Examples of motors that have melted due to ground fault

Going to ground

Tyler Klassen examines the various challenges with monitoring ground faults in high-resistance-grounded systems and explains how technology can resolve those challenges

> "Ground faults pose a shock hazard to workers and can cause costly damage and downtime"

Ground faults (also called earth faults) are a special concern in underground mines, where high-powered portable electrical equipment operates in a harsh environment. Trailing cables and couplers are exposed to moisture, dragged over rough surfaces and exposed to other equipment in the mine such as jeeps and loaders, all of which can cause damage.

Moveable and mobile electric equipment is transported and used throughout the mine, causing vibrations, mechanical stress, and general wear and tear. Shock-waves from blasting can also lead to untimely failure in underground electrical equipment. Many of these failures result in a ground fault.

The frame of portable equipment is typically bonded to the ground at the supply transformer in the upstream substation through a ground conductor in the trailing cable. A ground fault in portable equipment will cause current to flow through the ground conductor. This current will cause a ground-fault voltage to appear on the frame of the portable equipment, with the voltage level being equal to the product of ground-fault current multiplied by the ground-conductor resistance. Ground faults, if left undetected, pose a shock hazard to workers and can cause costly equipment damage and downtime.

To reduce or eliminate many ground-fault problems, including most arc-flash incidents, mines have long used high-resistance-grounded (HRG) systems. In these systems, the neutral point of the transformer is connected to ground through a neutral-grounding resistor (NGR), as shown in Figure 1.

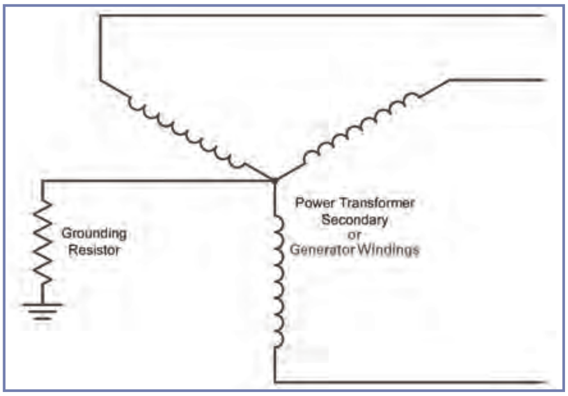

Figure 1: in HRG systems, the neutral point of a transformer is connected to ground through a neutral-grounding resistor

The NGR will limit ground-fault current to a small value, which limits the point-of-fault damage, reduces the ground-fault voltage at the equipment frame and eliminates the possibility of an arc flash during a phase-to-ground fault.

Even though HRG offers great benefits in improving safety, there are some important things to consider, including factors that can make it difficult to detect low-level ground faults. Several of these are exacerbated by variable-frequency drives (VFDs) used to control motors in conveyors, fans, pumps, drills, crushers and other mining machinery.

SENSING GROUND FAULTS

Since a HRG system prevents a ground fault from causing an overcurrent trip, there must be a way to detect when a ground fault has occurred. The best way to sense ground faults in a grounded system is to use current-sensing ground-fault relays (GFRs), which use core-balanced zero-sequence current transformers (CTs or ZSCTs) to detect currents flowing where they should not. This permits selective co-ordination and makes it easy to find a ground fault.

Any window-type current transformer becomes a core-balance ZSCT when all current-carrying conductors are passed through the CT window. If there is no ground fault, the output from the CT should be zero. If there is a ground fault, the currents will not add up to zero, and the difference can be detected and used to signal an alarm, or trip the faulted section.

LIMITING FACTORS

A number of factors can limit the ability to measure low-level ground-fault currents. These include system capacitance, unbalanced single-phase loads, current-sensor limitations, low-frequency operation, harmonic components and VFD carrier frequency.

System capacitance

All electrical systems have phase-to-ground capacitance. While in reality this capacitance is distributed throughout the system, it is usually modelled as 'lumped' values, as shown in Figure 2. On a grounded system, if the capacitances on all three phases are equal, a core-balance CT on the three phases together will read zero; however, if the capacitances or phase-to-ground voltage are unequal, the CT will have a non-zero output. This can cause nuisance tripping unless the trip threshold is increased, but this reduces the ability to detect low-level ground faults. This largely explains why people-protection levels are not possible in industrial systems.

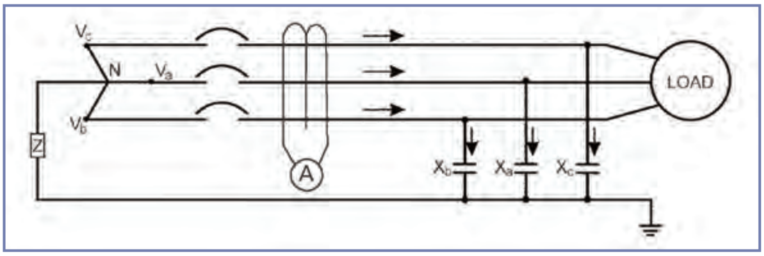

Figure 2: model of phase-to-ground capacitance

Charging current

When one phase of an ungrounded system is shorted to ground, current will flow through the capacitance to ground of the other two phases, as shown in Figure 3. A core-balance CT at 1 will measure the charging current, while a core-balance CT 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.

Voltage imbalance

If the line-to-neutral voltages of the three phases are not equal, the currents through the capacitances of the phases will be unequal, resulting in steady-state zero-sequence current. This sort of voltage imbalance may be the result of unbalanced single-phase utility loads. The effects are usually small, but may 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 CT.

Current transformer limitations

Current transformers have their own limitations with respect to both low and high currents. At the low-current end there is a minimum primary current that will give an output, and under some conditions this can make it necessary to use a specialised ZSCT. At the high-current end there can be problems with core saturation, with output no longer being proportional to primary current.

Even when primary current is not excessive, if the primary conductors are poorly placed, or there are large surge currents, portions of the transformer core can go into saturation, preventing 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 CT's window and reduces local saturation.

Transient currents

Transient currents can also cause a problem: when a motor is started across the line there is no way to predict the part of the AC cycle at which the switch will close; this can cause a momentary DC component that can cause an output from the CT. Fortunately, this is easily corrected by increasing the GFR's trip delay, or by using a digital filter to reject the DC component.

Problems with VFDs

VFDs (aka variable-speed drives or adjustable-speed drives) have proliferated in mining operations because they allow finer control over motor speed and thereby reduce energy consumption, which is a significant share of operating costs. ►

Unfortunately, they have their own problems in HRG systems.

In many VFDs, the built-in ground fault protection will trip only if current to ground reaches a fixed amount, such as 33% or 50% of full-load current. However, in a HRG system, the ground-fault current is limited to a small value (generally just a few amps), so the drive can never trip on a ground fault. Many mine managers are unaware that the ground fault protection on board their VFDs is not working, and are unknowingly putting workers and equipment at risk.

The solution is to back up the VFD with a ground-fault relay (GFR) – but the GFR must be chosen carefully. A conventional GFR detects ground-fault current at power line frequency (50/60Hz) and above. Higher-end GFRs filter high frequencies to prevent trips from harmonic noise. Some VFD applications (for example, a conveyor operating at creep mode) operate from 120Hz or more down to 0Hz (DC). Most GFRs do not work at low output frequencies (below about 20Hz) or with DC. There are DC ground-fault relays, but most cannot detect AC faults, so they cannot be used with VFDs.

Harmonic currents

The output waveform of a VFD is not a pure sine wave and for that reason contains several harmonic-frequency components (multiples of the fundamental output frequency). Since the reactance of the system capacitance is inversely proportional to frequency, higher-order harmonic currents more easily flow through the system capacitance to ground.

If capacitance and voltage are balanced, the harmonic currents on all three phases are the same, and they will add up to zero and have no effect on ground current. However, the effects of imbalance are magnified at higher frequencies.

The third harmonics (180Hz, etc, when the system is running at 60Hz), also called the triplen harmonics, are in phase with each other and can create enough ground current to cause a ground-fault trip. This can be dealt with by increasing the trip setting on the GFR, or by using a GFR with a built-in digital filter that can reject third-order harmonic currents.

Another problem with VFDs is carrier-frequency leakage current. The output of a VFD includes components of the carrier frequency. The effect of capacitive and voltage imbalance are greater at higher frequencies, with current flowing to ground with no fault present.

MOTOR OVERHEATING

Motors operating at low speeds lose cooling capacity because their shaft-mounted fans lose output at low speed (the amount of air moved by a centrifugal fan varies with the square of the shaft speed). Even motors cooled by separate fans can overheat if their air ducts are clogged with dirt.

Motor protection relays can help here, but they have features largely redundant to those offered by the VFD. Fortunately, some of today's ground-fault relays can accept inputs from the temperature sensors, such as resistance temperature detectors (RTDs) or positive temperature coefficient (PTC) thermistors, built into motor windings to provide warning of motor over-temperature at considerably less cost than a motor-protection relay.

LOW-FREQUENCY FAULTS

While it may seem counter-intuitive, a current transformer can be made to measure DC. In the case of ground-fault relays, the transformer detects changes in core saturation caused by DC current. A voltage is applied to the secondary of the transformer and as the current ramps up, the core begins to saturate. The circuitry detects this and reverses the applied voltage, creating a square wave as the system switches back and forth between saturation current levels in both directions.

Any DC or low-frequency AC current flowing through the primary will bias the magnetic field in the core in one direction, making the secondary current at which saturation occurs polarity-sensitive. The result is a change in duty cycle of the square wave that can be translated to a measurement of the current in the primary.

REGULATIONS

So far there are no official regulations requiring ground fault protection at low frequencies and DC, but the Mine Safety and Health Administration (MSHA) in the US recommends that mine operators install low-frequency ground-fault protection. Canada has not yet addressed the problem, while Australian mining authorities are keenly aware of it and are looking forward to the development of a solution.

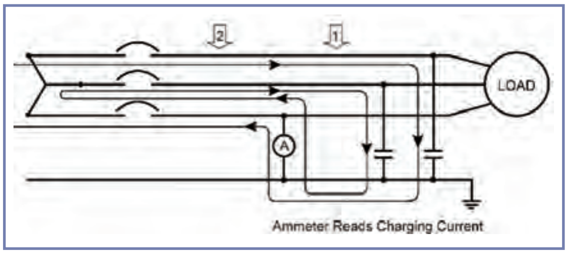

Figure 3: when one phase of an ungrounded system is shorted to ground, current will flow through the capacitance to ground of the other two phases

SOLUTIONS

Ground fault relays based on advanced microprocessor technology are now emerging as a solution to the challenge of reliably detecting ground faults on VFDs at low frequencies, without causing nuisance tripping. For example, Littelfuse has recently introduced a ground fault relay (Figure 4), which uses the technology described above to measure ground currents down to 0Hz – in fact, it can be powered by DC and used as a DC ground-fault relay.

It is most often used with one CT (for output frequencies between 0Hz and 100Hz), and can do this using the same current transformers as earlier models, which means it can be installed in place of an existing GFR without replacing the CTs.

Where higher motor frequencies are used or there is a need to measure harmonics and the carrier frequency, a second CT can be added to extend coverage to 15kHz.

In summary, HRG systems have many advantages, but the increasing use of VFDs can make it difficult to monitor them for ground faults.

New technologies can go a long way towards eliminating these problems, and can lead to safer and more reliable electrical systems.

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Figure 4: the Littelfuse EL731 is designed to detect ground faults down to 0Hz in resistance-grounded environments

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