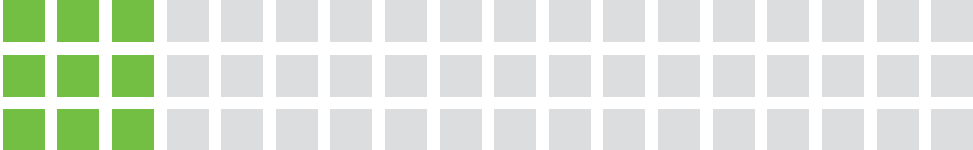


GROUND-FAULT PROTECTION AND VFDs

Variable-Frequency Drives Create a Blind Spot to Low-Level Ground Faults in High-Resistance Grounded Systems



TECHNICAL PAPER



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Overview

Death and injuries make ground (earth) faults one of the most essential hazards to mitigate. High-resistance grounding provides significant protection for equipment and personnel. Unfortunately, however, when variable frequency drives (VFDs) are used in resistance-grounded systems, the system may not be able to effectively detect low-level ground faults unless the equipment is adjusted accordingly.

When VFDs are used in high-resistance grounded systems, low-level ground faults can easily go undetected. Shorts to ground in a solidly grounded system create large currents that can damage equipment and require the system to be shut down, which is not only inconvenient, but can be expensive as well.

If left undetected, ground faults present significant electrical shock and arc-flash hazards. Ground faults are especially problematic in applications that use high-powered or portable equipment in a harsh environment, such as underground mines.

High-Resistance Grounding System Benefits

High-resistance grounding systems eliminate many ground-fault issues, including the possibility of an arc-flash incident on the first phase-to-ground fault.

In a high-resistance grounded system, the neutral point of the transformer is connected to ground through a neutral-grounding resistor (see **Figure 1**), which will limit the ground-fault current to a low value. This does three important things:

1. It limits the point-of-fault damage.
2. It reduces the ground-fault voltage at the equipment frame.
3. It eliminates the possibility of an arc flash during the first phase-to-ground fault. (High-resistance grounded systems prevent arc flashes from occurring on ground faults, which eliminates the possibility of an arc flash on 95 % of electrical faults.)

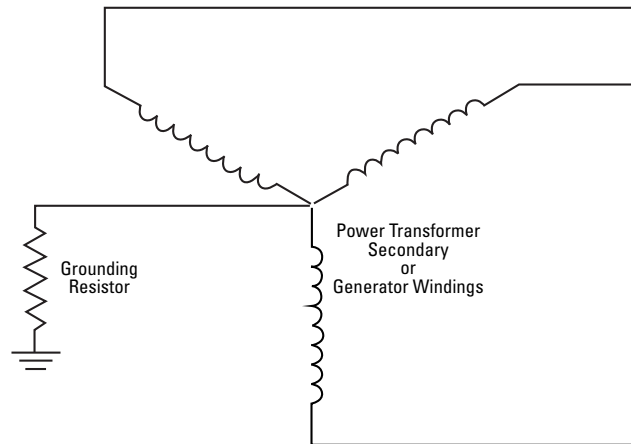


FIGURE 1: In a high-resistance-grounded system, the neutral point of the transformer (or the artificial neutral of a zigzag transformer) is connected to

This paper will explain how high-resistance grounded systems work and discuss the challenges and solutions for detecting ground faults when VFDs are used in high-resistance grounded systems. ground through a neutral-grounding resistor.

Sensing Ground Faults

Current-sensing ground-fault relays (also known as *earth-leakage relays*), which detect ground faults in grounded systems, must be sensitive enough to measure currents that are below the neutral-grounding resistor (NGR) rating and well below typical short-circuit current levels.

Additionally, the current-sensing ground-fault relays use zero-sequence current transformers (which are also known as core balance current transformers) to detect any current that is flowing where it should not be.

A window-type current transformer is referred to as a *zero-sequence current transformer* when all the current-carrying conductors pass through the current transformer window. If there is no ground fault, then the output from the current transformer will be zero. If there is a ground fault, then the vector sum of the currents will not add to zero. This value will be detected and either trigger an alarm signal or trip the faulted section.

Limiting Factors

Many factors can limit the system's ability to measure low-level ground-fault currents. These include system capacitance, charging current, voltage unbalance, current transformer limitations, as well as irregularities caused by VFDs (such as harmonics and switching frequencies).

System Capacitance

All electrical systems have phase-to-ground capacitance, which can be modeled as "lumped" values (see **Figure 2**). If the capacitances on all three phases in a grounded system are equal, then a zero-sequence current transformer on the three phases together will read zero.

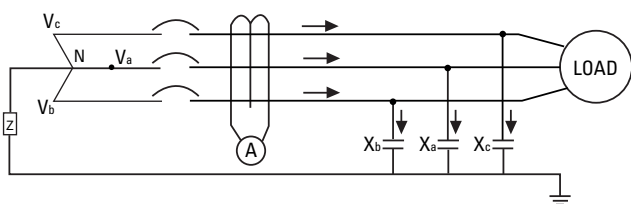


FIGURE 2: If the distributed capacitances on all three phases are equal, a core-balance current transformer on the three phases together will read zero, but if the capacitances or phase-to-ground voltage are unequal, the current transformer will have a non-zero output.

However, if the capacitances or the phase-to-ground voltage are unequal, then the current transformer will have a nonzero output. If the trip threshold is not increased, then nuisance tripping may occur. While this can be avoided by raising the trip threshold setting, doing so will reduce the system's ability to detect potentially damaging low-level ground faults.

The more uneven a system's distributed capacitance is, the higher you need to set the trip threshold to avoid nuisance tripping. Too much system capacitance makes personnel protection difficult, and a high-resistance grounded system's capacitance will increase if it has VFDs in use. This largely explains why protection levels for people are often not possible when VFDs are used in high-resistance grounded systems.

Charging Current

When one phase in an ungrounded system is shorted to ground, the capacitive charging current will flow through the capacitance to ground the other two phases (see **Figure 3**).¹

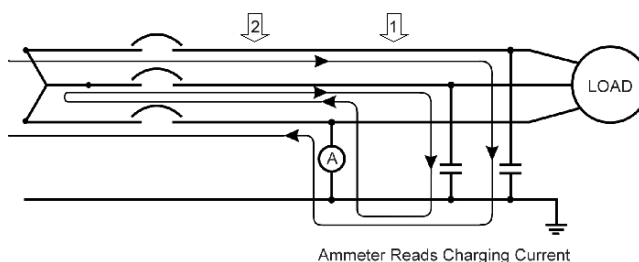


FIGURE 3: When one phase of an ungrounded system is shorted to ground, current will flow through the capacitance to ground of the other two phases. This charging current may be large enough to cause a sympathetic trip on an unfaulted feeder.

Voltage Unbalance

If the line-to-neutral voltages of the three phases are not equal, then the currents through the capacitances of the phases will be unequal. This will create a steady-state zero-sequence current. This sort of voltage unbalance may be the result of unbalanced single-phase utility loads, which can affect low-level ground-fault current detection. It is worth noting that in the absence of leakage to ground, unbalanced load currents will not cause a ground-fault trip because the phase currents will add to zero in a core-balance current transformer.

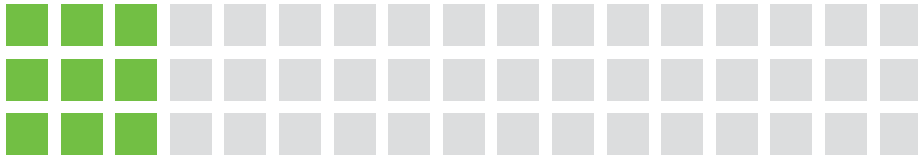
Current Transformer Limitations

Current transformers can be limited with respect to both low and high currents. With low currents, there is a minimum primary current that gives an output, and under some conditions this can make it necessary to use a specialized zero-sequence current transformer.

For high currents, there can be problems with core saturation and with the output no longer being proportional to the primary current. Even when the primary current is not excessive, if the primary conductors are poorly placed, or if there are large surge currents, then portions of the transformer core can go into saturation. This prevents balanced currents from summing properly and producing an output when there is no zero-sequence current.

One way to reduce this effect is to use a flux conditioner, which is a magnetically conductive sleeve that fits in the current transformer's window and reduces the local saturation. It is beneficial to center the phase conductors in the current transformer window, and when multiple conductors per phase are used it is important to bundle them ABC, ABC, etc., not AA, BB, CC, etc.

¹ A core-balance current transformer at "1" will measure the charging current, while a core-balance current transformer at "2" will measure zero. This charging current may be large enough to cause a ground-fault relay to operate on an unfaulted feeder. To avoid this so-called sympathetic tripping, the protection on those feeders must be set above the level of charging current; if sympathetic operation is acceptable, the protection level may be set lower.



Motor Inrush Current

Motor starting can be problematic because you cannot predict where the switch will close along the ac cycle. Sudden changes in current, like the inrush current of a motor, can cause a momentary dc offset which will result in temporary output current from the zero-sequence current transformer. This issue can be corrected by increasing the ground-fault relay's trip delay or by using a digital filter to reject the dc component.

The Challenges of Integrating VFDs in High-Resistance Grounded Systems

VFDs enable fine control over motor speed, resulting in energy cost savings and a popular choice for industrial applications.

However, VFDs must be properly applied in high-resistance grounded systems. This is because in many VFDs, the built-in ground-fault protection will only trip if the current to ground reaches a fixed amount, which is usually no lower than 20 % of the full-load current.

For VFDs to be safely used in a high-resistance grounded system, the ground-fault relay must have sensitive wideband ac- and dc- ground protection.

In high-resistance grounded systems, however, the ground-fault current is limited to a small value (usually only to a few amperes), which means that the drive will not see enough fault current to trip on a ground fault. Even at lower levels, undetected ground faults can eventually lead to severe equipment damage or even an arc flash event if an additional ground fault occurs on a separate phase. A dedicated and properly specified ground-fault relay can solve this problem, but the relay must be suitable for addressing this issue.

A conventional ground-fault relay detects ground-fault current at powerline frequency (50 or 60 Hz) and above. Higher-end ground-fault relays filter high frequencies

to prevent trips from harmonic noise. VFD applications often operate between a 0 Hz to 120 Hz (or more) range. However, most ground-fault relays do not work at low output frequencies (below approximately 20 Hz)—let alone dc. This can make it challenging to get comprehensive protection from a standard ground-fault relay with a VFD on the same system.

While dc ground-fault relays do exist, most cannot detect ac faults. Therefore, dc ground-fault relays are not adequate for system protection with VFDs.

For VFDs to be safely used in a high-resistance grounded system, the ground-fault relay must have sensitive wideband ac and dc ground-fault protection. The relay should be able to measure dc and ac up to the VFD frequency output. The Littelfuse EL731 can achieve this with a single current transformer that monitors current from 0 to 90 Hz, and thus covers standard VFD output frequencies (including dc) while ignoring high-frequency leakage currents.

Harmonic Currents

The output waveform of a VFD is not a pure sine wave and has several harmonic-frequency components (multiples of the fundamental output frequency). Because capacitive reactance is inversely proportional to frequency, higher-order harmonic currents can easily flow through the system capacitance to ground. If the capacitance and voltage are balanced, then the harmonic currents on all three phases will be the same and sum to zero, with no effect on the ground current.

However, the effects of unbalance are magnified at higher frequencies. The third harmonics, which are also called *triplen harmonics* (such as 180 Hz for a system that is running at 60 Hz), are in phase with each other when at higher frequencies. This can create enough ground current to cause a ground-fault trip. This issue can be resolved by increasing the trip setting on the ground-fault relay or by using a ground-fault relay that has a built-in digital filter that can reject third-order harmonic currents.

A VFD's output can include carrier frequency (or switching frequency) components, which can create additional challenges when it comes to sensitive-ground fault protection. The effect of capacitive and voltage unbalance is greater at higher frequencies, with current flowing to ground where there is no fault present.

How to Detect Low-Frequency Faults in Systems with VFDs

Ac-dc sensitive ground-fault relays (see **Figure 4**) measure ground currents as low as 6 mA, with some able to monitor across a wide frequency spectrum (including 0 Hz for dc applications).

Littelfuse model [EL731 microprocessor-based ac-dc sensitive ground-fault](#) relay (also referred to as an *earth-leakage relay*) is for use with up to two sensitive current transformers and can monitor output frequencies that are between 0 Hz and 6000 Hz. Existing EFCT-series ground-fault current transformers that were already in use with earlier Littelfuse sensitive earth-fault relays can be used with the EL731 relay.

A single ground-fault current transformer from the Littelfuse EFCT series provides ground-fault protection from 0 Hz to 90 Hz. If the application calls for the measurement of high-frequency components (such as those created by harmonics and high switching frequencies), a second current transformer can be added to extend EL731's protection to 6000 Hz. The EL731 also provides separate trip and alarm pickup levels, which range from 30 mA to 5 A each. The EL731 also has three programmable output relays.

EL731's temperature input works with resistance-temperature detectors and positive temperature coefficient devices, which are typically embedded in the motor. The EL731 can be used to display temperature readings and to trip on overtemperature. The programmable output relays can also be set to temperature-based alarm and trip events.



FIGURE 4: The EL731 is a sensitive ac-dc earth-leakage relay with programmable alarm and trip settings, relay, analog, and serial outputs, and a 32-character OLED display.

Other Features

Other features of the EL731 include a

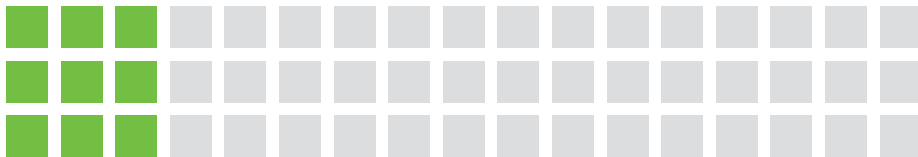
- 2 x 16-character OLED display
- current and temperature metering
- menu-navigation push buttons
- LED trip and alarm indications
- auto-reset alarms and latching trips with front-panel and remote reset trip memory
- 4- to 20-milliampere analog output
- current transformer verification with LED indication
- conformal coated circuits
- panel or surface mounting
- password protection for parameter setting
- either Modbus TCP, EtherNet/IP, or DeviceNet network communications
- easily upgradeable firmware

Conclusion

Variable frequency drives can make it difficult for high-resistance grounded systems to monitor ground faults. However, modern ground-fault relays are capable of solving these problems, and lead to safer and more reliable electrical systems.

References

- [1] J.R. Dunki-Jacobs, et al., *Industrial Power System Grounding Design Handbook*.
- [2] M.F. Baharom, M.H. Jali, M.N.M. Nasir, Z.H. Bohari, S.A. Tarusan, "Performance study in energy efficiency on variable speed drive, VSD design for setting high lift pumping station," in *2014 International Symposium on Technology Management and Emerging Technologies*, May, 2014, Bandung, Indonesia. Available: IEEE Xplore Digital Library. <https://ieeexplore.ieee.org/document/6936528> [Accessed: 07 Oct. 2019]



Definitions

Equipment Grounding Conductor: The conductive path(s) that provides a ground-fault current path and connects normally non-current-carrying metal parts of equipment N together and to the system grounded conductor or to the grounding electrode conductor, or both.

Fault Current: The current that flows when a phase conductor is faulted to another phase or ground.

Ground: The earth.

Grounded (Grounding): Connected (connecting) to ground or to a conductive body that extends the ground connection.

Ground Fault: Unintentional contact between a phase conductor and ground or equipment frame. The words “ground” and “earth” are used interchangeably when it comes to electrical applications.

Grounded Conductor: A system or circuit conductor that is intentionally grounded.

Ground-Fault Current Path: An 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.

Ground-Fault Protection of Equipment: A system intended to provide protection of equipment from damaging line-to ground fault currents by causing a disconnecting means to open all ungrounded conductors of the faulted circuit. This protection is provided at current levels less than those required to protect conductors from damage through the operation of a supply circuit overcurrent device.

Grounding Electrode: A conducting object through which a direct connection to earth is established.

Grounding Electrode Conductor: A conductor used to connect the system grounded conductor, or the equipment, to a grounding electrode or to a point on the grounding electrode system.

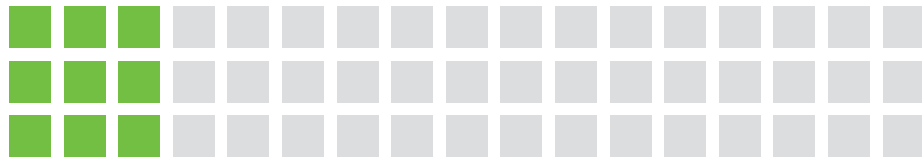
Harmonics: A voltage or current with a frequency that is an integer multiple of the fundamental frequency.

Heating: Heating occurs in every part of the system as the electrical current passes through the system. If the overcurrent is large enough, this will almost instantaneously occur. The energy in such overcurrents is measured in ampere-squared seconds (I²t). An overcurrent of 10,000 A that lasts for 0.01 s has a thermal energy of 1,000,000 I²t. A current of only 7,500 A can melt a #8 AWG copper wire in 0.1 s and within 8 ms (one-half electrical cycle). A current of 6,500 A can raise the temperature of an AWG THHN thermoplastic-insulated copper wire from its operating temperature of 75 °C to 150 °C. Currents higher than 150 °C can immediately vaporize organic insulations.

Overcurrent: Any current in excess of the rated current of equipment or the ampacity of a conductor. It may result from overload, short circuit, or ground fault.

Ungrounded: Not connected to ground or to a conductive body that extends the ground connection.

Voltage: The greatest root-mean-square (rms) difference of potential between any two conductors of the circuit concerned.



Notes



For more information, visit
[Littelfuse.com/EL731](https://www.littelfuse.com/EL731)