A NEW APPROACH TO MINING EARTH LEAKAGE PROTECTION WITH MEDIUM VOLTAGE DRIVES

Tino Wymann, Mark Pollock and Jochen Rees

***Abstract* — Reliable detection and limitation of earth currents is crucial to safety in underground mining. The risks and how to mitigate them have been discussed at length in literature. What was not considered in the past is that variable speed drives (VSD) are complex voltage sources which can bypass or disturb the conventional protection equipment. Even in earth fault limited networks, a VSD can create local leakage current loops which exceed the maximum level defined in the mining standard. In order to navigate this issue, this investigation demonstrates a setup with a protective zone (transformer, VSD, motor), galvanically isolated from the supply network. Thereby only one connection to the ground is needed. Regardless of the motor frequency range, our approach requires only one relay and has shown to be effective. The result reveals a safe, simple and reliable solution which complies with the applicable Australian mining standards.**

***Keywords* — AS/NZS 2081:2011, earth leakage protection, fault limited networks, medium voltage, protection relay, underground mining, variable speed drive (VSD)**

I. Introduction

Using a variable speed drive introduces two general problems which were not existent with fixed fundamental frequency systems (as used in the good old times):

- Earth current protection at variable frequency
- High frequency coupling through leakage capacitances (mainly in long cables)

The underground mining industry is aware of the danger that comes with these two properties of drives. In 2011 the NSW government issued a Safety Bulletin [1] discussing hazards associated with VSDs. The theory behind the phenomenon is well known within the field of science for many years [2] but the user is still missing a diversity of simple and reliable solutions. This paper presents a best practice approach to achieving safety, offering an array of simple but effective measures.

The first point (detecting earth faults for a variable fundamental frequency) can be solved with a proper relay. It is important to check the detection frequency range of the product. The range varies between manufacturers and does not always cover the desired operational range for the process. It gets more complicated with the second point because it’s an inherent property of the system and not a fault per se. High-frequency currents directed through leakage capacitances will be present when introducing a VSD. The magnitude of the current depends on two factors.

- Installation design (cable lengths, VSD, etc.)
- Presence of an earth fault

This means that if the electrical design is sub-optimal, an earth leakage relay would trip as soon as the drive starts. In the case where the electrical design is satisfactory, the relay only needs to trip when there is an earth fault present. It is only under this condition that the leakage currents would be big enough to create hazardous potential.

The next chapter is dedicated to the technology of the relay and how it is able to detect current over a wide frequency range, including DC current. Chapter three explains how to achieve acceptable earth leakage current under normal operation and how to detect earth faults. Chapter four will make the link from theory to practice and show the test results from the lab. The solution offered was specifically certified for the mining market and is successfully used in Australia.

II. Relay Capability

In the past, if an earth fault relay was designed for use with or near a VSD, it typically meant utilizing a fixed-frequency filtering algorithm centred near the fundamental frequency. For example, a Discrete Fourier Transform (DFT) filter can be used to achieve strong attenuation for signals outside of the 50-60 Hz range, resulting in effective rejection of harmonics and high-frequency currents. However, with VSD applications, the output frequency may not always be fixed at 50 or 60 Hz. Other filtering algorithms, such as peak detection, can be used to monitor a wider frequency range (drive output frequency) while still rejecting the majority of high-frequency currents. These algorithms can vary greatly from one manufacturer to another, and often have a slow roll-off that is included within the specified frequency range. As a result, although a specific frequency range may be listed in published documentation, significant attenuation can still occur within those frequencies. This can make it a challenge to apply and set an earth-fault relay to a system where a VSD is used.

One aspect that is often overlooked, is the possibility of a DC bus fault within the VSD, or elsewhere on the system. Due to the fact that a DC fault is not easily detected by standard AC earth-fault relays, the fault would likely go unnoticed until the system has already sustained significant damage. For this reason, and the challenges described above, a new relay was developed that would provide sensitive DC and wideband AC earth leakage protection.

A new, patented measurement method was developed to measure DC and AC up to 90 Hz using a standard current transformer (CT). To accomplish this, the relay injects a signal into the CT secondary, and monitors the output coming from the CT on the same terminals. The current flowing through the CT window affects the injected signal, and in turn, the CT output, in a way that allows the relay to determine the magnitude of that current. This method provides a significant benefit—a single CT can be used to monitor current from 0-90 Hz, which includes the typical VSD output frequencies, DC, and ignores the high-frequency leakage currents. A CT is simple to use and does not require a direct electrical connection to the circuit, to perform the measurement; this facilitates easy application to low and medium-voltage earthed systems.

The second important consideration, was to incorporate the more recent demands in order to monitor high-frequency currents instead of filtering them out. As already discussed, in a VSD application there is inherently some level of high-frequency current flowing due to leakage capacitance. As the relay will also be measuring these leakage currents, it would therefore be necessary to set the trip or alarm level above this current in order to avoid continuous nuisance operation of the relay. However, this would result in a trip level that is much higher than desired for the VSD output frequency.

A very effective way to avoid this issue, is to provide two independent sets of trip and alarm settings: one set to apply to the low-frequency range and another set to apply to the high-frequency range. This allows a sensitive setting to be used for the VSD output frequency, while a more accommodating value is chosen where the current through leakage capacitances are of concern. A second CT input capable of AC measurements from 20 to 6,000 Hz is provided for this purpose.

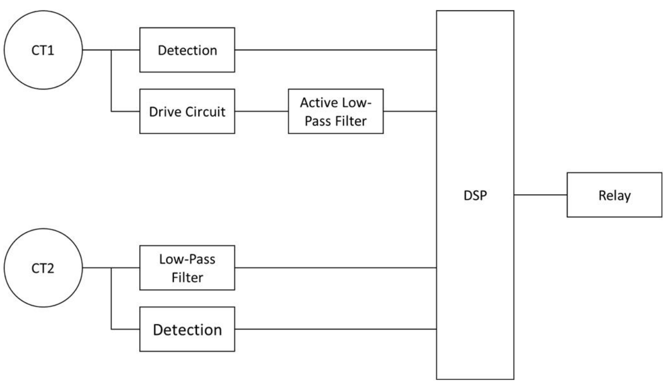

Figure 1: Block diagram of the relay

In order to achieve settings that are as sensitive as possible, it is also helpful to limit the frequencies being monitored to those that are of concern for a particular site or application. Adding user-selectable filters is an effective way to provide this flexibility, and ensures leakage current that is measured during ‘steady state’ is minimized. For example, frequency response options for the second CT input could be 20 to 6,000 Hz, 20 to 90 Hz, 190 to 6,000 Hz, or 20 to 3,000 Hz. This would provide the ability to have an independent setting for the full monitored frequency range, an independent setting for the fundamental frequency range, or to customize the high-frequency monitoring to exclude the third harmonic, or reduce some high-frequency measurements whilst including the switching frequency of the VSD.

III. Power Drive System Design

A. Protective Zone

A major problem seen in drives connected to a single feeding transformer, is the potential for cross-coupling to occur between the lengthy cables. Having multiple drives connected to one transformer often leads to high earth leakage currents under normal operation. The effect becomes more pronounced as higher system voltages are introduced. This implies that the jump from low-to-medium voltage requires a rethinking regarding the design. Especially (but not exclusively) for underground mining, high earth leakage currents are not acceptable and a protective zone has to be created. In the case of medium voltage VSDs it is common practice to use an input transformer in order to facilitate galvanic isolation.

The feeder transformer for medium voltage VSDs typically has multiple windings in order to build a higher pulse system for harmonic mitigation. Grounding on the secondary windings is not an option, as multiple grounding points are not possible, due to current loops. The optimal single point of grounding for the VSD topology utilized, is thus at the drive’s output. The principle is comparable to earth fault limited networks, as the grounding has to be high ohmic, in order to limit possible ground fault currents.

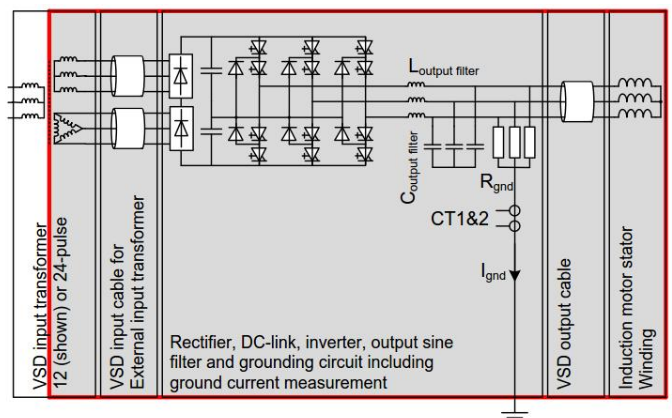

Figure 2: Protective zone for power drive systems

B. Earth fault detection

Under healthy operational conditions there is only one point of grounding in the protective zone. In case there is a second point of grounding, due to an earth fault the only path the current can take is via the star point of the resistor network. That’s also the point where the relay measures the earth fault current (see Figure 2). Any earth fault in the system can be immediately detected by this measurement. The other purpose of the resistor network is to limit a possible earth fault current until the drive ceases operation.

There is one critical operational condition where it is impossible to detect an earth fault on motor side with the method above (the supply side is not affected by this limitation). This is within low speed operating range of the motor (rule of thumb lower than 10% speed). At low motor speed, the output voltage becomes inadequate (voltage divided by frequency is always constant). An earth fault current on the output side of the drive would therefore sit below the trip level.

Normal operation of the motor happens above that speed but for start-up or inching, the drive operates for a short time within this speed range. The solution is to use an insulation measurement when the VFD is not running, which is interlocked with the circuit breaker close command. In the event where the level of resistance becomes too low, the drive is not allowed to start. The complete solution can be found on Figure 3. The ground resistance measurement will be disabled during VSD operation, as the reaction on an earth fault is not fast enough to comply with underground mining standards.

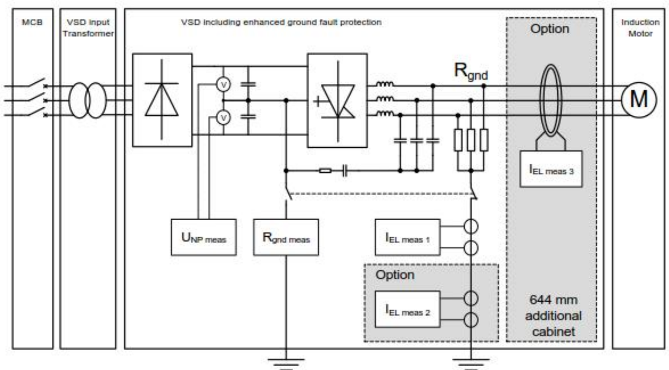

Figure 3: Complete underground mining solution

In order to comply with the applicable underground mining regulations, the options in Figure 3 are not necessarily required. If the end-user's regulation requires additional safety, it can also be added. The first option is a redundancy of ground current monitoring systems. The other option, is to add a zero-sequence CT on the output of the drive, in order to measure the earth leakage current. A detailed description of the proposed solution can be found in [4].

C. *Zero-sequence current*

Every VSD is a common mode voltage source. The finite number of output voltage levels do not allow to have: $u_u + u_v + u_w = 0, \forall t$ which would be approximately true for a conventional system (where u is the instantaneous motor terminal voltage of phase u, v and w). The averaged sum of all instantaneous output voltages is zero but not its RMS value. The common mode cannot be seen in the phase-to-phase voltages and thus, does not affect the electro-magnetic state of the motor (as long as the motor star point is not grounded). By contrast, the stray capacitances get exposed to the common mode voltage. Figure 4 shows the drive system from a common mode perspective, also known as, zero-sequence diagram (resistances and inductances are neglected for the matter of simplicity). Any common mode voltage jump drives a current through the leakage capacitances (towards ground) which is the cause for earth leakage current loops in drives without having a ground fault. This current cannot be avoided but reduced by control of the stray capacitances.

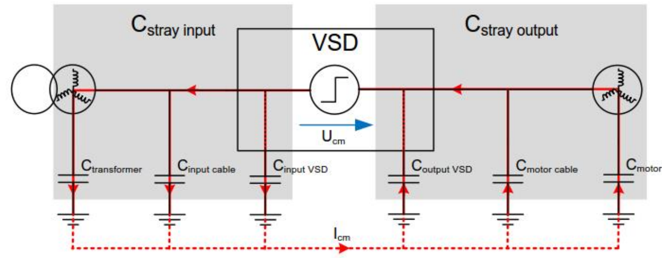

Figure 4: Zero-sequence diagram

The current in a capacitance can be defined as follows:

$$i_{cm} = C_{\sigma\,total} \frac{du_{cm}}{dt}$$

The input and the output capacitances can be summed together, such that we can only distinguish two capacitances $C_{\sigma in}$ and $C_{\sigma out}$. These two capacitances are now connected in series. This leads to:

$$C_{\sigma\,total} = \frac{C_{\sigma in} * C_{\sigma out}}{C_{\sigma in} + C_{\sigma out}}$$

As the du/dt is determined by the converter, the only way icm can be influenced is through the stray capacitances. The output stray capacitance is mainly determined by the length of the motor cable and is therefore not in the hand of the manufacturer. The only sufficient way to reduce the earth leakage current is to keep $C_{\sigma in}$ as small as possible, thus minimalising the distance between the transformer and the drive.

Any earth fault has the possibility of providing a low impedance path for earth leakage currents and therefore needs to be detected immediately with a relay that is fast enough, in order to protect persons working in close proximity to the equipment.

In drive systems without galvanic isolation $C_{\sigma in}$ won't be controllable and leads to a low impedance path back from the motor cables. Additionally there will be an interaction with other equipment in the plant favouring uncontrolled earth leakage currents. It is for this reason why it is recommended to have a protective zone for VSDs in underground mining applications.

IV. Test Results

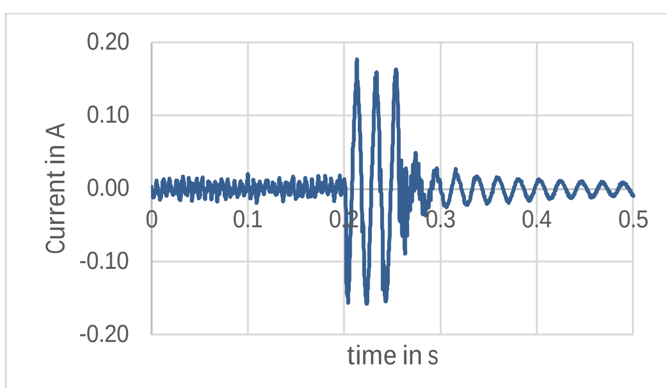

Figure 5: Fault current during a simulated earth fault on the motor terminal

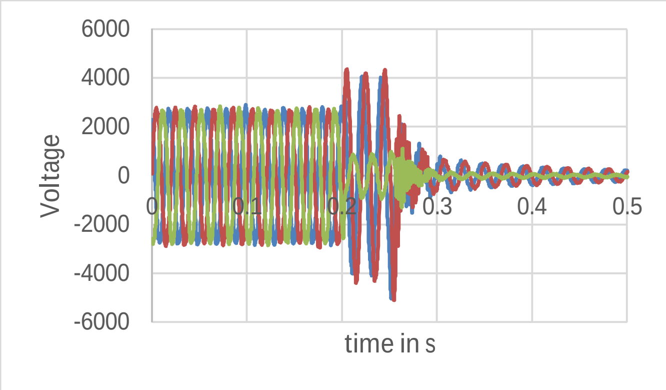

Figure 6: Motor terminal voltages during a simulated earth fault on the motor

Figure 5Figure 6 and show a motor earth fault simulated in the lab. The motor was running at 50Hz when a 1kOhm resistor had been connected (at 0.2s) between ground and one phase of the motor terminal. The drive eliminates the fault within 80ms and sends a trip signal to the main breaker. During this time the earth current is limited to an acceptable value. Figure 5 also shows a small earth leakage current during normal operation. This is the zero-sequence current loop between drive output and transformer secondary windings and cabling. A proper design according to chapter III. C. helps to maintain a good signal-to-noise ratio and leads to a reliable detection of an earth fault.

For the AS/NZS 2081:2011 certification a total of 121 measurements had been taken and evaluated. The following tests were done at different operating speeds of the motor.

- Low voltage tests with relay
- Medium voltage tests with ground faults provoked at transformer, dc-link and motor
- Special tests including insulation monitoring, maximum fault current, common mode voltage and ground resistor failure

Just to highlight some interesting results. Find below the maximum fault current under worst case condition. This means the relay disabled and a low impedance short-circuit of one motor phase to ground at maximum output voltage.

Maximum fault current limited by the grounding resistors	280 mA
Lowest motor frequency for detection of motor side earth faults	5.8 Hz
Insulation monitoring trip time when the drive is not operating	5 – 11 s

V. Conclusions

We have demonstrated that using VSDs in underground mining doesn’t mean that compromises need to be made with safety and that compliance with the actual regulations is possible. The paper also suggests that the following actions should be implemented in order to achieve maximum safety for the people working around the equipment:

- Selecting the right relay
- Set up of protective zone for each drive
- Keep input stray capacitances small, by minimising the distance between the transformer and the drive
- Maintain a single point of high impedance grounding at the output of the drive

The solution offered was certified by Bureau Veritas, in order to be compliant with the Australian standard AS/NZS 2081:2011. This approach is also used in other countries which have even more stringent regulations, such as Russia and China.

VI. Acknowledgments

The main drivers behind this solution are Nathan Muehlberg and Jochen Rees. They have a very deep understanding of the end-user’s needs and drive innovation in this direction.

Many thanks to John Rieusset who edited the first draft.

VII. References

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VIII. Biographies

Tino Wymann graduated from the Swiss Federal Institute of Technology Lausanne in 2009 with a M.Sc. in Power Conversion and Systems. He joined ABB Switzerland the same year to work in medium voltage drives R&D and technical sales before he transferred to ABB Australia in 2014 as a product manager. Email: tino.wymann@au.abb.com

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