DC FAULT DETECTION WITH VSDGUARD AND ELV RELAYS

Whitepaper

AMPCONTROL®

1 Introduction

Variable Speed Drives (VSDs) are now finding wide use in mining applications. Most of these drives use variable frequency outputs that are produced by rectifying the supply to dc and then inverting this dc voltage back into ac using a high frequency carrier and pulse width modulation (PWM) to produce variable frequency, variable voltage supply to the motor. The consequence of introducing a dc bus into the system is that there is now a possibility of the occurrence of dc earth faults.

The chance of an earth fault occurring on the dc bus of a variable speed drive is very unlikely, as the bus is usually installed entirely within the drive enclosure. However, in the event of a dc earth fault, it is prudent to have an earth leakage relay that is capable of detecting the leakage current.

This paper will demonstrate how a fault on the dc bus of a variable speed drive can be detected using a wideband earth leakage relay coupled with an earth leakage toroid. There are several factors that influence an earth leakage relay's ability to detect such a fault. These factors include: the structure of the VSD, the bandwidth of the relay and the quality of the toroid.

2 Investigating the Structure of a VSD

A typical VSD consists of a rectification circuit, dc voltage bus with filtering circuit and an output inverter circuit – refer to Figure 1 for a typical installation. In most applications an Electromagnetic Compatibility (EMC) filter is also installed on the front end of the drive to filter out any electromagnetic interference that the drive may impose onto the supply. There are many configurations of each of the above portions of a VSD, but for this paper the areas of concern are the rectification system and the dc bus.

The simplest types of rectifier are the line commutated types. These types of rectifier rely on the oscillation of the mains frequency to switch the devices. A diode based device requires no control input and is totally controlled by the supply frequency. A thyristor based rectifier allows partial control of the system via the adjustment of the firing angle of the thyristor. A larger firing angle will delay the turn-on of the thyristor and ultimately lower the average voltage on the dc bus. Standard configurations of line commuted rectifiers are the six pulse bridge and the twelve pulse bridge.

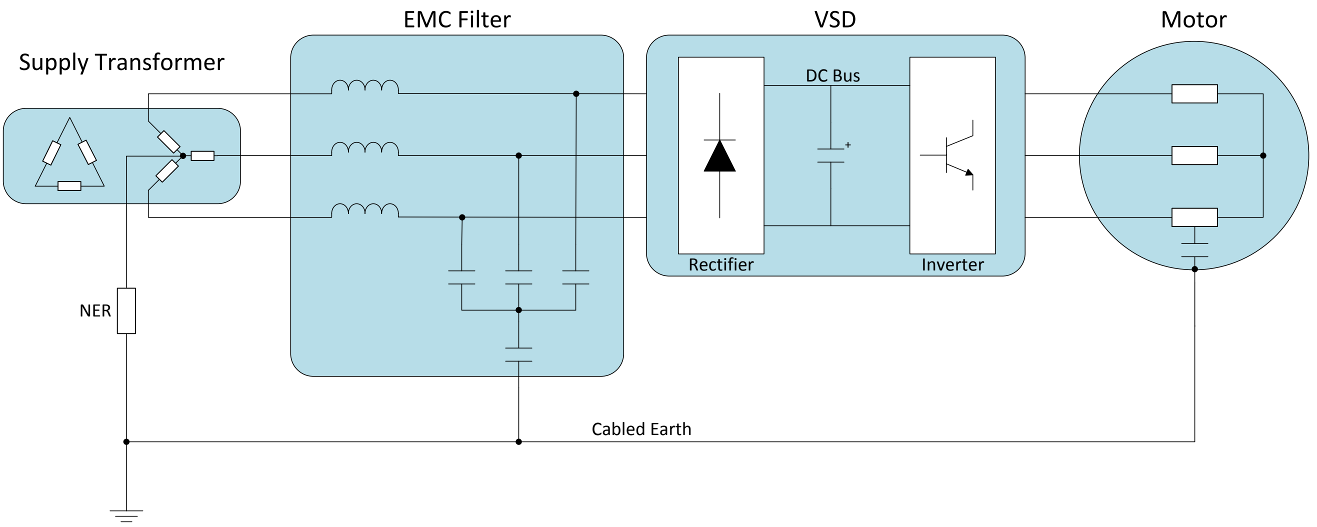

Figure 1: Block Diagram of a VSD Installation with a Six Pulse Diode Rectifier

Self-commutated switches allow for greater control over the dc output of the rectifier and can also be used to reduce the amount of harmonic distortion that is imposed upon the supply of a VSD. A self-commutated rectifier can manipulate the input current of a VSD to make it appear as a purely resistive load, allowing for unity power factor. The disadvantage of these systems is that the switches require a control system to be implemented, which is not required on line commutated rectifiers. A typical self-commutated rectifier type is the H-Bridge rectifier.

Regardless of the type of rectifier used, the voltage that appears on the dc bus of the drive will still have an ac component. In order to regulate the voltage that is seen on the output rails of the dc bus, a filtering capacitor is installed. This capacitor will stabilise the voltage on the two rails of the bus, reducing the magnitude of the ripple. The ripple that remains will have frequency elements related to the switching frequency of the rectifier, a multiple of six of the supply frequency (300Hz on a 50Hz system) and the switching frequency of the output inverter.

3 Examining Earth Fault Currents on the DC Bus of a VSD

In order to ascertain how to protect against earth faults on the dc bus of a VSD, it is necessary to investigate the currents that would flow through to earth if such a fault were to occur.

The voltage that exists on the dc bus of a VSD can be thought of as an ac waveform with a dc offset. The frequency of the ripple on the dc bus is related to the frequency of the switching components of the rectification unit on the front of the drive, as well as the supply frequency for the rectifier. These frequencies are typically well above the frequency of the mains supply, and can be anywhere from 300Hz for a naturally commutated rectifier, to several kilohertz for active front-end rectifiers.

NOTE	**Observation #1: The frequency of the ripple on the dc bus is well out of the pass band of a standard narrowband (50-60Hz) earth leakage relay.**

VSDs typically have a rectifier cabinet and an inverter cabinet installed side-by-side, with the dc bus connecting the two units internally. Situations where dc leakage current could develop on this type of dc bus include flashover due to creepage and an object coming into contact with the bus and creating a path to earth. In many cases, these types of faults are associated with rapidly developing, high magnitudes of current.

4 Reaction of an Earth Leakage Toroid to Pure DC Fault Currents

Toroidal transformers are used for measuring the amplitude of an alternating current in a primary conductor. As ac current passes through the cable in the centre of the toroid, a varying magnetic flux will be induced into the core of the toroid. As the magnetic flux in the core of the toroid varies, an opposing electromotive force (EMF) will develop in the secondary winding of the toroid. This alternating EMF has an amplitude that is related to the ratio between the primary and secondary windings, allowing a relay to accurately measure the primary current based upon the secondary current.

When a purely dc current is passed through the centre of the toroid a magnetic flux will still be induced into the core of the toroid. The initial step in dc current will be passed through the CT to the output, but as the current transformer's magnetising current increases (i.e. saturation is approached), the CT output falls.

Figure 2 shows the reaction of an EL500S series toroid when it is subjected to a dc step current. In this experiment, a constant dc input was applied through the primary of the toroid. The secondary winding was terminated into a known resistance which allowed the calculation of the perceived primary current. As expected, the secondary current decayed exponentially as the magnetising current increased.

During this experiment it was noted that if a dc step fault occurs, the sudden change in current will result in an induced current on the secondary side of the earth leakage toroid.

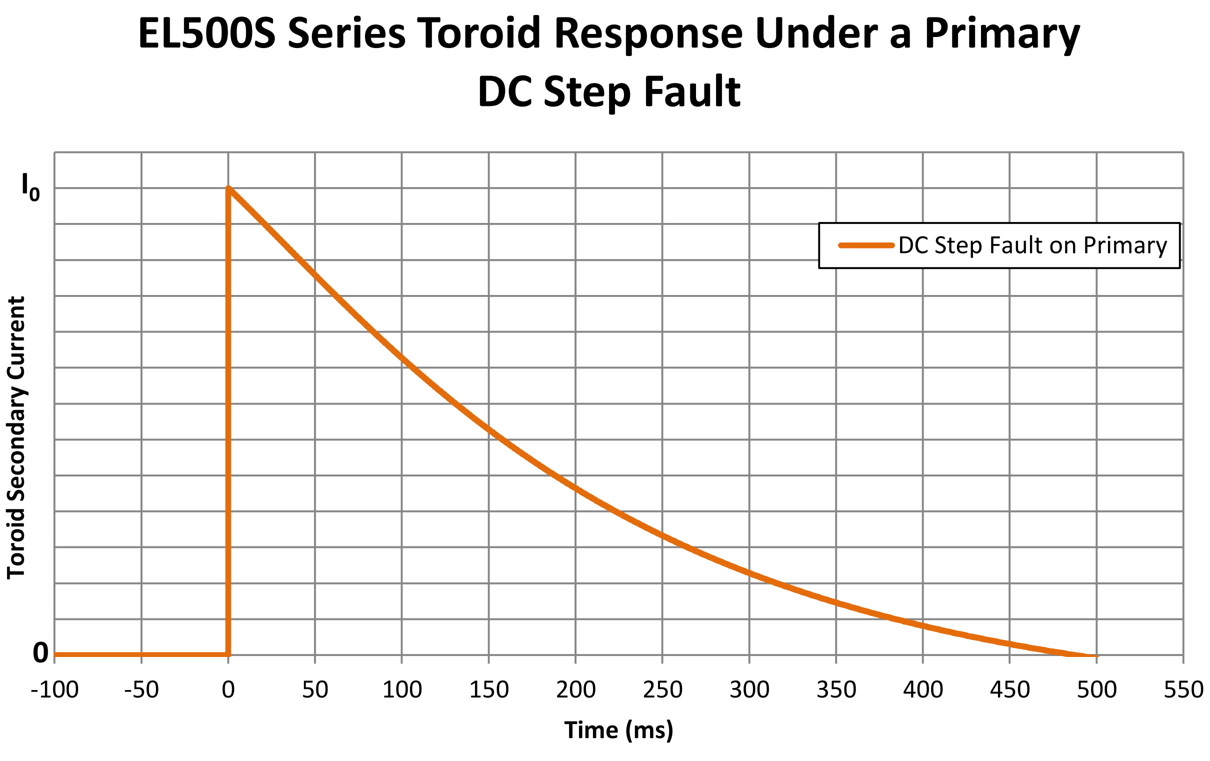

Figure 2: Secondary Reaction of an Ampcontrol EL500S to a DC Step Fault

It can be seen from the above experiment that during a dc step fault, the current induced in the secondary of the toroid initially matches the step current passing through the primary. This induced secondary current decays as the core of the toroid saturates. If the time delay on the relay is less than the duration of the period where the induced current is higher than the set trip level, then the relay would trip on this dc fault.

Observation #2: The initial transient stage of a dc fault can be considered to be a high frequency ac fault. This transient is initially transferred to the secondary of the earth leakage toroid before the core of the toroid saturates. During this period, detection of a pure dc fault using a toroid is possible.

5 Detection of the ac Components of a dc Bus Earth Fault

In all cases, the voltage on a dc bus will not be a pure dc voltage. This is due to the fact that dc buses are supplied by a rectified ac voltage. The rectified supply will result in a voltage ripple on the rails of the bus. The presence of this alternating voltage on the rails of the dc bus will allow a “dc” earth fault to be detected using an earth leakage toroid, if a wideband earth leakage relay is utilised.

The dc bus of a three phase six pulse rectifier will have a 300Hz voltage ripple. For this type of rectifier, a filter is installed on the dc bus to stabilise the differential voltage between the positive and negative voltage rails. The relative amplitude of the bus voltage ripple is then dependent upon the quality of the bus filtering system. It should be noted at this point that the bus filter does **not** stabilise the bus voltage with respect to the earth reference, only with respect to the other voltage rail.

To illustrate this concept, a simulation was performed where an earth fault was introduced onto the positive voltage rail of the dc bus of a VSD with a 6 Pulse Rectifier. Figure 3 shows the circuit for the simulation and Figure 4 displays the voltage and current waveforms associated this simulated fault. It can be seen that, with respect to earth, the voltages on the rails of the bus are not influenced by the rectifier’s filtering capacitor. The current that flows through the earth fault can be seen to be a combination of a dc current and an ac current with a frequency of 150Hz. The ac component of this earth fault is visible to an earth leakage toroid, provided that the dc offset component of the fault does not saturate the earth leakage toroid.

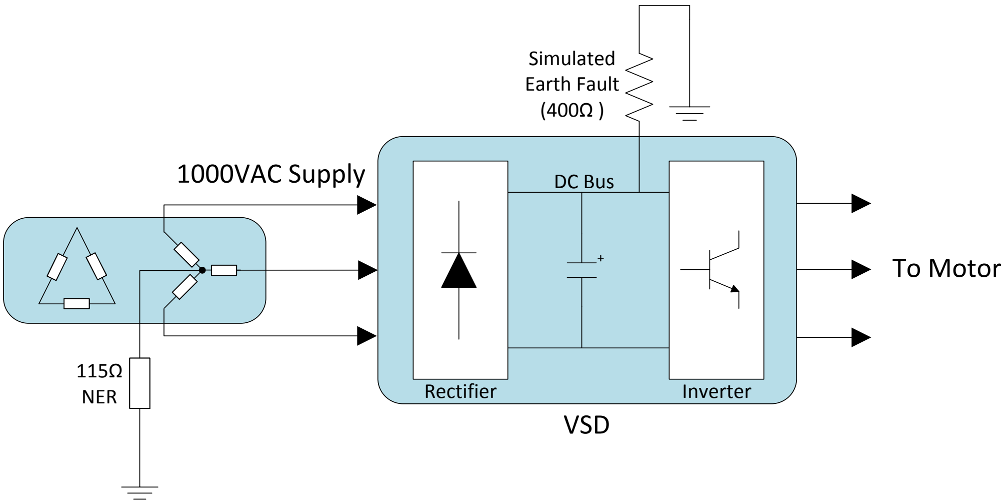

Figure 3: Circuit for a Simulated Earth Fault on the Positive Rail of a 6 Pulse Rectifier’s DC Bus

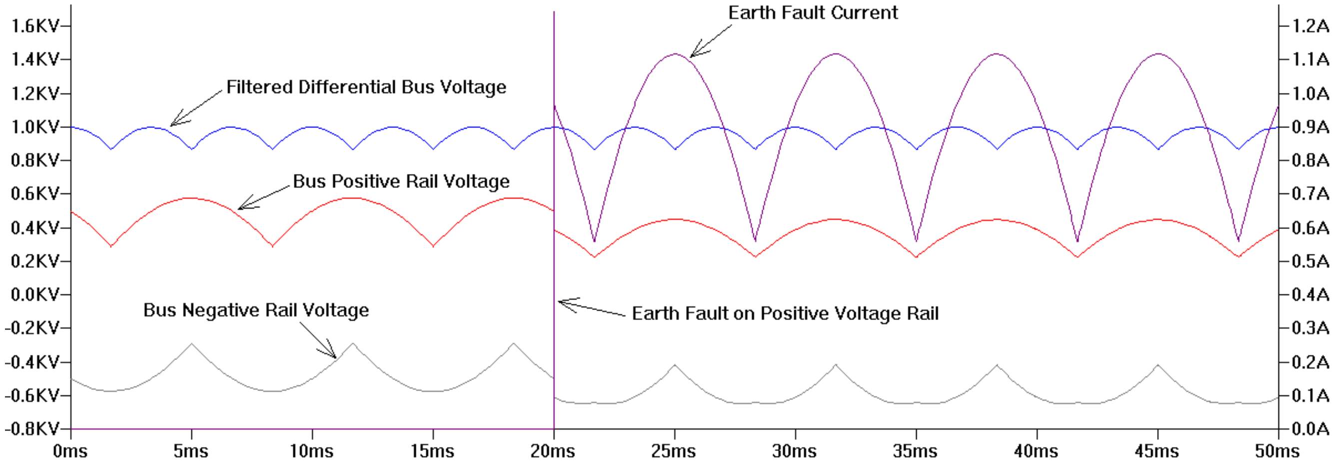

Figure 4: Simulation of an Earth Fault on the Positive Voltage Rail of a 1000VAC Supplied VSD with a 6 Pulse Rectifier

In order to quantify the effects of dc current flowing through an Ampcontrol EL500S series 25mm toroid, an experiment was performed. In this experiment a 150Hz input signal and a dc bias current were passed through the centre of the toroid. As the amplitude of the dc bias current was increased, the sensitivity of the toroid secondary decreased. With 11A of dc bias current flowing through the toroid, it could be seen that the sensitivity of the toroid decreased by approximately 80%. It should be noted that during these tests, the toroid did not completely saturate and the secondary response maintained a linear relationship with the primary input. Figure 5 illustrates the results of this experiment

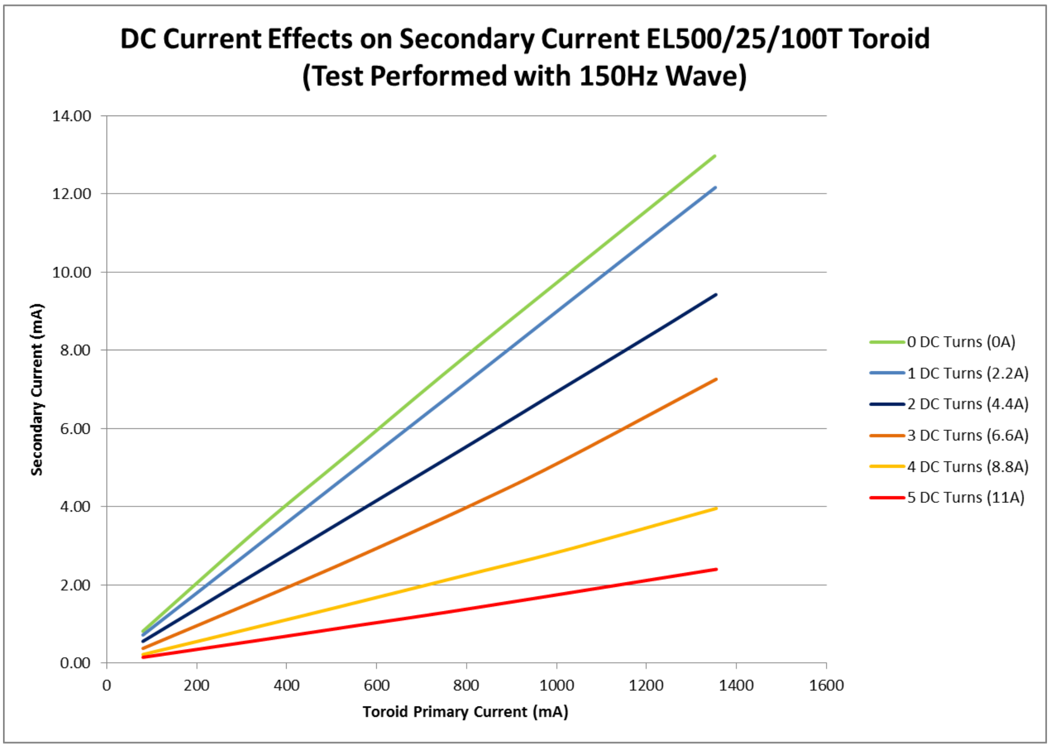

Figure 5: Secondary Reaction of an Ampcontrol EL500S to 150Hz Fault Currents under DC Offset Conditions

As the size of the toroid increases, so does the size of the core. This generally results in greater tolerance of dc bias current, although this depends on the B-H curve of the core material. During additional experimentation, the sensitivity reduction of an EL500S 45mm toroid was measured as 20% at 11A dc, compared to the 80% of the 25mm toroid.

Typically, the earth fault current on Australian mining networks is restricted to 5A. Using the Ampcontrol EL500S 25mm toroid it can be seen will result in a decrease in sensitivity of approximately 30% at this level of dc bias current. It is possible to reduce the drop in sensitivity by increasing the size of the toroid.

NOTE	**Observation #3: The tests performed on the EL500S series of toroids have proven that for the expected range of dc currents within mining installations, the toroids do not completely saturate but rather still give satisfactory results.**

Figure 6 demonstrates that VSDguard's ability to detect faults on a dc bus on a VSD. During an experiment performed at Rockwell's test laboratory in Cambridge, a VSDguard was used to monitor the earth leakage current when a 1.1A restricted fault was applied to the dc bus of a current source inverter VSD. The VSDguard was not wired to trip the supply during the fault, so the fault current is able to be examined in full. During this experiment, the VSDguard used a toroid which was not dc coupled to measure the fault current. At the onset of the fault, the current transient is able to be detected by the VSDguard and the current detected slowly decreases as explained in previous sections. As the transient subsides, the graph shows that the VSDguard is still detecting some fault current. This current is due to the voltage ripple that appears on the dc bus of all VSDs. The final peak seen in the graph is the transient that occurs when the fault is removed from the bus at the conclusion of the experiment.

During this experiment, the VSDguard was set to a trip level of 50mA on the instantaneous time setting. This trip level is represented by a red line on the graph in Figure 6. It is important to note that, although the VSDguard's output contact was not wired in to trip the supply to the drive, the VSDguard did initiate a trip upon detection of the earth fault.

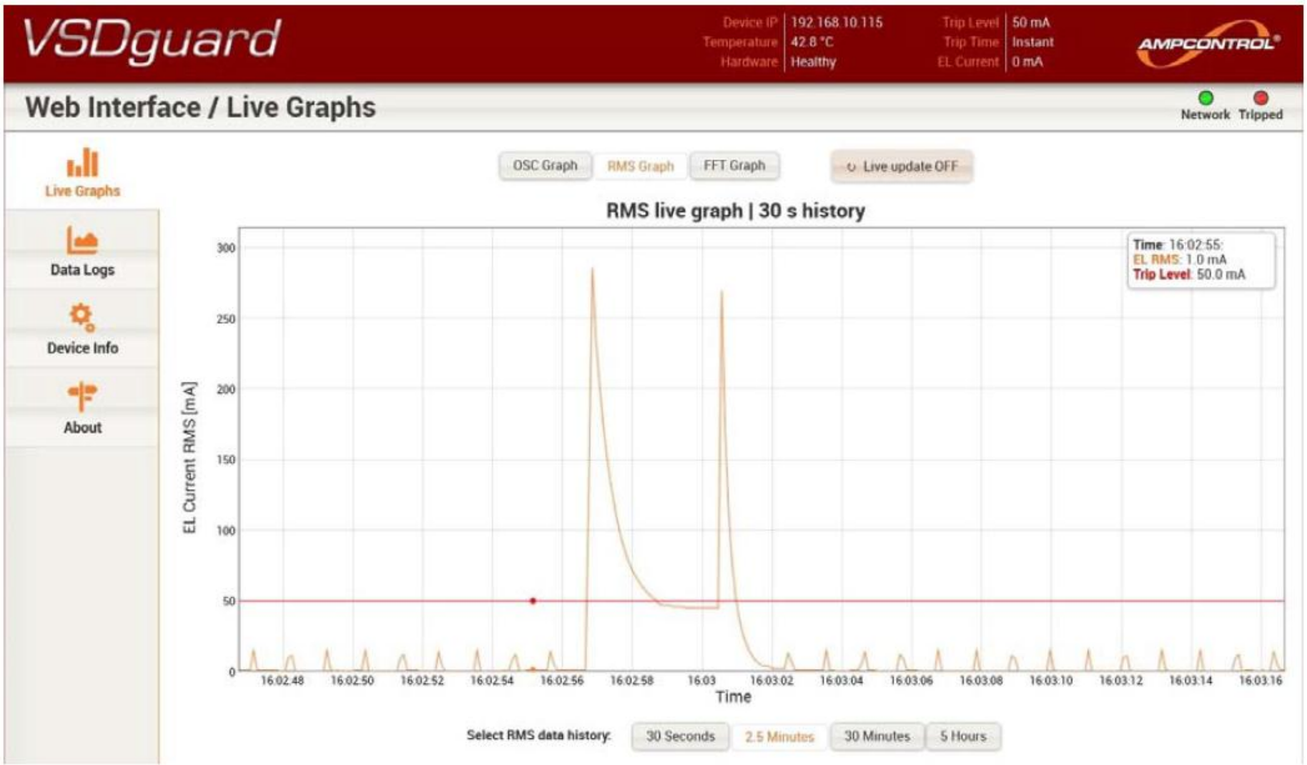

Figure 6: The VSDguard Detects a dc Bus Earth Fault on a Current-Source Inverter Drive during an Experiment Performed at Rockwell Test Laboratory in Cambridge

6 Sensitivity of the Human Body to AC & DC Currents

The standard that outlines the internationally accepted effects of voltage and current on the human body is the IEC60479.1 and IEC60479.2. An excerpt from page 17 of the IEC60479.1:2010 standard states the following:

> *"For shock durations longer than the cardiac cycle, the threshold of fibrillation for dc is several times higher than for ac. For shock durations shorter than 200 ms, the threshold of fibrillation is approximately the same as for ac measured in r.m.s. values."*

Comparing the curves that are presented in IEC60479.1:2010, it is possible to see that for contact durations longer than the cardiac cycle, the human body can withstand several times more dc current than ac current. These curves are presented in Figure 7 and Figure 8.

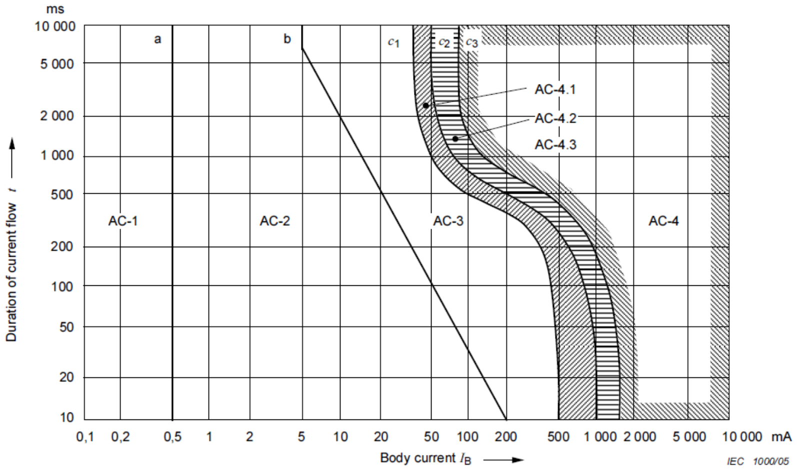

Figure 20 – Conventional time/current zones of effects of a.c. currents (15 Hz to 100 Hz) on persons for a current path corresponding to left hand to feet (for explanation see Table 11)

Figure 7: IEC60479.1 Table Detailing the Probability of Ventricular Fibrillation at AC Currents for a Given Exposure Time

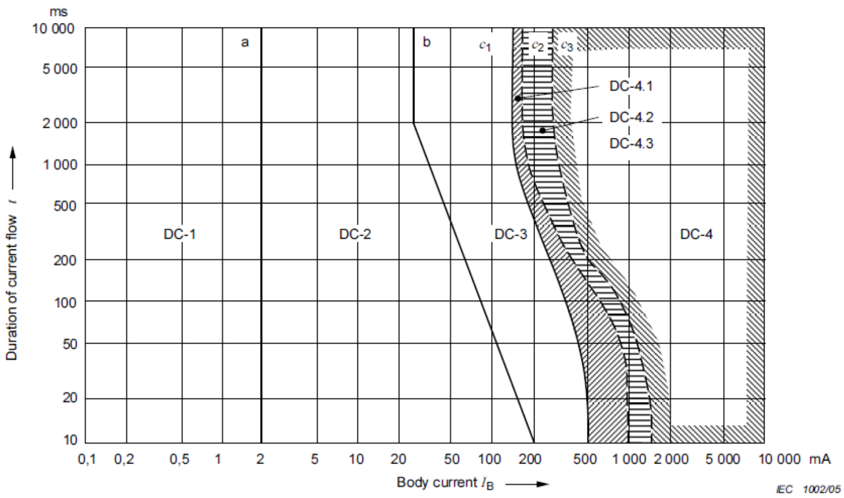

Figure 22 – Conventional time/current zones of effects of d.c. currents on persons for a longitudinal upward current path (for explanation see Table 13)

Figure 8: IEC60479.1 Table Detailing the Probability of Ventricular Fibrillation at DC Currents for a Given Exposure Time

Observation #4: Although the sensitivity of a wideband earth leakage protection relay may be decreased if a dc offset is present on the primary current, the tolerable current for a dc fault during continuous contact is several times that of an ac fault.

7 VSDguard & ELV Relays Detect DC Faults on AC Systems

Throughout the mining industry in Australia, the prevalence of ac-dc-ac variable speed drives is increasing. The installation of these systems requires careful consideration of the implications of the presence of a “dc” bus and high speed switching components. Although a VSD does not fall into the AS2081:2011 category of a “dc supplied system”, it is still necessary to install a protection relay that is capable of detecting a fault on the ac supplied dc bus of the drive.

Traditional narrowband earth leakage relays are unable to detect these dc faults. The high frequency components associated with the switching ripple on the bus and dc step fault transients would be filtered out as “noise” on a narrowband relay.

Ampcontrol’s new range of wideband earth leakage relays provides the solution for detecting these faults. The broad frequency detection range allows the relay to detect initial dc fault transients, as well as the ripple current that exists on the bus of all ac-dc-ac drives. Ampcontrol’s EL500S series of toroids has been proven to continue to provide a linear response curve under dc offset conditions – although a drop in sensitivity can be expected for larger dc currents.

It is financially unfeasible to install a protection system that is capable of providing levels of discrimination for dc earth faults. However, the VSDguard relay and the ELV relay are both capable of detecting the high frequency components associated with a step fault on the dc bus of a drive if the time setting and trip level are set appropriately.

For installations where it is necessary to install a protection relay with the ability to detect slow-onset dc faults, the VSDguard has been designed with an option for dc coupling. This solution involves the use of a dc flux balanced toroid or a shunt connection. Typically this unit would be installed at the NER of the supply. ELV and VSDguard relays would then be installed on individual outlets to provide time discrimination for fast-onset dc faults. Contact Ampcontrol for customised solutions for your installation.