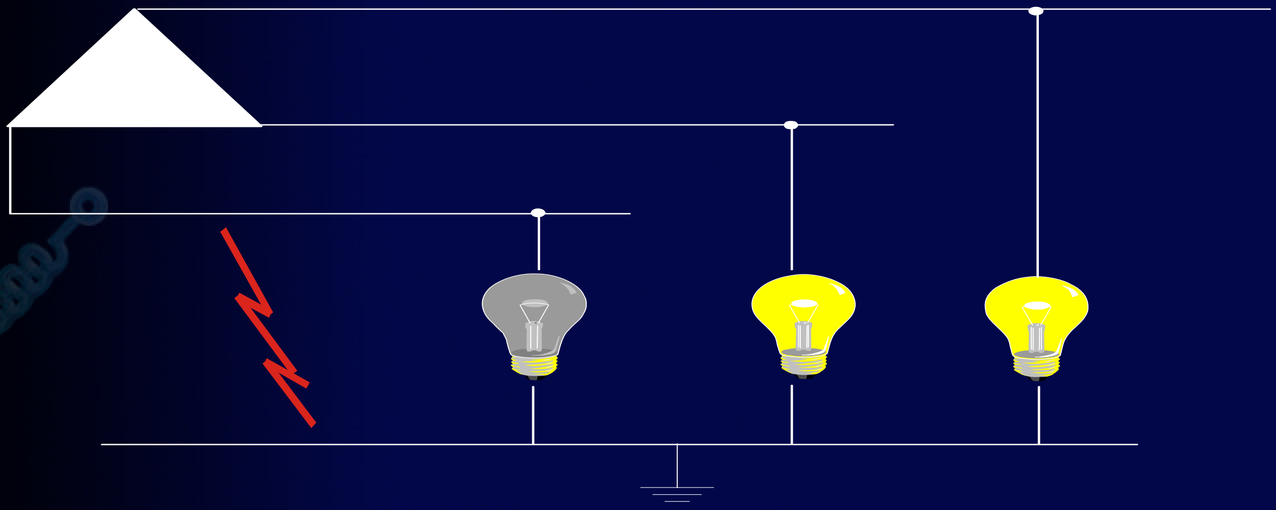
Relaying HRG Systems – Purpose

IEEE Buff Book Std 242-2001

8.2.5
Once the system is high-resistance grounded…modern, highly sensitive ground-fault protective equipment can identify the faulted feeder on first fault and open one or both feeders on second fault before an arcing burndown does serious damage.

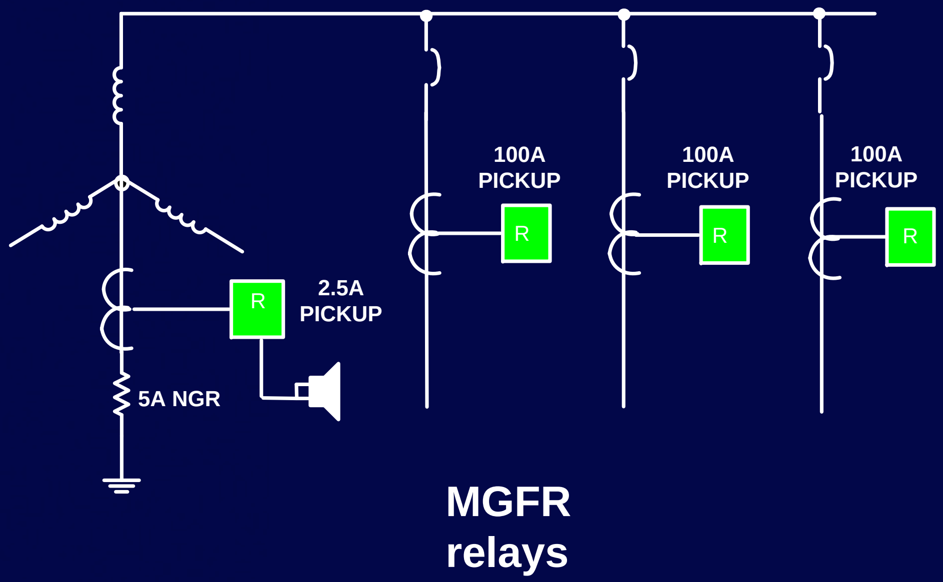
Ground Indicating Lights

- Provides visual indication only of a ground fault
- Should be inspected daily
- Minimum CEC requirement as per Rule 10-106(2)



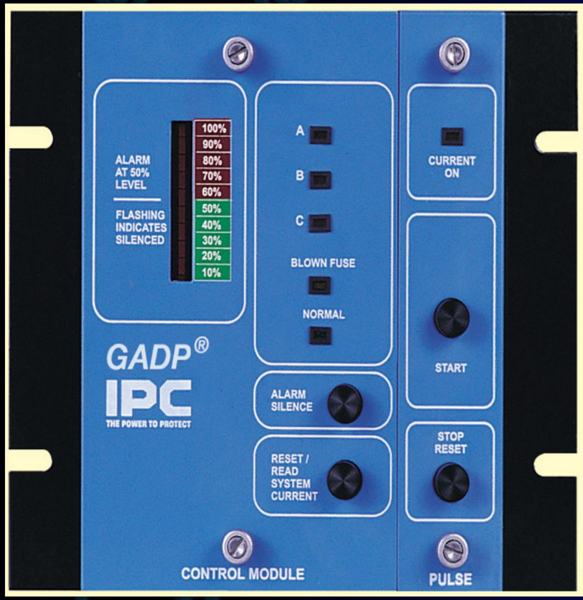
Current Sensing Ground Fault Relay

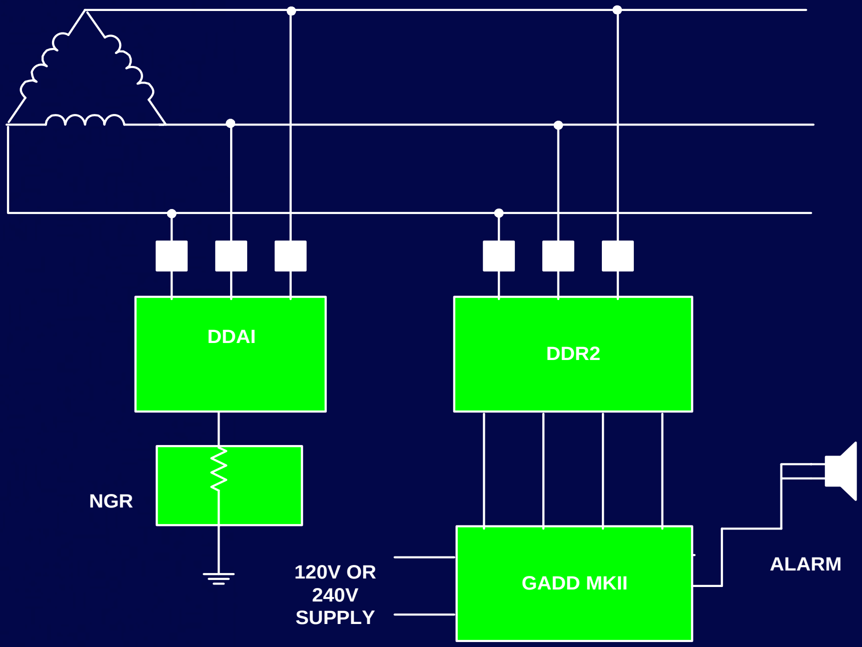
- Uses zero sequence CT
- Alarms and/or trips breaker



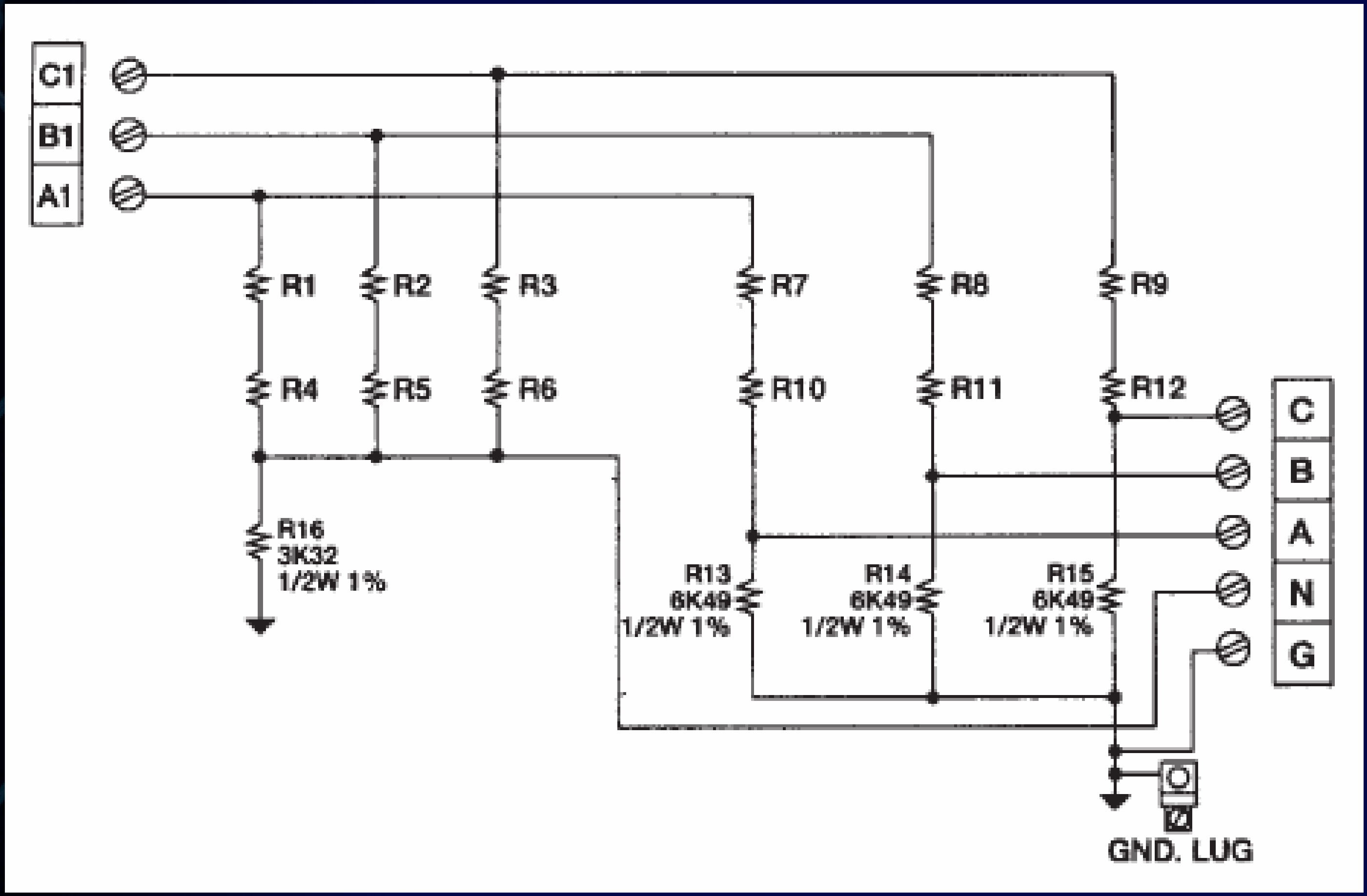
Voltage Sensing Ground Fault Relay

- Uses resistor divider network
- Faulted phase indication



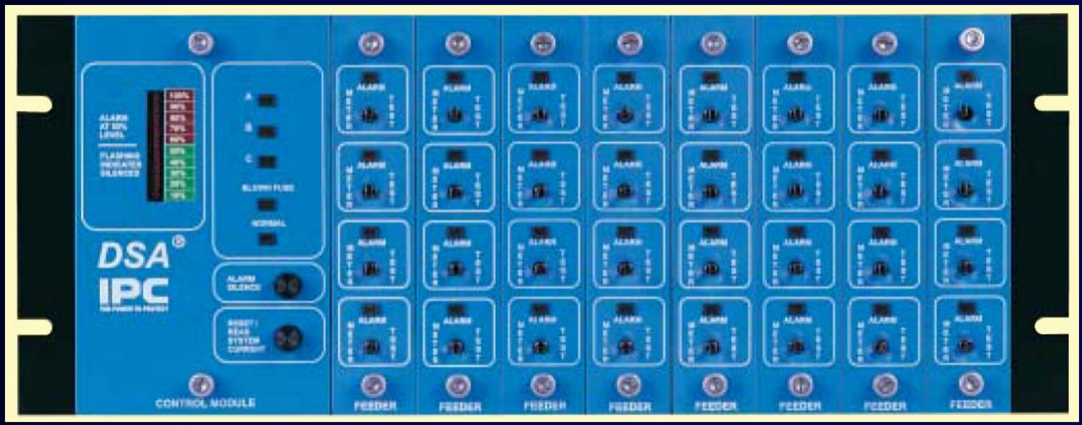


Resistor Divider Sensing Unit

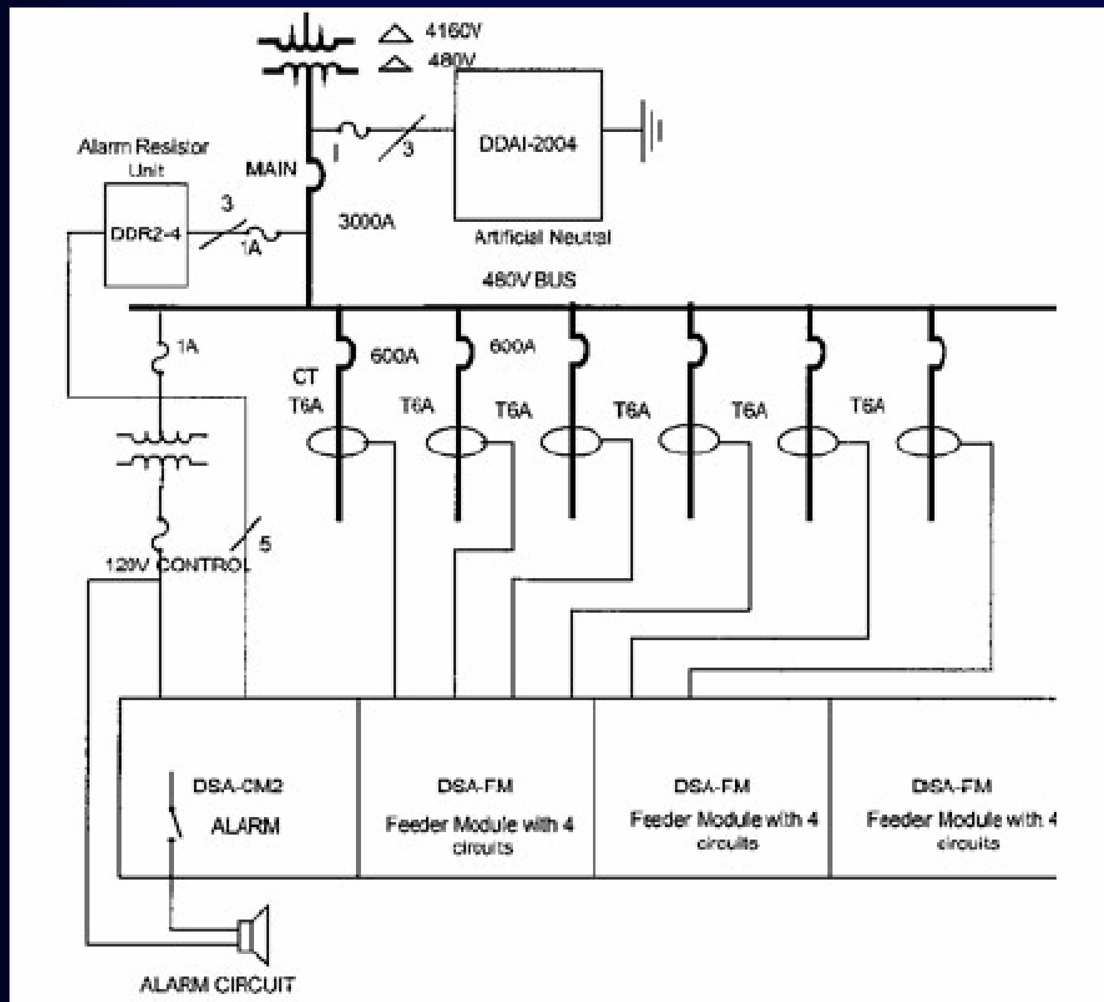


Multi-Feeder
Ground Fault Relay

- Multi-feeder alarm unit for switchboards
- Voltage Sensing Relay on Bus
- Current Sensing Relays on Feeders



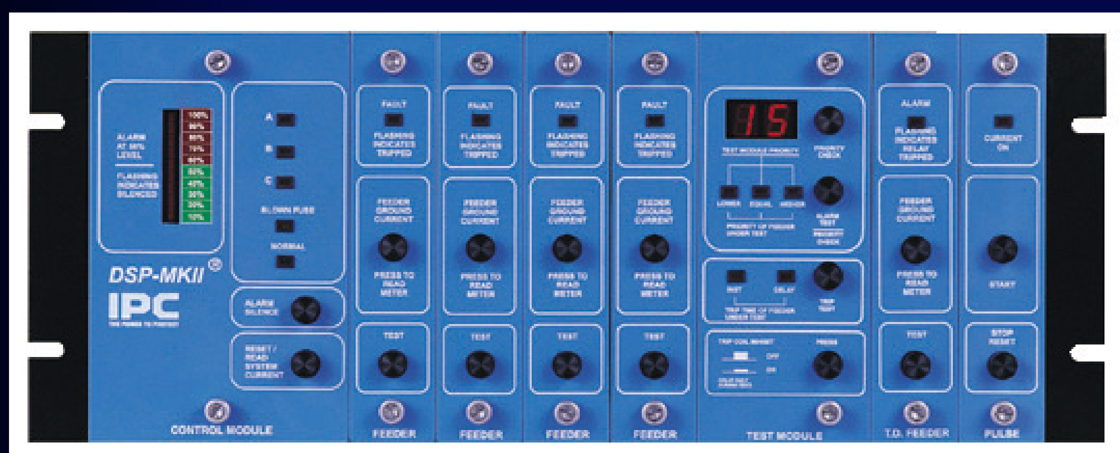
Multi-Feeder Ground Fault Relay



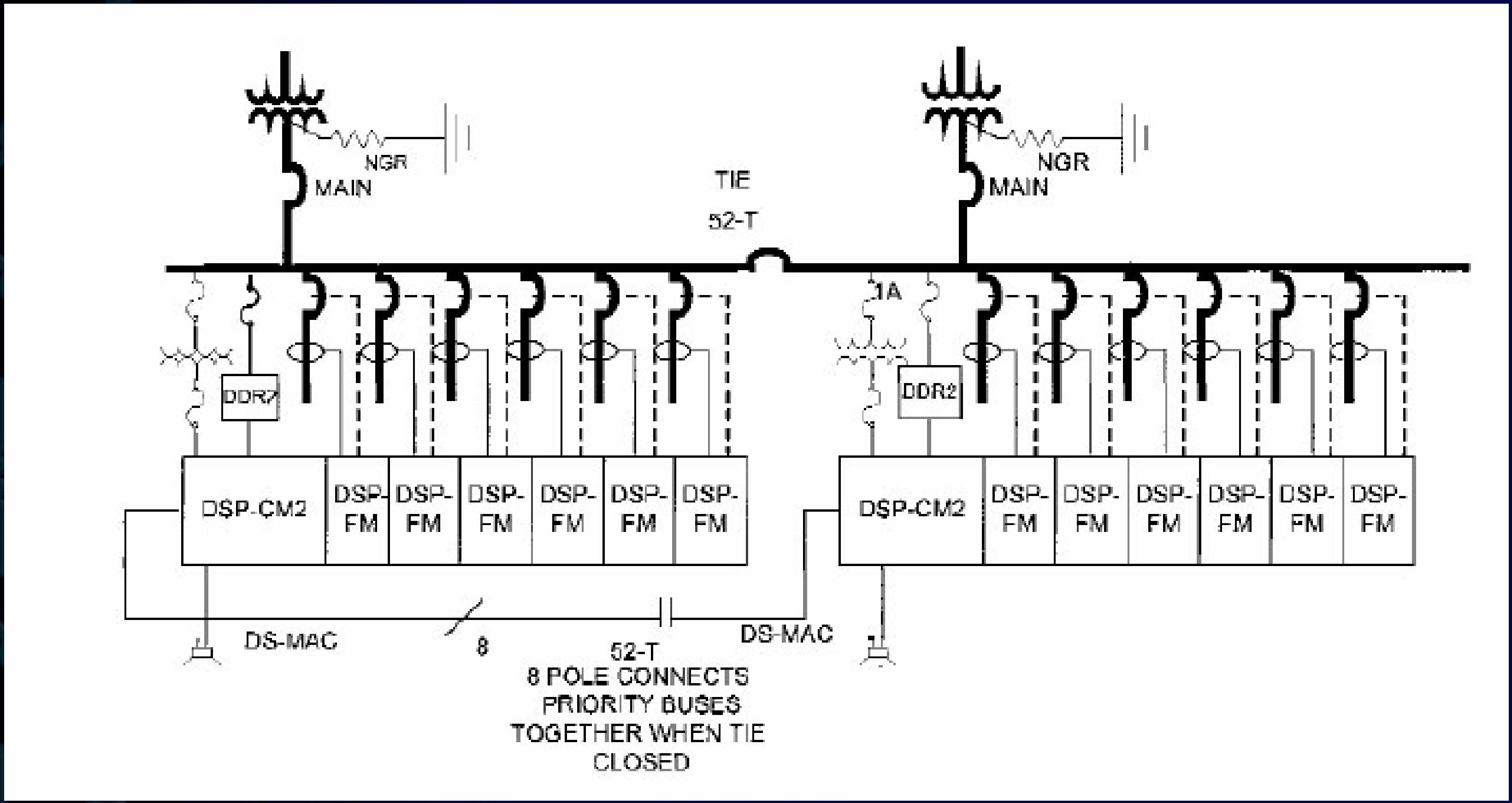
IPC
THE POWER TO PROTECT

Multi-Feeder Ground Fault Relay Selective Trip on 2nd Fault

- Multi-feeder alarm & trip unit for switchboards
- Alarms on first fault
- Trips lower-priority feeder on second fault



Double Ended Switchboard



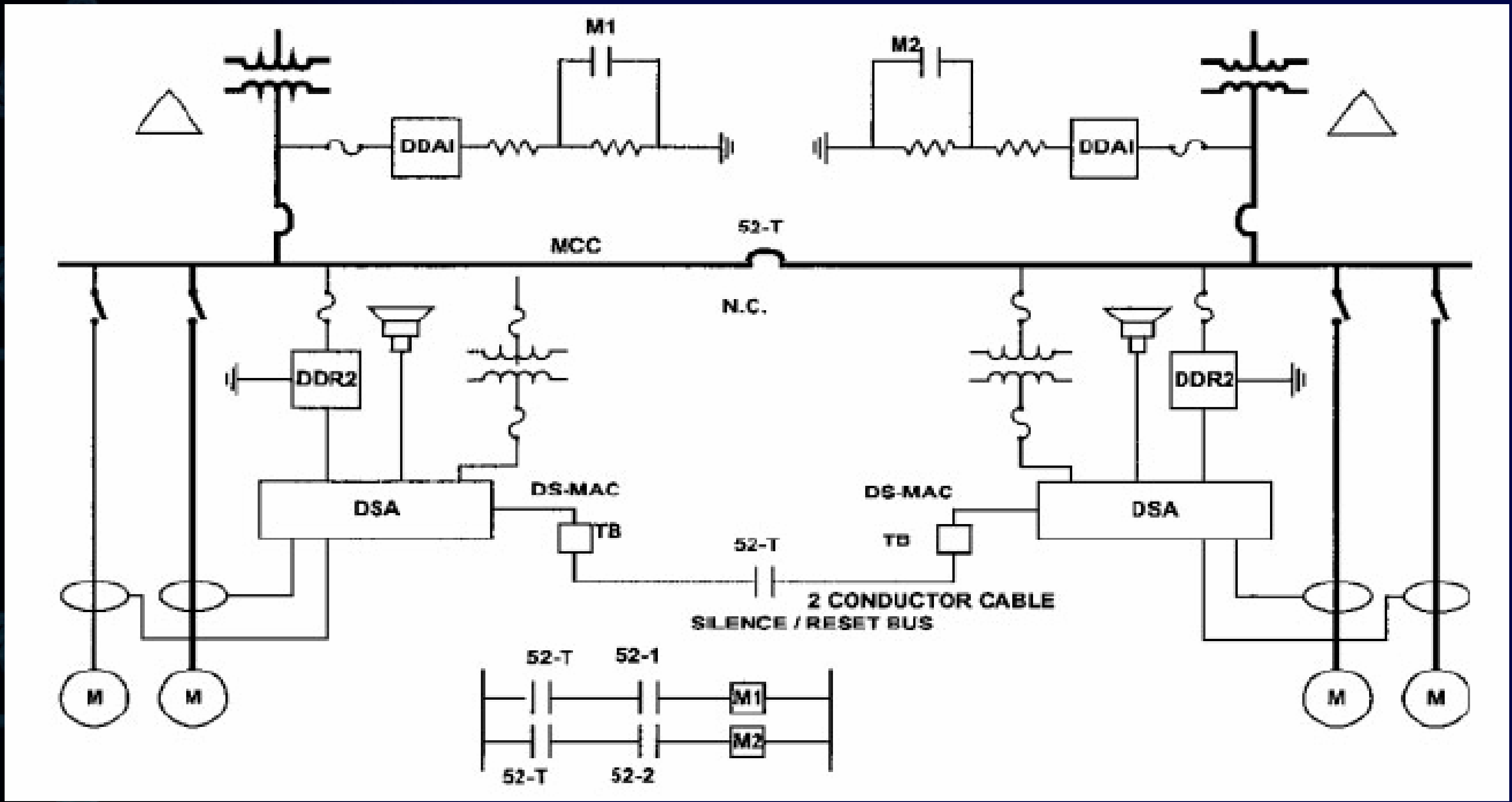
Topics

1. Grounding Overview
2. Resistance Grounding
3. Ground Fault Pulse Locating
4. Alarming and Relaying of resistance grounded systems.
5. Application Examples

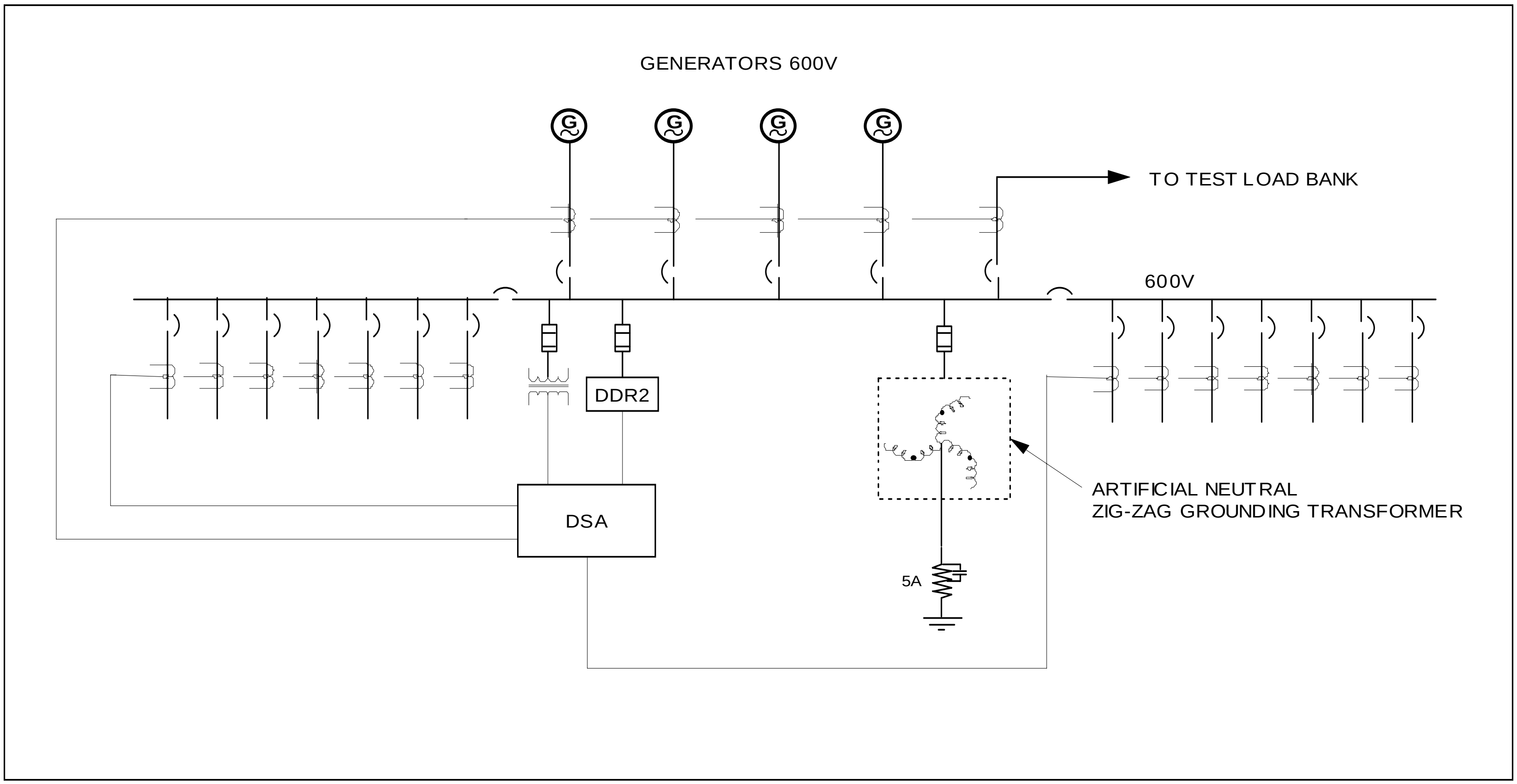
High Resistance Grounding - Applications

- Parallel Sources
- Generator Grounding

Parallel Sources – Maintain 5A Available Fault Current Under All Conditions



Parallel Generators



Generator Grounding – What Does IEEE Say?

IEEE Std. 142-1991 (Green Book)

1.8.1

- Generators have low zero sequence impedance compared to transformers.
- Thus a generator will have higher ground fault current than 3-phase fault current if solidly grounded.
- If a winding has 2/3 pitch to suppress 3rd harmonic voltage generation, then zero sequence impedance is still lower.
- Hence ground faults in solidly grounded generators can produce large fault currents, for which the generator is ill-equipped to withstand.

Generator Grounding – What Does IEEE Say?

IEEE Std 242-2001 (Buff Book)

Page 452:

- Solid grounding of a generator neutral is not recommended because this practice can result in high mechanical stresses and excessive fault damage to the machines.
- By ANSI, the max. stresses a generator is normally designed to meet are associated with the currents of a 3-phase fault at the machine terminals.
- To comply with ANSI C50.13-1989, generators should be grounded such that the max. phase-to-ground fault current is less than the 3-phase value.

IPC

THE POWER TO PROTECT

Generator Impedance

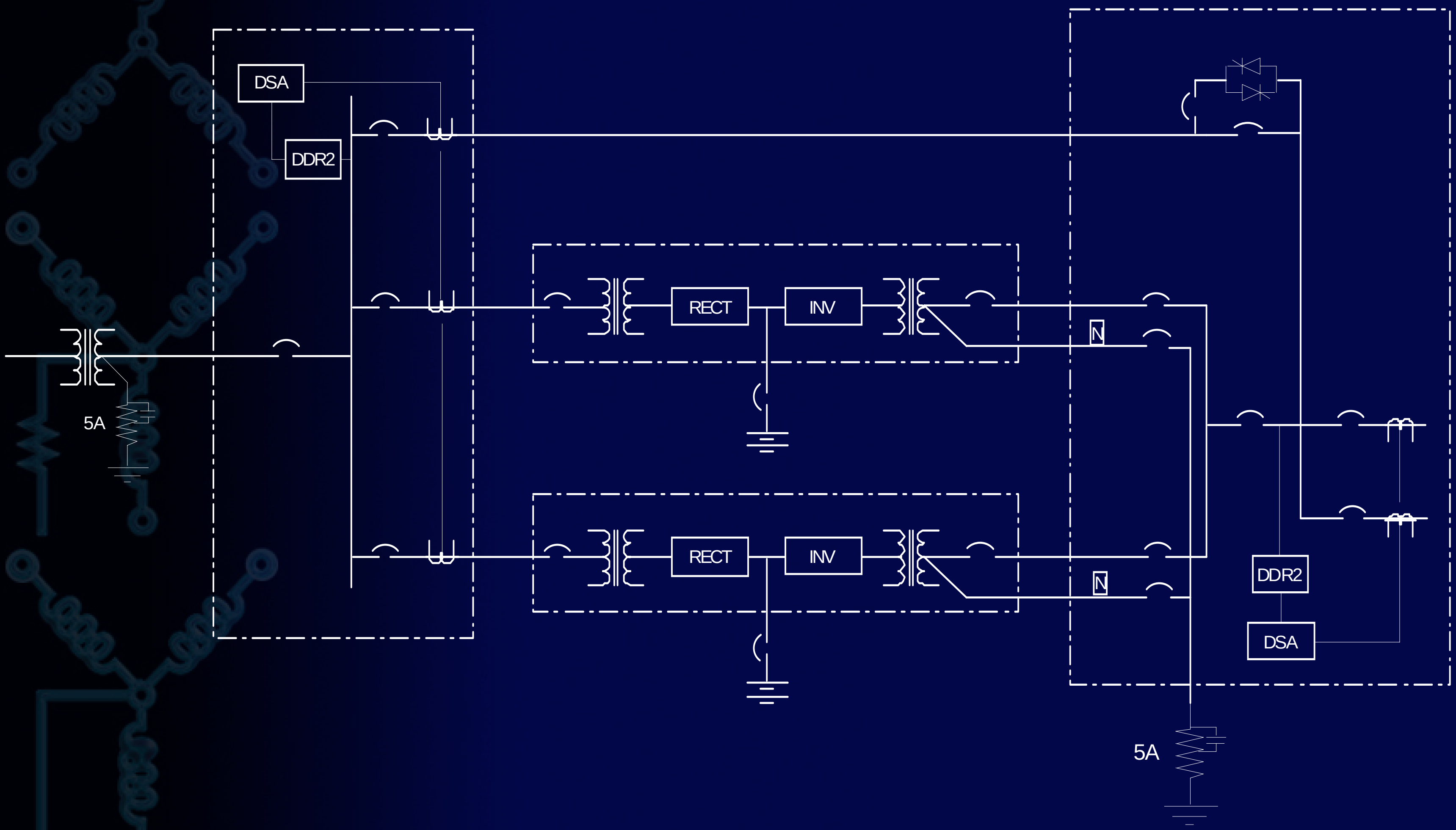
SR4B GENERATORS

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	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
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

High Resistance Grounding of UPS Systems



UPS System

Advantages of HRG:

- Critical load not transferred to raw utility for ground faults
- Faulted feeder remains operational, to be repaired later, when downtime can be scheduled
- Higher Availability for Critical Load
- No equipment damage on ground fault

Q & A