Electrical Connections

General

Vibration Isolation

All generator sets vibrate during normal operation, a fact that must be addressed. They are either designed with integral isolators or the entire skid is mounted on spring isolators to allow movement and to isolate vibrations from the building or other structures. Greater movement can also occur upon sudden load change or fault event and during startup or shutdown. Therefore, all connections to the generator set, mechanical and electrical, must be able to absorb the vibration movement and startup/shutdown movements. Power output, control function, annunciation, and accessory circuits all require stranded flexible leads and flexible conduits between the generator set and the building, mounting structure, or foundation.

Large stiff cables may not provide sufficient ability to bend even though they are considered flexible. This is also true of some conduit types, for example certain liquid–tight conduits that are quite stiff. Cables or conduits are not compressible along their length so flexibility in that dimension must be accommodated with sufficient length, offsets or bends.

Further, the electrical connection points on the generator set – bushings, bus–bars, terminal blocks, etc. – are not designed to absorb these movements and related stresses. (This is again especially notable for large stiff cables or stiff “flexible” conduits. Failure to allow sufficient flexibility will result in damage to enclosures, leads, cables, insulation, or connection points.

Note: Simply adding flex conduit or cabling may not result in sufficient capability to absorb the vibratory movement of a generator set. Cables and flexible conduits vary in flexibility and will not stretch or compress. This condition can be addressed by including at least one bend between the generator output enclosure and the structure (cement floor, raceway,wall, etc.) to allow for three dimensional movement.

Note: Control wiring should include strain relief to prevent motion at the point of connection that could potentially cause wiring failure.

Seismic Areas

In seismic risk areas, special electrical installation practices are required, including seismic mounting of equipment. The mass, center of gravity, and mounting dimensions of the equipment are indicated on the outline drawings.

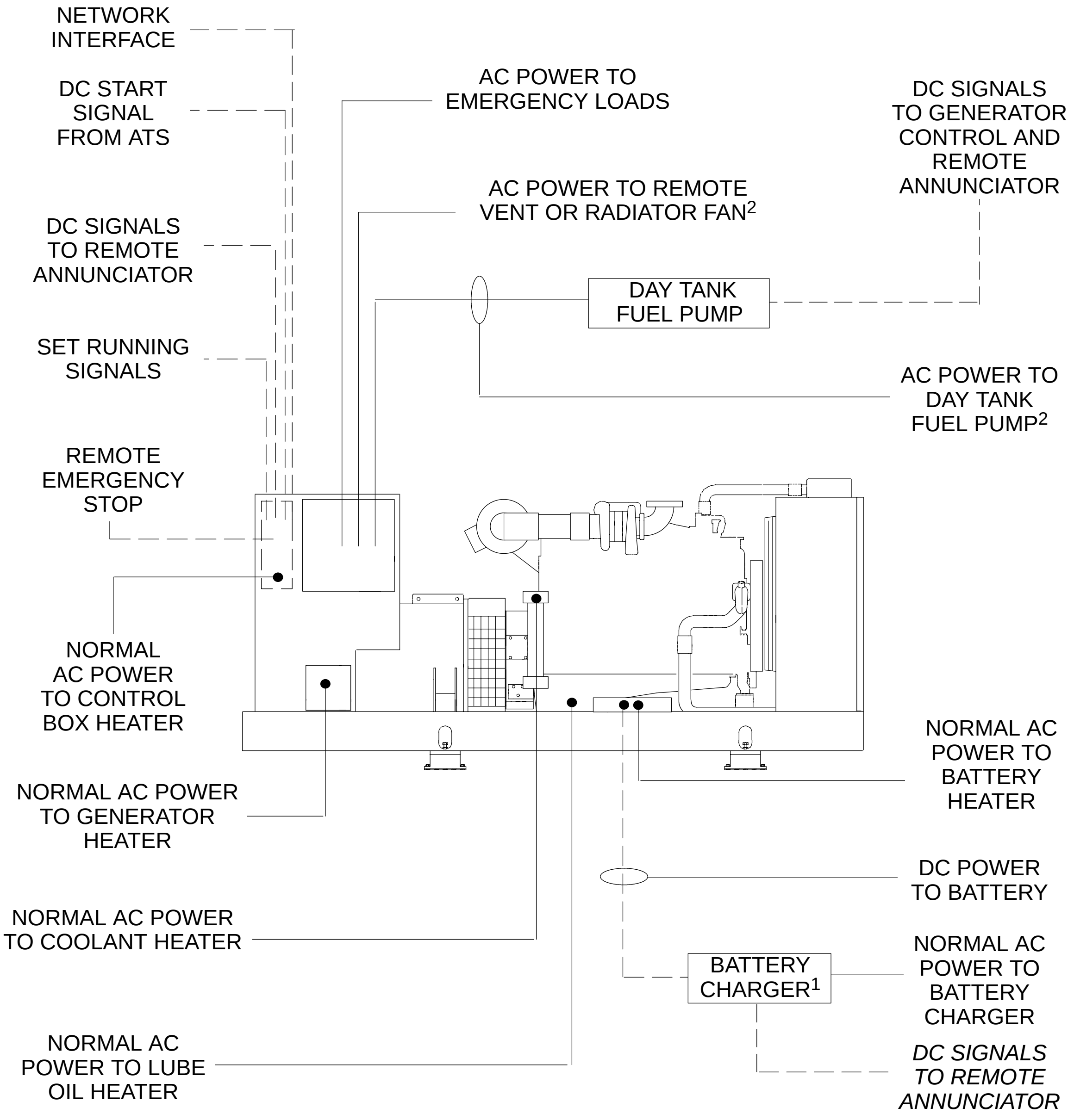
Control Wiring

AC and DC control wiring (to the remote control equipment and remote annunciators) must be run in separate conduit from the power cables to minimize power circuit interference in the control circuit. Stranded conductors and a section of flexible conduit must be used for connections at the set.

Accessory Branch Circuits

Branch circuits must be provided for all accessory equipment necessary for operation of the generator set. These circuits must be fed either from the load terminals of an automatic transfer switch or from the generator terminals. Examples of accessories include the fuel transfer pump, coolant pumps for remote radiators, and motorized louvers for ventilation.

Branch circuits, fed from the normal power panelboard, must be provided for the battery charger and coolant heaters, if used. See **Figure 5–10**.



NOTES:

1. WHEN A CUMMINS POWER GENERATION ATS (AUTOMATIC TRANSFER SWITCH) IS USED, THE BATTERY CHARGER CAN BE SUPPLIED WITH THE ATS. ATS MOUNTED BATTERY CHARGERS CANNOT BE USED IN PARALLELING APPLICATIONS.
2. THESE LOADS CAN BE POWERED DIRECTLY OFF THE GENERATOR (WITH APPROPRIATE OVERCURRENT PROTECTION) OR FROM THE LOAD SIDE OF THE FIRST PRIORITY ATS.
3. THE ITEMS IN *ITALICS* ARE NOT ALWAYS USED.
4 NETWORK INTERCONNECT MAY REPLACE SIGNALS FOR SOME CONTROL INTERCONNECTIONS.

Figure 5–10. Typical Generator Set Control and Accessory Wiring

AC Power Connections at Generator

Verify a proper match of the number of conductors per phase and their size with the published lug capacities of the equipment (circuit breakers and transfer switches).

A main disconnect device (circuit breaker/switch) should be supervised and arranged to activate an alarm when it is open. Some suppliers will initiate a “not in auto” alarm when the CB is open.

Connection options at the generator can include the following:

Generator-Mounted Molded Case Circuit Breakers (Thermal–Magnetic or Solid–State)

Connections can be made to a generator–mounted circuit breaker. The circuit breaker selected must have adequate interrupting capability based on the available short circuit current. With a single generator set the maximum available first cycle symmetrical short circuit current is typically in the range of 8 to 12 times the rated current. For a specific generator it equals the reciprocal of the generator per unit subtransient reactance, or $1/X''_d$. Use the minimum tolerance of subtransient reactance from the specific generator manufacturer's data for the calculation.

Generator-Mounted Disconnect (Molded Case) Switch

Connections can be made to a generator–mounted disconnect switch. This is allowable where the generator includes an inherent means of generator overcurrent protection, such as Power Command. The switch is not intended to interrupt fault level currents, having an interrupting rating sufficient only for the load currents.

Generator Terminals

Connections may be made to the generator terminals where no generator–mounted circuit breaker or disconnect switch is required and where the generator includes an inherent means of generator overload protection.

AC Power Conductors

The generator set AC output connects to field–installed conductors sized as required by the load currents, the application, and applicable codes. The conductors from the generator terminals to the first overcurrent device are considered tap conductors. A generator circuit breaker may be provided at the load end of the generator supply conductors (for example, paralleling breakers in the paralleling switchboard or main breaker in a distribution panel) and still provide overload protection for the conductors.

If the generator set is not factory–supplied with a main–line circuit breaker, the ampacity of the field–installed AC phase conductors from the generator output terminals to the first overcurrent device should be at least equal to 115 percent of the rated full–load current, without temperature or altitude de–ratings. The ampacity of the conductors may be 100 percent of rated full–load current if the generator set is equipped with Power Command. The generator set manufacturer will specify line–ampere ratings of a specific generator set at the specific voltage required. If unknown, calculate using one of the following formulae:

$$I_{LINE} = \frac{kW \bullet 1000}{V_{L\text{-}L} \bullet 0.8 \bullet 1.73} \quad \text{OR} \quad I_{LINE} = \frac{kVA \bullet 1000}{V_{L\text{-}L} \bullet 1.73}$$

Where:

I_{LINE} = Line Current (amps).
kW = Kilowatt rating of the genset.
kVA = kVA rating on the genset.
V_{L-L} = Rated line–to–line voltage.

See schematics (a) and (b) in **Figure 5–11**. The length of run for generator tap conductors to the first overcurrent device should be kept as short as possible (generally not more than 25 – 50 feet).

NOTE: If the generator is supplied with leads, the size of the leads may be smaller than required for field–installed conductors because generator leads have type CCXL or similar, high temperature insulation rated at or above 125° C.

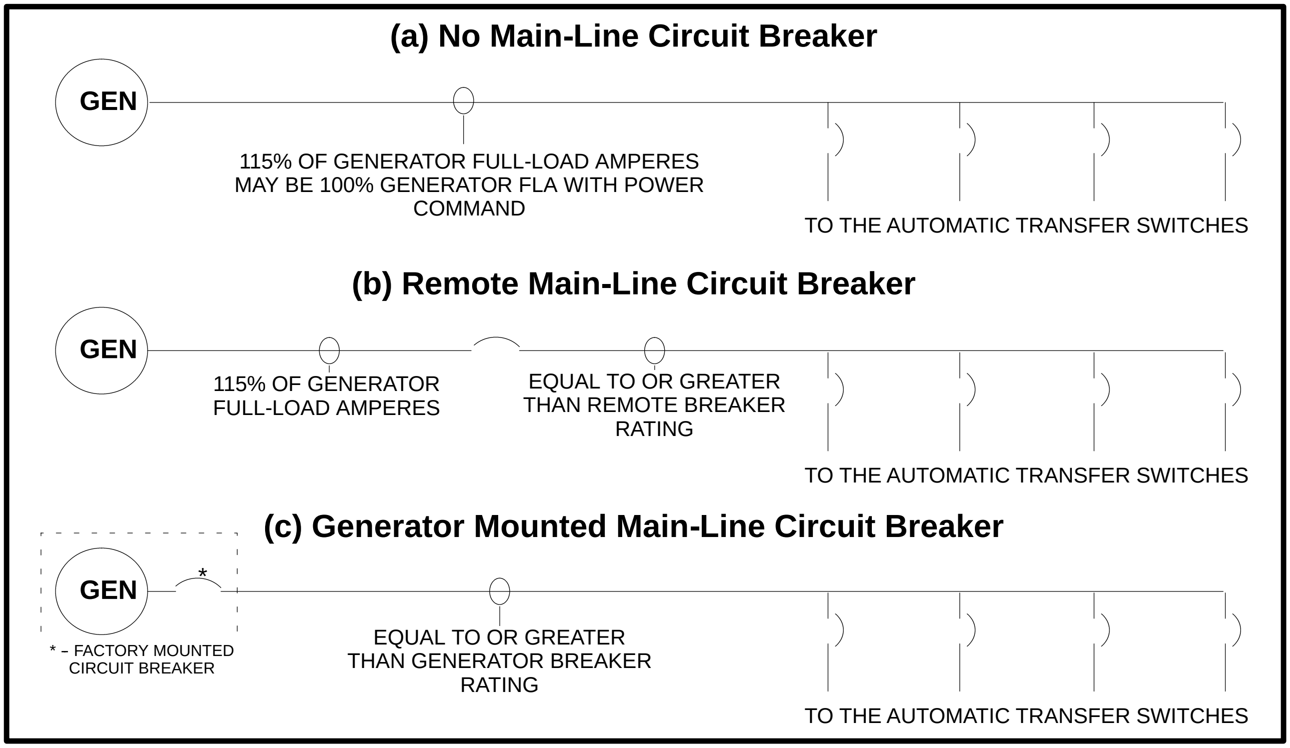


Figure 5–11. Feeder Ampacity

If the generator set is factory–equipped with a main–line circuit breaker, the ampacity of the field–installed AC phase conductors connected to the load terminals of the circuit breaker should be equal to or greater than the circuit breaker rating. See Schematic (c) in **Figure 5–11**.

The minimum ampacity of the neutral conductor is generally permitted to be equal to or greater than the calculated maximum single–phase unbalance of the load. Where a significant portion of the load is non–linear, the neutral should be sized in accordance with anticipated neutral current but never less than 100 percent rated. The generator neutral supplied by Cummins Power Generation is equal in ampacity to the phase conductors.

Note: Medium voltage cable (greater than 600 VAC) must be installed and terminated exactly as recommended by the cable manufacturer, by persons who have learned the procedures through training and practice under close supervision.

Voltage Drop Calculations

Conductor impedance due to resistance and reactance causes voltage to drop in an AC circuit. To obtain the performance expected of load equipment, conductors usually should be sized so that voltage does not drop more than 3 percent in a branch or feeder circuit or more than 5 percent overall between the service drop and the load equipment. While exact calculations are complex, reasonably close approximations can be made using the following relation:

$$V_{DROP} = \frac{(I_{PHASE} \bullet Z_{CONDUCTOR})}{V_{RATED}}$$

For Example: Calculate percentage voltage drop in 500 feet of 1/0 AWG copper cable in steel conduit supplying a 3–phase, 100 kW, 480 volt, (line–to–line) load imposing a 0.91 PF (Power Factor).

$$Z(\text{ohms}) = \frac{L}{(1000 \bullet N)} [(R \bullet pf)+X\sqrt{(1-pf^2)}]$$

Where:

Z = Impedance of conductor
R = Resistance of conductor
X = Reactance of conductor
L = Conductor length in feet
N = Number of conductors per phase
pf = Power Factor
R = 0.12 ohms/1000 feet (NEC Chapter 9, Table 9, Resistance for 1/0 AWG copper conductors in steel conduit.)
X = 0.055 ohms/1000 feet (NEC Chapter 9, Table 9, Reactance for 1/0 AWG copper conductors in steel conduit.)

$$Z = \frac{500}{(1000 \bullet 1)} [0.12 \bullet 0.91) + 0.055 \sqrt{(1-0.91^2)}]$$

$$= 0.066 \text{ percent}$$

$$I_{PHASE} = \frac{kW}{kV \bullet 1.73} = \frac{100}{0.48 \bullet 1.73}$$

$$= 120.3 \text{ amps}$$

$$V_{DROP}\ (\%) = 100 \bullet \frac{120.3 \bullet 0.066}{480}$$

$$= 1.65 \text{ percent}$$

Allowable Single-Phase Load Unbalance

Single–phase loads should be distributed as evenly as possible between the three phases of a three–phase generator set in order to fully utilize the rated capacity (kVA and kW) of the set and to limit voltage imbalance. **Figure 5–12** can be used to determine the maximum permissible percentage of unbalanced single–phase load, as shown in the example.

Single phase power can be taken for up to 67 percent of the three–phase rating on Cummins Power Generation generator sets, up through 200/175 kW.

Generally, the larger the generator set, the lower the percentage of single–phase power that can be taken. **Figure 5–12** includes single–phase percentage lines for Cummins Power Generation intermediate–size Frame–4 and Frame–5 generators. Confirm the frame size by referring to the applicable Alternator Data Sheet referenced by the generator set Specification Sheet. Single–phase load unbalance should not exceed 10 percent.

For Example: Find the maximum single–phase load that can be powered in conjunction with a total three–phase load of 62 kVA by a generator set rated 100kW/125 kVA.

1. Find the three-phase load as a percentage of the generator kVA rating:

$$\text{Three-Phase Load Percentage} = \left(\frac{62 \text{ kVA}}{125 \text{ kVA}}\right) \bullet 100\% = 50\%$$

2. Find the percentage of allowable single–phase load, as shown by the arrows in **Figure 5–12.** In this case, it is approximately 34 percent of the three–phase rating.

3. Find the maximum single–phase load:

$$\text{Maximum Single Phase Load} = \left(\frac{125\text{ kVA} \bullet 34\%}{100\%}\right) = 42.5\text{ kVA}$$

4. Note, as follows, that the sum of the three–phase and maximum permissible single–phase loads is less than the kVA rating of the generator set:

$$62\text{ kVA} + 42.5\text{ kVA} = 104.5\text{ kVA}$$

and

$$104.5\text{ kVA} < 125\text{ kVA} \left(\text{Rating of the Generator Set}\right)$$

NOTE: Unbalanced loading of a generator set causes unbalanced phase voltages. The levels of load imbalance anticipated by these guidelines should not result in harm to the generator set itself. The corresponding levels of voltage imbalance, however, may not be acceptable for loads such as three–phase motors.

Because of unbalanced phase voltages, critical loads should be connected to the phase that the voltage regulator uses as the reference voltage (L_1–L_2 as defined in the generator set schematic) when only one phase is used as a reference.

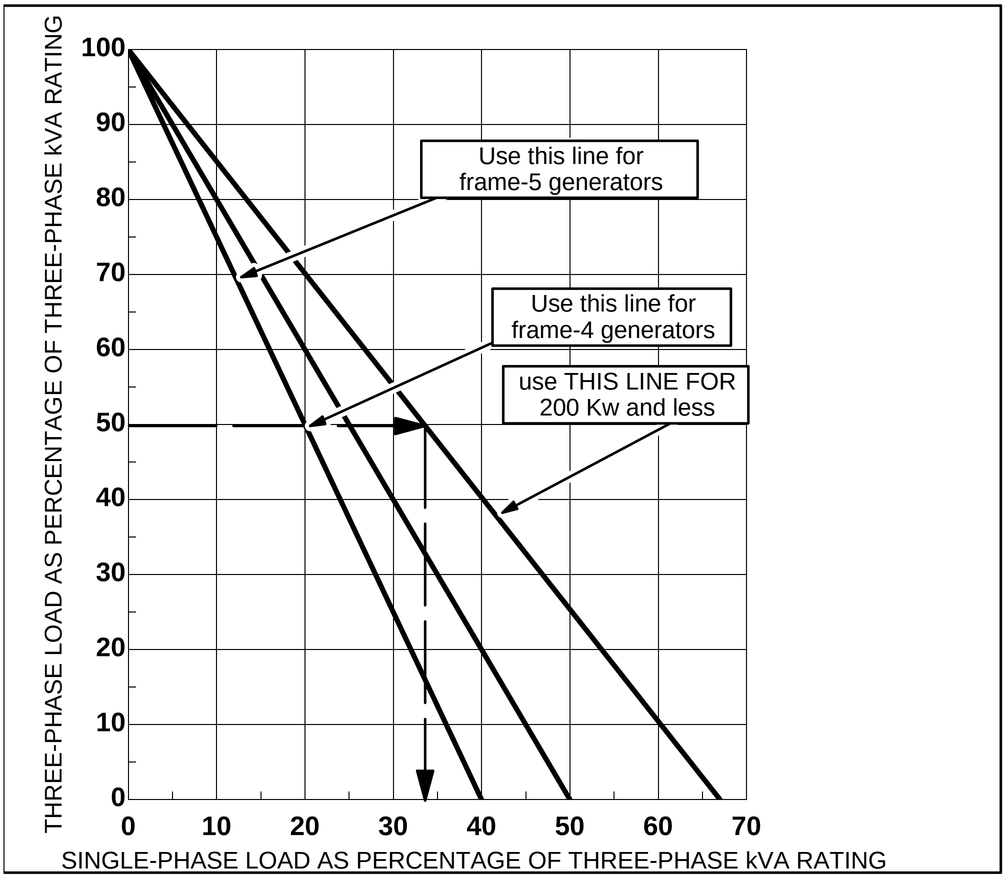


Figure 5–12. Allowable Unbalanced Single-Phase Load (Typical Three–Phase Generator From Cummins Power Generation)

Leading Power Factor Load

Three phase generator sets are rated for continuous operation at 0.8 PF (lagging) and can operate for short periods of time at lower power factors, such as when starting motors. Reactive loads that cause leading power factor can provide excitation power to the alternator, and if high enough, can cause alternator voltage to rise uncontrollably, damaging the alternator or loads or tripping protective equipment. **Figure 5–13** is a typical alternator curve of reactive power (kVAR) capability. A reasonable guideline is that a generator set can carry up to 10 percent of its rated kVAR capability in leading power factor loads without being damaged or losing control of output voltage.

Note: The reasonable guideline is based on the alternator rating, not the genset rating, and in critical applications the alternator supplier should be consulted and the exact reactive capability curve should be used to make engineering decisions, rather than estimates, because actual performance can vary considerably from this estimate.

The most common sources of leading power factor are lightly loaded UPS systems with input filters and power factor correction devices for motors. Loading the generator set with lagging power factor loads prior to the leading power factor loads can improve stability. It is also advisable to switch power factor correction capacitors on and off with the load. It is generally impractical to oversize a generator set (thus reducing the percentage of nonlinear load) to correct for this problem.

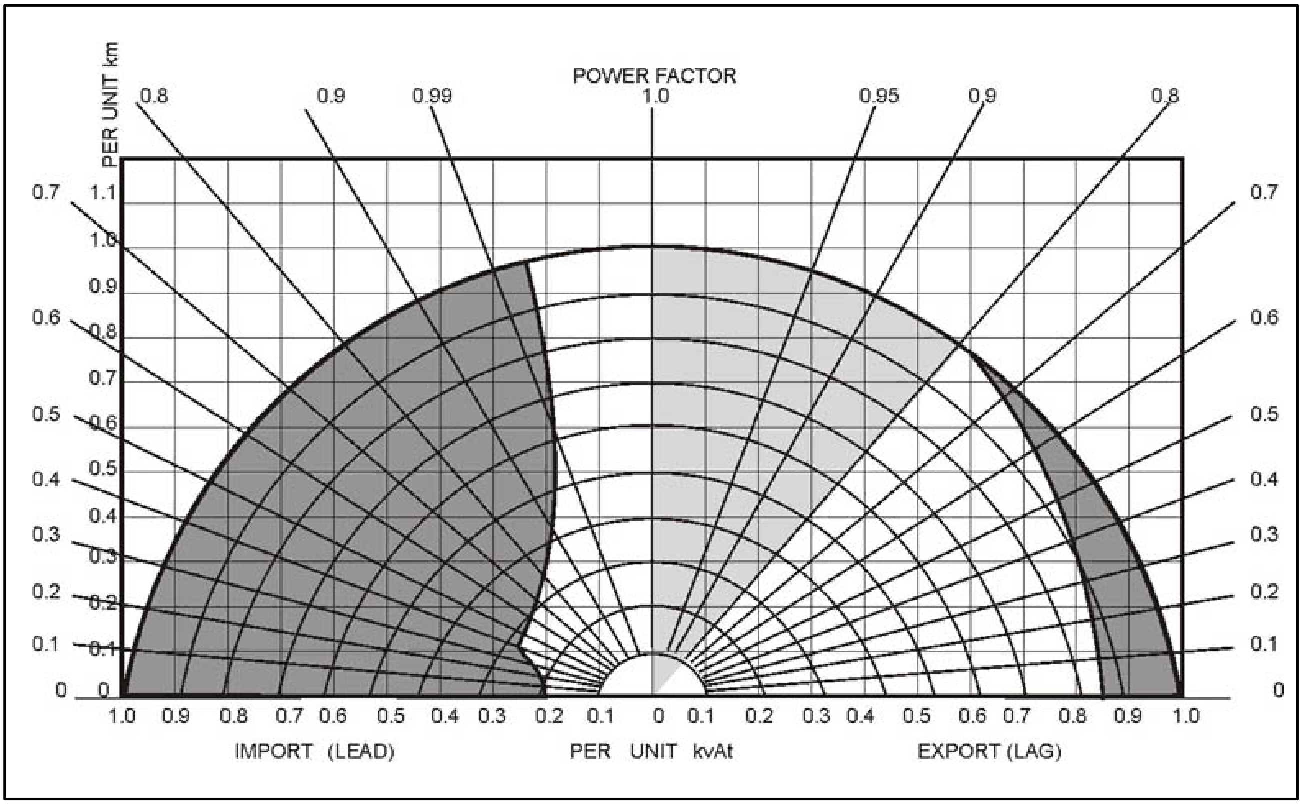
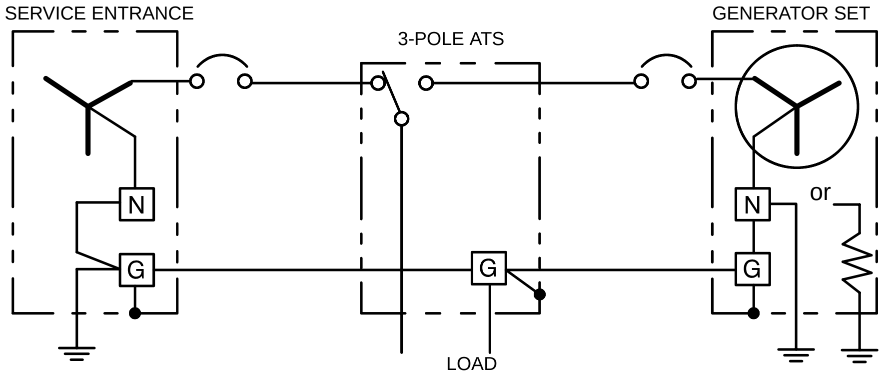


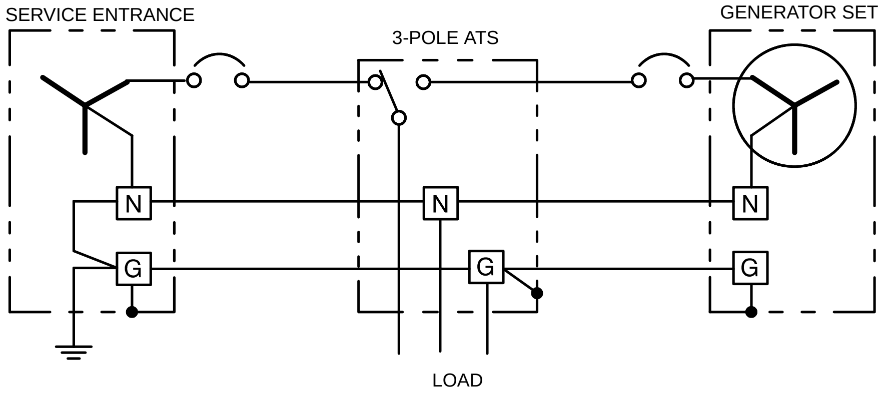
Figure 5–13. Typical Steady State Alternator Reactive Power Capability Curve

System and Equipment Grounding

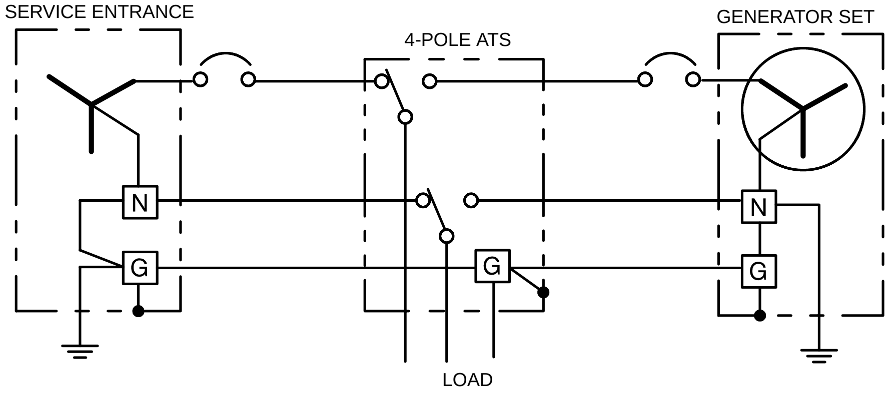
The following is a general description of system and equipment grounding for AC generators permanently installed within a facility. While this is intended as a guide, it is important to follow local electrical code.



THREE-PHASE, THREE-WIRE UTILITY, THREE-POLE ATS
Generator Neutral may be solidly grounded, resistance grounded or ungrounded with a three-wire system



THREE-PHASE, FOUR-WIRE UTILITY, THREE-POLE ATS
Generator Neutral is grounded at service entrance only with a three-pole ATS



THREE-PHASE, FOUR-WIRE UTILITY, FOUR-POLE ATS
Generator Neutral must be solidly grounded when a separately derived source with a four-pole ATS

Figure 5–14. Typical One-Line Diagrams of Alternative System Grounding Methods

System Grounding (Earthing)

System grounding (earthing) is the intentional grounding of the neutral point of a wye–connected generator, the corner of a delta–connected generator, or the mid–point of one–phase winding of a delta–connected generator, to ground (earth). It is most common to ground the neutral point of a wye–connected generator and bring out the neutral (grounded circuit conductor) in a three–phase, four–wire system.

A corner–grounded delta system has a grounded circuit conductor that is not a neutral. It also has a "wild leg" that must be identified by orange color coding and be connected to the middle pole of three–phase equipment.

Solid Grounding

A solidly grounded system is grounded directly by a conductor (the grounding electrode conductor) with no intentional impedance to earth (grounding electrode). This method is typically used, and required by electrical code on all low voltage systems (600 volts and below) with a grounded circuit conductor (most often a neutral) that serves L–N loads.

Correct grounding in standby systems that are solidly grounded is a function of the transfer switch equipment used (solid neutral or switched neutral). See **Figure 5–14**.

In some regions, the neutral terminal of a Cummins Power Generation generator is not bonded to ground. If the generator is a separately derived power source (i.e. 4–pole transfer switch) then the neutral will have to be bonded to ground and a grounding electrode conductor connected to the grounding electrode system by the installing electrician. However, when ground fault protection is provided in the generator, the neutral is factory–bonded to ground.

If the generator neutral connects to a service–supplied grounded neutral, typically at the neutral block of a 3–pole transfer switch, then the generator neutral should not be grounded at the generator. In this case, the electrical code may require a sign to be placed at the service supply indicating that the generator neutral is grounded at that location.

Impedance (Resistance) Grounding

A grounding resistor is permanently installed in the path from the neutral point of the generator to the grounding electrode. This method is occasionally used on three–phase, three–wire systems (no grounded circuit conductor) operating at 600 volts or below, where it is desirable to maintain continuity of power with the first and only accidental ground fault. However, this practice is not permitted by regulatory code in some regions. Delta–wye transformers may be used in the distribution system to derive a neutral for line–to–neutral load equipment.

Typically, a high–resistance grounded, low voltage system uses a grounding resistor sized to limit ground fault current, at line–to–neutral voltage, to 25, 10, or 5 amps nominal (continuous time rating). The resistance grounding is done for the system, to enable sustained operation with a ground fault in place; or to protect the generator. Generator protection is used on MV and especially HV systems to limit the impact of groundfault on the alternator: over volts and very short duration for thermal damage. Ground fault detection and alarm systems are also typically installed.

Select a grounding resistor based on:

1. Voltage Rating: Phase–to–phase voltage (system voltage) divided by the square root of three (1.73).
2. Current Rating: Low enough to limit damage but high enough to reliably operate the protective relaying.
3. Time Rating: Most often 10 seconds for protective relayed systems, and extended time for non–relayed systems.

Solid or Effectively Grounded Neutral Systems

Solid or effective grounding is defined as the intentional connection of a system conductor to a ground connection or connections of sufficiently low impedance and having sufficient current–carrying capacity to prevent the build–up of voltages that may result in undue hazards to connected equipment or to persons. This method is used worldwide. The effective grounding system reduces the maximum line to ground voltage during a fault since the system remains referenced and therefore the cost of insulating the system is reduced.

Due to the magnitude of currents flowing under earth fault conditions with this type of system, protection settings are relatively straightforward to coordinate and the effect of faults can be localized to the system or part of the system where they occur.

NOTE: Low-resistance grounding is recommended on generator systems operating from 601 through 15,000 volts in order to limit the level of ground fault current (most often 200-400 amps) and permit time for selective coordination of protective relaying. See **Figure 5-15** *and Medium Voltage Grounding.*

Ungrounded

No intentional connection is made between the AC generator system and earth. This method is occasionally used on three–phase, three–wire systems (no grounded circuit conductor) operating at 600 volts or below, where it is required or desirable to maintain continuity of power with one ground fault, and qualified service electricians are on site. An example would be supplying a critical process load. Delta–wye transformers may be used in the distribution system to derive a neutral for line–to–neutral load equipment.

Equipment Grounding (Earthing)

Equipment grounding (earthing) is the bonding together and connection to ground (earth) of all non–current carrying (during normal operation) metallic conduit, equipment enclosures, generator frame, etc. Equipment grounding provides a permanent, continuous, low–impedance electrical path back to the power source. Proper grounding practically eliminates “touch potential” and facilitates clearing of protective devices during ground faults. A main bonding jumper at the source bonds the equipment grounding system to the grounded circuit conductor (neutral) of the AC system at a single point. A grounding connection location is provided on the alternator frame or, if a set–mounted circuit breaker is provided, a grounding terminal is provided inside the circuit breaker enclosure. See **Figure 5–16**.

Selective Coordination

Selective coordination is the positive clearing of a short circuit fault at all levels of fault current by the overcurrent device immediately on the line–side of the fault, and only by that device. “Nuisance clearing” of a fault by overcurrent devices upstream of the one closest to the fault causes unnecessary disruption of unfaulted branches in the distribution system and may cause the emergency system to start unnecessarily.

Electrical power failures include external failures, such as utility outage or brownout and internal failures within a building distribution system, such as a short circuit fault or overload that causes an overcurrent protection device to open the circuit. Because emergency and standby generator systems are intended to maintain power for selected critical loads, the electrical distribution system should be designed to maximize continuity of power in the event of a fault within the system. The overcurrent protection system should therefore be selectively coordinated.

Overcurrent protection for the equipment and conductors that are part of the emergency or standby power system, including the on–site generator, should follow applicable electrical codes. However, where the emergency power system serves loads that are critical to life safety, as in hospitals or high–rise buildings, more priority should be given to maintaining the continuity of power than to protecting the emergency system. For example, it would be more appropriate to have an alarm–only indication of an overload or ground fault than to have a circuit breaker open to protect the equipment if the result would be the loss of emergency power to loads critical for safety of life.

Resistance grounding can be done for the system to enable sustained operation with a ground fault in place; or to protect the generator. Generator protection is used on MV and especially HV systems to limit the impact of groundfault on the alternator: over volts and very short duration for thermal damage

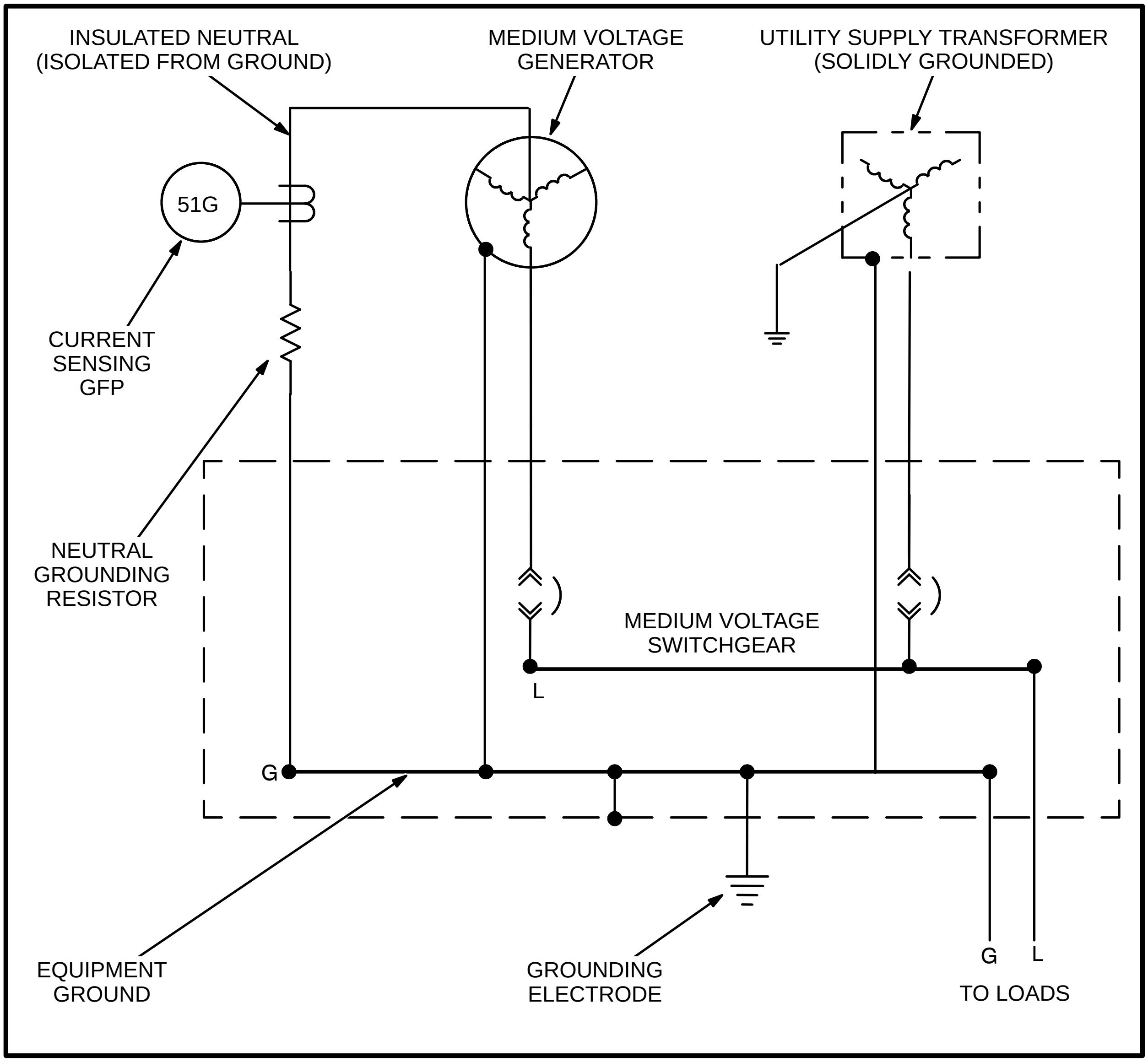


Figure 5–15. Typical Low-Resistance Grounding System for a Medium Voltage Generator Set and Load Transfer Equipment

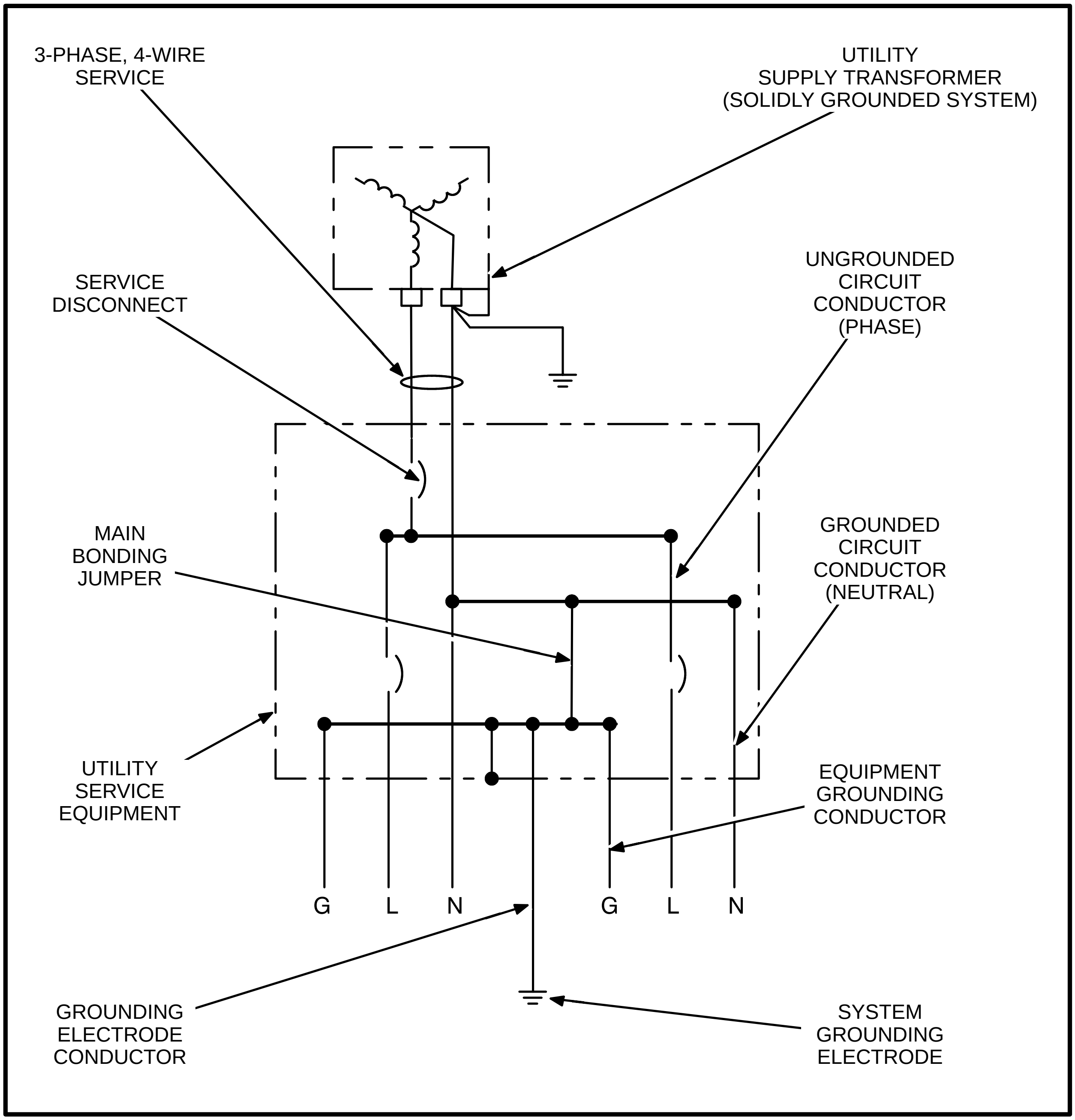


Figure 5–16. Typical System and Equipment Grounding Connections at the Utility Service Equipment

For the purposes of coordination, the available short circuit current in the first few cycles from a generator set is important. This current is independent of the excitation system and is solely dependent on the magnetic and electrical characteristics of the generator itself. The maximum first cycle bolted three–phase, symmetrical short circuit current (I_{SC}) available from a generator at its terminals is:

$$I_{SC} \text{ P.U.} = \frac{1}{X''_d}$$

E_{AC} is the open circuit voltage and X''_d is the per–unit direct axis subtransient reactance of the generator. A typical Cummins Power Generation generator set will deliver 8 to12 times (instantaneous) or 3 times (sustained) its rated current on a three–phase bolted fault, regardless of the type of excitation system used. (Refer to the generator set Specification Sheets and alternator data sheets for X''_d.)

Generator reactances are published in per unit to a specified base alternator rating. Generator sets, however, have various base ratings. Therefore, to convert per unit reactances from the alternator base to the generator set base use the following formula:

$$P.U.Z_{new}=P.U.Z_{given}\left(\frac{\text{base kV}_{given}}{\text{base kV}_{new}}\right)^2\left(\frac{\text{base kVA}_{new}}{\text{base kVA}_{given}}\right)$$

Example Calculation: Find X''_d (alternator subtransient reactance) for Cummins Power Generation Model 230DFAB diesel generator set rated 230 kW/288 kVA at 277/480 VAC. Bulletin S–1009a for this model references Alternator Data Sheet No. 303. ADS No. 303 indicates that $X''_d = 0.13$ for the alternator at a full–load rating point of 335 kW/419 kVA and 277/480 VAC (125°C temperature rise). Substituting these values into the preceding equation:

$$X''_{d(Genset)} = X''_{d(ADS)}\left(\frac{kV_{ADS}}{kV_{Genset}}\right)^2\left(\frac{kVA_{Genset}}{kVA_{ADS}}\right)$$

$$X''_{d(Genset)} = 0.13\left(\frac{0.48}{0.48}\right)^2\left(\frac{288}{419}\right) = 0.089$$

Equipment Location Recommendations

It is recommended for selective coordination that transfer switches be located on the load side of the branch circuit overcurrent device, where possible on the line side of a branch circuit panel board. With the transfer switch located on the load side of the branch circuit overcurrent device, faults on the load side of the transfer switch will not result in unfaulted branches of the emergency system being transferred to the generator along with the faulted branch.

This recommendation is consistent with the recommendations for overall reliability to physically locate transfer switches as close to the load equipment as possible, and to divide the emergency system loads into the smallest circuits practical using multiple transfer switches.

A second recommendation is to use a sustaining generator (separate or PMG excitation) to positively clear molded case branch circuit breakers. A sustaining generator can provide an advantage in clearing molded case circuit breakers of the same current rating but different time–current characteristics.

Fault and Overcurrent Protection with Generator Sets

Sizing a Main–Line Generator Circuit Breaker

One of three approaches described below are usually followed when sizing a main–line generator circuit breaker:

The most common approach is to size the circuit breaker equal to or the next rating up from the generator full–load current rating. For example, an 800–ampere circuit breaker would be selected for a generator with a 751–ampere full load current rating. The advantage in this approach is one of cost; the cables and distribution panel or transfer switch can be sized to the breaker rating of 800 amperes. If the circuit breaker is standard rated (80% continuous) it may open automatically at levels below the generator full–load current rating. However, the generator set is not likely to be run near or at full kW load and at rated power factor long enough to trip the breaker in actual use. Alternatively, a 100% rated 800–ampere circuit breaker may be used that will carry 800 amperes continuously.

A second approach using standard (80% continuous) rated circuit breakers is to oversize the circuit breaker by 1.25 times the generator full load current. For example, a 1000–ampere circuit breaker would be selected for a generator with a 751–ampere full load current rating (751 amperes x 1.25 = 939 amperes, the next higher standard breaker rating equals 1000 amperes). A breaker selected this way should not trip under full kW load at rated power factor (rated kVA). The disadvantage of this approach is that the cables and distribution panel or transfer switch would need to be sized up to at least 1000 amperes.

Yet a third approach is to size the circuit breaker as the result of the design calculations for a feeder and its overcurrent device, recognizing that the principal purpose of the circuit breaker is to protect the feeder conductors. Feeder ampacity and overcurrent device rating are calculated by summing the load currents of the branch circuits multiplied by any applicable demand factors (DF) that are allowed by applicable electrical codes. *Without allowing for future capacity*, the minimum required feeder ampacity for a typical generator set application involving both motor and non–motor loads must equal or exceed:

- 1.25 x continuous non–motor load current, plus
- 1.00 x DF (demand factor) x non–continuous, non–motor load current, plus
- 1.25 x largest motor full–load current, plus
- 1.00 x sum of full–load currents of all other motors.

Add sizing gensets for transformers.

Because the generator set is sized for both starting (surge) and running load, and may also be sized to include future capacity, the generator set full–load current may be greater than the calculated ampacity of the generator feeder conductors and circuit breaker. If this is the case, consider increasing both the feeder conductor ampacity and the circuit breaker rating so that the breaker will not trip at full generator nameplate current. This would also provide future capacity for the addition of branch circuits.

NOTE: Feeder conductor ampacity is regulated and determined by codes, such as NFPA or CSA. While it is based on generator and CB capacity, other critical factors are also applied. Refer to applicable codes for correct feeder conductor sizing.

NOTE: Extended full-load testing may trip a main-line circuit breaker sized at or below the full-load current rating of the generator set.

Generator Set Sources

When the energy for the emergency system is provided by a generator set, it is necessary to provide branch circuit breakers (usually of the molded case type) with a high probability of tripping, regardless of the type of fault which could occur in a branch circuit.

When a generator set is subjected to a phase–to–ground fault, or some phase–to–phase faults, it will supply several times more than rated current, regardless of the type of excitation system. Generally, this trips the magnetic element of a branch circuit breaker and clears the fault. With a self–excited generator set, there are instances of three–phase faults and certain phase–phase faults where the output current of the generator will initially rise to a value of about 10 times rated current, and then rapidly decay to a value well below rated current within a matter of cycles. With a sustaining (PMG) generator set, the initial fault currents are the same, but the current decays to a sustained short circuit current ranging from about 3 times rated current for a three–phase fault to about 7–1/2 times rated current for a phase–to–ground fault.

The decay in fault current of a self–excited generator requires that branch circuit breakers unlatch and clear in the 0.025 seconds during which the maximum current flows. A branch circuit breaker that does not trip and clear a fault can cause the self–excited generator to collapse, interrupting power to the un–faulted branches of the emergency system. A sustaining (PMG) generator does not collapse and has the advantage of providing about three times rated current for several seconds, which should be sufficient for clearing branch circuit breakers.

Using the full load current ratings of the generator set and of the branch circuit breaker, the following method determines if a branch breaker will trip on a three–phase or phase–to–phase symmetrical fault. The method only determines if tripping is possible under short circuit conditions with the available fault current, and does not guarantee tripping for all values of fault current (in arcing faults, for instance, where fault impedance is high).

Because most circuit breaker charts express current as a percentage of the breaker rating, the available fault current must be converted to a percentage of the circuit breaker rating. Use the following formula to determine the available fault current as a percentage of the circuit breaker (CB) rating for an AC generator capable of delivering 10 times rated current initially ($X''_d = 0.10$), ignoring circuit impedance between the generator and the breaker:

$$\begin{array}{c}\text{Fault Current as}\\ \text{\% of CB rating}\end{array} = \left(\frac{10 \bullet \text{Rated Generator Amps}}{\text{Rated CB Amps}}\right) \bullet 100\%$$

Consider the effect of a fault (short circuit) on a 100 ampere branch circuit breaker when power is supplied by a generator set having a rated current of 347 amperes. In this example, the fault current available for the first 0.025 seconds, regardless of excitation system, is:

$$\begin{array}{c}\text{Fault Current}\\ \text{as \% of CB rating}\end{array} = \left(\frac{10 \bullet 347}{100}\right) \bullet 100\% = 3470\%$$

If the AC generator is of the type that can sustain three times rated current, use the following formula to determine the approximate current available as a percentage of the circuit breaker rating:

$$\begin{array}{c}\text{Sustained Current}\\ \text{as \% of CB rating}\end{array} = \left(\frac{3 \bullet 347}{100}\right) \bullet 100\% = 1040\%$$

Figure 5–18 and **Figure 5–19** show the results with two 100 ampere thermal–magnetic molded case circuit breakers having different trip characteristics, “A” and “B.” With trip characteristic “A” (**Figure 5–18**), the initial fault current of 3470% will trip the breaker within 0.025 seconds. With trip characteristic “B” (**Figure 5–19**), the breaker may not trip with the 3470% current available initially, but will trip in approximately three seconds if fault current is sustained at 1040% of the breaker rating (three times the generator rating). The conclusion is that a sustaining (PMG) generator offers an advantage in providing sufficient fault current to clear branch circuit breakers.

The application of the generator, its excitation system, and operating voltage, determine the extent of overload protection provided for generators and the protective devices used.

NOTE: The following discussion applies for single-unit installations, 2000 kW and below. Refer to Cummins Power Generation publication T–016, Paralleling and Paralleling Switchgear, for protection requirements of multiple generators in parallel.

Generator Decrement Curves

For the purposes of protection coordination, and to determine the magnetic and mechanical stresses on the electrical system components, it is necessary to know the available short circuit current during the initial few cycles from a generator set. The generator decrement curve represents the fault current during Sub transient, Transient and steady state periods. A typical Generator decrement curve is shown in **Figure 5–17**.

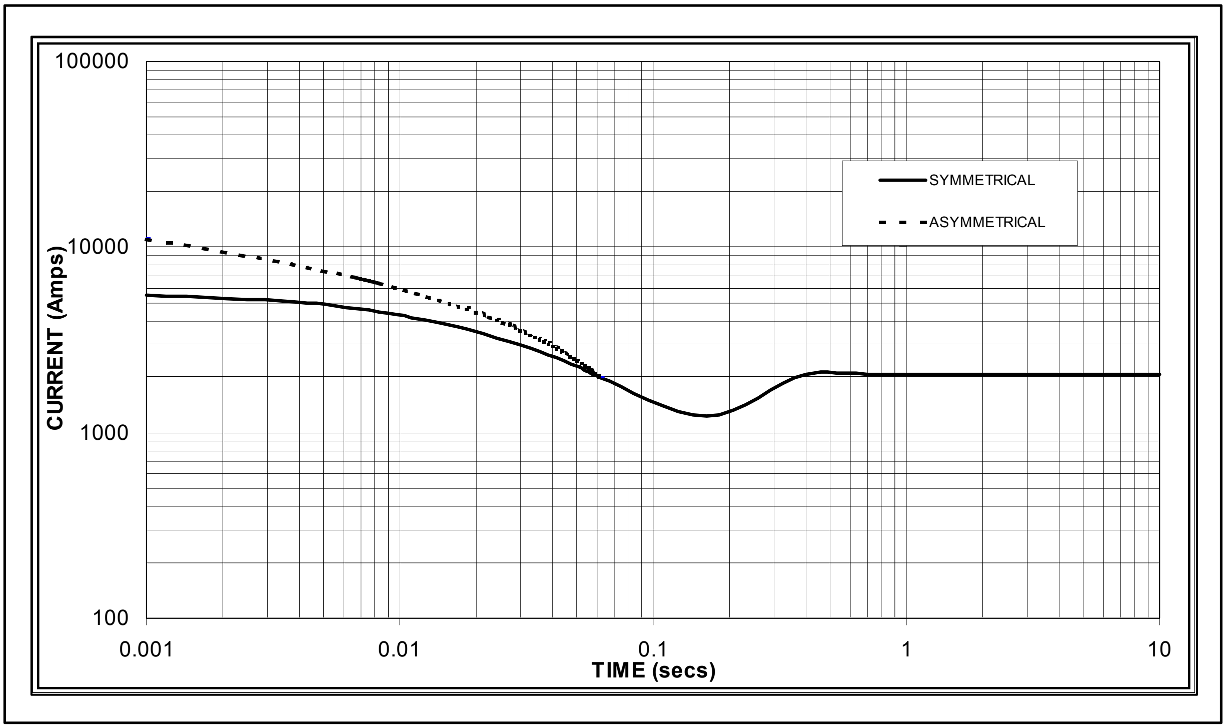


Figure 5–17 Generator Decrement Curve

When the Generator is provided with separate excitation, (e.g. a Permanent Magnet Generator or PMG) the sustained short circuit current will flow until the inbuilt protection operates after about 8–10 seconds. For self excited machines, the initial current decay continues without the recovery illustrated and tends to a very low value in approximately 1 second.

Where Cummins PCC (PowerCommand Control) controls are provided with AmpSentry™ the sustained short circuit current will be limited by excitation control to approximately three–times full load current for both symmetrical and asymmetrical cases. In cases where PCC controls fitted with AmpSentry™ are not used, it is essential that an independent protection device such as a circuit breaker is fitted to limit the current / time to within the alternator thermal damage curve (see below), particularly for Line–to–Line and Line–to–Neutral faults. This may require the fitting of additional protection such as ground–fault.

Multiplication factors for various voltage ratings and for 50 and 60 Hz are provided in the data sheet, together with factors representing the symmetrical, 2–phase and single phase cases with waveform asymmetry. The multiplication factors listed in **Table 5–2** should be used to adjust the values from curves between 0.001 seconds and the minimum current point in respect of nominal operating voltage.

Voltage	Factor
380	x 1.00
400	x 1.03
415	x 1.05
440	x 1.07

Table 5-2 Multiplication Factors for Minimum Current Point

NOTE: The sustained current value is constant in ***Table 5–2****, irrespective of Voltage Level.*

The multiplication factors listed in **Table 5–3** should be used to convert the values calculated in accordance with **Table 5–2** to those applicable in various types of short circuit.

	3 Phase	2 Phase L–L	1 Phase L–N
Instantaneous	x 1.0	x 0.87	x 1.3
Minimum	x 1.0	x 1.80	x 3.20
Sustained	x 1.0	x 1.50	x 2.50
Max Sustained Duration	10 sec	5 sec	2 sec

Table 5-3 Multiplication Factors for Short Circuit Types

NOTE: All times other than those listed in ***Table 5–3*** *are unchanged.*

Overload Protection of Generators

In low voltage (600 volts and below) emergency/standby applications where critical loads are being served and the generator set runs a relatively small number of hours per year, the minimum protection requirements of applicable electrical codes should be met. Beyond that, the specifying engineer should consider the tradeoff between equipment protection and continuity of power to critical loads, and may decide to provide more than the minimum level of protection.

In low–voltage prime power or interruptible applications, the loss of power that would result from operation of the protective devices may be tolerable and, therefore, a higher level of equipment protection would be appropriate.

Protection Zone

The zone of protection for generators includes the generator and the conductors from the generator terminals to the first overcurrent device; a main–line overcurrent device (if used), or the feeder overcurrent device bus. Thermal overcurrent protection is achieved by comparing the thermal damage curve of the alternator to the trip or operation curve of the protective device. Overcurrent protection for the generator should include protection for short circuit faults anywhere within this zone.

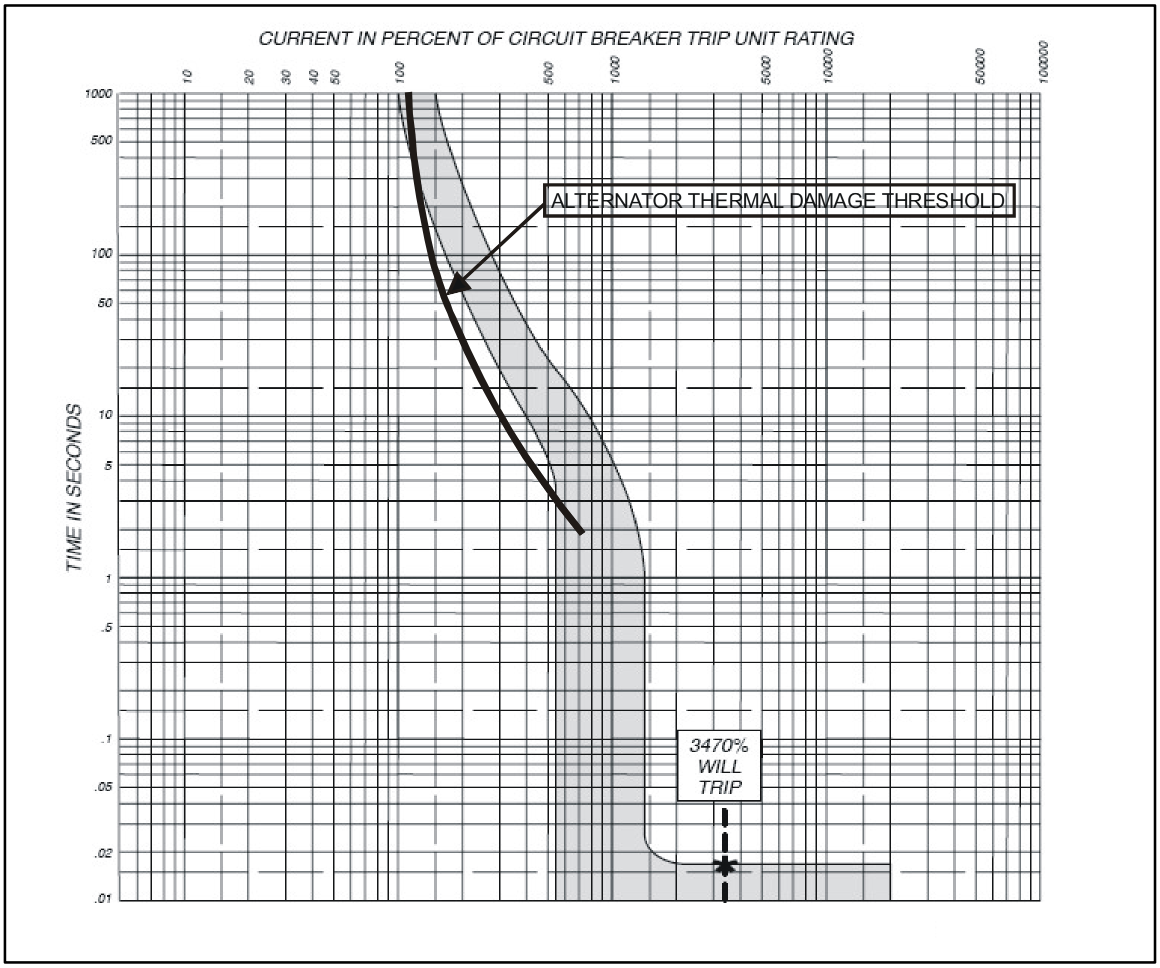


Figure 5–18. Fault Effect on a 100 Ampere Breaker with Trip Characteristic “A”

On the downstream side of the feeder bus, standard practice for overcurrent protection of conductors and equipment applies. The ratio of generator rated current to the rating of downstream overcurrent devices, multiplied by the short circuit current available from the generator in the first few cycles, should be sufficient for tripping these devices within one to two cycles.

Emergency/Standby Systems 600 Volts and Below

The minimum generator overload protection required by applicable electrical codes is recommended for Emergency/Standby applications 600 volts and below. Typically, this means the generator should be provided with phase overcurrent devices such as fuses or circuit breakers, or be protected by inherent design, such as PowerCommand AmpSentry™. In some applications, the electrical code may also require ground fault indication.

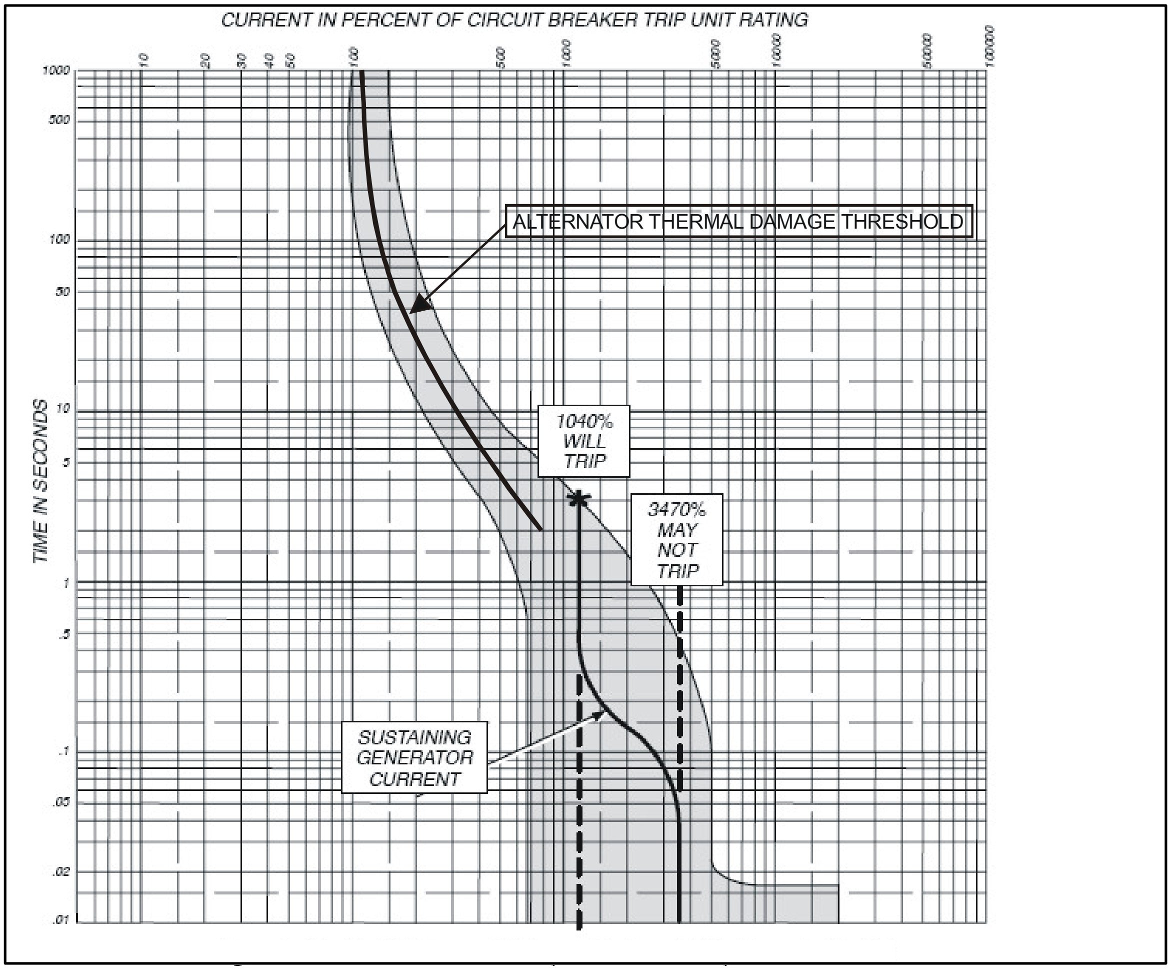


Figure 5–19. Fault Effect on a 100 Ampere Breaker with Trip Characteristic "B"

Generator Circuit Breaker

Conventional practice on generators without inherent overcurrent protection is to provide a molded case circuit breaker (MCCB), either thermal–magnetic or solid–state, sized to protect the generator feeder conductors, in order to satisfy electrical code requirements for generator overload protection. However, a typical thermal–magnetic MCCB sized to carry generator rated current does not provide effective generator protection. Generally, if circuit breakers are used for generator protection, a solid–state circuit breaker with full adjustments (Long time, Short time and Instantaneous, LSI) will be required to coordinate the breaker protection curve within the generator thermal capability curve. Where the generator is protected by inherent design, as generators with PowerCommand Amp Sentry™, the use of a main–line circuit breaker for generator overload protection is not required.

Inherent Design, Balanced Faults

A self–excited (Shunt) generator may be considered to be protected by inherent design since it is not capable of sustaining short circuit current into balanced three–phase faults long enough for serious damage to occur to the generator. Considering the need for high reliability of power to critical loads, use of shunt excitation is sometimes considered sufficient to meet the minimum generator protection required by electrical code by inherent design and make generator overcurrent protective devices (fuses or circuit breakers) unnecessary.

A generator with PMG excitation, but without PowerCommand, is capable of sustaining short circuit current with an unbalanced or balanced fault. If overcurrent devices downstream of the generator should fail to clear a balanced three–phase short circuit fault, the PMG excitation system includes an over–excitation shutdown function that will serve as “backup”. This over–excitation function will shut down the voltage regulator after about 8 to10 seconds. This backup protection is suitable for three–phase faults only and generally will not protect the generator from damage due to single–phase faults.

There are other reasons to consider use of a circuit breaker; including protecting the generator feeder conductors, and to have a disconnecting means. In order to improve the overall reliability of the system, a disconnecting means may be provided by a molded case switch or other non–automatic means.

PowerCommand Controls and AmpSentry™

PowerCommand uses a microcontroller (microprocessor) with three–phase current sensors to continuously monitor current in each phase. Under single– or three–phase fault conditions, current is regulated to approximately 300 percent of the generator rating. The microcontroller integrates current vs. time and compares the result to a stored generator thermal damage curve. Before reaching the damage curve, the microcontroller protects the generator by shutting down excitation and the engine. **Figure 5–20** shows the Amp Sentry protection curve[1] as available for use in protection and coordination studies. The alternator thermal damage curve is shown on the right side of the Amp Sentry protection curve. An overload current of 110 percent of rated for 60 seconds causes an overload alarm and operation of load shed contacts. An overload above 110% will cause the protective response at a time determined by the inverse time protection curve. These controls provide generator protection over the full range of time and current, from instantaneous short circuits, both single and three phase, to overloads of several minutes in duration. In terms of selective coordination one important advantage of Amp Sentry versus a main circuit breaker is that Amp Sentry includes an inherent delay of about 0.6 seconds for all fault currents above 4 per unit. This delay allows the instantaneous response of downstream breakers to clear faults without tripping the generator off–line, providing selective coordination with the first level of downstream breakers.

Ground Fault Indication/Protection

In America, the electrical code requires an indication of a ground fault on emergency and standby (life safety) generators that are solidly grounded, operating at more than 150 volts to ground, and with main overcurrent devices rated 1000 amperes or more, while optional standby machines are required to trip on ground fault. If required, standard practice in emergency applications is to provide a latching indication only of a ground fault, and not to trip a circuit breaker. Although ground fault protection of equipment that opens a main generator circuit breaker may be provided, it is not required by code nor recommended on emergency (life safety) generators.

Proper operation of ground fault sensors on generator sets typically requires that the generator is separately–derived and the use of a 4–pole (switched neutral) transfer switch[2].

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[1] Power Command Amp Sentry protection curve is available from Cummins Power Generation representatives; order form R–1053.

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[2] See Cummins Power Generation publication T–016, Paralleling and Paralleling Switchgear.

Prime Power and Interruptible, 600 Volts and Below

The generator overcurrent protection required by the North American electrical code is recommended for prime power and interruptible applications 600 volts and below. Typically, this means the generator should be provided with phase overcurrent devices such as fuses or circuit breakers, or be protected by inherent design.

Units equipped with the PowerCommand control with AmpSentry™ provide this protection. If a higher level of protection is desired, PowerCommand also provides the following inherent protections on all phases:

- Short circuit
- Over voltage
- Under voltage
- Loss of field
- Reverse power

As stated previously, PowerCommand control with AmpSentry™ provides the overcurrent and loss of field protection inherent in it design.

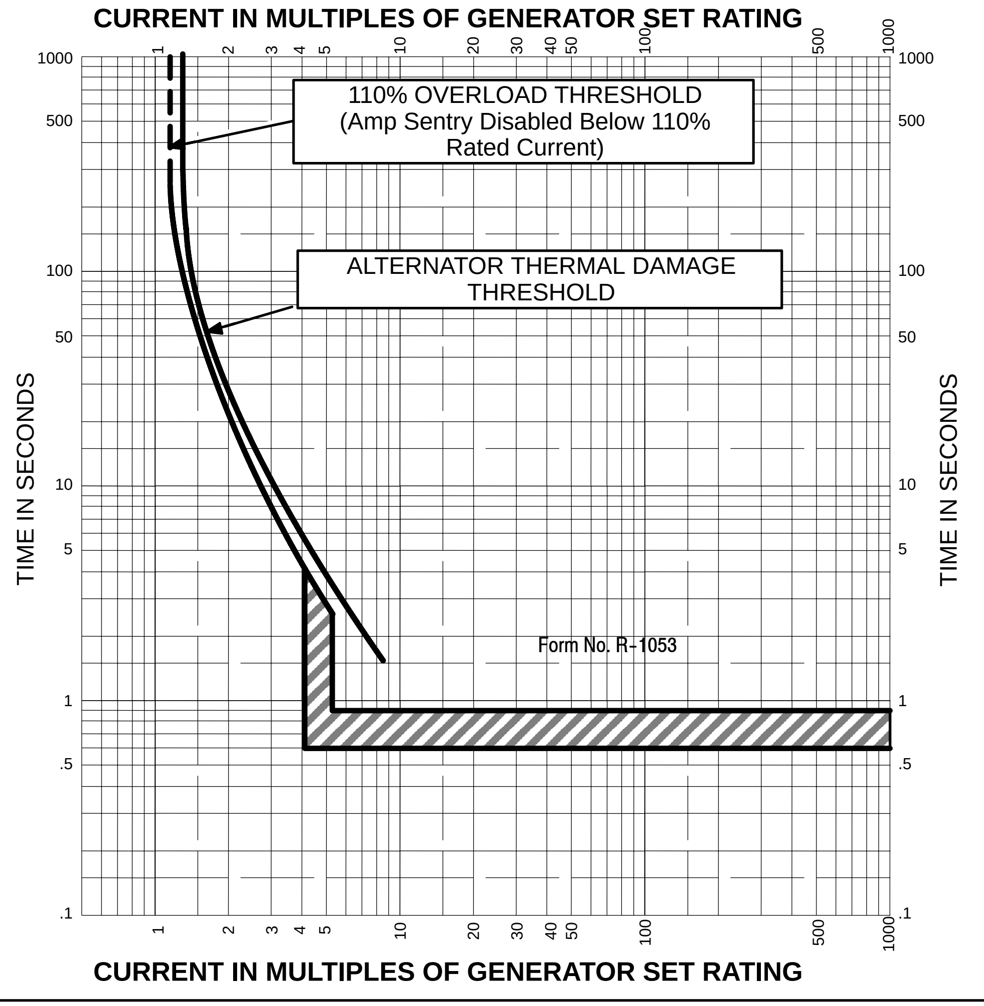

Figure 5–20. PowerCommand® Control AmpSentry™ Time-Over-Current Characteristic Curve Plus Alternator Damage Curve. *(Note: This curve is applicable to all Cummins PowerCommand® Generator Sets.)*

Medium Voltage, All Applications

In medium voltage applications (601 – 15,000 volts), the standard practice of providing generator protection will not typically compromise the reliability of the power supply since selectivity of devices is achievable. The cost of the investment in equipment also warrants a higher level of protection. The basic minimum protection includes (see **Figure 5–21**):

- Three phase backup overcurrent sensing (51V)
- One backup ground time–overcurrent relay (51G)
- Field loss sensing (40)
- Three phase instantaneous overcurrent sensing for differential protection (87).

NOTE: Refer to ANSI/IEEE Standard No. 242 for additional information about overcurrent protection of these generators.

Note: MV/HV machines in emergency/standby service have the same protection requirements as LV machines. They need to have thermal overload protection, and probably over voltage protection, if not protected by AmpSentry™. Differential ”protection” is most suitable for prime power applications, where repair of the machine is desired and the differential is used to limit damage. Also point out that the overcurrent sensing CT location impacts on overcurrent protection effectiveness; since if it is at star point of altenator internal faults are also sensed by the protection.

Surge Protection of Medium-Voltage Generators

Consideration should be given to protecting medium–voltage generators against voltage surges caused by lightning strikes on the distribution lines and by switching operations. Minimum protection includes:

- Line arrestors on the distribution lines
- Surge arrestors at the terminals of the generator
- Surge capacitors at the terminals of the generator
- Strict adherence to good grounding practice.

Protection for Utility (mains) Paralleled Generators

Note that where a generator system is being run in parallel with the utility supply, the two systems are combined and any incident on the utility system may also involve the generators. The requirements for utility parallel operation protection are highly variable according to the type of system being installed and the characteristics of the site and utility’s distribution system.

Generator sets that operate in parallel with the utility are typically provided with reverse power relative to the grid (32) and loss of field (40) protection . Diode failure may be fitted, but is not required by statute.

The utility protection is typically provided by over/under voltage (59/27) protection and over/under (81O/U) protection . In many regions equipment to detect ’island’ condition and disconnect the generator sets is also required.

In many regions equipment to detect ’island’ condition and disconnect the generator sets is also required. An Island condition occurs when the utility power fails while a genset system is connected, and the protective system does not sense the failure and disconnect the generator system. As a result, the genset system may energize not only intended loads, but also the utility distribution system and other customers’ loads. This causes danger to utility workmen, can disrupt utility distribution system protective devices, and can result in damage to utility and customer–owned equipment.

Anti–island equipment varies with the nature of the application, the region of the world, and local codes and standards. For example, in Europe and elsewhere, anti–island protection commonly includes rate of change of frequency (ROCOF) and vector–shift protection. This equipment may be specified when operating for more than 5 minutes per month in parallel with the grid. In the US, requirements vary considerably by state.ROCOF and Vector Shift equipment both work by analyzing the rotation of the voltage vector and detecting a change, either in frequency (Hz/sec) or in degrees/sec. Other protections such as reverse kVAr, and directional current may also be used.See T–016 for more information on interconnection requirements. Other helpful information is in IEEE1547, Standard for Interconnecting Distributed Resources with Electric Power Systems. Engineering recommendation G59/1 sets out recommendations for the connection of embedded generation plant to the regional electricity company's distribution systems (connection of embedded generation less than 20kV and less than 5MVA).

NOTE: Generators that parallel with the utility for short periods of time are often not required to incorporate loss of utility protection. However, the risk of damage that can be caused in the event of a momentary utility supply failure should be assessed and the appropriate decision made.

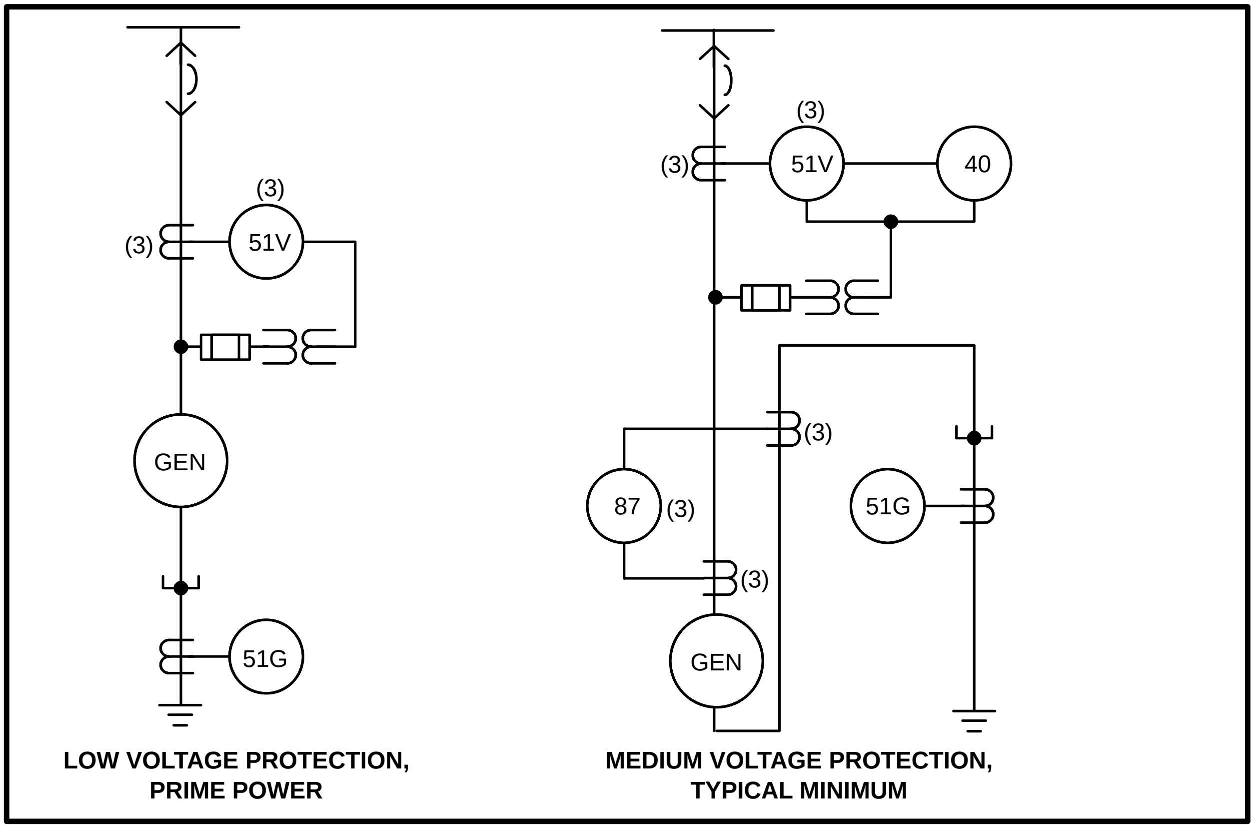

Figure 5–21. Typical Protective Scheme