Investigation of Earth Potential Rise on a typical single phase HV network

A report submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering

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1 Abstract
The hazards from Earth Potential Rise (EPR) at existing distribution steel poles installed in a rural farming property were investigated. Different fault scenarios were identified as part of the project. The software package CDEGS was used to determine conservative allowable voltage criteria for the various fault scenarios and applicable fault clearing times. Touch voltages modelled in CDEGS were all below the allowable voltage criteria for the different size fault currents at all fault locations. Risk was calculated to quantify the hazard. The hazard from EPR can be considered low and the risk can be categorised as negligible.

Voltages were modelled in CDEGS to assess the impact on animals, especially cattle. These voltages were also below the tolerable voltage criteria for the different fault scenarios, hence no mitigation was required.

A safety analysis on the transfer to the Transmission Distribution -Multiple Earth Neutral (TD MEN) using the ARGON software package indicates that at the steel poles which have distribution transformers, the probability of fatality is already below 1 in 1,000,000 and can be further reduced by the installation of 6m deep earth rods adjacent and bonded to the steel poles.

A study on increased generation caused increased fault currents which increased EPR levels causing a breach of allowable voltage limits and therefore creating a potential hazard at the site.

Transmission level faults at the zone substation did not have an unsafe impact at the site.
2 Acknowledgements

I would like to thank my project supervisor, Dr Gregory Crebbin (Murdoch University) for his enthusiasm and supervision of this thesis project. I would also like to acknowledge Western Power for their continuous support throughout my university studies.
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LIST OF ACRONYMS

CDEGS – Current distribution, electromagnetic fields, grounding and soil structure analysis software package.

EPR – Earth potential rise

MV – Medium voltage (22kV)

HV - High voltage (22kV)

LV – Low voltage (415V)

TD MEN – Transmission Distribution Multiple Earth Neutral

SESCAD – Safe Engineering Services Computer Aided Design

XS'' – Generator Sub-transient Reactance

FL – Fault Level

ABB – Asea Brown Boveri

ENA – Energy Networks Association

E/F – Earth fault

TMS – Time Multiplier Setting

VI – Very Inverse

IEEE – Institute of Electronic and Electrical Engineers
3 Introduction
This thesis investigates fault events on a model of a typical single phase spur on an overhead high voltage distribution network. An Earth Potential Rise (EPR) study is conducted using the Current Distribution, Electromagnetic fields, Grounding and Soil structure analysis software package (CDEGS) and a safety/risk analysis done on the EPR levels with the use of the ARGON software. DlgSILENT’s Power Factory is used to calculate the existing network fault current levels for the specified single phase spur. A three phase synchronous generator is added to the grid to see the impact on network fault currents and EPR.

3.1 The death of a policemen horse
In 2011 a Policeman’s horse died after walking past a light pole in Kalamunda. Energy safety staff examined the light pole which was thought to be linked to the death of the police horse (Cox 2011). The investigation is ongoing to date. If the light pole was at fault then the death of the horse could have been caused by ventricular fibrillation of the horse’s heart due to Step Potential which is relatively large due to the stride distance of the EPR rise.

3.2 Purpose
This document captures the information, assumptions, and calculations used to perform earthing assessment at accessible conductive points located in the vicinity of MV earths introduced and/or affected as a consequence of steel poles as distribution poles
The main aim of this report is to investigate hazards to the general public and animals from EPR (Earth potential rise) around steel poles.
4 Background

4.1 Earthing of a single phase network

Earthing is used as a means of protection on electrical utility's assets as well as a means of ensuring safety to humans and animals. When a fault occurs in a network the majority of the fault current is diverted into the ground and source (generator) via an earthing conductor. The earthing system is used to detect fault currents so that protection equipment such as fuses and reclosers can operate and clear the fault.

Western Power operates a Single Phase Earth Conductor (SPEC) configuration for its single phase networks. Single phase networks are only used in areas where loads are small and far apart, such as rural or semi rural areas, which includes farm properties.

In this configuration no neutral wire is run for the return of normal load current. Instead, an earth wire is used as a return path for normal load current as well as earth fault current.

4.2 Generation

Generation is directly proportional to network fault levels. As generation is increased, say by the addition of generators on the network either by the network operator or a private entity, so are the fault levels on that network. This increase on fault levels can cause an increase in EPR levels which can then have a negative impact on the safety of humans and/or animals as will be discussed in the chapters to come where the addition of a synchronous generator on the network is modeled. There are two main types of generators in use in large power systems. These are synchronous generators and induction generators.

4.2.1 Synchronous machines

Synchronous machines require the rotor to spin at a fixed speed which is relative to the frequency of the power grid (WesternPower 2011).
A synchronous generator can control its output voltage by changing the amount of current fed into the rotor winding. This method of voltage control has been the most cost effective in the history of generation. For this reason almost all generators are synchronous machines (WesternPower 2011). When there is a fault on the system, there is a rapid change in operation that creates a short-term difference between rotor speed and voltage frequency. This effect can be modelled by a different reactance called a sub-transient reactance, $X_{S''}$ (Crebbin 2009). This reactance is usually smaller in value than the synchronous reactance, and leads to larger initial fault currents. Generator fault capability is usually measured by a generator's fault level. This is the current supplied by the generator when the terminals are short-circuited. A per phase impedance diagram for this short circuit is shown below.

![Figure 4-1 - short circuit single line diagram (Crebbin 2009)](image)

The internal voltage is the line to line voltage and therefore the fault level is defined as

$$FL = \sqrt{3} V_{nom} I_f \quad (MVA)$$

where $I_f$ is the fault current, which, from figure 4-1, is given by

$$I_f = \frac{V_{nom}}{\sqrt{3} X_5}$$

Alternatively, if the fault level is specified for a generator, then its sub-transient reactance is given by
4.2.2 Induction machines

Induction generators can be divided into three categories. These are fixed speed generators, Doubly Fed semi-variable speed generators and full variable speed generators (ABB 2013).

Induction generators are used for wind power systems. The variable differences between rotor and stator frequencies can be used to moderate the variable speed of the wind (WesternPower 2011).

Induction generators are not covered further in this report.

4.3 Faults

A fault on a power system is caused by a breakdown of insulation between the main electrical conductor(s) causing an interruption to normal power flow (WesternPower 2011). This insulation could be anything from air for an overhead line to the XLPE insulation layer of an underground power cable. A typical case of a fault to an overhead power line is when a vehicle crashes into a power pole and, as a consequence, the live conductor(s) fall to earth hence causing a short circuit fault i.e. insulation (gap) is removed. In order to avoid damage to the rest of the network, the faulted components are usually disconnected by ‘protection devices’ which consist of relays, circuit breakers and fuses.

Some other factors that may cause the insulation to breakdown are (WesternPower 2011):

• Temporary over-voltages on the power system, caused by system resonance, lightly loaded circuits etc.

• Atmospheric conditions, such as lightning, wind, bush fires etc.

• Pollution forming a current leakage path across exposed insulator pins
• Vermin (parrots are known to eat the insulation from an overhead High Voltage Aerial Bundled Conductor (HV ABC))
• Equipment failure due to old and outdated equipment
• Human error (incorrect switching during a scheduled switching operation)

Short circuit faults in a power system can be categorised into either balanced faults or unbalanced faults.

4.3.1 Balanced fault
A balanced three-phase fault occurs when all of the three phases of a power network are short circuited. In these faults the fault current flows through the conductors only and does not flow through ground, hence all three phases are affected evenly by the fault. A three-phase fault on a system generally causes the greatest amount of disruption to the power system. This is because the short-circuit disturbs all of the three phases (WesternPower 2011). These types of faults are very rare in a power system as all three phases are usually spaced apart in an overhead network. Bays, also known as a section of overhead conductor between two distribution power poles are kept short in order to stop conductors from clashing into each other. Over head LV networks use spacers which are placed at the centre of a bay to stop conductors from moving and clashing due to winds. A spacer is a non-conductive long stick which is placed perpendicular to and on top of the overhead LV wires.

4.3.2 Unbalanced fault
An unbalanced fault occurs when fault currents flow unevenly through the phases. The most common kind of unbalanced fault is a ‘single-phase to ground’ fault. Other less common types of unbalanced faults are ‘two phase to ground’ faults and ‘two phase short circuit to ground’ faults. A common example of a single phase to ground fault is when a tree trunk falls on one of the phase conductors of an overhead network hence causing the conductor to break and fall to ground.
Single phase to ground faults can be intermittent, such as between trees and a phase conductor during high wind conditions. Intermittent faults are seen but ignored as they usually clear themselves hence the term intermittent. If however the fault event persists, then the protection device will usually clear the fault by isolating that particular section so that the cause of the fault can be determined and removed.

4.3.3 Network impedance
The total fault current in a network is a contribution of currents from all the generation sources as well as the stored energy in the magnetic fields of some motors.

The impedance of a typical network increases with the installed length of conductors. If a fault occurs far from the source, this will result in a smaller short circuit current at the faulted location due to the large network impedance. Conversely, if a fault occurs close to the source/generation, the fault current at the faulted location will be very large due to the smaller impedance at this point. Ohms law is the basis to this effect because the voltage is constant and so the fault current is inversely proportional to the network impedance.

When HV networks undergo maintenance due to poor conductors, or if the network capacity needs to be expanded due to increased loads, the distribution conductors are usually upgraded in order to allow for larger load currents to flow. New conductors have reduced impedances. Reduced impedances in a network reduce network losses but also cause an increase in the fault currents. This can be a problem, as will be detailed in the following sections of this report.
5 Network modeling approach

5.1 Software packages

5.1.1 DlgSILENT PowerFactory

This software is a digital simulation and Network calculation package. It is used for the analysis of industrial, utility, and commercial electrical power systems (DlgSILENT 2013). Version 14.0.525.1 of the software was used in this project. Some of the functions of the software include (DlgSILENT 2013):

- Load Flow Calculation
- Short-Circuit Calculation
- Harmonics Calculation
- Network Reduction
- Parameter Identification

The Short-Circuit Calculation function of PowerFactory was used to define the fault currents at several locations along the single phase spur line, shown in figure 5-2.

The actual HV network was extracted from the Western Power database and was imported into the software. Single phase to ground faults were simulated at 3 sections of the spur line. Faults were simulated at:

- Start of spur line
- Centre of spur line
- End of spur line

Figure 5-1 summarises the calculated fault current size with respect to the fault location along the spur line. Fault currents are averaged out to three sizes for simplification.
5.1.2 CDEGS
The CDEGS software package was developed by Safe Engineering Services and Technologies Ltd (SESTech) for the purposes of accurately analysing problems such as grounding, electromagnetic fields and electromagnetic interference (SESTech 2013). The following functions of the CDEGS software were used for this project:

- RESAP – Used for Soil Resistivity Analysis
- SESCAD – Used for drawing/modeling the earthing network
- HIFREQ – Electromagnetic Fields Analysis for the network (for overhead objects)
- MALZ – Frequency Domain Grounding / Earthing Analysis (for underground objects)

CDEGS was used to calculate Earth Potential Rise, Step Voltage, Touch voltage, Transfer Voltage as well as the Allowable Voltage limits, which will be discussed in the upcoming chapters of this report.

5.1.3 ARGON
ARGON is produced by the Network Earthing Development team of Ausgrid and will be used in conjunction with the EG0, a power system earthing guide that was developed by the Energy Networks Association (Ausgrid 2013). ARGON is used to calculate the probabilities of fibrillation as well as the probabilities of fatality to a human being. This software will be used in Section 8.2.1 of this report.
5.2 **Project background**
The steel poles are located on various farms. Figure 5-2 shows the site area layout and locations of steel poles. An earthing analysis was carried out to determine the impact on safety in the vicinity of the steel poles.

No further upgrade and/or reconfiguration work directly upstream of the project location are known at the time this study was carried out. Soil resistivity information was based on soil resistivity measurements that were done at two separate locations in the surrounding area.

![Figure 5-2 - Site plan with steel pole locations](image)

5.3 **Assumptions and information**
Faults at the transmission level have not been considered for this report.

The soil model was considered to be alike for all locations as well as the zone substation location. Any assessment done in this document is based on information available at the time of study. Whilst reasonable care has been taken in compiling the report and design assessment, the recommendations are believed to be conservative.
5.4 Protection data
The protection information is summarised in table 5-1 below. This information was sent by the Western Power Distribution Network Planning Section.

Table 5-1 - Protection settings

<table>
<thead>
<tr>
<th>Closest upstream protection for unfused earth location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection equipment</td>
</tr>
<tr>
<td>Location</td>
</tr>
<tr>
<td>E/F Pickup current (A)</td>
</tr>
<tr>
<td>Time multiplier settings (TMS)</td>
</tr>
<tr>
<td>Time current characteristics</td>
</tr>
</tbody>
</table>

5.5 Soil resistivity
Before undertaking a detailed design or assessment of a new or existing earthing system or earthing point, it is necessary to determine the electrical characteristic of the soil. This is done through a series of measurements. Soil resistivity measurements are taken by injecting current into the earth between two outer electrodes and measuring the resulting voltage difference between two potential probes placed along a straight line between the current-injection electrodes.

The electrical properties of the earth are commonly characterised by its resistivity, $\rho$, or the resistance measured between two opposite faces of a one metre cube of earth (Figure 5-3), expressed in $\Omega \cdot m$ (Markiewicz 2004).

Figure 5-3 - Physical sense of earth resistivity (Markiewicz 2004)
Earth resistivity varies not only with the type of soil, but with moisture, temperature, salt content and compactness (see Figure 5-4). Usually in a section of earth, there are several layers, each having a different resistivity. Lateral changes may occur, but usually these are so gradual that they can be ignored because of its unpredictable behaviour. Resistivity is usually expressed and modelled as a function of depth. (IEEE 2012)

![Figure 5-4 - Effects of added salt, moisture and temperature on soil resistivity](IEEE 2012)

Typical values for the resistivity of different kinds of soils are provided in Figure 5-5 and should serve only as an approximation to the resistivity of soil at given site. Further testing should always be carried out to determine the true resistivity of the soil and the depth at which these resistivities start to change.
5.5.1 Methods of soil resistivity testing

There are two main methods for measuring soil resistivity - The Wenner Method and the Schlumberger Method (IEEE 2012). The equipment is the same for both methods. Four stakes are driven into the soil, all at depth ‘b’ and at intervals ‘a’. A test current is passed between the two outer electrodes and the voltage is measured between the inner electrodes. The apparent resistance is calculated by dividing the measured voltage by the current injected.
Wenner Method (IEEE 2012):

Electrodes are equally separated by a distance ‘a’. Then the resistivity in terms of the length units in which ‘a’ and ‘b’ are measured is:

$$\rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

If ‘b’ is small, then the formula becomes:

$$\rho = 2\pi aR$$

A rule of thumb is that *approximately* the average resistivity of the soil to the depth ‘a’ is given by a stake separation of ‘a’. The Wenner array is easy to apply and interpret but is the less effective of the two methods from an operational perspective. It requires the longest cable layout, largest electrode spreads, and because all four electrodes are moved simultaneously, it is more vulnerable to lateral variation effects (AS/NZS 2006). Spacing can be done up to approximately 150m between stakes before interference between test leads becomes a concern.

![Figure 5-6 - Wenner Method (Danieleccc 2011)](image)

Schlumberger Method (IEEE 2012)

This method can be used when low potential readings are obtained with the Wenner method. Potential probes are brought nearer to the corresponding current electrodes.

If the depth of burial of the electrodes ‘b’ is small compared to their separation ‘a’ and ‘c’, then the measured resistivity can be calculated as follows:

$$\rho = \frac{\pi(c + a)R}{a}$$
5.5.2 Soil resistivity test equipment

The soil resistivity testing was done with the AEMC Model 6472 Ground Resistance Tester (see figure 5-8). This device is designed to measure Bond Resistance, Ground Resistance, Soil Resistivity, Earth Coupling and Step & Touch Potential (AEMC 2013).
5.5.3 Soil resistivity test results

Four Soil Resistivity Tests were carried out. Tests 1 and 2 were conducted next to each other and Tests 3 and 4 were conducted together but at a good distance from the location of Tests 1 and 2. The RESAP soil model plots are shown in the appendices. The following set of tables shows the test results.

Table 5-2 - Soil resistivity Test 1 Results

<table>
<thead>
<tr>
<th>Rod Spacing (m)</th>
<th>Resistance (Ohm)</th>
<th>Resistivity(Ohm.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>418</td>
<td>525.3</td>
</tr>
<tr>
<td>0.4</td>
<td>92.1</td>
<td>231.5</td>
</tr>
<tr>
<td>1</td>
<td>9.95</td>
<td>62.5</td>
</tr>
<tr>
<td>2</td>
<td>3.81</td>
<td>47.9</td>
</tr>
<tr>
<td>4</td>
<td>1.97</td>
<td>49.5</td>
</tr>
<tr>
<td>8</td>
<td>1.08</td>
<td>54.3</td>
</tr>
<tr>
<td>16</td>
<td>0.93</td>
<td>93.5</td>
</tr>
<tr>
<td>32</td>
<td>0.85</td>
<td>170.9</td>
</tr>
<tr>
<td>64</td>
<td>1.41</td>
<td>567.0</td>
</tr>
</tbody>
</table>

Table 5-3 - Soil resistivity Test 2 Results

<table>
<thead>
<tr>
<th>Rod Spacing (m)</th>
<th>Resistance (Ohm)</th>
<th>Resistivity(Ohm.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>366</td>
<td>459.9</td>
</tr>
<tr>
<td>0.4</td>
<td>59.2</td>
<td>148.8</td>
</tr>
<tr>
<td>1</td>
<td>19.39</td>
<td>121.8</td>
</tr>
<tr>
<td>2</td>
<td>3.52</td>
<td>44.2</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>35.2</td>
</tr>
<tr>
<td>8</td>
<td>0.98</td>
<td>49.3</td>
</tr>
<tr>
<td>16</td>
<td>0.99</td>
<td>99.5</td>
</tr>
<tr>
<td>32</td>
<td>1.24</td>
<td>249.3</td>
</tr>
<tr>
<td>64</td>
<td>1.18</td>
<td>474.5</td>
</tr>
</tbody>
</table>
Table 5-4 - Soil resistivity Test 3 Results

<table>
<thead>
<tr>
<th>Rod Spacing (m)</th>
<th>Resistance (Ohm)</th>
<th>Resistivity (Ohm.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>366</td>
<td>459.9</td>
</tr>
<tr>
<td>0.4</td>
<td>92.2</td>
<td>231.7</td>
</tr>
<tr>
<td>1</td>
<td>63.1</td>
<td>396.5</td>
</tr>
<tr>
<td>2</td>
<td>26.2</td>
<td>329.2</td>
</tr>
<tr>
<td>4</td>
<td>5.58</td>
<td>140.2</td>
</tr>
<tr>
<td>8</td>
<td>1.51</td>
<td>75.9</td>
</tr>
<tr>
<td>16</td>
<td>0.17</td>
<td>17.1</td>
</tr>
<tr>
<td>32</td>
<td>0.2</td>
<td>40.2</td>
</tr>
<tr>
<td>64</td>
<td>0.25</td>
<td>100.5</td>
</tr>
</tbody>
</table>

Table 5-5 - Soil resistivity Test 4 Results

<table>
<thead>
<tr>
<th>Rod Spacing (m)</th>
<th>Resistance (Ohm)</th>
<th>Resistivity (Ohm.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>370</td>
<td>465.0</td>
</tr>
<tr>
<td>0.4</td>
<td>107</td>
<td>268.9</td>
</tr>
<tr>
<td>1</td>
<td>57.5</td>
<td>361.3</td>
</tr>
<tr>
<td>2</td>
<td>30.6</td>
<td>384.5</td>
</tr>
<tr>
<td>4</td>
<td>4.94</td>
<td>124.2</td>
</tr>
<tr>
<td>8</td>
<td>0.37</td>
<td>18.6</td>
</tr>
<tr>
<td>16</td>
<td>0.13</td>
<td>13.1</td>
</tr>
<tr>
<td>32</td>
<td>0.08</td>
<td>16.1</td>
</tr>
<tr>
<td>64</td>
<td>0.16</td>
<td>64.3</td>
</tr>
</tbody>
</table>

Table 5-6 below shows the 3 layer soil model produced by RESAP. All 4 soil resistivity tests were combined in the RESAP module of CDEGS in order to produce the 3 layer soil model.

Table 5-6 - CDEGS 3 layer soil model

<table>
<thead>
<tr>
<th>Recommended model:</th>
<th>Impedance (ohm.m)</th>
<th>Layer thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top layer</td>
<td>348</td>
<td>0.4</td>
</tr>
<tr>
<td>Middle layer</td>
<td>23</td>
<td>41</td>
</tr>
<tr>
<td>Bottom layer</td>
<td>173</td>
<td>infinite</td>
</tr>
</tbody>
</table>
5.6 **Modeling of Zone Substation**

The Zone Sub earth grid was originally modelled in MALZ as a single rod with a depth of 400m into the ground in order to attain 0.5 $\Omega$ for the total resistance of the zone substation earth grid. This rod was then modelled in SESCAD for analysis in HIFREQ.

The actual Zone sub earth grid file which was produced for the design of the Zone substation was imported into this model for comparison with the 400m single stake. Figure 5-9 shows the zone substation earth grid in 3D.

The touch voltages at several locations were analysed for both the actual Zone sub earthing file and the 400m earth rod. No difference in touch voltage at the single phase spur was observed for the two cases. The reason for this may be to do with the Zone sub being located over 63km from this single phase spur.

*Figure 5-9 - Zone Substation earthing grid SESCAD model*
5.7  **SESCAD Line model**
Table 5-7 summarizes the asset specifications as modeled in SESCAD. Wooden pole down earths were simulated at an average of every 450m. This means that down earths were installed at every second or third pole. Table 5-8 shows the average bay lengths for the different conductor types where steel poles are installed.

<table>
<thead>
<tr>
<th>Impedance specification</th>
<th>Relative Resistivity</th>
<th>Relative permeability</th>
<th>Internal Radius (m)</th>
<th>Identification</th>
<th>Radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Copper Earth rods</td>
<td>0.0075</td>
</tr>
<tr>
<td>Computed</td>
<td>13</td>
<td>1</td>
<td>0.13015</td>
<td>steel poles</td>
<td>0.13655</td>
</tr>
<tr>
<td>Computed</td>
<td>1.64</td>
<td>1</td>
<td>0</td>
<td>7/4.75 AAAC</td>
<td>0.00715</td>
</tr>
<tr>
<td>Computed</td>
<td>13</td>
<td>1</td>
<td>0</td>
<td>SCAC conductor</td>
<td>0.00295</td>
</tr>
<tr>
<td>Computed</td>
<td>5.7</td>
<td>1</td>
<td>0</td>
<td>Fe conductor</td>
<td>0.002625</td>
</tr>
<tr>
<td>Computed</td>
<td>13</td>
<td>1</td>
<td>0.1315</td>
<td>steel poles</td>
<td>0.137</td>
</tr>
<tr>
<td>Computed</td>
<td>1.64</td>
<td>1</td>
<td>0</td>
<td>aluminium conductor</td>
<td>0.00375</td>
</tr>
</tbody>
</table>

**Table 5-8 - Single phase spur steel pole average bay lengths**

<table>
<thead>
<tr>
<th>Conductor type</th>
<th>Average bay length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/4.75 AAAC</td>
<td>175</td>
</tr>
<tr>
<td>3/2.75 SCAC</td>
<td>120</td>
</tr>
</tbody>
</table>
5.8  **Fault clearing time**

The fault clearing times of the upstream protection device for fault currents of 200A, 100A and 40A were calculated by using the IEC Very Inverse Curve Equation which is shown below. The protection data from table 5-1 is used for this calculation.

\[
T = \frac{13.5}{\frac{If}{IpU} - 1} \times TMS
\]

where,

\(T\) = Fault clearing time  
\(If\) = Fault current  
\(IpU\) = Pickup current  
\(TMS\) = Time Multiplier Setting

Table 5-9 shows the calculated fault clearing times for the three different fault currents that were derived from the Power Factory model.

<table>
<thead>
<tr>
<th>Fault current (A)</th>
<th>200</th>
<th>100</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault clearing time (s)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>
### 6 Faults and hazard scenarios

Three risk scenarios have been identified for single phase networks. The first two are the risks of step and touch voltages at the equipment pole sites at the time of an earth fault. The third, a more onerous risk, is that of direct transfer onto the LV neutral in the event of an earth fault (TD MEN).

Single phase to earth faults were simulated in SESCAD at locations indicated in figure 6-1. Three different fault currents and clearing times as per table 5-9 were considered for the fault locations. Faults at the beginning of the single phase spur were considered to be 200A, faults at the middle of the spur to be 100A and faults at the end of the spur to be 40A. The applicable hazard scenarios are shown in Table 6-1.

![Figure 6-1 – SESCAD – simulated fault locations](image)
### Table 6-1 – Hazard scenario table

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Hazard scenario</th>
<th>Contact scenario</th>
<th>Applicable limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Step-Touch voltages at contact point between the earth and metallic pole</td>
<td>Operator and public contact with metallic pole</td>
<td>EG0 2010</td>
</tr>
<tr>
<td>2. see figure 6-3</td>
<td>Step voltages between two points on the earth’s surface that are 2m distance from each other</td>
<td>Animal (cattle) step voltage</td>
<td>AS/NZS 60479.3:2002</td>
</tr>
<tr>
<td>3.</td>
<td>Direct transfer onto the LV neutral in the event of an earth fault (TD MEN).</td>
<td>Contact with household assets connected to the MEN. (e.g. taps)</td>
<td>EG0 2010</td>
</tr>
</tbody>
</table>

### 6.1 Allowable voltage criteria (Human Beings)

Table 6-2 below shows the conservative allowable touch voltages for the different fault currents. The allowable touch voltages were calculated as per the IEC fibrillation current curve (C1) in CDEGS. Section 5.5 of AS60479.1 2010 states that the “C1 curve was established for a current path left hand to both feet, below which fibrillation is unlikely to occur. On and above this curve the chances of ventricular fibrillation increases” (AS/NZS 2010), which is unacceptable. For this reason the allowable touch voltages were calculated as per the C1 curve. Refer to figure 13-2 and Table 13-3 for the C1 curve and explanation respectively.
Table 6-2 – Allowable voltage Limits for different fault currents

<table>
<thead>
<tr>
<th>Safety Calculations Table</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault current (A)</td>
<td>200</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>Fault clearing time (s)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Allowable Touch Voltage (V)</td>
<td>373.6</td>
<td>335.1</td>
<td>78</td>
</tr>
<tr>
<td>IEC Standard Revision</td>
<td>2005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibrillation Current Calculation</td>
<td>IEC C1 curve</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent of Hand-to-Hand Resistance</td>
<td>75% (hand to 2 feet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body Resistance Exceeded by</td>
<td>95% of population</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface layer</td>
<td>No surface layer installed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.2 **Allowable voltage criteria (Cattle)**

Voltage differences in the vicinity of the steel poles had to be analysed for the effect of EPR on cattle, as most farms have cattle. Curves used in the study were compiled for calves only, and can be considered as conservative.

The minimum fibrillation current for a calf for a duration of 3 seconds is 0.31 A (AS/NZS 2002). The total body impedance used for this analysis was 850 Ω for current path from forelegs to hind legs as per Table 2 of AS/NZS 60479.3:2002(refer to section 13 of this report for Table 2). Figure 6-2 below illustrates the current path circuit (ENA 2010). Figure 6-3 shows a typical animal step voltage scenario.

The impedance of the top layer soil is considered conservative and is derived from IEEE 80 – 2000 – Guide for Safety in AC Substation Grounding (IEEE 2000).

![Figure 6-2 – prospective step voltage circuit (ENA 2010)](Image)
Figure 6-3 - 2m Step voltage for a calf

where,

Vsp – Prospective Step voltage
Zb – body impedance = 850 Ω
Zss – shoe resistance = 0
Zcs – impedance of top layer soil = 6 x ρ (top soil) = 6 x 348.87 (IEEE 2000)
Ib – 3sec current that will cause fibrillation = 0.31A

The prospective step voltage can be calculated as following;

\[ Vsp = Ib (Zb + Zss + Zcs) \]
\[ Vsp = 0.31(850 + (6 \times 348.87)) \]
\[ Vsp = 912 \text{ V} \]
7 Effects of an increase in the Earth Fault pick up current

Earth fault pick up current on the protection device may increase due to future increases in the load hence requiring the installation of additional transformers. This will cause an increase in the fault clearing times which will then decrease the allowable voltage limits.

Table 7-1 shows the effect on fault clearing times when the pickup current is increased from the original 15A to a new value of 20A, which is typical of a load increase. The results were obtained with the use of the IEC very inverse curve equation (SchneiderElectric 2013) which is shown again below for convenience.

\[ T = \frac{13.5}{\frac{I_f}{I_{pu}}} \times T_{MS} \times 1 \]  
(SchneiderElectric 2013)

<table>
<thead>
<tr>
<th>Effects of an increase in the E/F pick up current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault current (A)</td>
</tr>
<tr>
<td>Fault clearing time (s)</td>
</tr>
<tr>
<td>Allowable Touch Voltage (V)</td>
</tr>
</tbody>
</table>
8 Results
This section will summarize the results for the following events:

- Touch and Step voltages for Humans and Cattle
- TD MEN levels for Humans
- Risk/cost analysis for the Reduction of the Transferred voltages to acceptable levels
- Effects of increased generation
- Effects of a transmission level fault at the zone substation

8.1 Touch and Step Voltages
Table 8-1 shows the maximum touch voltage for fault currents of 200A, 100A and 40A. These faults have been simulated at several different locations within the site of the project. Refer to Figure 5-1 for the likely fault current magnitude with respect to the location within the spur and also for a visual location of these faults. It can be seen that the maximum touch voltage of 308.9V occurs at location A for a 200A fault. However, this is still below the safety threshold limit of 373.6V. Fault location H has the highest touch voltage of 178.6V for a 100A fault. The highest touch voltage for a 40A fault occurs at locations E and F of 47.9 and 47.8 respectively. These voltages again are below the specified allowable voltage limit of 78V.

Table 8-2 shows the maximum 2m step voltages for a calf. A maximum step voltage of 352.2V occurs for a 200 Amp fault at location A. This step voltage is below the safety threshold limit of 912V.
### Table 8-1 - reach Touch voltages at different fault locations

<table>
<thead>
<tr>
<th>Fault location</th>
<th>Allowable Voltage limit (V)</th>
<th>1m Reach touch voltage at steel pole</th>
<th>1m Reach touch voltage at Wood pole down earth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>200A fault</td>
<td>100A fault</td>
</tr>
<tr>
<td>A</td>
<td>373.6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>373.6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>C</td>
<td>335.1</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>78</td>
<td></td>
<td>6.9</td>
</tr>
<tr>
<td>E</td>
<td>78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>78</td>
<td></td>
<td>47.8</td>
</tr>
<tr>
<td>G</td>
<td>335.1</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>H</td>
<td>335.1</td>
<td></td>
<td>178.6</td>
</tr>
</tbody>
</table>

The values highlighted in green correspond to the touch voltage at the faulted structure. The size of the fault current is determined by the location of the fault on the single phase spur. Refer to figure 5-1 for a summary of the fault sizes with respect to location.

### Table 8-2 - 2m step voltages for calves at fault locations adjacent to poles

<table>
<thead>
<tr>
<th>Fault location</th>
<th>Allowable Voltage limit (V)</th>
<th>2m step voltage for calves adjacent to pole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>200A fault</td>
</tr>
<tr>
<td>A</td>
<td>912</td>
<td>352.2</td>
</tr>
<tr>
<td>B</td>
<td>912</td>
<td>154.1</td>
</tr>
<tr>
<td>C</td>
<td>912</td>
<td>21.6</td>
</tr>
<tr>
<td>D</td>
<td>912</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>912</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>912</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>912</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>912</td>
<td></td>
</tr>
</tbody>
</table>
8.2 Transmission Distribution Multiple Earth Neutral (TDMEN)

TD MEN is contact with Multiple Earth Neutral (MEN) connected metalwork (around a house) where the MEN or soil is affected by either Transmission or Distribution assets (ENA 2010).

The EPR transfer to the MEN will be considered because of the existence of transformers which supply the rural properties that are connected to the MEN, and because any contact with LV MEN interconnected metalwork (for example, household taps) during either LV MEN voltage rise and/or soil potential rise could be dangerous.

The plot in Figure 8-2 shows that only the faulted structure produces an EPR of 88V, which is above the maximum allowable voltage limit of 78V for a 40A fault with a clearing time of 0.8 seconds, as per Table 6-2. The EPR from the adjacent steel pole is below the allowable voltage limit. Hence TD MEN need only be considered for one structure - where there is a distribution transformer located on a steel pole - as this will be the only hazardous structure. On the plots in figures 8-2 and 8-3, Profile Number 1 refers to voltage rise at the structure and Profile Number 2 refers to the voltage rise one meter from the structure as shown in figure 8-1. Each spike on the plots represents a steel pole.

The plot in Figure 8-3 shows the effect on EPR when installing a 6m earth rod adjacent to the steel pole. For a visual representation please of this refer to figure 8-1.

With the installation of the 6m earth rod the EPR at the faulted pole is reduced to 72V, which is now below the maximum allowable limit of 78V.
Figure 8-1 - SESCAD model with 6m earth rod

Figure 8-2 - TD MEN Scalar Potential without earth rod
8.2.1 TD MEN Risk Assessment

A risk assessment was conducted in ARGON for the EPR to the MEN which is described in section 8.2 of this report. The probability of single fatality was calculated using ARGON. Below is a list of the input data used in ARGON:

**ARGON Input Data**

- Fault Frequency/ year: 0.1
- Fault duration (s): 0.8
- Contact scenario: MEN
- Risk Assessment: Individual
- Current Path: Touch voltage
- Footwear Type: standard footwear
- Soil resistivity (Ω): 200

The overhead line fault rate is measured in faults/100km/year. For 11kV-33kV networks, the fault rate is 10 faults/100 km/year (ENA 2010). From Section 8.2 it is clear that only the faulted structure breaches the allowable EPR limit and the adjacent structures have much lower EPR values that are below the maximum allowable voltage limit. Therefore faults anywhere else on the
network should not cause unsafe EPR values on adjacent structures, and for this reason a value of 0.1 has been used as the fault rate (ENA 2010). Refer to Table E2 of EG0 for further information in regards to this value.

The Energy Networks Association describes the Probability of Fatality as, “one in a million” (ENA 2010). In ARGON, for this particular case a voltage of 158 V sets the Probability of Fatality below one in a million. Table 8-3 summarizes the probabilities for fibrillation and fatality with and without the installation of a 6m earth rod. The probability of fatality for both cases is less than one in a million. The probability of fatality reduces by about a factor of 3 with the installation of the 6m earth rod. The probability of fibrillation is also reduced by a factor of 3.

<table>
<thead>
<tr>
<th>Description</th>
<th>Applied Voltage</th>
<th>Probability of fibrillation</th>
<th>Probability of fatality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault location <strong>without</strong> 6m earth rod</td>
<td>88</td>
<td>0.0014</td>
<td>4.115e^-8</td>
</tr>
<tr>
<td>Fault location <strong>with</strong> 6m earth rod</td>
<td>72</td>
<td>0.0004062</td>
<td>1.236e^-8</td>
</tr>
</tbody>
</table>

8.2.2 Risk cost benefit analysis

A risk cost benefit analysis was conducted in order to see how much it would cost to reduce the risks that are shown in Table 8-3. Figure 8-4 shows the location and number of steel poles that would need to be deep earthed. The following is a summary of the potential costs that would be involved;

**Earth rod specifications and material/labor costing**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>15mm</td>
</tr>
<tr>
<td>Length</td>
<td>2.4m</td>
</tr>
<tr>
<td>Cost per rod (labor exclusive)</td>
<td>$18</td>
</tr>
<tr>
<td>Number of rods required for 6m deep earth rod</td>
<td>2.5</td>
</tr>
<tr>
<td>Number of Steel poles that have transformers</td>
<td>3</td>
</tr>
<tr>
<td>Total number of poles to be deep earthed</td>
<td>3</td>
</tr>
<tr>
<td>Number of earth rods required</td>
<td>3 x 2.5 = 7.5 (say 8)</td>
</tr>
<tr>
<td>Total cost of Rods</td>
<td>18 x 8 = $144</td>
</tr>
</tbody>
</table>
Total Labor costing (including travel)  =  $1300

Total cost  =  $1444

The total cost of $1444 is very small compared to the capital costs for the initial maintenance project. For this relatively small investment, the probabilities of fibrillation and fatality will be reduced as shown in Table 8-3. It is therefore recommended that 6m earth rods are installed at these steel poles.

Figure 8-4 - Location of Steel poles with Transformers
8.3 **Effects on EPR with added generation**

Generators are added to a network due to the increases in load in order to meet the increased demand. Other methods of meeting the demand are to increase generation at the source however that may involve the reinforcement of the existing network in order to transmit the increased power efficiently. This can be a very expensive and sometimes unfeasible option. A 1.0 MVA 22kV 3phase Synchronous Generator was connected to the 3phase side of the single phase spur using the DlgSILENT Power Factory software. This was done in order to see the effect on network fault currents and EPR levels.

Table 8-4 summarise the new fault currents and their respective touch voltages due to the added generation for all the faulted locations. When Table 8-4 is compared with Table 8-1, it is clear that the fault currents have increased at all the fault locations. The effect of the added generator is more visible near the start of the spur line where the fault current has increased from the original 200A to 388A. The effects are not as visible at the end of the line as can be seen by the 10A increase from the original 40A to a new 50A. This is because of the increased network impedance at the end of the line due to the increased length of the line. The following facts can be drawn from this investigation:

- Fault currents increased at all locations (with largest increases at the start of Spur)
- EPR levels are increased

**Table 8-4 - Effect of added generation on fault currents and EPR levels**

<table>
<thead>
<tr>
<th>Fault location</th>
<th>Allowable Voltage limit (V)</th>
<th>1m Reach touch voltage at steel pole</th>
<th>1m Reach touch voltage At Wood pole down earth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>388 A fault</td>
<td>137 A fault</td>
</tr>
<tr>
<td>A</td>
<td>373.6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>373.6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>C</td>
<td>335.1</td>
<td>N/A</td>
<td>23.3</td>
</tr>
<tr>
<td>D</td>
<td>78</td>
<td>N/A</td>
<td>8.7</td>
</tr>
<tr>
<td>E</td>
<td>78</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>F</td>
<td>78</td>
<td>N/A</td>
<td>60</td>
</tr>
<tr>
<td>G</td>
<td>335.1</td>
<td>137.4</td>
<td>N/A</td>
</tr>
<tr>
<td>H</td>
<td>335.1</td>
<td>244.6</td>
<td>N/A</td>
</tr>
</tbody>
</table>
8.4 **Effects of a 132kV Transmissions fault at the Zone Substation**

A single phase to ground transmission fault was simulated at the zone substation in order to see the EPR at Location A, as shown in figure 5-1. The voltage profile was drawn in SESCAD under the first couple of bays at the beginning of the spur in order to analyse the EPR. The value of the single phase to ground transmission fault was given as 5.104kA.

Figure 8-5 illustrates an earthing grid for a typical 132kV/22kV zone substation. During a fault at the zone substation some of the fault current can flow through the earthing wire to other locations which could cause unsafe EPR levels at those locations. In this particular case, 2927 Amps travels through the earth wire away from the zone substation.

Figure 8-6 shows the current flowing along the down earth at location A. The figure is a plan view of Location A, the top two horizontal conductors represent the Phase and the earth conductors and the vertical conductors represent down earths at power poles. Clearly this current is very small because of the large distance between location A and the zone substation.

Figure 8-7 shows the maximum touch reach voltage at 1m from the down earth. This figure is a bird's eye view of Location A. The maximum touch reach voltage is approximately 16.2 mV hence there is no breach of any voltage criteria.
Figure 8-5 - A 5.104kA transmission fault at zone substation

Figure 8-6 - fault current at beginning of the single phase spur
Figure 8-7 - Touch voltage at the beginning of single phase spur
9 Conclusion

The following facts can be concluded from this EPR assessment:

1. The maximum allowable touch voltage criteria determined by CDEGS are 373.6V, 335.1V and 78V for fault clearing times of 0.1 s, 0.2 s and 0.8 s respectively. This is based on the IEC fibrillation current curve C1 (AS/NZS 2010) and IEEE 80 (IEEE 2000).

2. Touch reach voltages modelled in CDEGS for the specified fault currents at the selected areas for contact with the steel poles were within the allowable voltage limits. Therefore, no further action is required.

3. Step voltages modelled in CDEGS for animal safety were also below the allowable voltage limits for the different size fault currents at all the simulated fault locations, hence no mitigation was required.

4. A safety assessment using ARGON on TD MEN indicates that at the steel transformer poles the probabilities of fatality are below the negligible risk value of one in a million. However these risks could be further reduced by installing 6m deep earths adjacent to the poles.

5. Increased generation caused increased fault currents and this increased EPR levels which then caused a breach of allowable voltage limits. This increased EPR level can have a negative impact on the safety of humans and/or animals. It is however very unlikely that a generator of this size will be added to this area in the network.

6. Transmission level faults at the zone substation did not have an unsafe impact at the site.
10 Recommendation and future work

Although the probability of fatality (for the case where deep earth rods are not installed) is already below the negligible risk levels as calculated in ARGON (i.e. < $10^{-6}$), it is recommended that 6m deep earth rods are installed at the three steel transformer poles as per Section 8.2.2 of this report. By doing this, the probabilities can be even further reduced, at modest cost.

A three phase network could be modelled to investigate metro locations instead of rural areas. Fault types (such as three phases to ground) can be investigated. An EPR study can be conducted to investigate step potentials on other animals such as horses. Individual soil resistivity tests could be conducted and used individually for the fault location closest to the test points instead of merging all soil tests into one. This will reduce errors however not significantly as the soil structure is normally uniform for large distances.
11 Validity
This assessment needs to be reviewed if any major change in site configuration.
The scope of the project is based on the current design standards and external regulations and requirements. Should any of these change, the scope might be affected.
The results and conclusions produced are valid based on the given inputs and assumptions mentioned in this report. Any significant change in assumptions and/or the system specifications (i.e. significant increase in the fault level, etc.), could exceed the safety criteria set by this investigation.
12 References


Cox, N. (2011) "Police horse killed, two officers suffer electric shocks ".


SchneiderElectric (2013) "Protection Tripping Curves." document can be found on the Schneider Electric web page.


WesternPower (2011) "Generator grid connection guide V2 - An introduction to power systems and the connection process."
13 Appendices

13.1 Tables and Figures from AS60479 and EG0

Table 13-1 - Table 4 (AS/NZS 2002)

<table>
<thead>
<tr>
<th>Species</th>
<th>Average weight</th>
<th>Minimum fibrillating current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Body kg</td>
<td>Heart g</td>
</tr>
<tr>
<td>Pig</td>
<td>79</td>
<td>300</td>
</tr>
<tr>
<td>Sheep</td>
<td>56</td>
<td>270</td>
</tr>
<tr>
<td>Calf</td>
<td>70</td>
<td>420</td>
</tr>
<tr>
<td>Pony</td>
<td>115</td>
<td>–</td>
</tr>
</tbody>
</table>

NOTE – Too little data is available for horses to be included in this table.

Table 13-2 - Table 2 (AS/NZS 2002)

<table>
<thead>
<tr>
<th>Current path</th>
<th>Values for total body impedance (Ω) that are not exceeded for a percentage of the population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 %</td>
</tr>
<tr>
<td>Nose to all four legs</td>
<td>220</td>
</tr>
<tr>
<td>Forelegs to hindlegs</td>
<td>800</td>
</tr>
</tbody>
</table>

NOTE – The values are rounded off from statistical analysis of 80 cattle measured.

B.1.4 Step voltage circuit

A typical step voltage shock circuit for the situation depicted in Figure B.3 is shown in Figure B.4.

The prospective step voltage \( V_{sp} \) for a fault duration, \( t \), may be determined by the acceptable body current, \( I_{HCF} \), multiplied by the sum of the various resistances considered in the shock circuit. The factor, \( HCF \), is the heart-current factor as detailed in Table 8.2 (from Section 5.9 of IEC 60479-1:2005).

\[
V_{sp} = \frac{I}{HCF} (Z_a + Z_n + Z_y) \quad B-11
\]

\[
Z_{st} = \rho_s \quad B-12
\]

If \( Z_s \) is the resistance of one shoe, then:

\[
Z_{st} = 2Z_s \quad B-13
\]

\[
V_{sp} = \frac{I}{HCF} (Z_a + Z_n + Z_s) \quad B-14
\]

\[
V_{sp} = \frac{I}{HCF} Z_a + \frac{I}{HCF} (Z_n + Z_s) \quad \text{or}
\]

\[
V_{sp} = \frac{I}{HCF} Z_a + \frac{I}{HCF} (Z_n + Z_y) \quad B-15
\]

For a foot-to-foot path, the heart-current factor of 0.04 is given in Table 8.2 (from IEC 60479-1:2005). This implies that 25 times more current flowing through the foot to foot path is required to create the same risk of ventricular fibrillation compared to the current flowing in the left hand to feet path. The current is lowered further still by the added effect of having two sets of footwear and/or foot-to-ground resistances in series.

Figure 13-1 - B.1.4 from EG-0- Power System Earthing Guide(ENA 2010)
Figure 13-2 - Figure 20 of AS/NZS 60479.1 2010 (AS/NZS 2010)

Table 13-3 - Table 11 of AS/NZS 60479.1 2010 (AS/NZS 2010)

<table>
<thead>
<tr>
<th>Zones</th>
<th>Boundaries</th>
<th>Physiological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-1</td>
<td>Up to 0.5 mA curve a</td>
<td>Perception possible but usually no &quot;startled&quot; reaction</td>
</tr>
<tr>
<td>AC-2</td>
<td>0.5 mA up to curve b</td>
<td>Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects</td>
</tr>
<tr>
<td>AC-3</td>
<td>Curve b and above</td>
<td>Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected</td>
</tr>
<tr>
<td>AC-4 ¹</td>
<td>Above curve c₁</td>
<td>Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time</td>
</tr>
<tr>
<td></td>
<td>c₁ - c₂</td>
<td>AC-4.1 Probability of ventricular fibrillation increasing up to about 5%</td>
</tr>
<tr>
<td></td>
<td>c₂ - c₃</td>
<td>AC-4.2 Probability of ventricular fibrillation up to about 50%</td>
</tr>
<tr>
<td></td>
<td>Beyond curve c₃</td>
<td>AC-4.3 Probability of ventricular fibrillation above 50%</td>
</tr>
</tbody>
</table>

¹ For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation, this figure relates to the effects of current which flows in the path left hand to foot. For other current paths, the heart current factor has to be considered.
13.2 **RESAP soil model plots**

**Figure 13-3 - Plot for Soil Test 1**

**Figure 13-4 - Plot for Soil Test 2**
Figure 13-5 - Plot for Soil Test 3

Figure 13-6 - Plot for Soil Test 4
Figure 13-7 - Plot for 4 Soil Tests combined
13.3 **Power Factory Model**

**Figure 13-8 - Power Factory Model**

**Figure 13-9 - Power Factory Model - Single Phase Spur**
Figure 13-10 - Power Factory Model - Synchronous Generator Connection
13.4 ARGON Reports

ARGON - SAFETY ASSESSMENT REPORT

Report Generated On: 11 June 2013

Report Generated By:

Design Location: Rural Farm

INTRODUCTION

Individual Probability of Fatality

This report outlines the results of a risk-based safety criteria assessment study for the above location. The analysis is based on the fact that a fatality occurs when a fault occurs and the touch (or step) voltage generated is sufficient to allow a large enough current to pass through the body for sufficient time to cause fibrillation of the heart muscle. The probability that an individual will be present and in contact with an item at the same time that the item is affected by a fault is defined as the Probability of Coincidence (P_coinc). The probability that the heart will enter ventricular fibrillation due to contact with an external voltage is the Probability of Fibrillation (P_fibrillation). This situation can be described by the following simple equation:

\[ P_{\text{fatality}} = P_{\text{coinc}} \times P_{\text{fibrillation}} \]

The probability of coincidence has been calculated using contact and fault data as detailed in this report. The probability of fibrillation has been calculated using the impedance and applied voltage/clearing time information as detailed in this report.

The calculation of the probability of fatality allows the design to be classified according to accepted risk targets (1e-6 to 1e-4) as either negligible risk, intermediate risk or intolerable risk.

Design Compliance

Designs with low risk determination are accepted and the attached design curve(s) may be used at locations with similar contact, fault and series impedance characteristics. Designs which are determined as high risk are not acceptable and there is no valid design curve available until mitigation results in a compliant design. Designs placed in the intermediate risk range may be considered compliant as a result of applying the ALARA (As Low As Reasonably Achievable) principle. For designs of this type, documentation is supplied at the end of this report outlining the justification.

The following information outlines the design assumptions and classifies the compliance of the design.

APPLICATION NOTES

Surface Soil Resistivity

Surface soil resistivity has a significant effect on the current that can pass through a body. The effect of soil resistivity is linear with the effect on the body and results can be interpolated linearly between two resistivities to provide the effect at the required resistivity when undertaking Argon based analysis.

Footwear

Appropriate footwear can significantly reduce the current that can pass through a body. Under dry conditions any encased leather or non-conductive rubber or plastic footwear in good condition is as effective as electrical safety boots in reducing the risk. Without such footwear the risk is equivalent to bare foot. Under wet conditions appropriate gum boots in good condition are as effective as electrical safety boots in dry conditions. Without such gum boots in wet conditions the risk is as with bare foot.

Appropriate gum boots are those which pass the following test to ensure that material from which they are made is adequately insulating:

- Fill the boot to approximately 90% of it's height with salt water and place it in a container of salt water that reaches the same water level. The resistance between electrodes inserted in the water inside the boot and outside of the boot should be determined with a high voltage resistance tester. The resistance should not be less than 1 megohm.

Gum boots should be maintained in good condition and replaced if any splits or cracks appear.
13.4.1 Voltage for Risk below 1 in 1,000,000

COINCIDENCE PROBABILITY

<table>
<thead>
<tr>
<th>Access / Fault Assumptions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario Name</td>
<td>MEN</td>
</tr>
<tr>
<td>Description</td>
<td>Multiple contacts with items associated with the MEN or a daily basis</td>
</tr>
</tbody>
</table>

| Fault Frequency | 0.1 per year | Contact Frequency | 2000 per Year |
| Fault Duration  | 0.6 seconds  | Contact Duration  | 4 seconds    |

Coincidence Reduction

<table>
<thead>
<tr>
<th>Coincidence Reduction Method</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coincidence Reduction Factor</td>
<td>1</td>
</tr>
</tbody>
</table>

Individual Coincidence Probability = 3.04e-5

Fibrillation Probability

<table>
<thead>
<tr>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Path</td>
</tr>
<tr>
<td>Footwear</td>
</tr>
<tr>
<td>Wet/Dry</td>
</tr>
<tr>
<td>Soil Resistivity</td>
</tr>
<tr>
<td>Applied Voltage</td>
</tr>
<tr>
<td>Fault Duration</td>
</tr>
</tbody>
</table>

Surface Layer

<table>
<thead>
<tr>
<th>Type</th>
<th>Redistility</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 metres</td>
<td></td>
</tr>
</tbody>
</table>

Flashover Voltage Not Specified Volts

Fibrillation Probability = 0.0325

RISK DETERMINATION

Individual

Risk Zone: Negligible

Probability of Fatality = 9.907e-7

DESIGN CURVE

This curve is valid for designs which have contact, fault, and series resistance characteristics similar to those outlined in this report. Fault duration need not remain the same.

Individual

RISK MITIGATION COMMENTS

No additional mitigation comments provided.

SUMMARY

Based on the information supplied in this report, the design is considered to be COMPLIANT.
13.4.2 Risks at 88V

**COCINCIDENCE PROBABILITY**

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>MCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Multiple contacts with items associated with the MCH on a daily basis</td>
</tr>
</tbody>
</table>

| Fault Frequency | 0.1 per year |
| Contact Frequency | 2000 per year |
| Fault Duration | 0.6 seconds |
| Contact Duration | 4 seconds |

**Coincidence Reduction**

| Coincidence Reduction Method | None |
| Coincidence Reduction Factor | 1 |

Individual Coincidence Probability = 3.04e-5

**FIBRILLATION PROBABILITY**

<table>
<thead>
<tr>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet/Dry?</td>
</tr>
<tr>
<td>Soil Resistivity</td>
</tr>
<tr>
<td>Applied Voltage</td>
</tr>
<tr>
<td>Fault Duration</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Resistivity</td>
</tr>
<tr>
<td>Depth</td>
</tr>
<tr>
<td>Flashover Voltage</td>
</tr>
</tbody>
</table>

Fibrillation Probability = 0.0014

**RISK DETERMINATION**

Individual

Risk Zone: Negligible

Probability of Fatality = 1.115e-8

**DESIGN CURVE**

This curve is valid for designs which have contact, fault, and series resistance characteristics similar to those outlined in this report. Fault duration need not remain the same.

Individual

**RISK MITIGATION COMMENTS**

No additional mitigative comments provided.

**SUMMARY**

Based on the information supplied in this report, the design is considered to be COMPLIANT.
13.4.3 Risks at 72V

**COINCIDENCE PROBABILITY**

<table>
<thead>
<tr>
<th>Access / Fault Assumptions</th>
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</thead>
<tbody>
<tr>
<td>Scenario Name</td>
</tr>
<tr>
<td>Description</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event</th>
<th>Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Frequency</td>
<td>0.1 per year</td>
</tr>
<tr>
<td>Fault Duration</td>
<td>0.6 seconds</td>
</tr>
<tr>
<td>Contact Frequency</td>
<td>2000 per year</td>
</tr>
<tr>
<td>Contact Duration</td>
<td>4 seconds</td>
</tr>
</tbody>
</table>

**Coincidence Reduction**

<table>
<thead>
<tr>
<th>Coincidence Reduction Method</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coincidence Reduction Factor</td>
<td>1</td>
</tr>
</tbody>
</table>

Individual Coincidence Probability = 3.64e-5

**Fibrillation Probability**

<table>
<thead>
<tr>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Path</td>
</tr>
<tr>
<td>Footwear</td>
</tr>
<tr>
<td>Wet / Dry</td>
</tr>
<tr>
<td>Soil Resistivity</td>
</tr>
<tr>
<td>Applied Voltage</td>
</tr>
<tr>
<td>Fault Duration</td>
</tr>
</tbody>
</table>

| Surface Layer | 
| Type | None |
| Resistivity | 0 Ωm |
| Depth | 0 metres |
| Flashover Voltage | Not Specified |

Fibrillation Probability = 4.852e-4

**Risk Determination**

Individual

<table>
<thead>
<tr>
<th>Risk Zone</th>
<th>Negligible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of Fatality</td>
<td>1.239e-8</td>
</tr>
</tbody>
</table>

**Design Curve**

This curve is valid for designs which have compact, fault, and series resistance characteristics similar to those outlined in this report. Fault duration need not remain the same.

**Individual**

![Design Curve](image)

**Risk Mitigation Comments**

No additional mitigation comments provided.

**Summary**

Based on the information supplied in this report, the design is considered to be **COMPLIANT**.