



BENDER[®]

The Power in Electrical Safety

Electrical Safety in Solidly Grounded, Resistance Grounded and Ungrounded Power Systems

Detailed Guidelines for Installers, System Designers and Technical Personnel

Introduction

Ground Faults in Modern Power Systems

Introduction

Hazardous ground faults occur frequently in electrical systems. There are multiple ways to describe a ground fault. Some typical definitions are:

- A leakage current from a conductor to frame or ground measured in milliamperes or amperes
- An insulation breakdown measured in Ω or kilo- Ω
- A charging current leaking to ground (capacitive leakage)

The 2017 NEC describes a ground fault as an unintentional, electrically conductive connection between an ungrounded conductor of an electrical circuit and the normally non-current-carrying conductors, metallic enclosures, metallic raceways, metallic equipment, or earth. Different countries use the term earth fault as it is synonymous with ground fault. Throughout this text, the classic North American terminology will be used.

Why do we have different terms to describe similar occurrences?
What amount of current can be expected in a power system?
What does the resistor do in a resistance grounded power system?
What type of ground-fault monitors does Bender recommend for my system?

These questions are generated due to the variety of power systems employed. There is a huge variety of relays on the market to protect these systems. This booklet has been written to provide a brief introduction to the major power systems and the devices manufactured by Bender which are best suited to protect these systems in case of a ground fault. The calculations made in the following examples were based on simple forms assuming test bench or ideal conditions. Values were chosen randomly to support the basic ideas and fundamentals. The following information can be used as a guideline for an integrator or as a reference for a system designer who is facing the first hurdle of identifying a product for a ground-fault problem.

Detailed information including manuals and datasheets for each product can be found at www.benderinc.com.

This booklet covers the three most common power-system grounding types and their ground-fault protective devices:
Solidly Grounded, Resistance Grounded, and Ungrounded.

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General Information

Detection Technologies for different power system types

No single type of ground-fault detector works on every type of power system. For instance, a residual-current monitor (RCM) ground-fault relay (GFR) in combination with a zero-sequence current transformer (CT) can be used on solidly grounded or resistance grounded systems, but will need very special consideration if employed on an ungrounded (floating) system. Similarly, an insulation monitoring device (IMD) can be used on an ungrounded system, but will nuisance trip or false alarm in a grounded system.

Case # 1

The IMD installation below will not work! The IMD (online megaohmmeter) applies a measuring signal onto a three-phase ac system. The signal will immediately find the neutral ground bonding jumper and indicate a ground fault. This is equally true for resistance-grounded systems.

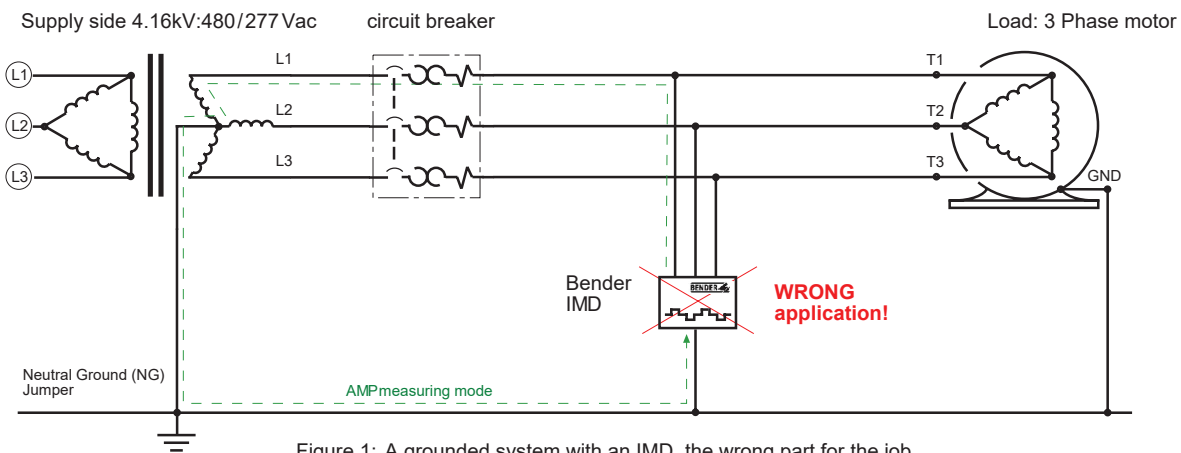


Figure 1: A grounded system with an IMD, the wrong part for the job

Case # 2

The GFR installation below will not work! The current transformer (CT) in combination with this particular GFR requires a large amount of current to operate. A floating delta cannot create the fault current magnitude needed since it does not have a low impedance ground return path, and typically the system charging current is lower than the operating point of most GFR's. The device will never trip, not even if a bolted fault (a very low impedance connection between a phase and ground) existed for multiple days.

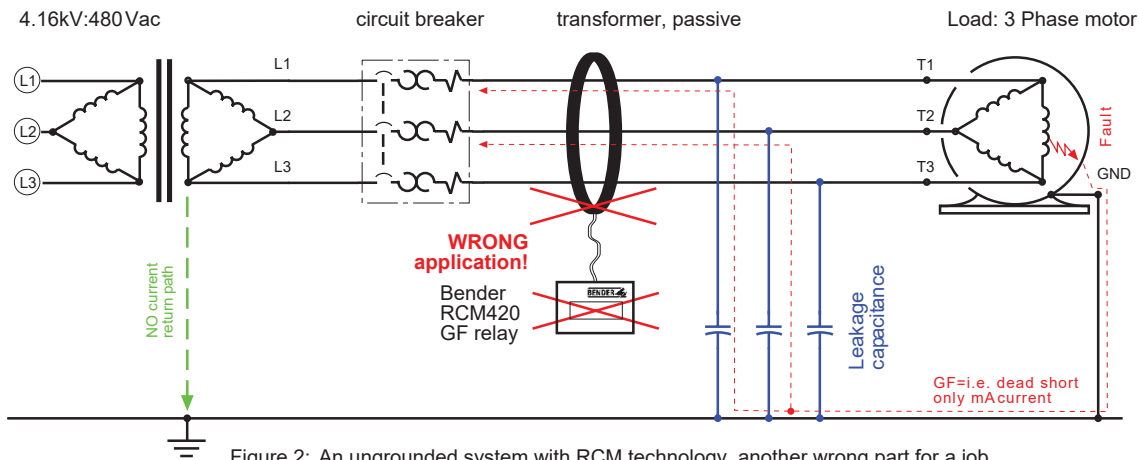


Figure 2: An ungrounded system with RCM technology, another wrong part for a job

Solidly Grounded Systems

Basic Power Systems - Solidly Grounded

Solidly grounded systems have a power source in which the neutral or X0 point of the transformer or generator is connected to ground through a solid bonding jumper. This jumper has minimal resistance or impedance to ground - it does not appreciably limit ground-fault current. Common examples are three-phase 208/120-V Wye or 480/277-V Wye configurations, as well as single-phase transformers with the secondary neutral connected to ground (in rare instances, corner-grounded delta). North Americans are very familiar with solidly grounded systems as household power typically a split-phase 240/120-V system with its neutral bonded solidly to ground. The center tap is bonded solidly to ground.

There are advantages and disadvantages to this grounding method. One disadvantage is the large prospective ground-fault current. Fire, electrical-component damage, or personnel injury can occur. Nevertheless, a tripped overcurrent device (circuit breaker or fuse) or ground-fault circuit-interrupter (GFCI) enables the electrician to quickly locate the faulted circuit. Corrective action will often take place after the fault has occurred and the damage is done. Preventative maintenance is not necessarily associated with the solidly grounded system.

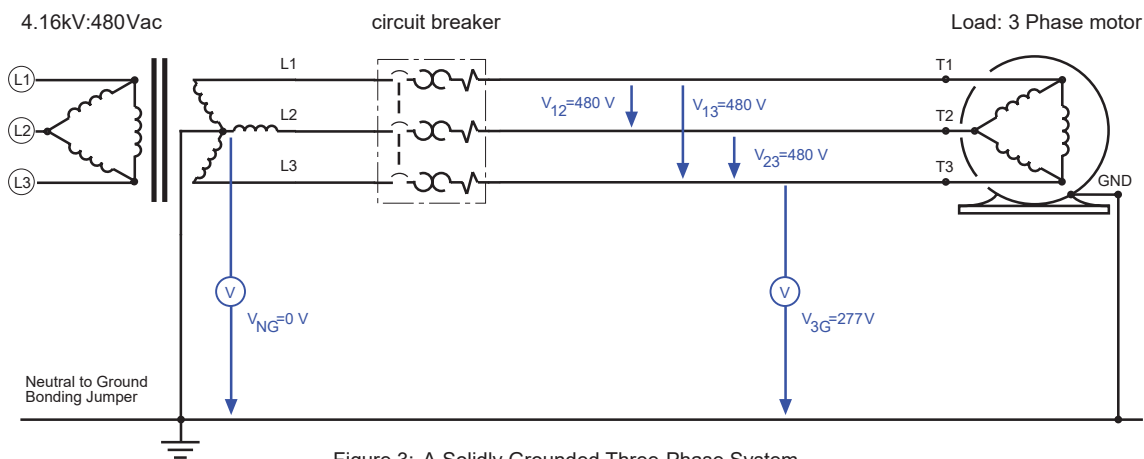


Figure 3: A Solidly Grounded Three-Phase System

Solidly Grounded Systems

The Ground Fault

The magnitude of ground-fault current in a solidly grounded system can be very large and is dependent on the system voltage and the resistance of the ground-fault current path. This, by NEC definition, is the electrically conductive path from the point of a ground fault on a wiring system through normally non-current-carrying conductors, equipment, or the earth to the electrical supply source. The ground-fault current can easily reach a value that is much higher than the nominal load current. Ground-fault current is also commonly referred to as residual current and as zero-sequence current. A simplified calculation explains the high currents:

Please review the schematic at the bottom of this page. Fault current I_F is defined as:

$$I_F = \frac{V_{3G}}{R_{GF} + R_{GR} + R_{NG}}$$

I_F = Fault Current, in amperes

V_{3G} = Voltage between faulted phase and ground, in volts

R_{GF} = Resistance of the ground fault, in ohms

R_{GR} = Resistance of the ground-return path

R_{NG} = Resistance of neutral-to-ground bonding jumper

(Please note: The resistance values are selectively chosen for illustration)

$$I_F = \frac{277\text{ V}}{0.1\Omega + 0.2\Omega + 0.1\Omega} = 692.5\text{ A}$$

Power dissipated at the point-of-fault is:

$$P = I^2 R = 692.5^2 * 0.1 = 48\text{ kW}$$

This is released as heat.

The amount of energy released by the ground fault depends on how long the fault is allowed to persist. It can be shown with this example that fault current can be severe if a dead short occurs. Nevertheless, a ground-fault relay or over current protective device should trip very quickly to interrupt power to the load. How much current would flow if a person would create the fault by touching the same circuit? Answer: Replace the dead-short value of 0.1 Ohm with the typically resistance of a human body. Assume that a person is touching the frame of a faulted motor, and is the only path to ground. We will presume 1,000 Ω of resistance for a human body. The calculation for fault current is now:

$$I_F = \frac{277\text{ V}}{1000\Omega + 0.2\Omega + 0.1\Omega} = 277\text{ mA}$$

The current is several times 15 mA, which is the let-go threshold. 50 mA can be lethal. Overcurrent-protection devices will not trip--a supplemental low-level GFR must be used to guard against this scenario.

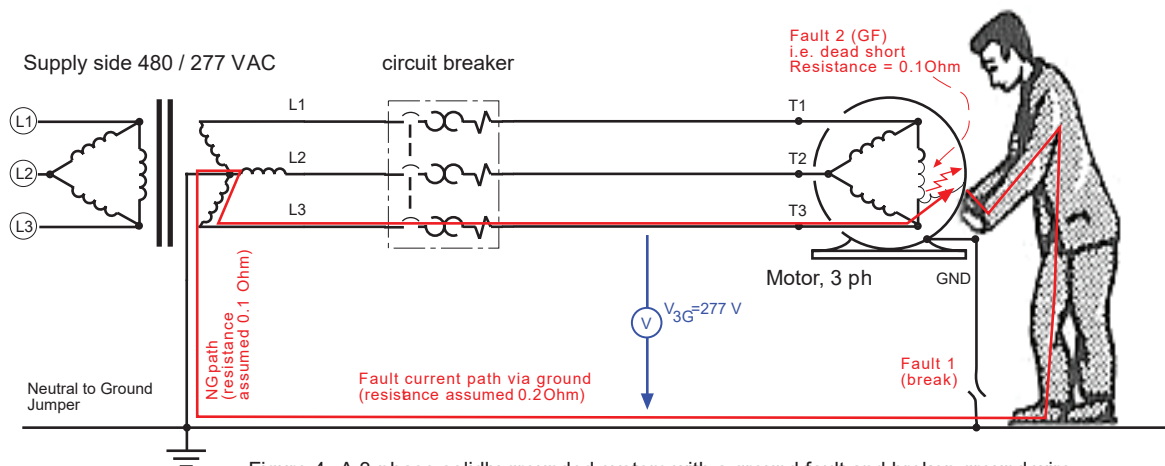


Figure 4: A 3-phase solidly grounded system with a ground fault and broken ground wire

Solidly Grounded Systems

Solidly Grounded AC Systems 60 Hz - The Ground Fault Device

Most technicians are very familiar with current transformer-based, ground-fault current relays. Non-technical people also encounter them on a daily basis - GFCI's protect wall outlets in wet areas such as kitchens and restrooms. The operating theory behind the relay is as follows. The power wires leading to the protected load are passed through a current transformer (CT). It is important that all hot and neutral wires are fed through the CT, and that ground conductors are not. This applies to both, single and three-phase systems, and CT's used in this fashion are sometimes referred to as zero-sequence CT's.

Some solidly-grounded three-phase systems do not have a distributed neutral, and may power a pump or other industrial motor. In this case the three phases only will be fed through the CT. Basic rule for three-phase systems: If the neutral is carried out to the load, feed it through the CT. If there is no neutral, only the phase conductors pass through the CT window. The CT and ground-fault relay will always read zero current in a healthy system, even under a full-load or overload condition. Assuming that there is no ground-fault, incoming and outgoing current through the CT window will cancel each other out, adding to zero. Assume a 10 A load connected to a 480/277 ac system. 10 A will be fed from the source into the load, therefore 10 A will have to return from the load back to the source. The CT will measure both simultaneously, since it is placed around all conductors and measures the sum of the currents carried by all conductors - zero.

$$\sum I_1, I_2, I_3, \dots, I_x = 0$$

Here is what the CT would measure at a specific moment in time. In accordance with the schematic below (for a healthy system):

$$10A - 5A - 5A - 0A$$

Suppose a ground fault (assume $I_F = 1A$) occurs and diverts some of current I_3 to the frame, with I_F bypassing the CT as I_F returns back to the source through the ground-return path. The new equation for the CT is now:

$$10A - 5A - 4A = 1A$$

Whereas 10 A goes out to the load on L1, 9A return to the source via phases L2 and L3, and 1 A returns to the source via the ground wire. The sum of currents through the CT is now 1A instead of 0A. The CT output signal increases, which will cause the GFR to signal an alarm if the measured value (1A) and duration exceeds the GFR's pickup value and delay time. A GFR in combination with a zero sequence CT can work in resistance grounded systems as well. Basic GFR devices may have performance issues when used on circuits with waveform modifying elements, such as Variable Frequency Drives (VFDs) or rectifier components.

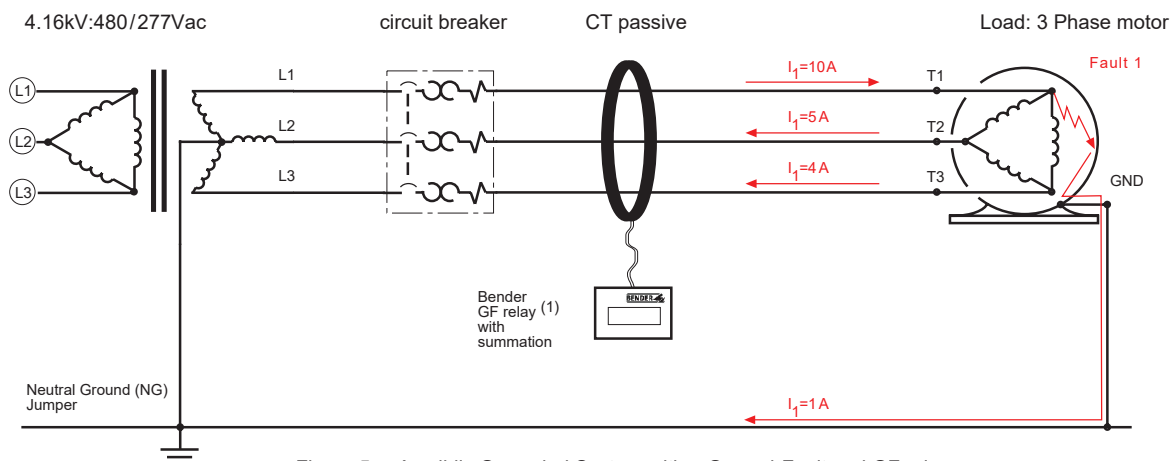


Figure 5: A solidly Grounded System with a Ground-Fault and GF relay

(1) Relays:
RCM series, CT: W-Series

Solidly Grounded Systems

Ground-fault protection – Shunt-trip circuit breaker

Some solidly grounded and resistance grounded systems require power interruption when a ground fault occurs. The ground fault has to be sensed and power has to be removed (often in milli-seconds). Trip levels for ground-fault protection vary depending on the application. In the U.S., Canada, and Mexico, personnel protection on systems up to 240VAC is defined by the standard UL 943 to be 6 mA. Trip levels for equipment protection ranges from 10 mA to multiple amperes. Industrial branch-circuit or load protection is often set to 5 A. Service entrance protection is most likely set to trip at levels in hundreds of Amps. The U.S. NEC and Canadian CEC mandate ground-fault protection on solidly grounded systems, usually at rather high levels, and 6-mA personnel protection for specific circuits. Below is a wiring schematic that shows the connections between a typical Bender RCM-type device, a shunt-trip circuit breaker, and a three phase load.

RCM Terminals: A1, A2 = external power supply; k,L = CT connection; 11,12 = contacts that close and apply 120VAC to the shunt trip coil when ground-fault current through the CT exceeds the RCM set point. The shunt-trip circuit breaker then trips and interrupts power to the load. The circuit breaker must be manually reset after a trip and after the ground fault is removed or repaired.

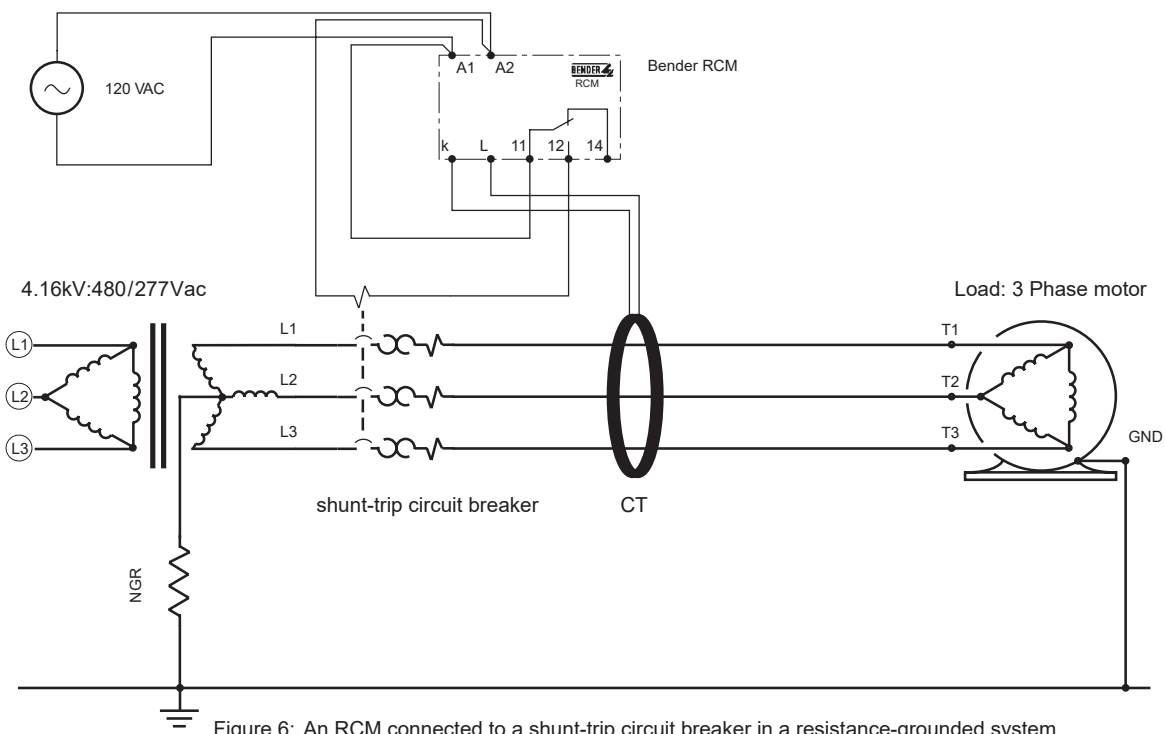


Figure 6: An RCM connected to a shunt-trip circuit breaker in a resistance-grounded system

Solidly Grounded Systems

Ground-fault protection - Contactor

The wiring schematic on page 8 employed a shunt-trip circuit breaker. A contactor can accomplish the same task when upstream overcurrent protection is installed. Please review the schematic below:

A1, A2 = external power supply; k, L = CT connection; 11, 14 = alarm contacts will open and remove power (120 VAC) from the contactor holding coil (also known as an under-voltage release coil) when ground-fault current exceeds the set point. The contactor will drop (open) and interrupt power to the load. The contactor can be configured to automatically reset after the fault has been cleared and the RCM ground-fault relay is locally or remotely reset.

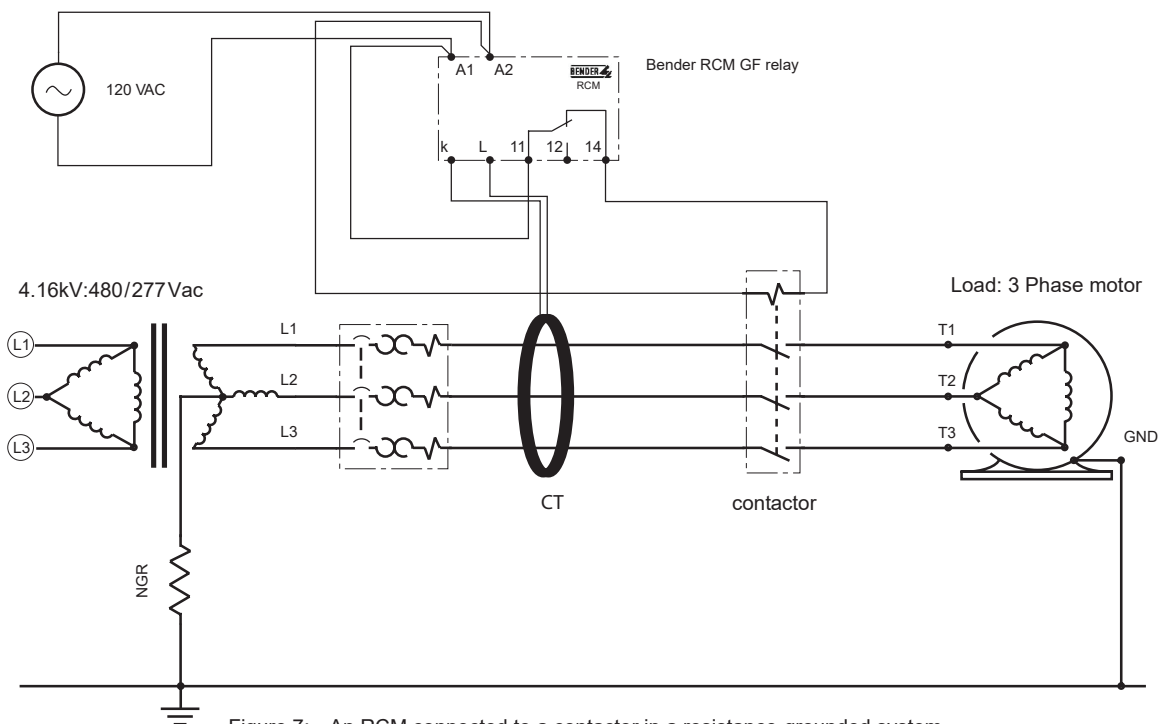


Figure 7: An RCM connected to a contactor in a resistance-grounded system

Solidly Grounded Systems

Grounded AC systems with VFDs

60 Hz GFRs have performance limitations when the power system includes Variable Frequency Drives (VFDs). Tests have shown that the typical GFR will not accurately detect a ground fault when the VFD output frequency is significantly below 60 Hz. A total inability to detect a ground fault can be expected at frequencies below 12 Hz. A VFD rectifies the incoming AC voltage to a DC voltage, which is then modulated into an adjustable-frequency AC voltage to control the speed of a typical induction motor. A DC ground-fault internal to the VFD cannot be detected using conventional GFR technology, nor can a ground-fault in the motor or cable when the VFD is operating at a low speed. A typical CT can only detect AC current and therefore DC fault currents are not detected. Some drives are equipped with their own internal scheme to detect ground faults to protect themselves against high-current AC faults. Often drives are manufactured to operate on solidly grounded systems where there is no limitation to the ground-fault current. The ground-fault current sensitivity of the drive should be checked to determine if it is compatible with resistance-grounded systems and lower-current ground faults. Early warning or personnel protection quite likely requires a supplemental GFR.

Other issues with VFDs:

- VFDs often include power quality and EMI filters. Filters and surge protection devices provide leakage paths to ground and add to the overall system leakage current.
- Filter components may be rated for line-to-neutral voltage. When installed on an ungrounded or resistance-grounded system, catastrophic component and drive failure can occur during a ground fault.
- VFDs switch at a kHz carrier frequency. Capacitive reactance decreases as frequency increases, therefore higher frequencies generate higher levels of leakage. Carrier frequencies across insulation, which is a distributed capacitance, adds further to the leakage inherent to the device.
- Harmonic frequencies that are a result of the switching operations further adds to the impact of these leakage paths.
- Transient voltage spikes are a known issue on drives, in particular when the manufacturer's recommended separation distance between the drive and the motor is exceeded.

The solution: VFD's on grounded systems should be protected with GFR's capable of detecting AC and DC faults. The Bender NGRM, RCMA, RCMB, and RCMS-series GFM's, in combination with an active CT employ a dual winding system, which accurately measures AC, DC, and mixed AC/DC currents. Trip/ alarm settings range from 6 mA to 10 A.

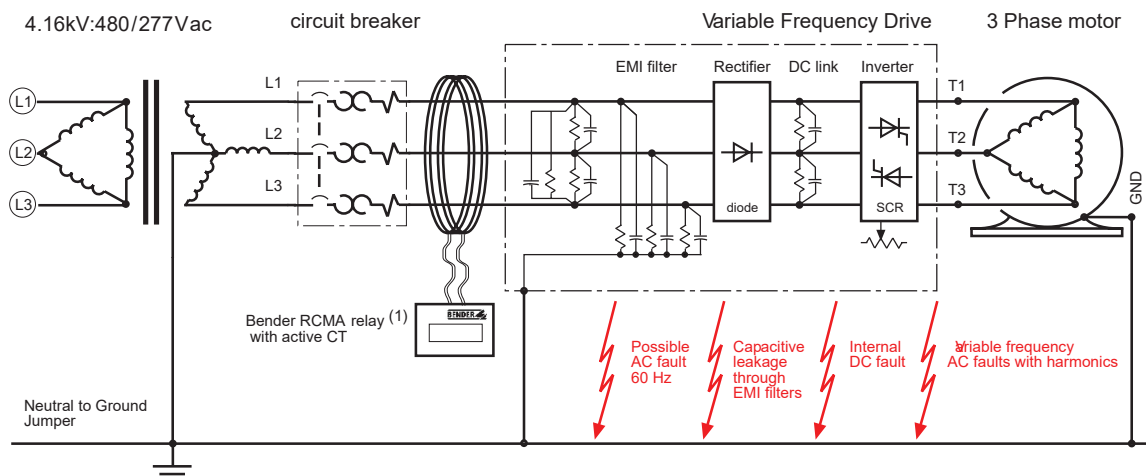


Figure 8: An grounded AC system with a variable-frequency drive & RCMA AC/DC ground-fault protection

(1) Relays:
NGRM series, RCMA series, RCMB series, RCMS series.
CT's: CTUB series, W-AB series

Solidly Grounded Systems

DC systems

Bender RCMA and RCMB GFR's monitor DC and mixed AC/DC systems. The unique measuring principle can be used for protection if the DC system is grounded as shown below. In this example, the negative pole of the DC power supply or battery is connected to the ground. Both the negative and positive conductors leading to the load are passed through the active-CT window. When a ground fault occurs, DC fault current will flow through ground back to the supply, bypassing the CT. Its magnitude will be calculated by the AC/DC GFM and an alarm will be signaled or the system will trip if so configured. One key advantage over voltage-based DC fault detection is that this method can be used to locate a ground fault. It's important to note that this technology works on AC, DC and mixed AC/DC circuits. For example: A single RCMA relay can protect a DC and an AC system at the same time. Consider a DC control circuit and a 120 VAC power wire going through the same CT. A standard GFR would only monitor the AC line; the RCMA will protect both.

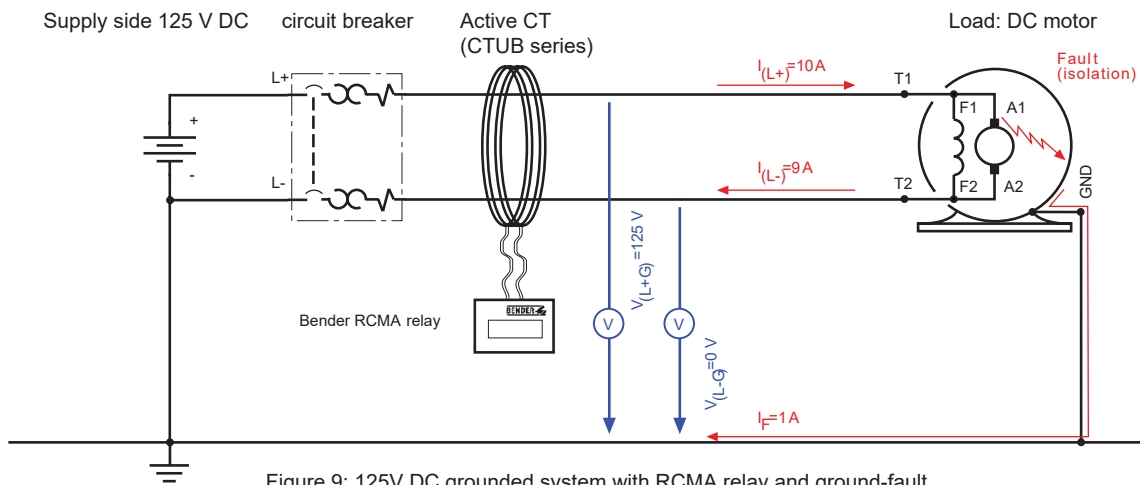


Figure 9: 125V DC grounded system with RCMA relay and ground-fault

Solidly Grounded Systems

Locating ground faults with portable equipment

Normally, it is not too difficult to locate a ground fault in a solidly-grounded system. As described above, the ground fault current is usually large and will force the overcurrent device or the ground-fault relay to trip the faulty circuit. A ground-fault relay trip can cause unwanted downtime when there is only a single ground-fault relay, protecting multiple feeders and loads, installed at the power source. A single fault anywhere on that system will cause the power to be disconnected. A typical situation in an industrial plant with a roof-mounted air conditioner that develops a ground fault which trips the main service entrance, because no branch-level protection was installed. It is not a simple task to find the faulted unit when there are 50 other loads on the system. One solution to the problem is shown below:

Locating faults in de-energized systems (Offline search)

A typical means of checking for a ground fault in a de-energized system uses a megaohmmeter, also known as a hi-pot tester or “Meggering device”. The megaohmmeter is connected across the motor leads and ground (chassis), and applies a high voltage (normally at least 500 V) to the motor circuit. A ground fault is indicated if the test voltage causes current to flow, which indicates a path to ground in the circuit. Note: The megaohmmeter only works on disconnected systems. Make sure that the system being tested is locked out from power before applying the megaohmmeter test.

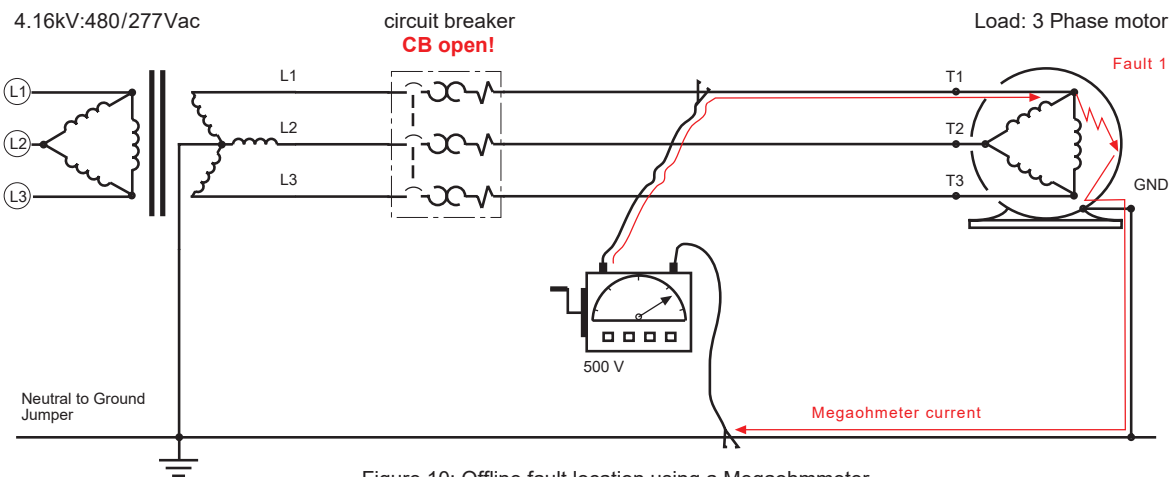


Figure 10: Offline fault location using a Megaohmmeter

Solidly Grounded Systems

Locating ground faults with a current clamp Locating faults in live systems (Online search)

Current-transformer-based ground-fault relays are similar to a sensitive ammeter with a set point. The typical clamp-on type ammeter is used to measure load currents by clamping it around a single conductor. The same ammeter will read zero if it is clamped around all conductors (including the neutral, if there is one present) in a healthy system. This is the zero-sequence principle described earlier in the Grounded AC system 60 Hz section on page 7. A healthy system will reveal zero current, but a ground-fault current will show up on the clamp. Please note: Do not include the ground conductor when placing the clamp around the power wires. The ground fault can be found by clamping around the conductors coming from the power supply first. From there measure individual branch feeders. After the feeder is located, the fault can be further tracked by measuring each load (for example, the circuits from each breaker in a distribution panel can be measured). Proper safety procedures and personal protective equipment must be worn when using this method.

A typical clamp-type ammeter designed for measuring load currents will work to locate faults if the magnitude of the ground-fault current exceeds a few amperes. A more sensitive ammeter has to be used if the ground fault has a magnitude less than one ampere. Illustration 1 below shows an ammeter which is capable of detecting faults below 10 mA. Note the clamp jaw size may limit application on many circuits. Please be advised that using a clamp meter to find a bolted fault on a solidly grounded system is ineffective, as the overcurrent devices will have tripped long before the handheld ammeter can be used. The methods described above will work for ground faults below the trip level of the circuit breakers that protect the feeder, which on high-resistance grounded systems is all ground faults. The charging current from unfaulted feeders in the system flow to the ground-fault through system capacitance, which can make recognizing the actual fault current difficult. A rule of thumb for estimating system charging current is 1/2 A per 1000 kVA of load for low-voltage systems and 1 A per 1000 kVA for medium-voltage systems. Charging current can also be measured or more-accurately calculated.

Effect of Leakage Capacitance: A motor consists of windings, wire and insulation enclosed by a metal frame. The insulation that separates a conductor from ground acts as a small capacitor between the two. The insulation also has a certain resistance. The capacitance is usually extremely small and the resistance is in general in the Megohm range. Nevertheless, the leakage current through the combined paths can add up. The larger a power system is, the larger the overall natural leakage will be. Imagine a motor in an industrial plant which leaks a minor fraction of current to ground (e.g. 1 mA = 1/1000 of an ampere). That does not sound like very much and the decision is made to employ a ground-fault relay with a 10 mA set point. The GFR trips immediately because it was overlooked that there are 15 similar motors connected to this branch. $15 \times 1 \text{ mA} = 15 \text{ mA}$ leakage already present in the system. This does not even account for the capacitive leakage of cabling, surge arrestors, or drive components such as filters.

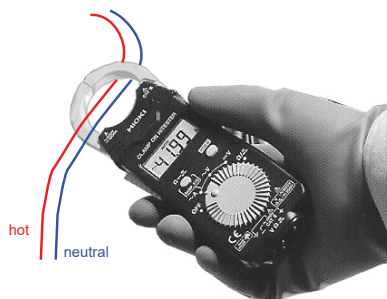


Illustration 01: Measuring fault and leakage current with a clamp meter

Solidly Grounded Systems

Locating Ground Faults in Large Systems using Fixed Equipment

Online system

Assume that there is a 208-VAC three phase system with 120 branch feeders installed in a facility. Management wants to know at all times if the system is in good condition or if there is a problem. A problem has to be indicated immediately, identified and repaired. The zero-sequence ground-fault measuring technology described earlier can help. A permanently installed ground-fault monitoring system can monitor an unlimited numbers of circuits 24/7. In this case, a CT will be installed at each feeder and branch feeder. The CTs will connect to 12 channel Residual Current Monitoring Systems (RCMS). The RCMS's can be connected to a central processing system complete with a display unit (CP700). Ground-fault current will flow from the source into the faulty branch, into the faulty load and from the fault back to the source. Zero-sequence CTs in this path will detect the fault current and the RCMS will indicate the channel representing the faulted feeder or load. The central processing unit will display the amount of fault current and the fault location. The faulted circuit can be de-energized if so configured. The ground-fault information can be sent to local indication or externally via communications to PLC's or even text messages to mobile devices. Fixed ground fault location systems are tremendously beneficial to maximize uptime and quickly locate and repair faulted equipment.

Note that the CTs can measure very low levels of ground-fault current and are designed to detect leaks at an early stage. Fast-developing ground faults, such as a bolted fault on a solidly grounded system, may trip the overcurrent device before the RCMS will locate the fault. The RCMS in a solidly grounded system will perform at its best when the fault level is below the branch overcurrent-trip levels. Ground-fault protection is meant to be low level protection and must be co-ordinated with higher-level fault protection.

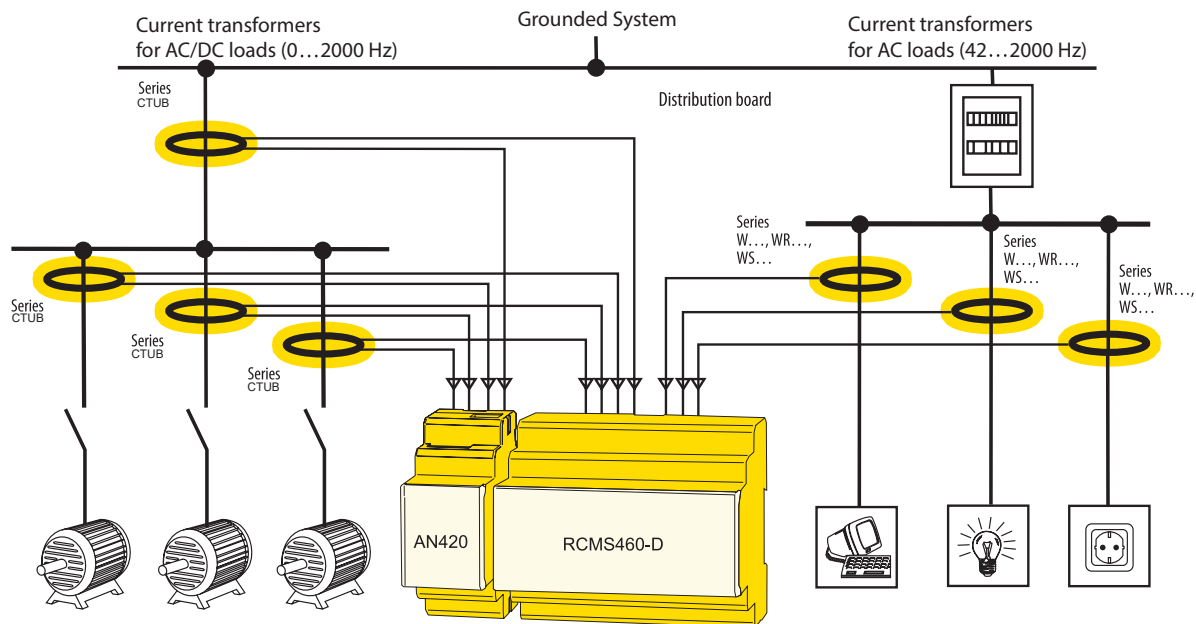


Illustration 2: Application of RCMS460-D in a multi-branch system

Resistance Grounded Systems

Basic Power Systems - Resistance Grounded

A resistance-grounded power system has a fault-current limiting neutral-grounding resistor (NGR) installed between system neutral and ground. Typically these are in three-phase, three-wire (no neutral) wye configured power systems, but sometimes are connected to the “artificial neutral” of a zigzag transformer. As with ungrounded systems, high-resistance grounded (HRG) systems can be allowed to operate with one phase faulted to ground, and industrial plants where continuity of service is critical often use HRG systems. Other facilities, such as in mining, use HRG systems that trip on a ground fault, for maximum safety. A main advantage of the resistance-grounded system is that the resistor limits the amount of current available to a ground fault, dramatically reducing point-of-fault damage and the probability of an arc flash.

The Ground Fault

Ground-fault current in a resistance grounded system is limited in magnitude. This is the main difference when compared to the solidly grounded systems discussed earlier. The ground-fault magnitude depends on the NGR rating, and the return-path and ground-fault impedances. Typical HRG and NGR ratings are 5, 10, or 25 A. The resistor must be rated for continuous duty use for non-tripping systems and is usually 10-s rated on tripping systems.

The resistance-grounded system also allows for selective ground-fault tripping which is achieved by monitoring all feeders and with adjustable time delays on cascaded relays.

$$I_F = \frac{V_{LG}}{R_{GF} + R_{GR} + R_{NGR}}$$

(3)

I_F = Fault Current

V_{LG} = Voltage between faulted phase and ground

R_{GF} = Resistance value at point of fault

R_{GR} = Resistance of ground return path

R_{NGR} = Resistance of neutral grounding resistor

Example calculation:

$$I_F = \frac{277 \text{ V}}{0.1 \Omega + 0.2 \Omega + 55 \Omega} = 5 \text{ A}$$

Power dissipated at the point-of-fault is:

$$P = I^2 R = 5^2 * 0.1 = 2.5 \text{ W}$$

The calculation shows that the ground-fault current will not be as devastating as in a solidly grounded system if a bolted ground fault occurs. The maximum fault current will be limited, therefore vital machinery can be kept running until the process is finished. Another approach is to trip on non-critical loads faults and alarm for those loads that are critical.

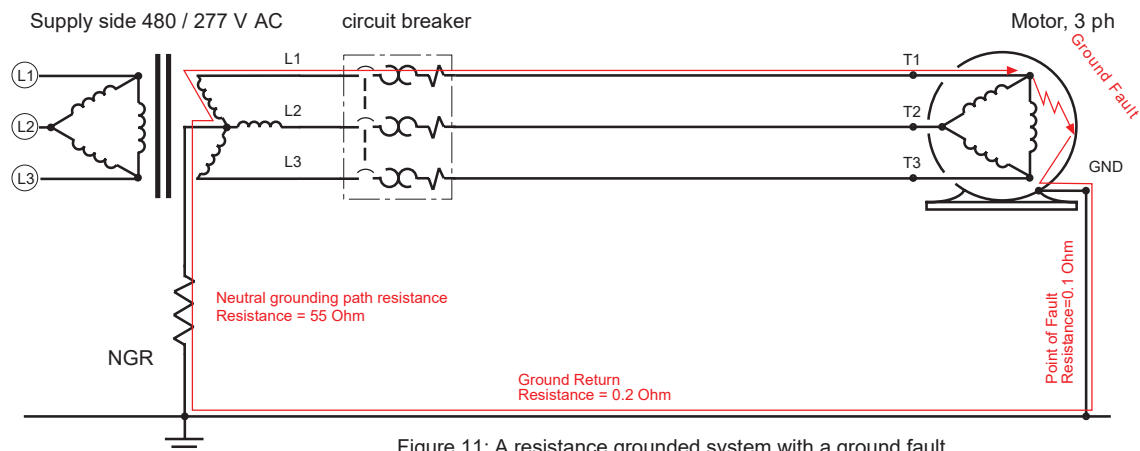


Figure 11: A resistance grounded system with a ground fault

Resistance Grounded Systems

Resistance Grounded AC systems

Ground Fault Ground Check

An open-NGR failure leaves a power system ungrounded and therefore without ground-fault detection. Similarly, the failure of the bonding connection to ground at a feeder or piece of equipment leaves a portion of the system without protection. As a result, a hazardous touch voltage can exist. This problem is especially important for mobile or movable loads that rely on the cable ground conductor as the ground-return path. Ground-check monitors protect against the open-ground-path condition by monitoring the continuity of the circuit consisting of a ground-check (pilot) conductor and ground conductor in the cable, terminated at the load by a specialized component that is recognized by the monitor. The ground-check fault condition is directly related to a ground-fault hazard, therefore the Bender RC48C combines both GF and GC functions.

If ground-fault current exceeds the pickup value, the “Alarm Ground Fault” LED lights and the alarm relays change state after the selected delay time. The alarm remains latched until the RESET button is pressed. The ground-check circuit monitors the resistance of the ground-check loop (ground-check conductor, ground conductor, and termination device). For that purpose, the relay injects a small dc current on the ground-check conductor that then travels down the trailing cable to a termination device. The termination device is connected between the ground-check conductor and ground of the portable load. The ground-check circuit detects and trips when the ground-check loop is shorted, opened or if the maximum resistance is exceeded.

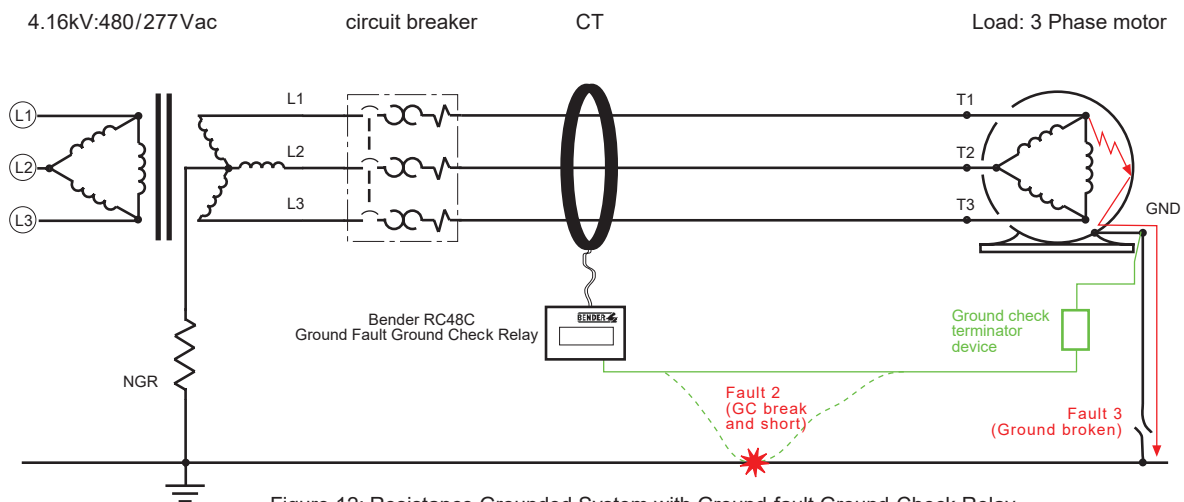


Figure 12: Resistance Grounded System with Ground-fault Ground-Check Relay

Resistance Grounded Systems

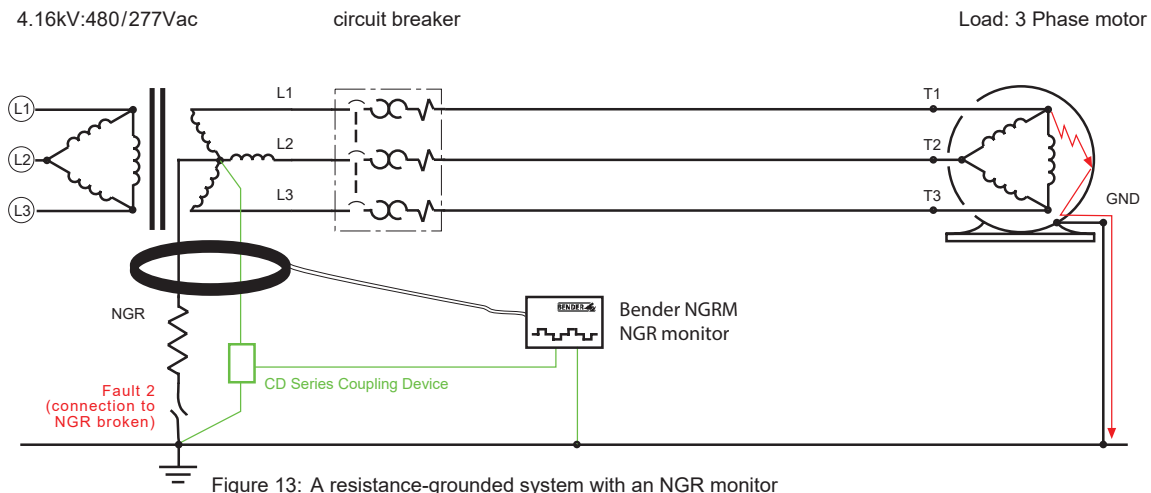
Resistance Grounded AC Systems

Ground Fault - NGR Monitor

While the NGR's used in resistance-grounded power systems are built-for-purpose, they are subject to thermal stresses, environmental degradation, maintenance errors, and damage from wildlife. If an NGR, or any of the neutral-to-ground path fails open, the power system is ungrounded and ground-fault detectors will not function. If the NGR is shorted, the system is solidly grounded and ground-fault current will be very large. For these reasons, NGR health and its connection to the system should be continuously monitored.

NGR monitoring should be performed with a device that can detect NGR failure whether or not the power system is energized, and whether or not a ground fault is present. Examples include NGRM-series and RC48N NGR monitors. Neither the use of a current-sensing ground-fault monitor, or a neutral-to-ground connected overvoltage relay, or the combination, can detect NGR failure. However, an NGR monitor can detect ground faults and abnormal neutral currents in addition to NGR failure.

In the schematic below, a Bender NGRM-series NGR monitor detects ground faults with a CT and will detect an open or short NGR by measuring resistance via a voltage-rated CD-series coupling device. If GF current or Neutral voltage exceed their setpoint value, a ground-fault LED lights and relay outputs change state. If NGR resistance is outside of the settings, a Resistor Fault LED lights and relay outputs change state. The NGR monitoring circuit measures the resistance of the neutral grounding resistor, connections to the transformer neutral, and the connection to ground. NGR resistance and the voltage drop across the NGR are measured using a coupling device that also safely isolates the NGR monitor from system voltage. If required by the application, the NGR monitor can be configured to trip the power system on a resistor fault, a ground fault, or both.



Resistance Grounded Systems

Locating Ground Faults

Resistance-grounded power systems can use the same current-based fault location techniques as in solidly grounded systems. The main differences are that the prospective ground-fault current is limited to the NGR rating and that ground-fault currents typically will not be high enough to trip an overcurrent device.



Illustration 3: HRG control panel powered with the RCMS490 & NGRM700 relays inside

Ungrounded Systems

Basic Power Systems - Ungrounded (Floating)

Floating systems are derived from a power source with no intentional connection to ground. 480V AC delta-configured transformers are the typical supply for a floating system. The mining industry often uses ungrounded delta systems in hoist applications. 480V AC deltas are also in wide spread use to supply 1,000 to 2,000 Amp main feeder circuits. Floating systems are often used in areas where a sudden shut down must not occur. Examples are hospital intensive care units (ICUs), signal circuits, and emergency backup systems.

The Ground Fault

The magnitude of ground-fault current in an ungrounded system is very small. It depends on the system voltage, the impedance of the ground fault and the system capacitances.

Example: If a grounded object with low resistance touches a live conductor, the resulting current flow will be very small. The ground-fault loop will be incomplete because the return path to the source is only through system capacitance. The resulting current is also known as charging current. Never assume that it is safe to touch a bare conductor in a floating system. The charging current will be extremely hazardous. The example below reflects resistive values only. The capacitance, though important, was not added to the equation.

$$I_F = \frac{V_{3G}}{R_{GF} + R_{GR} + R_{NG}}$$

I_F = Fault Current

V_{3G} = Voltage between faulted phase and ground

R_{GF} = Resistance value at shorted point

R_{GR} = Resistance of ground path

R_{NG} = Resistance of neutral ground bonding jumper [in this case: $M\Omega$ through air]

$$I_F = \frac{277V}{0.1\Omega + 0.2\Omega + 1M\Omega} = 0.00027mA = 0.27mA$$

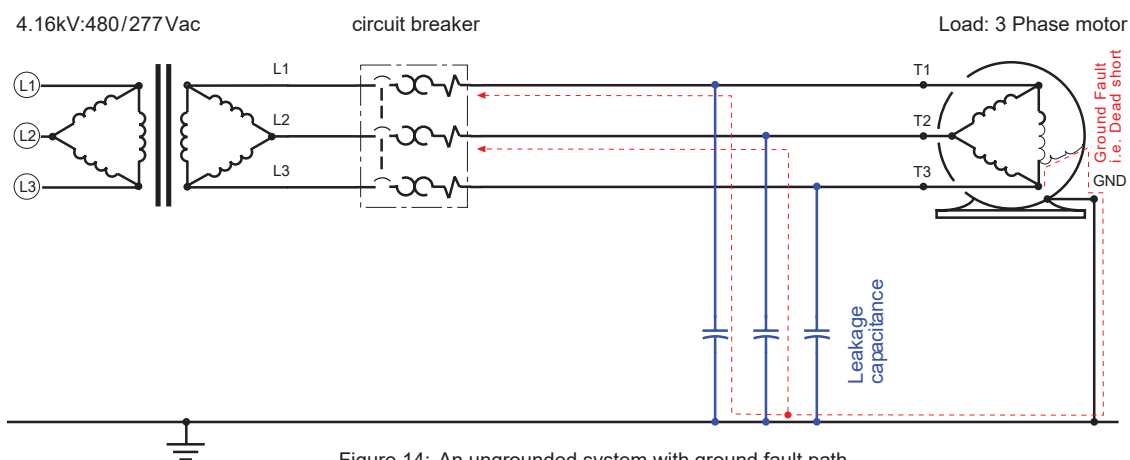


Figure 14: An ungrounded system with ground fault path

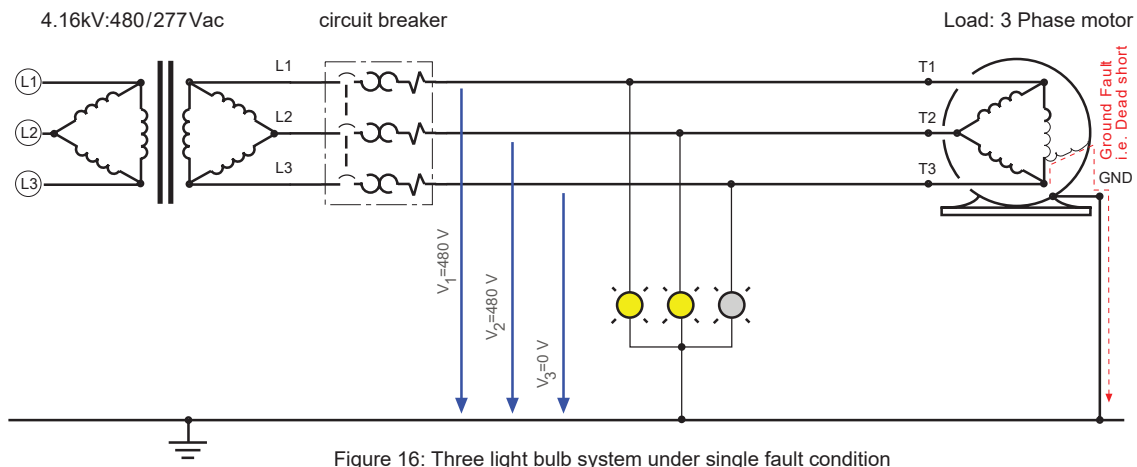
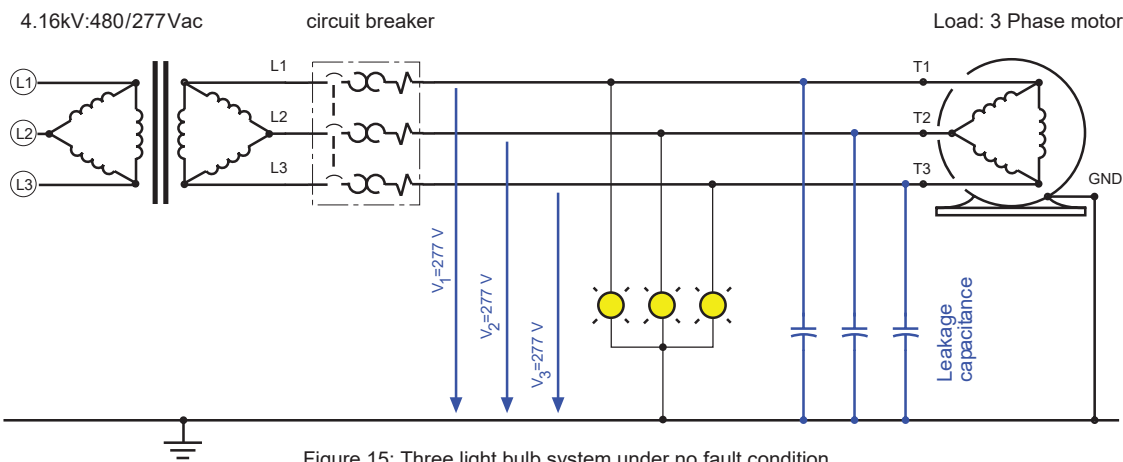
Ungrounded Systems

Insulation Monitoring Device (IMD, iso685, isoPV)

Ungrounded systems do not produce the amount of fault current needed to trip a common GFR. Insulation-resistance monitoring with an IMD is the best method to detect ground faults in floating systems.

Ground Fault Protection with Voltage Monitoring

The most common passive device is the three light bulb system in industrial 480V delta systems. This technology was used before the invention of insulation monitoring and has several drawbacks. The operating theory is explained for thoroughness, but this method is not recommended. Three lamps are connected phase-to-ground (Star or Y configuration). In a healthy system, all three lights will illuminate with the same intensity. In case of a ground fault, the faulted phase will assume a value close to ground potential. The respective light will dim, while the other two will get brighter. The light bulb system often does not offer additional trip indicators for remote alarms. It also needs to experience a serious fault condition before the indication is apparent. The same elevated voltage that causes the lights on the unfaulted phases to go brighter also stress the insulation. This can lead to phase to phase failure. Even worse, symmetrical ground faults (a balanced fault on all three phases) will not be detected.



Ungrounded Systems

Insulation Monitoring Device IMD

Active IMDs

Active IMD's are like an online mega-ohmmeter. They connect between the system phase conductors and ground. A measuring signal is constantly applied to the phase conductors and will detect an insulation fault anywhere on the system from the secondary side of the supply transformer to the connected loads. If this signal finds a path to ground, it will return to the monitor. The IMDs internal circuitry processes the return signal and trips a set of indicators when the set point is exceeded. IMDs measure in Ohms (Resistance) and not in Amps (Current). A ground fault will be indicated as "insulation breakdown".

Great insulation = healthy system = multiple kohm or Mohm
 Faulty insulation = ground fault = less than one kohm or low ohm range

A power system's overall insulation resistance depends on the number of loads, the type of insulation used, the age of the installation, environmental conditions, etc. A typical question when it comes to floating deltas is always: "Where should my trip level be?" The typical "ball park" figure for industrial applications is 100 kΩ per volt.

Example: An IMD monitoring a 480 V delta system would be set to trip at $480 \times 100 = 48 \text{ k}\Omega$. However, this calculation cannot be used for all situations. Example: A customer has meggered a motor and determines that the system has about 1 MΩ insulation resistance. However, the installed IMD keeps alarming and indicates lower levels than previously assumed. The answer: It was forgotten that there are 10 of these motors connected to the same system. The IMD measures and indicates the overall system resistance. Here we are dealing with 10 parallel resistances of 1 MΩ each. The overall resistance is less than 100 kΩ in this case.

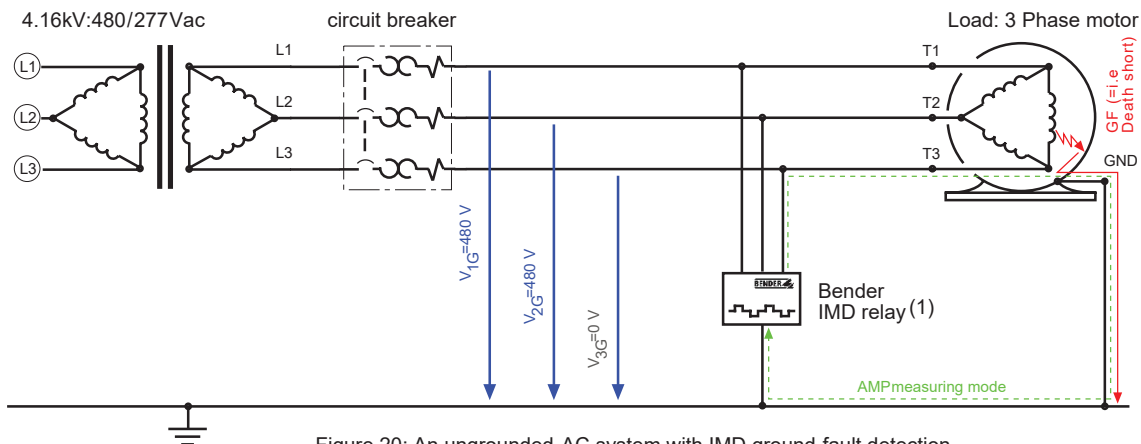


Figure 20: An ungrounded AC system with IMD ground-fault detection

- Single phase pure-AC systems => IR420 series
- Single phase AC, DC or mixed systems => IR425 series
- Three phase AC, DC or mixed systems => iso685 series
- Voltages above 1,000VDC, 690VAC => AGH couplers

Ungrounded DC Systems

Active IMDs

An active IMD is the preferred choice for detecting ground-faults in ungrounded DC systems as well. As in floating AC systems, a DC IMD connects to system positive and negative buses and ground. Some Bender IMD's work equally well on both AC and DC systems. A constant measuring signal from the IMD is applied to the power system, from where it can detect a ground fault anywhere on secondary side of the supply (e.g. battery) and the attached loads. If this signal finds a break through path to ground, it will return to the monitor. The IMD's internal circuitry will process the signal and trip a set of indicators when the setpoint is exceeded.

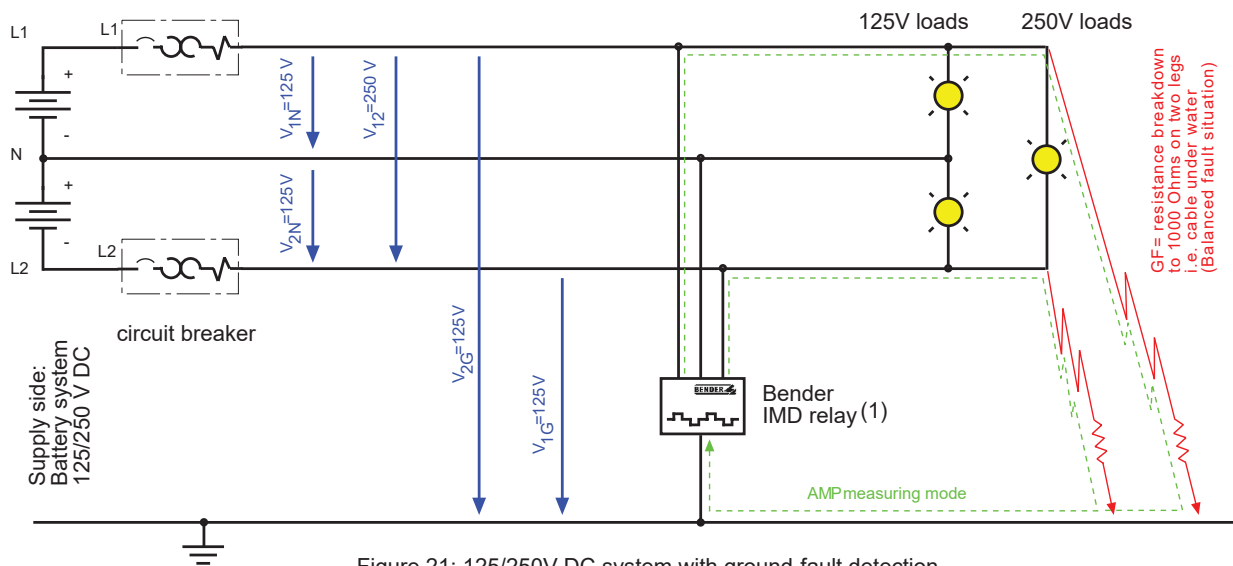


Figure 21: 125/250V DC system with ground-fault detection

Ungrounded Systems

Ungrounded systems - Locating ground faults with portable equipment

Locating faults in ungrounded systems is different from doing so in grounded systems. A typical leakage current clamp is not effective. As discussed earlier, even a dead short to ground will not create large currents in floating systems. Because there is no measurable ground-fault current, a standard fault-current detector cannot be used. The solution is to measure insulation resistance with a low level signal via pulse generator into the faulted system. The signal will follow the ground fault path into ground and return to the pulse generator. This signal can be traced with a specialized hand-held probe which is similar in appearance to the current probe discussed earlier. Nevertheless, it has to be emphasized that this is a specially designed clamp which will trace the pulse, not a ground-fault current. The clamp and pulse generator work in unison -- the generator creates the pulse and the clamp locates a ground fault by detection the pulse. This equipment can be used on both AC and DC systems, energized or de-energized.

EDS 3091PG Ground-fault location kit for AC/DC systems below 300V

EDS 3090PG Ground-fault location kit for AC/DC systems above 300V



Illustration 06: Ground-fault location kit



Illustration 07: Application of Ground-fault location kit

Ungrounded Systems

Ground fault location in a 480V delta fed system

A manufacturing plant experienced a decrease in the insulation value in a 480-V power system. The measured insulation resistance decreased from 45 k Ω to less than 5 k Ω . Shutting off breakers did not reveal any improvement. The EDS3090 fault locator was chosen for the fault-location task since we were dealing with a 480V 3-phase system. (2000A main bus, 42 branches)



Illustration 08: Location I

The PGH pulse generator was connected to the circuit. The injected signal can be seen on the hand held EDS165 evaluator device. There are 12 branches in this panel. Each one had to be checked for the pulse signal, taking approximately 30 seconds each. The pulse signal was detected in branch 2F7.



Illustration 10: Location III

The evaluator showed 15 mA going through these water cooled transformers into ground. The transformer specs and the local electricians verify that this is a normal situation. But there was still 10 mA vanishing beyond this point. The hunt continued.



Illustration 09: Location II

Branch 2F7 led further into the production area. The pulse was still strong. It is amazing how accurate the device is, considering the fact that we are only sending 25 mA into the system. We arrived at a sub panel supplying various machines and water-cooled transformers.



Illustration 11: Location IV

The culprit was found. The remaining 10 mA led to this transformer which was well hidden inside a metal-bending machine. There was a need for a replacement part.

Ungrounded Systems

Ungrounded systems - Locating Ground Faults with Fixed Equipment

A ground-fault location system can be installed as a fixed installation if 24/7 monitoring and immediate fault location is required. A complete ground-fault detection and location scheme for an ungrounded system incorporates:

IMD Insulation Monitoring device (iso685 and iso1685 series)

Function: Detects the fault and alarms when the set point has been reached. IMDs were discussed on pages 23 & 24

Pulse generator ("P" pulse option for iso685 & iso1685)

Function: Sends the trace pulse into the power wires once a fault is detected

Central Control Unit (Incorporated into the iso685 & iso1685)

Function: Gathers the information from the evaluators and displays alarms

EDS Evaluators (EDS440 series)

Function: Fault location with CT's and reporting to IMD

CTs Current Transformers

Function: Specially designed for sensing the trace pulse and sending information back to the EDS evaluator

Network Communications (included with iso685 and iso1685 series)

Function: Connect to plant industrial communications network with Modbus RTU or Modbus TCP/IP. Additional protocols are possible with a Bender communications gateway.

Permanently installed Bender ground-fault detection and location systems are excellent tools for maintaining large facilities with ungrounded power-distribution systems. Faults can be located automatically during normal operation. With no shutdown required. No handheld tracing and/or accessing inside electrical panels is necessary. If the case study on page 25 had been equipped with a fixed location system, the faulty branch and its connected machine would have been identified within the first 120 seconds of the first alarm. On an ungrounded system a ground fault should be quickly removed. If not, the increased line-to-ground voltages on the unfaulted phases can lead to a second ground fault on another phase--a potentially dangerous and catastrophic phase-to-ground-to-phase fault.

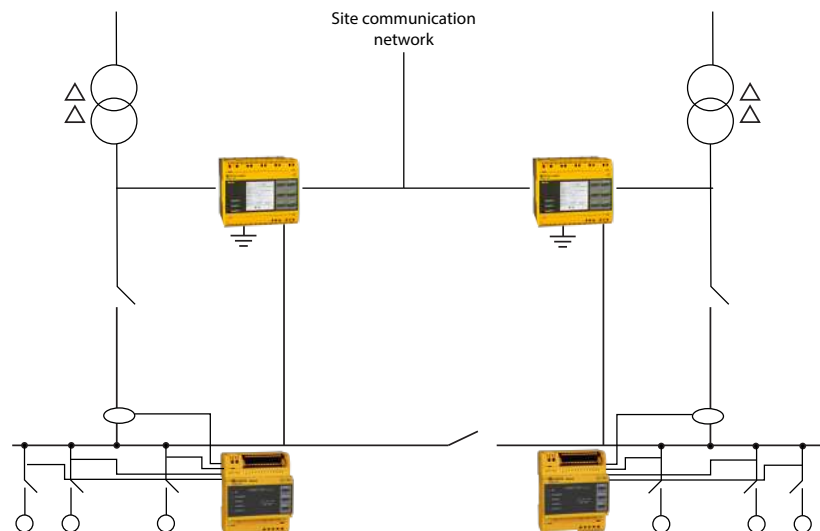


Illustration 12: Ground-fault detection & location in an ungrounded main-tie-main

Off-Line Monitoring

Off-line monitoring with the Bender IR 420-D6

Off-line monitoring allows ground-fault detection before energization of a circuit. This can prevent closing a circuit into a fault, prevent damage and may avoid a hazardous situation.

The off-line monitor is a fixed installed control relay, which replaces the function of a technician who “hipots” or “meggers” a generator winding or a load to check for ground faults or insulation break downs. These loads can be dewatering pumps, fire pumps, motors or any other electrical equipment which does not operate continually. In many installations, even continuously running equipment will be shut down at certain intervals to perform a high voltage line-to-ground test. The megohmmeter test involves disconnecting the load from the power system, connecting the high voltage device or megohmmeter, and applying a voltage will onto the wires and windings for a brief moment during which the technician measures for current leakage as an indication of an insulation failure. The procedure takes a considerable amount of time. The job sites are often in remote areas, wiring and disconnecting tasks have to be performed and safety regulations must be met. This manual task can be fully automated by using a low-cost relay.

Off-line IMD's (Insulation Monitoring Devices) superimpose a DC measuring signal to the system being monitored and are being used on thousands of applications. The relay alarms if the superimposed signal finds an insulation failure that would allow high leakage to ground.

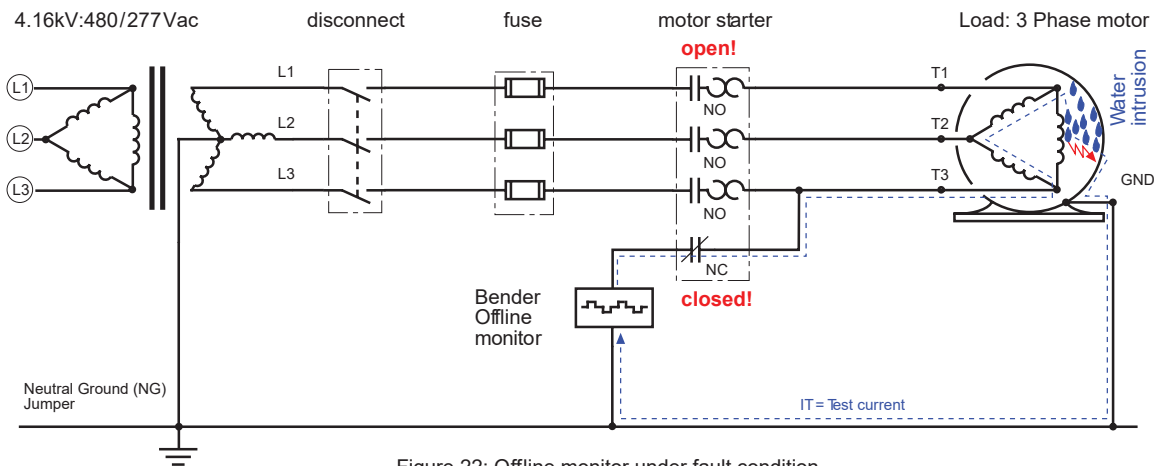


Figure 22: Offline monitor under fault condition

Off-line IMDs provide good return on investment. They often pay for themselves within the first year of operation. A typical 100hp pump motor whose seals have failed can easily be put back into operation by repairing the seals and drying out the stator windings. This will work only if an off-line monitor prevents a “wet start-up”. Rewinding the stator instead will cost thousands of dollars and unnecessary down time.

A

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Solidly and Resistance Grounded Power Systems

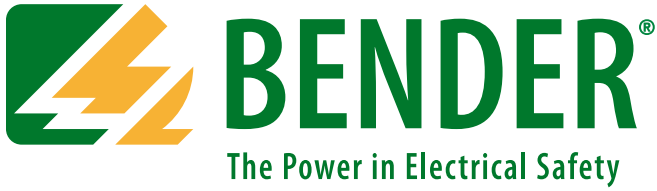
Model Series	AC Ground Faults	AC&DC Ground Faults	NGR Open	NGR Short	Voltage Monitor	Ground Continuity	Loop Monitor	EV Chargers	Service Entry Rated
CMGF420	✓								✓
COM465									
CP700									
GM420							✓		
IR420-D6									
NGRM500	✓	✓	✓	✓					
NGRM700	✓	✓	✓	✓	✓				
RCM420	✓								
RCMA420		✓							
RCMA423		✓							
RCMB20-500-01; RCMB35-500-01		✓							
RCMB104		✓						✓	
RCMB121; RCMB131; RCMB132		✓							
RCMB300		✓							
RCMS150		✓							
RCMS460, RCMS490	✓	✓							
RC48C	✓					✓			
RC48N	✓		✓						

Comm. with Gateway	Comm. without gateway	Comm. Gateway	Alpha Numeric Display	Relay Output(s)	Analog Output	One Channel Input	Multi-Channel Inputs	Integrated CT	Offline Insulation Monitor
			✓	✓		✓			
		✓							
		✓	✓						
			✓	✓					
			✓	✓					✓
✓	✓		✓	✓	✓	✓			
✓	✓		✓	✓	✓	✓			
			✓	✓		✓			
			✓	✓		✓			
			✓	✓		✓			
					✓			✓	
				✓		✓			
	✓			✓				✓	
	✓			✓		✓		✓	
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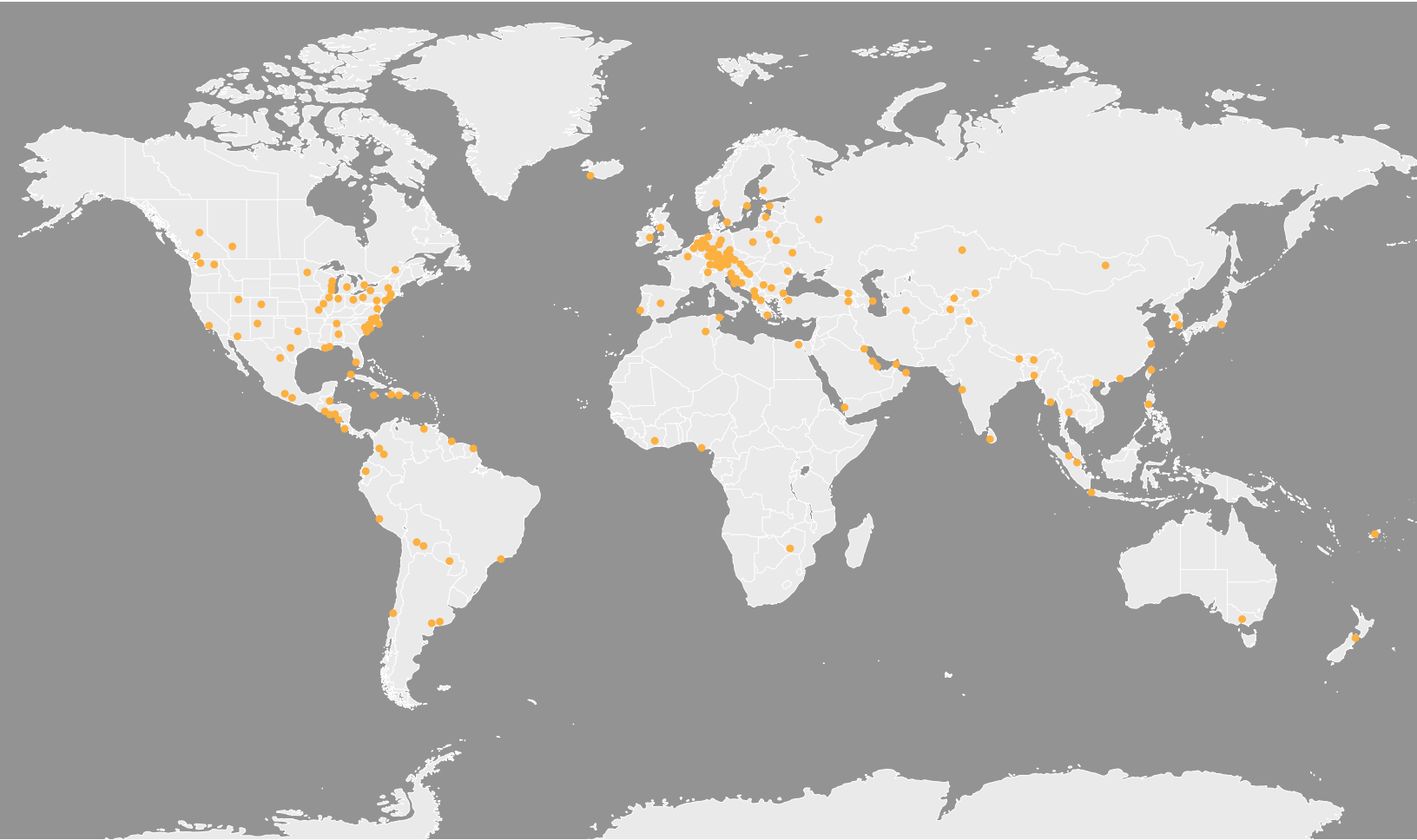
Ungrounded Electrical Systems

Model Series	Insulation Monitor	Fault Locator	Loop Monitor	Portable	AC Systems	DC Systems	AC/DC Systems	Fault Locator Output	PV System Monitor	Generator Monitor
COM465										
CP700										
EDS3090	✓	✓		✓	✓	✓	✓	✓		
EDS440		✓								
IR155	✓					✓				
IR420-D6			✓		✓	✓	✓			
isoGEN423	✓									✓
IR420-D4	✓				✓					
IR420-D6	✓				✓	✓	✓			
isoLR275	✓				✓	✓	✓			
isoPV	✓				✓	✓	✓		✓	
iso165C	✓					✓				
iso1685	✓				✓	✓	✓	✓	✓	
iso685	✓				✓	✓	✓	✓		
iso425	✓				✓	✓	✓		✓	

EV Monitor	EV Charger Monitor	Railway Applications	Offline Monitor	Network Comms w/ Gateway	Network Comms w/o Gateway	Comms. Gateway	Alpha Numeric Display	Relay Output(s)	Analog Output
						✓			
						✓	✓		
							✓		
✓									
							✓	✓	
				✓				✓	
							✓	✓	
			✓						
				✓			✓	✓	✓
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✓					✓				
		✓		✓	✓		✓		
				✓	✓		✓	✓	✓
	✓	✓		✓	✓		✓	✓	



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