Faculty of Health, Engineering and Sciences

Feasibility of Remote Earth Monitoring for SWER Systems

A dissertation submitted by

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Abstract

Single Wire Earth Return (SWER) is an example of engineering brilliance which is elegant in its simplicity. The design involves one high voltage conductor with the mass of the earth acting as the path for the return current and as a protective measure to dissipate fault currents. The connection between the earthing conductors and ground is an integral component of the SWER distribution system and it is essential for electricity providers to maintain reliable low resistance connections. SWER was originally developed as a cost-effective alternative to supply customers in rural and remote areas. Australia has approximately 200,000km of active SWER line across the States and Territories with Queensland's Energy Queensland operating and maintaining the largest portion of 65,000km. Ergon Energy, a subsidiary of Energy Queensland, has 26,066 SWER earths to maintain on a rolling six year cycle.

Currently the only inspection method for SWER earth connections is with an instantaneous reading taken via a field visit to each site. Soil is non-homogeneous by structure causing this instantaneous measurement to reflect the chemical composition and level of moisture in the soil at one point in time. This can cause erroneous measurement results due to the influence of seasonal and local effects on soil conditions and makes trending analysis difficult.

This research project provides a feasible theoretical non-intrusive method to remotely monitor live SWER earths without the need to drive test electrodes. The calculations and simulated models are correlated against baseline conventional earth testing methods and field test results. The stretch target aims to procure a prototype online monitoring unit and build a test site.

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Certificate of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Amy Ferrari

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Signature

__16th October 2019___
Date

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Thank you to my wonderful husband and two sons, you have provided unconditional love and support for the past five years. Thank you for the sacrifices you have made to enable me to complete an external degree. Thank you to my parents who have continued to support and encourage me through this lengthy journey.

Table of Contents

List of Figures

List of Tables

Glossary of Terms

4G - Mobile communications standard for the 4th generation wireless cellular network

5G - Mobile communications standard for the 5th generation wireless cellular network

ADC – Analog-to-Digital Converter

AC – Alternating Current

CCA - Copper, Chromium and Arsenic

CT – Current Transformer

DTRMP - Daily Task Risk Management Plan

Duplex SWER - A two wire SWER arrangement used to cancel earth currents

Earth – The conductive mass of the earth, whose electric potential at any point is conventionally taken as zero.

Earthing - A system of electrical connections to the general body of earth

ESAA - The Electricity Supply Association of Australia

FOP - Fall of Potential

GIS – Geographic Information System

GPR - Ground Potential Rise

Ground - The soil and subsoil forming the surface of the planet and a conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth or to some conducting body of relatively large extent that serves in place of the earth.

GUI - Graphical User Interface

GUSS – Grid Utility Support System

High Pass Filter – Electronic filter that passes signals with frequencies higher than the cut-off frequency

HV - High Voltage - greater than 1000V

Hybrid SWER - Consists of a mixture of single and multi-wire systems

IPTC - Insulation Piercing Test Clamp

Isolated SWER - Standard configuration using a HV to SWER single phase transformer

LV - Low Voltage - 1000V and below

MATLAB - Programming platform for engineers and scientists

MEN – Multiple Earthed Neutral

Non-homogeneous - Non uniform

Pi Section – Line block in MATLAB that implements a single-phase transmission line with lumped parameters

PV – Photo voltaic

SMS – Short Message Service

Simulink - Graphical programming environment for modelling dynamic systems

SWER - Single Wire Earth Return

Triplex SWER - A three wire SWER arrangement

Un-isolated SWER - Where a SWER line taps directly off a three phase back bone line

Var - Volt Ampere Reactive or reactive power

Variac – Variable autotransformer

VSC - Voltage Source Converter

VT – Voltage Transformer

Glossary of Terms

This document refers to earthing stakes, earthing rods and earthing electrode; these terms are interchangeable and refer to the conductor that provides the earthing connection to the mass of the earth.

Energy Queensland was formed in 2018, it has two subsidiary electrical distribution companies Ergon Energy (founded in 1999 from the then six regional Queensland electricity distributors) and Energex (foundered in 1922, prior to 1997 was referred to as South East Queensland Electricity Board - SEQEB). Ergon Energy distribution assets comprise all of regional Queensland, Energex distribution assets comprise the South East Corner of Queensland. Energy Queensland and Ergon Energy companies are referred to throughout this dissertation and they both refer to the same regional Queensland electrical asset base.

Chapter 1 - Introduction

1.1 Background and Idea Initiation

Single Wire Earth Return (SWER) is a single wire distribution system that relies on the earth/ground as the return current path. SWER is a low cost solution in comparison to three phase networks and is installed in low density rural areas and remote communities where there is considerable distance between each distribution transformer. In Queensland, Energy Queensland owns approximately 65,000 kilometres of SWER lines that supply approximately 26,000 customers. Although SWER is simplistic in physical construction, it is technically complex in design with various configurations: un-isolated, isolated, hybrid, duplex and triplex systems all of which integrate with the existing three phase network.

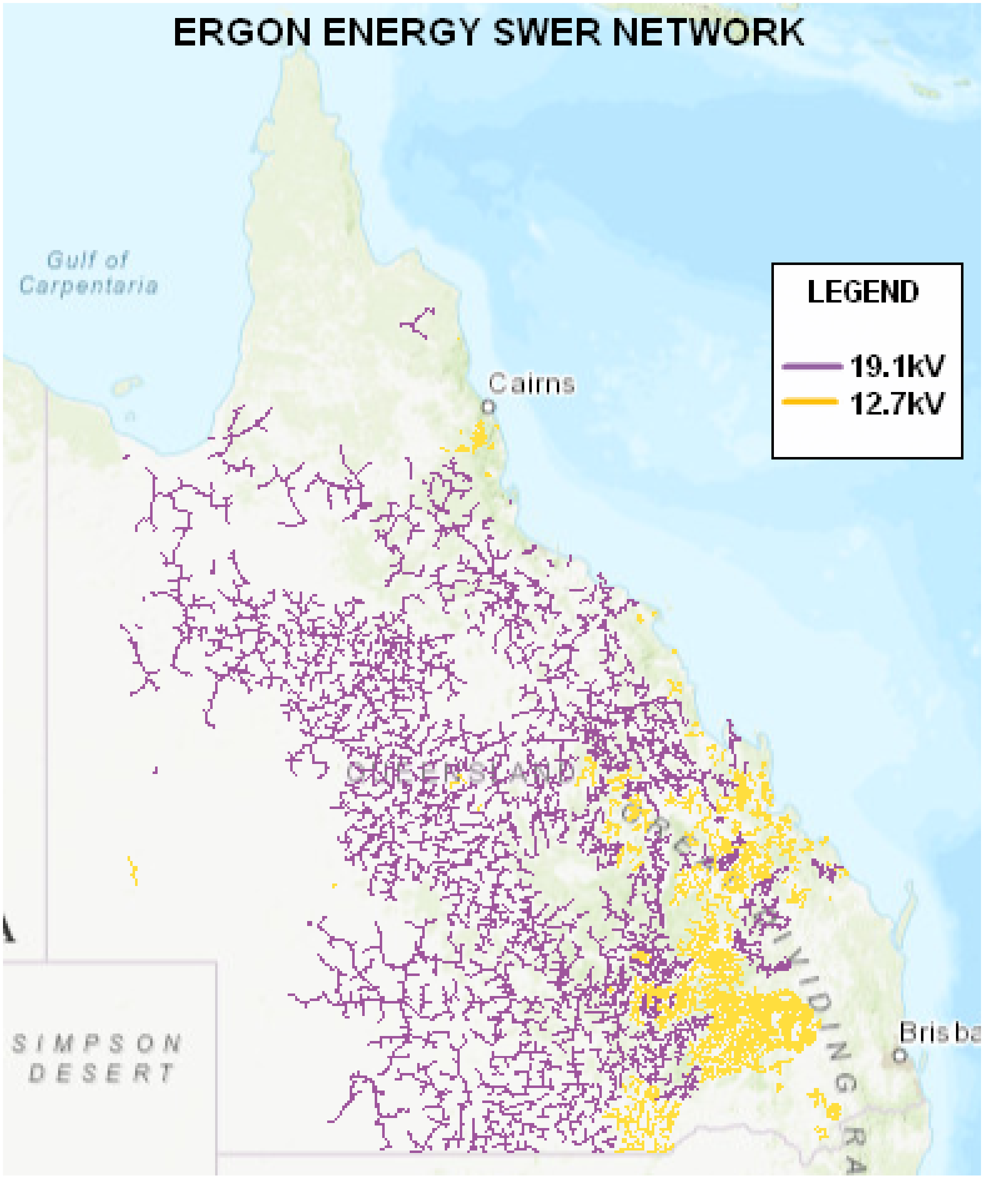


Figure 1: Map of Ergon Energy's SWER Network

Due to capacity constraints, power quality and reliability issues, energy suppliers have developed strategies to improve SWER performance and reliability.

These include:

- Upgrading to three phase where justified and;
- Introduction of alternative technologies for:
  - voltage regulation;
  - var compensation;
  - demand reduction;
  - load control;
  - load support and;
  - off-grid solutions.

Remote management and monitoring of the SWER network forms a key portion of the SWER strategy, predominantly to reduce the cost of fault management and equipment configuration on long radial networks (SWER Improvement Group 2012).

A number of power quality meters have been deployed on the SWER network to monitor load and power quality events. Ergon Energy's routine earth testing is carried out on six yearly intervals. It has been found that the results of the earth tests can be influenced by weather, soil conditions, test and auxiliary equipment condition, actions of the technician executing the test and results interpretation. All of these factors can lead to considerable errors in the results which cause a cascade effect with wasted resources remediating earthing that is not defective and defective earths inadvertently being overlooked.

Earthing is an integral component of SWER distribution systems with the mass of earth or ground being used as a conductor at all times. Three phase systems use the earth as a protective measure to dissipate fault currents; SWER uses the earth as an active conductor to carry the return load current as well as dissipation of fault currents. Low resistance SWER earth connections are essential for the operation of upstream and downstream protective devices, maintaining low step touch potentials for safety to the public, livestock and the surrounding environment.

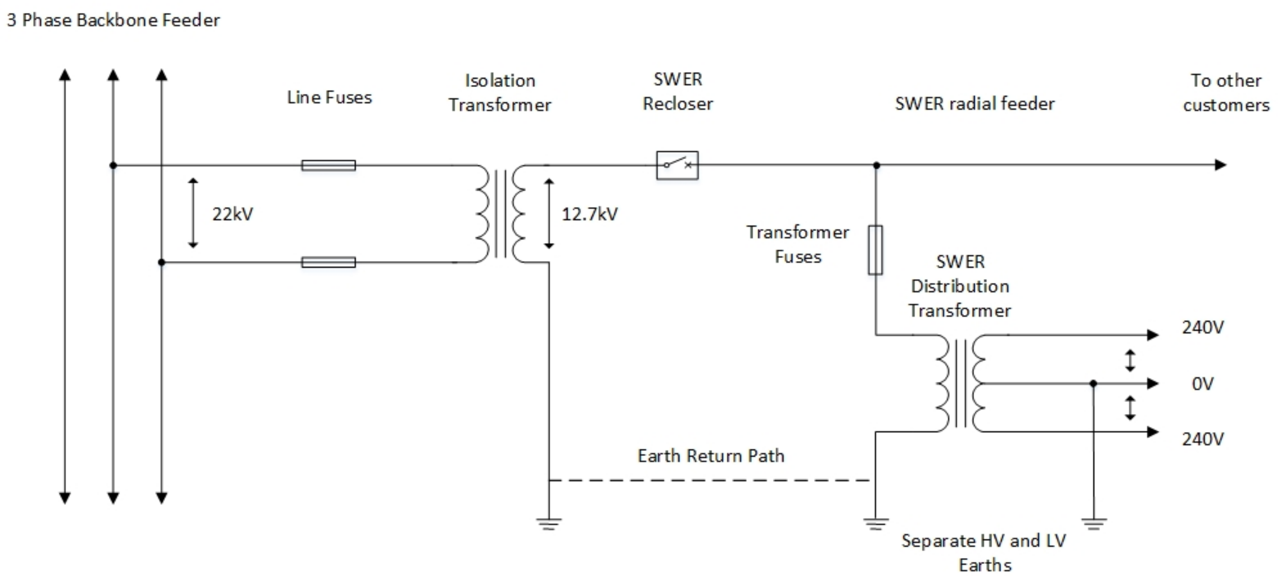


Figure 2: Isolated SWER Network Configuration (The Electricity Authority of New South Wales 1978)

For the year of 2017/18, 5,708 SWER earth sites across Queensland were inspected and tested with an inspection budget of $4.16M. 2,393 high resistance earth readings were recorded by contractors and defect repairs amounted to $8.027M. Costs to test one SWER earth including travel are approximately $728 per site. The inspection cost for SWER earthing is considerably higher than the standard SWER timber pole inspection cost and this alone justifies the need to look at cost effective solutions to monitor the condition of SWER earth systems.

1.2 Aim

The aim of the research project is to develop a method for remote monitoring of SWER isolator and distribution transformer earths. SWER networks use the mass of the earth for the return current and therefore the earth and associated conductive hardware can be considered an active component of the distribution system. It is essential to maintain the integrity of all components of the earthing system to ensure safety of the public, electrical industry employees and livestock.

Exhaustive research has been carried out in other research papers on methods for earthing, soil condition factors, earth probe types, earth grids, earth design proximity and monitoring of zone substation grids. Attributes from these previous studies will be evaluated to ensure any errors in design; environmental and geographical conditions will be reduced or ultimately eliminated. Initial analytical modelling of the HV and LV earth system will be carried out to establish a safe and achievable online monitoring connection method due to the radial nature of SWER earth design.

Research modelling will be created in MATLAB to establish predictive patterns and design limitations. The final research report will provide recommendations into the feasibility of SWER earth testing with references to current test practices, field testing and results, functional specifications, test site requirements and construction.

1.3 Objectives

The project objective is to develop a method to monitor the connections of all the earth conductors and the connection to the mass of earth. Recommendations for SWER earth online monitoring devices will be developed from theoretical and real life analysis of baseline conventional earth testing methods and clamp-on injection methods. The modelled monitoring device will be non-intrusive and consist of a main injection unit with real time monitoring capabilities, field sensors, data analytical capabilities, IoT platform, local Bluetooth capabilities and ability to enable alerts to corporate subsystems. The project is divided into the following stages:

Stage 1. Research existing SWER earth testing methods with comparison between the traditional combination of 4 pole Wenner earth resistivity method and 3 pole fall of potential method and the more recent stake-less/ clamp-on method.

Stage 2. Conduct onsite monitoring of an existing energised SWER distribution transformer and LV system using a PowerMonic meter and onsite testing using the traditional 3 pole fall of potential test method.

Stage 3. Collate test results, review and analyse. Evaluate the advantage/disadvantage of current test methods.

Stage 4. Develop a system model using MATLAB Simulink modelling software to theoretically verify a non-intrusive test method for online SWER earth testing and monitoring.

Stage 5. Develop a functional specification with requirements for online SWER earth test equipment to release for manufacture.

Stage 6. Develop recommendations and a cost estimate for a test site location, design and construction requirements.

If time and resources permit (stretch target):

Stage 7. Purchase online monitoring equipment.

Stage 8. Build test site.

Stage 9. Complete onsite testing.

Stage 10. Analyse results.

1.3.1 Limitations

- **Compliance with safety -** Establishing a safe method to create a loop test on a HV SWER earth whilst maintaining compliance with operational separation to the LV system. The high impedance value of the transformer will create issues with modelling.
- **Financial resources -** Budget limitations will be incurred if Energy Queensland does not support the research project business case.
- **Communication constraints –** Limitations associated with establishing on-line communications for remote SWER locations. Communication black-spots will be taken into consideration with recommended test site locations governed by 4G coverage.

1.3.2 Expected Outcomes and Benefits

Inspection and repair of SWER earth costs Ergon Energy 5 to 8 million dollars per annum. The final project analysis will provide the following:

- Explanation of SWER earthing theory.
- Proven models for SWER earth monitoring.
- A method for trending of SWER earth conditions.
- A method to obtain data to improve management of the maintenance lifecycle of Energy Queensland’s SWER network earth system.
- Cost benefits from reduced on-site earth testing and collation of remediation works from early detection of high resistance earth fault.

- Reductions in human error results through the duplication of testing devices installed across the network.
- Improved identification of earth resistivity "black-spots" to enable future studies.

A major benefit of the research project will be to identify the feasibility of on-line monitoring of SWER earths and the ability of the system to deliver reliable condition monitoring data.

1.3.3 Project Feasibility

Ergon Energy currently has 26,066 SWER earths to maintain on a rolling six year cycle. Current results show considerable errors and anomalies which require further investigation and site re-testing costing the business significant funds. Discussions with field staff reveal there are erroneous differences in results between crews and also when visiting the same site at different intervals. Energy Queensland requires the earth resistance to be under 10Ω for LV and 1Ω to 25Ω for HV. It is known that errors can occur from faulty leads or connections to the meter before the earth is placed under test. The outcome from this project could provide a reliable method of SWER earth online condition monitoring and early fault detection of poor earth connections leading to a reduction in the risk of high step-touch potentials, pole fires and equipment failure.

1.4 Methodology

Chapter 2 - Project Development and Literature Review

No evidence was found of modelling or implementation of remote monitoring of SWER earth connections. This project aims to investigate the variables associated with modelling SWER earthing and develop a non-intrusive method that utilises the existing equipment at an energised SWER distribution transformer.

The proposed methodology aligns with the project objectives outlined in section 1.3.

Chapter 3 - Why SWER and the emerging distributed network?

This section will discuss the advantages and disadvantages of SWER on distribution networks and whether there is a future for SWER with emerging technology. Standard configurations and construction will be discussed with information related to loading and customer densities, different earthing models, network influences and protection. SWER earth safety will be reviewed with reference to Australian and International Earthing Standards, previous bushfire disasters originating from SWER line hardware failures, earth potential rise, step potentials, touch potentials and soil conditions.

Chapter 4 - SWER Earth Construction

This section will focus on the general construction characteristics of SWER with sub-sections to soil type and conditions, electrode installations in mediums and the integrity of connecting to the earth, resistivity of soil and external effects, theory and calculations relating to the return earth current path to help understand the behaviour of earth as a conductor, standard earthing configurations, current Ergon Energy SWER distribution earthing standards, heating of electrodes and earthing compounds.

Chapter 5 - SWER Earth Testing – Theory and Standards

This section will provide details relating to current business test practices, test equipment attributes and limitations and the Australian Standards for consumer earthing. Testing methodologies will be explained to help understand the different testing methods.

Chapter 6 - SWER Earth Testing – Field Testing and Results

This section will outline the onsite field testing that was completed to provide an accurate set of benchmark field test data to analyse. The test site requirements, selection, existing earthing and plant attributes, upstream assets and network configuration will be explained. The field test raw data results will be analysed with theoretical calculations to verify against the raw data. This section will formulate a new method to measure the resistance of a HV SWER earth.

Chapter 7 - SWER Earth Modelling

Equivalent circuits will be established to represent a base SWER earth system. Circuits will be modelled using MATLAB’s Simulink analytical tool, the earthing system will be broken into different resistive components to represent electrode to soil connections. Downstream network influences will be built into the base model. Two test models will be created, one for the LV system earth monitoring using existing technology and a new method to monitor the HV SWER earth using the theoretical analysis from Chapter 6.

Chapter 8 - Functional Specification

This section will outline the equipment specifications required to procure a remote SWER earth monitoring unit.

Chapter 9 – Test Site Requirements and Construction

This section will outline the requirements for a trail site to test the new proposed remote SWER earth monitoring unit. The design and construction of the new site will be detailed.

Chapter 10 - Conclusion

This section will contain the project summary with reference to the successful outcomes of the project and further research.

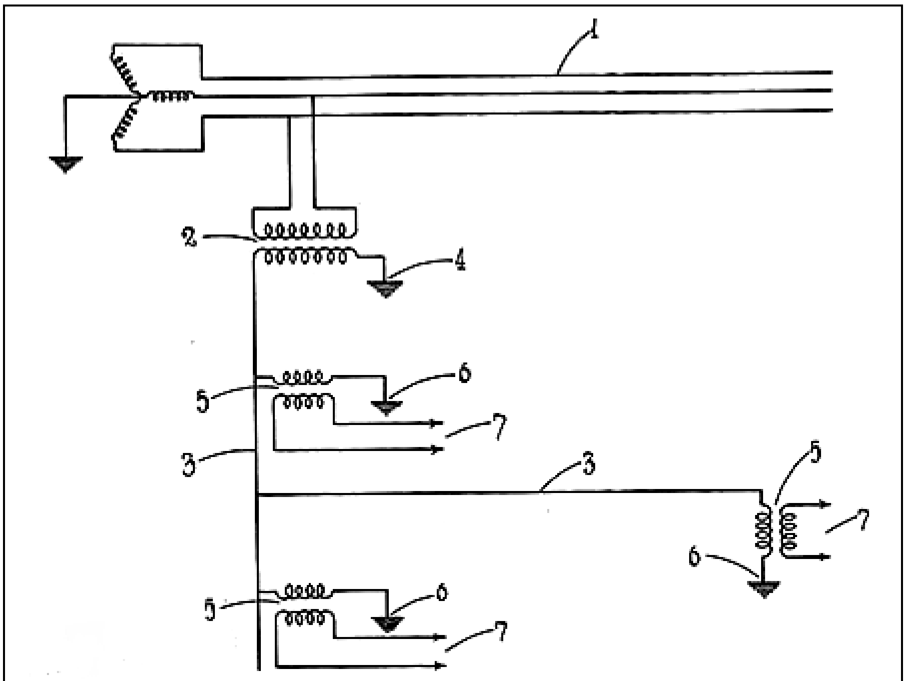
Chapter 2 - Literature Review

2.1 The Origin of SWER

The first innovation of single wire transmission using a return ground path was used by Carl August von Steinheil of Munich, Germany in 1837. He experimented with one wire telegraphic communication lines utilising metal plates buried in the ground as the return electrical path (Hyde 2007). Single Wire High Tension Earth Return (SWER) was developed by New Zealand engineer Lloyd Mandeno (1888 – 1973) in the early 1920's. The first known construction was built in Tauranga, New Zealand in 1925/6, as a part of the Tauranga Electric Power Board Scheme. Lloyd Mandeno documented in an article that 4,000 Australian hard wood poles were used to start the rural line construction utilising supply from the newly constructed McLaren Falls Hydro Electric Power Station (Hyde 2007). Lloyd Mandeno patented the SWER system in 1940 following updated provisions in the 1935 Supply Regulations permitting its use (Mandeno 1940).

SWER is a single wire high voltage distribution system that relies on the earth/ground as the return current path. The concept was developed as a cost effective, reliable form of electrical reticulation to supply customers in sparsely settled rural areas (Mandeno 1947).

Figure 3 shows Lloyd Mandeno's original patent diagram with the SWER system originating as a single phase spur line connecting two phases of the three phase feeder to an isolation transformer. The single wire spur line is connected to one leg of the secondary of the isolation transformer allowing multiple transformers to be connected in a parallel configuration. The second leg of the isolation transformer winding is connected to ground.



Circuit diagram for Patent No. 83946 - SWER System - Lloyd Mandeno

Figure 3: SWER System Patent No. 83946 (Mandeno 1940)

This configuration is commonly used in present day SWER system designs with the isolation transformer neutral/ earth connection point providing a path for the HV earth return currents from the distribution transformers.

2.2 What is Earth/ Ground and its importance to SWER

Earth is defined as the conductive mass of the earth, whose electric potential at any point is conventionally taken as zero (Ergon Energy Substation Standards 2007).

Earthing is described as a system of electrical connections to the general body of the earth (Dulmison 1986).

Ground is defined as the soil and subsoil forming the surface of the planet. The National Electrical Code Article 100 defines it as “A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth or to some conducting body of relatively large extent that serves in place of the earth” (National Electric Code 2015).

SWER systems rely on the earth through a ground connection as a return current path. Around every earth electrode a potential gradient area can develop referred to as the step potentials and touch potentials. Without a properly designed and maintained earth system a fault current will travel via the least resistive path and that can be a person or metallic object in contact that person. This can result in electrocution and/or damage to plant and equipment (ANSI/IEEE 1984).

An ideal earth or ground connection is zero ohms; realistically this is not possible due to the length, depth, diameter and number of the earth electrodes installed in an earthing system design. The earthing system design, installation and maintenance are essential to maintain a low resistance ground connection. The overall system can be divided into two simple elements; the controlled being the electrode, the uncontrolled being the soil.

Due to the non-homogeneous structure of soil, the chemical composition and concentration of salts dissolved in any contained moisture, the soil and environmental conditions determine the resistivity measurement. IEEE Std 80-200 states the electrical conduction in soil is essentially ionic thus causing the resistivity of most soils to rise abruptly when the moisture accounts for less than 15% of the soil weight (IEEE 2000). Figure 4 highlights the effects of moisture, temperature and salt on soil resistivity.

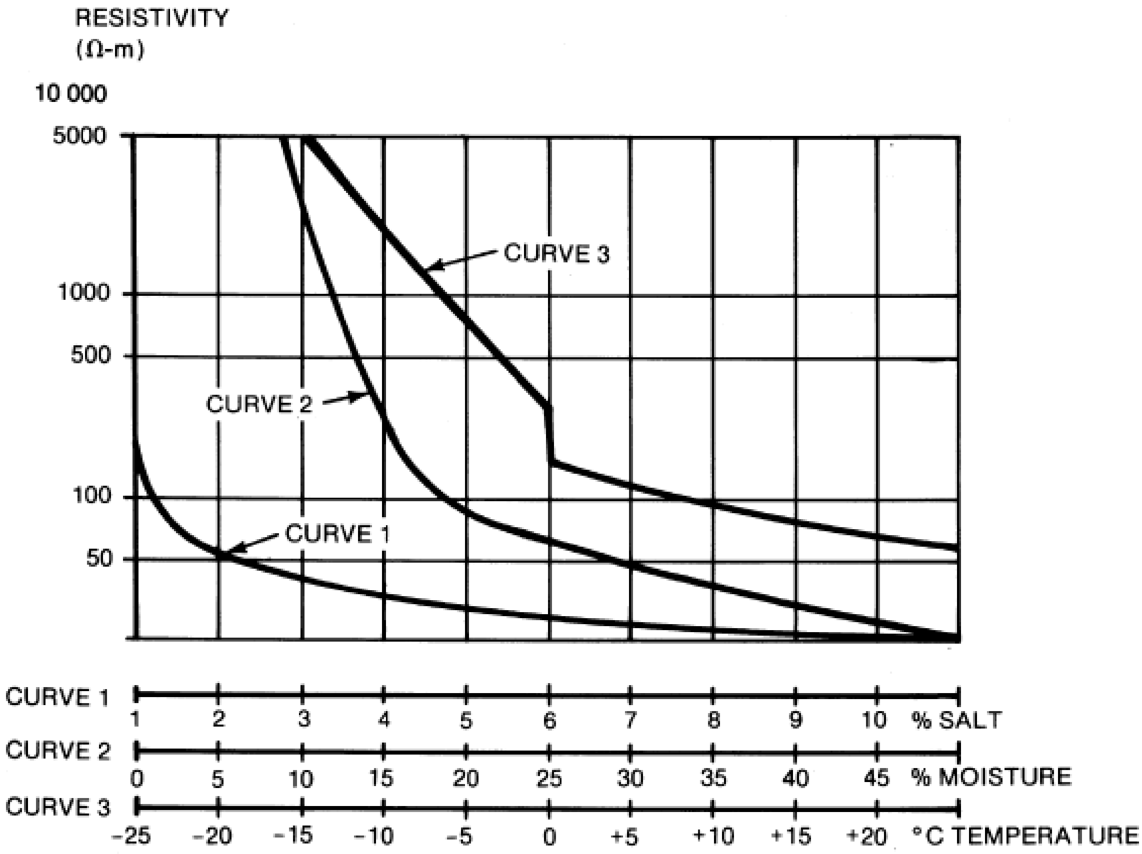


Figure 4: Effect of Moisture, Temperature and Salt Upon Soil Resistivity (ANSI/IEEE 1984)

Australia has a diverse range of soil conditions, the soil triangle in Figure 5 refers to the proportion of sand, silt and clay particles that form the composition of soils and enable soil texture categorisation. Studies such as the 'Temperature Rise in Continuously Loaded Distribution Earthing Electrodes' carried out by the Central Queensland University have shown that electrode resistances can increase dramatically under extreme drought conditions. Moisture and soil structure continuity are essential to maintaining mobility of ions essential for enhanced conductivity (Noorudheen, Wolfs & Alahakoon 2016). Adiabatic heating can result in electrode and conductor connection failures from climatic conditions causing soil contraction and dry pockets in voids and sandy soils. Although soil textures can be predicted, it is essential to carry out onsite tests to establish benchmark conditions before construction.

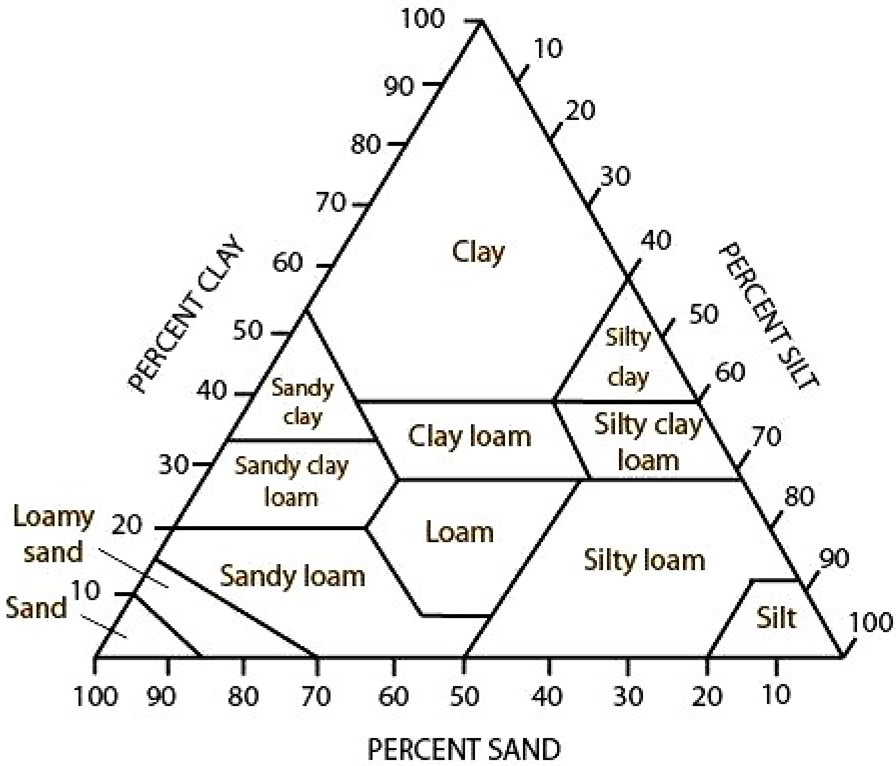


Figure 5: Soil Triangle (Queensland Government 2019)

2.3 Earthing Stake/Rod Sphere of Influence

Conducting objects that are buried in the ground exhibit areas of resistance that form concentric earth shells or sheaths of ever increasing diameter around the object. As the current flows to each shell section it is dissipated and the resistance decreases in an inverse proportion to the increase in area of each section as shown in Figure 6 and Figure 7. The shells or sheaths around a conductive earth stake are referred to as the 'spheres of influence'. The Earthing Handbook 1975 describes "the resistance area is that area surrounding the electrode to a radius where the decrease in resistance due to the growth of the hemispherical shells is negligible" (The Electricity Authority of New South Wales 1975). The size of the shell is dependent on the depth and diameter of the stake/electrode, increasing the diameter of the electrode has negligible effect to the overall surface area. It is therefore more effective to increase the length of the electrode to effectively reduce the electrode resistance.

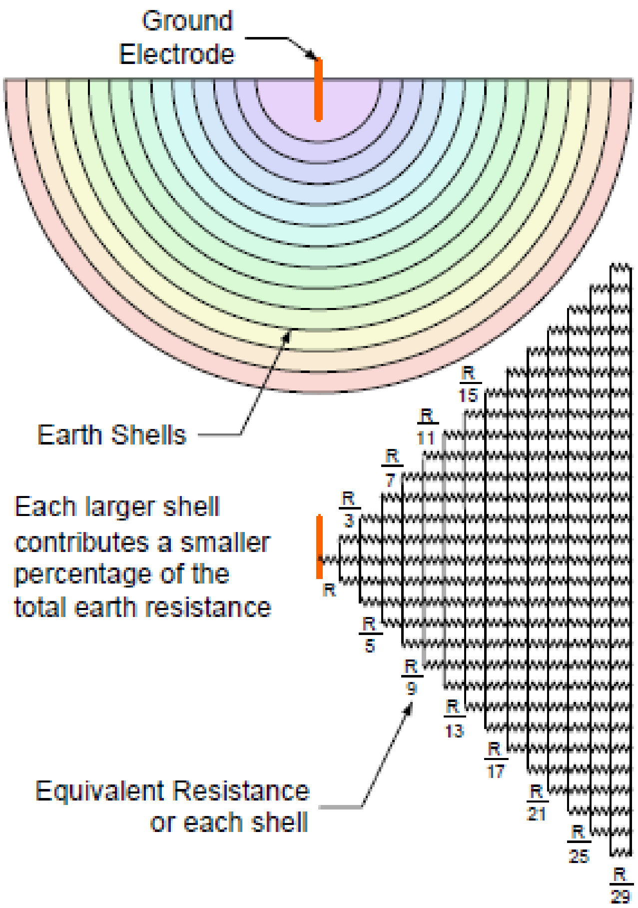


Figure 6: Concentric Earth Shells Around an Earth Electrode (Gill 2009) (Reeve Engineers 2008)

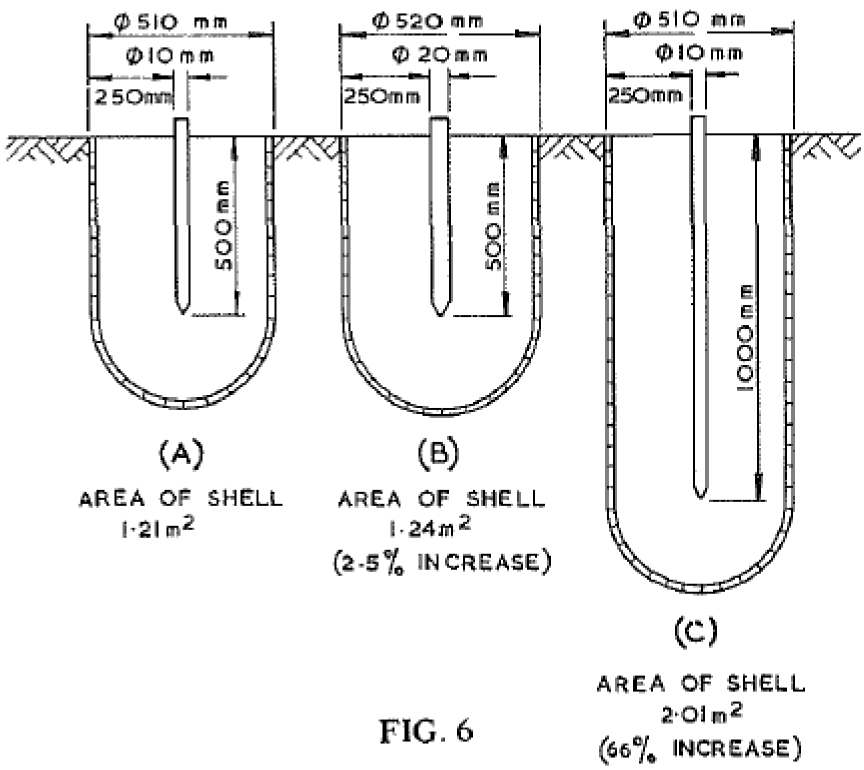


Figure 7: Shell Hemispheres around Electrodes (The Electricity Authority of New South Wales 1975)

It is important when designing an earth system that the shells or spheres of influence of each earth stake do not overlap; if they intersect then the resistance will not be lowered in the corresponding portion resulting in additional stakes and unnecessary expense.

There are other types of earthing such as earth plates and grids; these have not been investigated as a part of this dissertation due to the expense of these systems and no known SWER earthing system with this configuration.

2.4 Traditional Earth Measurement Techniques

2.4.1 Soil Resistivity

Soil resistivity is defined as the resistance between opposite faces of a unit length cube, measured in ohm-metres as represented in Figure 8 (Birtwhistle & Pearl 1997).

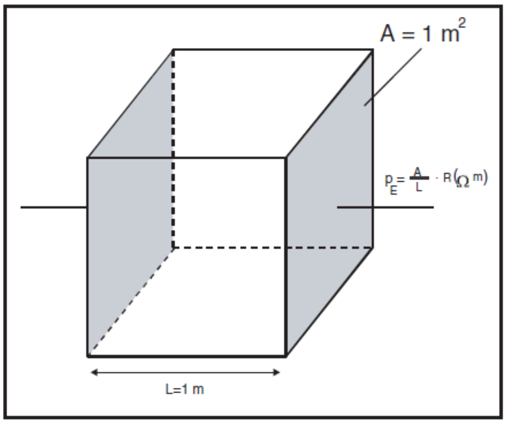


Figure 8: Resistivity Unit Length Cube (Birtwhistle & Pearl 1997)

Soil resistivity measurements are essential to establish the correct design of the earthing system. Variations in soil resistivity can occur geographically, at different depths and seasonally although the main factors for adequate conduction is soil moisture content, dissolved salts, temperature, grain size and pressure. Soil resistivity values are generally more stable at deeper strata due to the lack of influence from short-term weather variations and it is recommended to install earthing rods as deep as possible (Fluke Corporation 2014). It must be noted that soil structures are very complex and rarely identical as shown in Table 1, therefore the test methods mentioned below make the following assumptions: a) Uniform resistivity; b) Horizontal layers of uniform resistivity; c) Exponential variation of the resistivity.

Soil Resistivity Values	
Types of Soil	**Typical Resistivity (Ω.m)**
Ashes of Cinders	6-70
Clay (Damp)	14-30
Clay (Dry/ Compacted)	100-200
Granite	2000-3000
Gravel (River Bed)	1000-5000
Limestone	200-400
Loam (Humus)	30-50
Loam (with Sand and Gravel)	100-300
Loam (with some stones)	200-350
Loam (with stones and poor vegetation)	300-400
Marshy Soils	5-40
Mountain Rocks (with little or no soil)	1000-15000
Mountain Soil (Damp Peat over Rock Base)	150-300
Mountain Soil (Over Rock Base)	300-1000
Salt Pans	6-70
Sand (Below Water Tables)	60-130
Sand (Damp)	200-500
Sand (Dry)	1000-2500
Sand (Leached)	1000-5000
Sandstone	120-7000
Shales	100-160

Table 1: Soil Resistivity Values (Birtwhistle & Pearl 1997)

Electrical resistivity was first discovered by Gray and Wheeler in 1720 whilst establishing the conductivity of rock for geology studies. In the 1800's Robert W Fox determined the presence of a natural current in a copper electrode whilst observing electrical current flowing in copper mines and Dr Carl Barus is known for the introduction of non-polarising electrodes. Conrod Schlumberger formed a method of measuring resistivity originally as a method to map self-potential over metallic deposits for pyrite mining in 1913; he published his findings in 1918. Dr Frank Wenner released his method of measuring resistivity in 1915.

The two test methods below, the Wenner Four-Pin Method (equally spaced) and the Schlumberger-Palmer Method (unequally spaced), are used to measure the resistivity of soil (ANSI/IEEE 1984).

2.4.1.1 Wenner Four-Pin Method (equally spaced)

The Wenner four-pin method is one of the most common test techniques for measuring the resistivity of large volumes of undisturbed earth (Birtwhistle & Pearl 1997). The Wenner method, shown in Figure 9, involves driving four test probes into the earth to a depth of 'b' along a straight line and equidistant of 'a' metres apart. The distance between each probe should be at least three times greater than the depth of the probe (Fluke Corporation 2014). The probes are connected to a test unit that applies a known current to the two farthest probes and measures the potential difference between the two closest probes. Ohm's Law is used to calculate the mutual resistance as seen in equation (2-1).

$$Soil\ Resistance\ R = \frac{V}{I}\ \Omega \tag{2-1}$$

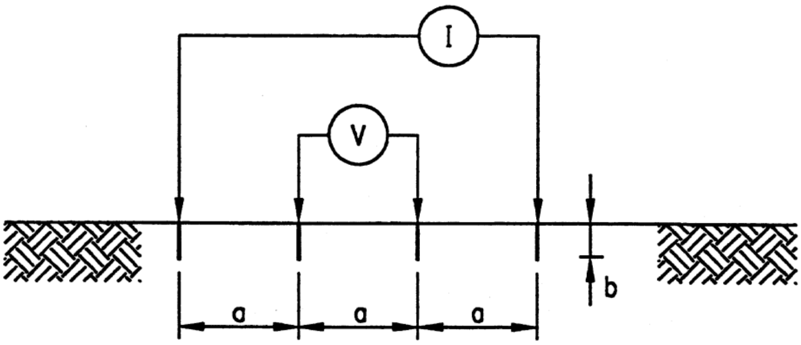


Figure 9: Wenner Four-Pin Method from (IEEE 2000)

With the value of soil resistance calculated from the field measurements, the value of apparent soil resistivity in ohm-metres can be established using equations (2-2) and (2-3):

$$R = \frac{\rho_a}{4\pi a}\left(1 + \frac{2a}{\sqrt{a^2+b^2}} - \frac{2a}{\sqrt{4a^2+4b^2}}\right)\ \Omega \tag{2-2}$$

$$\rho_a = \frac{4\pi a R}{1+\frac{2a}{\sqrt{a^2+b^2}}-\frac{2a}{\sqrt{4a^2+4b^2}}}\ \Omega\text{m} \tag{2-3}$$

ρ_a = apparent resistivity of the soil in Ωm

R = measured resistance in Ω

a = the distance between adjacent electrodes in m

b = the depth of the electrodes in m

For cases when 'b' is much smaller than 'a' equation (2-4) can be used:

$$\rho_a = 2\pi a R\ \ \Omega\text{m} \tag{2-4}$$

2.4.1.2 Schlumberger-Palmer Method (unequally spaced)

When using the Wenner method to measure large distances between probes, the potential difference between the two inner probes can reduce dramatically. This can cause issues with evaluation of results and can potentially result in calculation errors. The Schlumberger-Palmer method, shown in Figure 10, uses the same configuration of the Wenner four-pin method except the distance between the two inner probes is increased so the inner probes are closer to the outer current probes. This method increases the potential difference reading and increases the result accuracy. Equation (2-5) corresponds to the Schlumberger-Palmer method: (ANSI/IEEE 1984).

$$\rho_a = \frac{\pi c(c+d)R}{d} \quad \Omega\text{m} \tag{2-5}$$

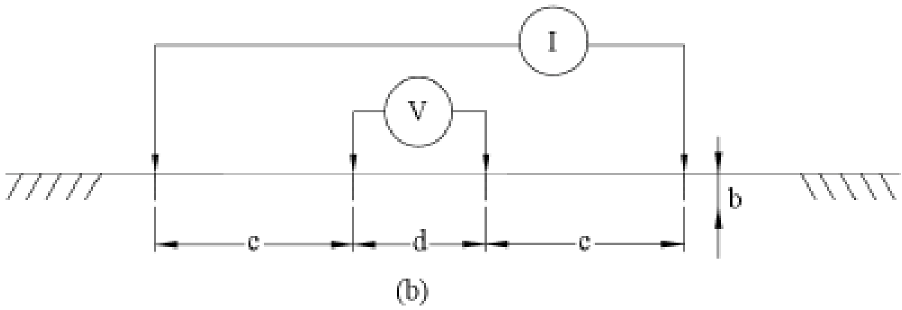


Figure 10: Schlumberger-Palmer Method (ANSI/IEEE 1984)

2.4.1.3 Earth System Resistance

The resistance of an earth system is influenced by the electrolytic characteristics of soil which can produce local stray DC currents (The Electricity Authority of New South Wales 1975). The 2.4.1.4 Voltmeter-Ammeter Method and 2.4.1.5 Three Point Method below were developed as quick experimental techniques to obtain field test values. Unfortunately, current errors were experienced and the Fall of Potential, selective and stakeless methods were developed to reduce introduced errors.

2.4.1.4 Voltmeter-Ammeter Method

This method is used when there is a reliably low resistance earth reference available such as a buried conductive object like a water pipe located a distance from the system under test. A known voltage is applied to the conductive object and system under test, the resulting current is measured and Ohm's Law, equation (2-6), is used to determine the resistance which is the sum of the earth connections including the leads and reference connection (The Electricity Authority of New South Wales 1975).

$$R = \frac{E}{I} \ \Omega \tag{2-6}$$

This method is not commonly used as there is rarely an earth reference point available and stray DC currents produced by electrolysis can be present in independently buried conductive objects.

2.4.1.5 Three Point Method

This method involves installing two reference earth probes in a triangular formation to the earth system under test. Figure 11 shows how a resistance meter is used to measure the three triangulated resistance values R1, R2 and R3. This value of resistance includes the resistance value of the earth system or test probe:

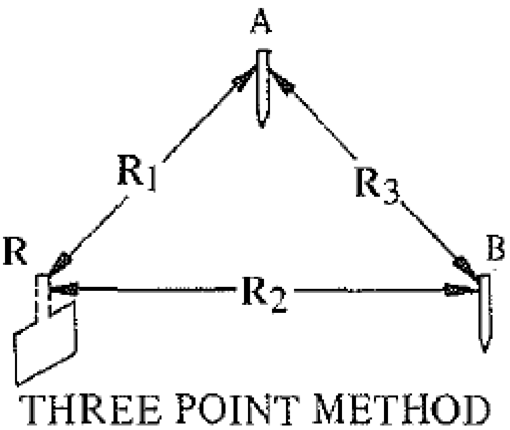


Figure 11: Three Point Method Configuration

R1 = the resistance of R + A in series

R2 = the resistance of R + B in series

R3 = the resistance of A + B in series

Therefore, the total resistance is calculated by R = the resistance of the earthing system under test including test stakes A and B

$$R = \frac{R1 + R2 - R3}{2}\ \Omega \tag{2-7}$$

The Three Point Method is similar to the Voltmeter-Ammeter Method where the obtained readings are influenced by DC currents produced by electrolysis. The main reason this method is not commonly used is due to errors caused by the test equipment being induced on the R3 value, resulting in an increase in R1 and R2 (The Electricity Authority of New South Wales 1975).

2.4.1.6 Fall of potential method (3 pin method)

The Fall of Potential Method has proven to be a reliable method of testing earthing resistance since the 1930's. The Fall of Potential test method is used to measure the ability of an earth system and/ or individual electrode to dissipate energy from a site (Fluke Corporation 2014). This method involves testing a system with the earth connected or by disconnecting an individual earth stake then installing two earth test probes in a straight line at set distances away from the earth stake in test. The stake and two test probes are connected to an electronic test unit and a current is induced between the outer probe and the earth stake. The potential difference between the earth stake and the inner probes is measured and Ohm's Law is applied to establish the resistance of the stake or system. A benefit in using this method is the two test probe resistances only affect the results indirectly and do not introduce considerable errors to the final values. The resistance of the outer current test probe affects the value of the main current; this is counteracted by the proportional drop in the potential on the inner voltage test probe. Any change in resistance on the potential test probe will affect the total resistance; it is important that the test unit has a high internal resistance in order for any high resistance with the potential test probe to have negligible effect on the final result (The Electricity Authority of New South Wales 1975). A measuring unit with low internal resistance should not be used or potential errors could occur with the final measurements and calculations. Formula (2-8) is used to determine the resistance with assumed earth resistivity values as shown in Table 2.

$$R = \frac{\rho}{2\pi r}\ \Omega \tag{2-8}$$

r = earthing system hemispherical electrode

ρ = distance between the earth stake in test and the first test electrode

Table 8—Range of earth resistivity

Type of earth	Average resistivity (Ω·m)
Wet organic soil	10
Moist soil	10^2
Dry soil	10^3
Bedrock	10^4

Table 2: Range of Assumed Earth Resistivity (IEEE 2000)

The inner potential probe is initially placed outside of the sphere of influence of the earth stake in test, then placed at different intervals towards the outer current injection probe and tested. Figure 12 shows the earth stake resistance is a reflection of a standard data set for resistance measurements taken by moving the voltage test probe between the earth electrode under test towards the outer current injection probe. The area along this curve where it flattens out is outside of the 'sphere of influence' and is taken to be the true value of earth resistance (Birtwhistle & Pearl 1997). The non-linear areas at the beginning and end of the plot in Figure 12 shows 'sphere of influence' or the inaccuracy in measured resistance when the test probes are places in close proximity to the earth electrode under test or to the outer current test probe.

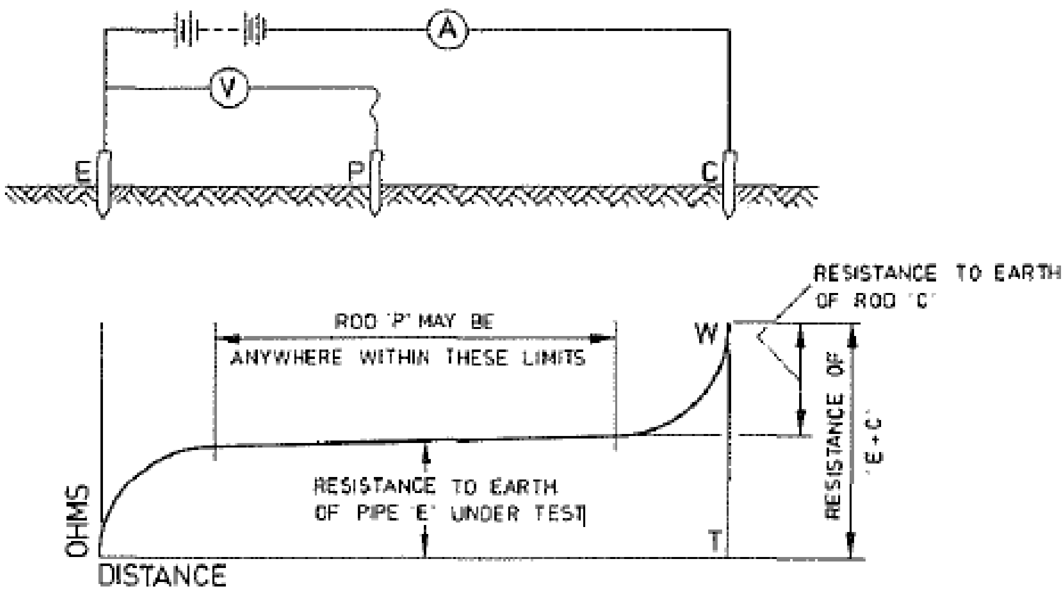


Figure 12: Fall of Potential Generic Resistance Plot (The Electricity Authority of New South Wales 1975)

It is important to note that test leads should not be run in parallel in order to rule out any mutual inductance errors (ANSI/IEEE 1984).

There are two alternatives to complete the Fall-of-Potential test:

- **Full Fall of Potential** – a number of tests are made at different distances between the earth stake under test and the outer current injection probe. The resulting resistances are plotted with the corresponding distances and the true resistance value is deduced from the area were the curve flattens out. This flat area is referred to as the true resistance as it is the area that is not under influence from the earth stake under test or the current injection probe.

- **Simplified Fall of Potential 62% Rule** – One measurement is taken with the potential test probe at a distance 61.8% of the total distance between the electrode under test and the current injection probe, as shown in Figure 13. The 61.8% is a calculated value for the mathematical root of a polynomial for a hemispherical earth stake in contact with uniformly distributed soil. The distance between the earth stake under test and the current injection probe should be 8 to 10 times the depth of the earth stake under test to reduce errors from the sphere of influence (Birtwhistle & Pearl 1997). The 62% rule works well for short electrodes, for deeper earth electrodes, if the depth is known, the correct calculation for the distance can be established but the distances for the test probes may be impractical.

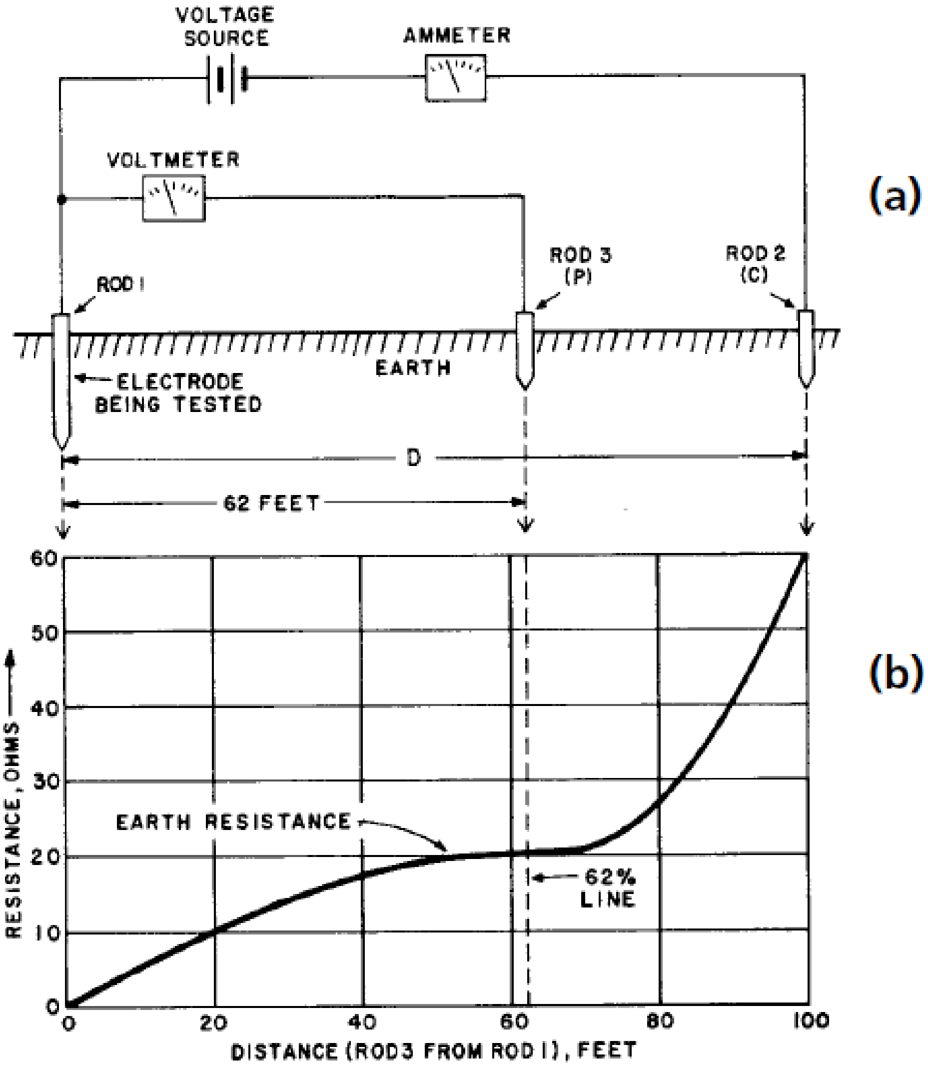


Figure 13: Simplified Fall of Potential 62% Rule (Birtwhistle & Pearl 1997)

2.4.1.7 Stakeless and Clamp-on Method (Selective and Stakeless)

Clamp on meters were first introduced to the electrical supply industry in the late 1990's and have gradually been adopted as the technology has advanced and become affordable. There are several variations using clamp-on style techniques as described in the sections below 2.4.1.8, 2.4.1.9 and 2.4.1.10.

2.4.1.8 Selective 4-Pole Earth Resistance Measurement Method

This method is a variation of the Fall-of-Potential method with the addition of a current transformer clamp, as shown in Figure 14. The additional clamp enables selective testing of individual earth stakes in parallel earthing systems. The clamp is place around the earth under test and measures the exact current flowing through it for improved selectivity and precision (Arnoux 2010). This method can be adapted to measure different earth stakes by moving the current clamp to the different stakes; distance and lead length remaining the limiting factor.

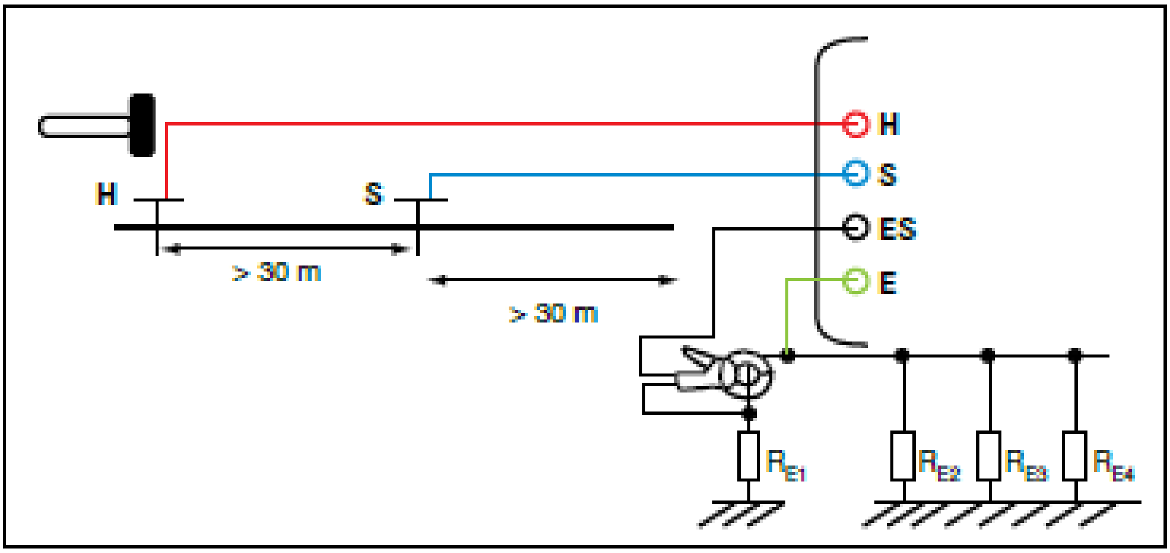


Figure 14: Selective 4-Pole Earth Resistance Measurement Method (Arnoux 2010)

2.4.1.9 Earth Loop Resistance Measurement with Two Clamps Method

This method requires no test probes and uses two individual clamps to establish the loop resistance value of the earth system. The technique eliminates the need to disconnect parallel earths and install test probes. As shown in Figure 15, the injection clamp is placed on the outgoing earth conductor whilst the receiving clamp is placed on the stake under test. This method works on the principle that the multiple parallel paths will amount to a resistance value that is negligible compared to any single path, as shown in equation (2-9), and therefore requires more than one upstream electrode. Accuracy issues can be experienced when using this method due to high impedance earth loop paths from lack of parallel earth stakes, disconnected mains earth neutral connections and induction from parallel circuits such as railway lines.

$$Rmeasured = Rtest + \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \cdots \frac{1}{Rn}} \, \Omega \qquad (2\text{-}9)$$

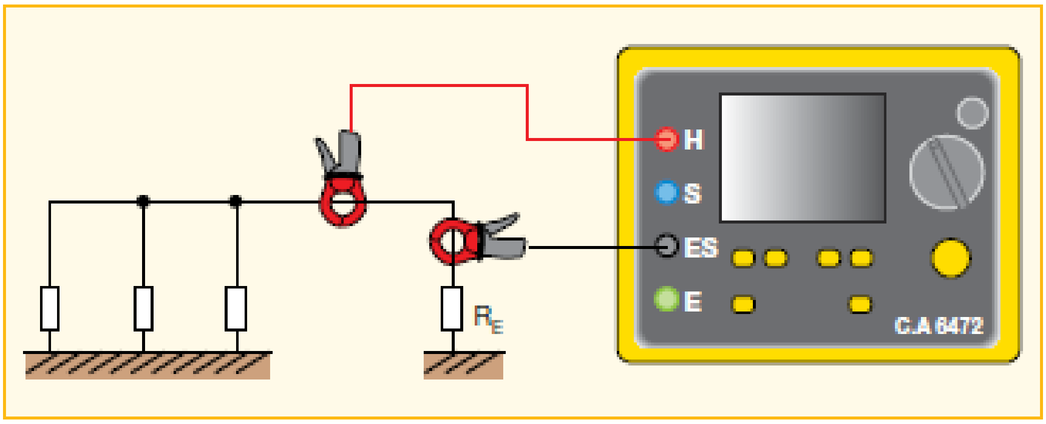


Figure 15: Earth Loop Resistance Measurement with Two Clamps Method (Megger 2010)

2.4.1.10 Stake-less Clamp-On Method

The stake-less clamp-on method or two clamp method is a relatively new technique for measuring the resistance of the earth stake. It works on the same principles as the Earth Loop Resistance Measurement with Two Clamps method, the difference being the clamps and unit are compacted into one handheld device. The method is non-intrusive and quick to perform although it is not able to measure the resistance of the entire earthing system. As shown in Figure 16 and Figure 17, the unit consists of two coils with separation between them to avoid any direct electromagnetic influences. The transmitting/injection coil utilises an alternative square waveform of constant voltage to induce a current on the earth conductor. The frequency of the waveform injected through the transmitting coil is selected to avoid harmonic or inductive effects. The receiving coil measures the return current enabling the resistance to be calculated using Ohm's Law.

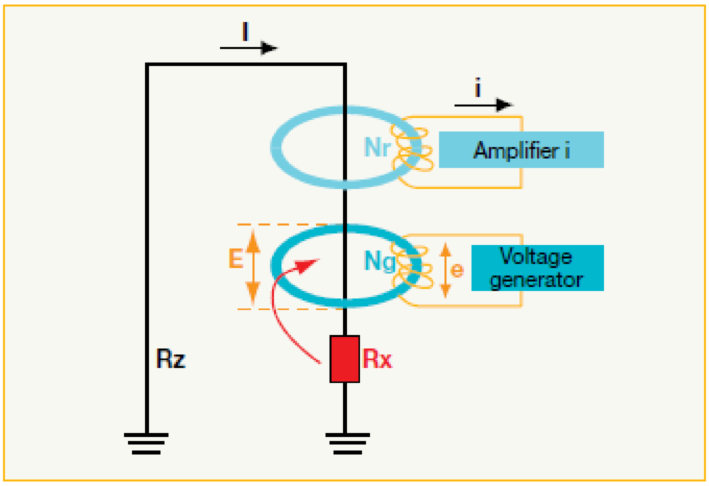


Figure 16: Stake-less Clamp-On Method Diagram (Megger 2010)

Figure 17: Stake-less Clamp-On Method Unit (Megger 2010)

2.5 Earth Grid Monitoring Systems

Grounding/Earthing systems play an important role in maintaining electrical safety whilst preventing ground potential rise. As electrical substations age, engineers are always searching for technological advances to reduce lifecycle maintenance costs and improve techniques. This literature review has revealed there is continued research into monitoring the condition of earth grids and reducing the effects of corrosion in zone substations. Section 2.5.1 considers recent journal articles related to the field of remote earth monitoring.

2.5.1 Alternative Methods for on-line monitoring of earths

In 2000 a journal article titled "Automatic Maintenance of Substation Ground Resistance" was released by three engineers from Malaysia, Indonesia and the United States of America (Jambak, Ahmad & Baker 2000). They recognized the importance of monitoring the condition of earth mats in substations to maintain safe ground potential levels for personnel and reliable operation of protection equipment. The proposed PC-Based system was named Amomagsys – Automatic Monitoring and Maintenance of Grounding System. The system comprised a PC-Interface System, Ground Resistance Measurement Unit (GRMU) and a Signal Conditioning Unit (SCU) with auxiliary connections to a fluid sprinkler system and burglar alarm.

As seen in Figure 18, the systems operation was based on the Fall-of-Potential Method by injecting a controlled electrical frequency into an existing ground stake and monitoring the calculated resistance through the change in potential via additional test probes. If the resistance of the earth grid rises above set thresholds, then a sprinkler system can be activated to assist the dispersion of moisture over the earth grid and/or a burglar alarm can be activated. It is unknown if the system was built or implemented.

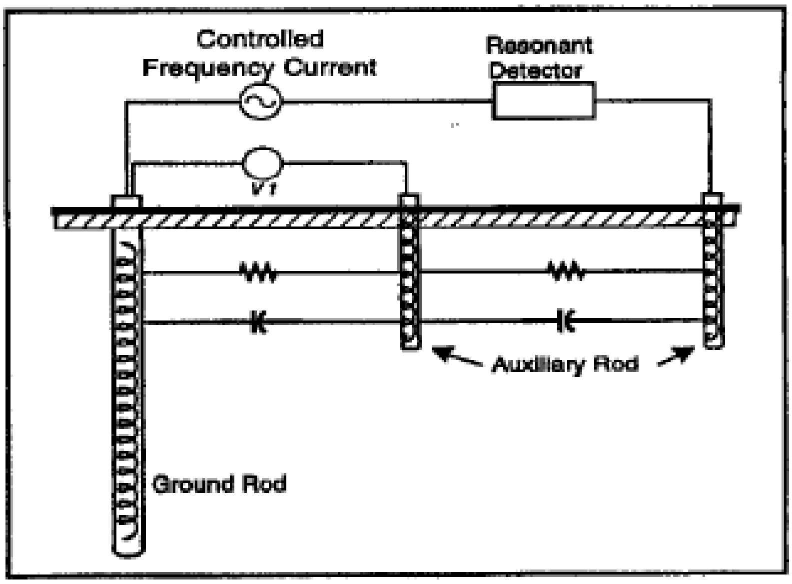


Figure 18: Field Measurement Arrangement, Based on Modified Fall-of-Potential Method (Jambak, Ahmad, & Baker 2000)

In 2007 the Hunan University in China released a paper titled "A New Approach for Monitoring Grounding Grid of Electrical Power System". The paper was developed as a result of costs incurred to repair corrosion to steel and galvanized steel grounding grids and the need for early detection of issues and potential failures.

The circuit theory used a model with sacrificial conductive elements to simulate the corrosion process. The circuit model in Figure 19 then became a three pole system with a sacrificial anode and cathode, the measured values were the corrosion potential, port potential and the test current, the software computed the polarization resistance, corrosion current densities, corrosion rate and corrosion depth (Cong-li & Minfang 2007).

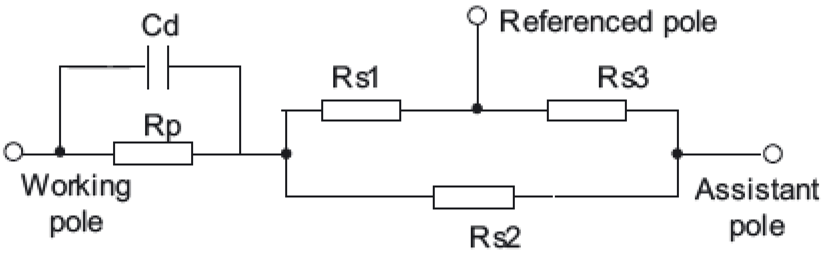


Figure 19: Circuit Model for Three-Pole System (Cong-li & Minfang 2007)

In 2016 the Campina Grande Federal University in Brazil completed a research paper investigating a new data acquisition system (CVAU – current and voltage acquisition unit) for continuously monitoring grounding grids in energised substations (Ramalho et al. 2016). The paper proposed a new data acquisition system, shown in Figure 20, based on the Earth Loop Resistance Measurement with Two Clamps using wireless sensor networks via a coordinator, voltage node and a current node. The CVAU comprised the following:

- Data acquisition unit: microcontroller, analog-to-digital converter, signal conditioning circuits and user interface;
- Current Conditioning Circuit: current transformer, hall-effect sensor, PGA and anti-aliasing filter;
- Supply circuit: 4.8V rechargeable batteries and low dropout regulator.

The concept used an ATmega12RFA1 microcontroller communicating over a ZigBee network, as shown in Figure 21. The system was tested in a laboratory environment with a scaled model earth grid; the proposed system was not tested in a real substation.

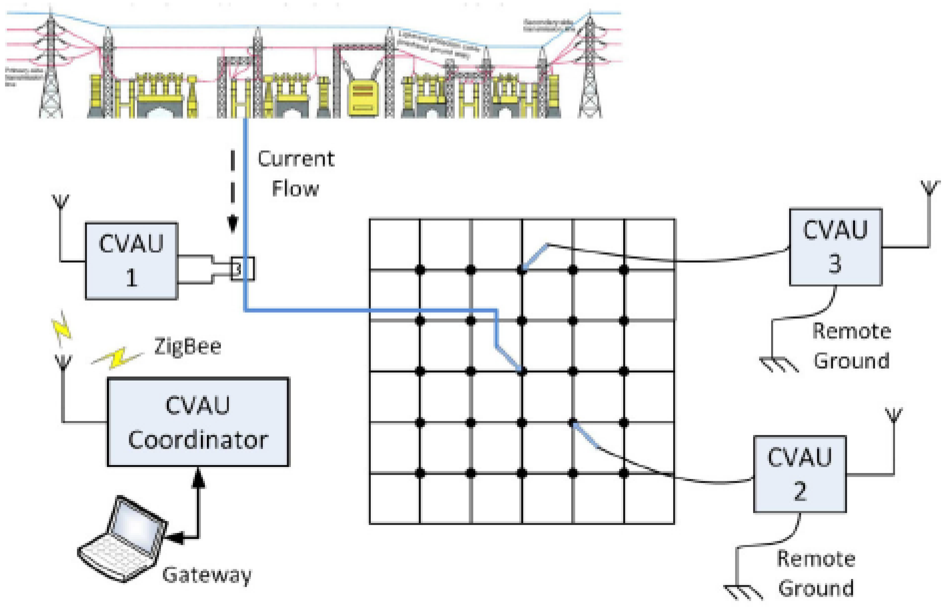


Fig. 1. Overview of the current and voltage acquisition unit (CVAU) arranged to monitor current and voltage at certain points of the electrical grounding grid.

Figure 20: CVAU – Current and Voltage Acquisition Unit Overview (Ramalho et al. 2016)

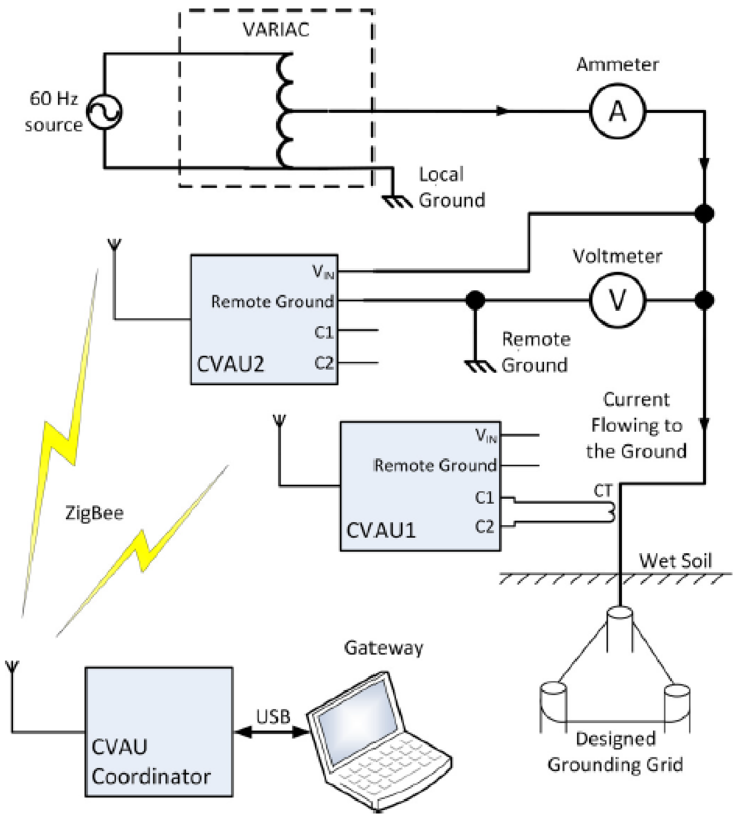


Fig. 5. Testbed for evaluation of the proposed system.

Figure 21: CVAU – Current and Voltage Acquisition Unit Communication Flow (Ramalho et al. 2016)

2.6 Earth System Modelling

Overall electrical system modelling is generally undertaken for protection and voltage studies, SWER earth systems form a small part of these models. In 2009 a journal paper was released by the Federal University of Mato Grosso do Sul titles "Modelling and Simulation of a Grounding System using Simulink" (Aguiar et al. 2009). The study investigated the behaviour of simulated grounding systems by separating them into two distinct systems, the stake/rod behaviour and the soil behaviour. The resulting simulation used a grounding system of 28 rods configured in an earth grid pattern.

The soil was modelled using a branch resistance and a capacitance in parallel. The frequency was chosen based upon effects from corrosion, electrode polarization and electrical resonance. Soil stratification was set at four levels and based upon values using equations from the Wenner Method, shown in Table 3.

Resistance and resistivity measurements

A (m)	Resistance (Ω)	Resistivity (Ωm)
1	1.32	10.16
2	0.38	5.09
3	0.30	5.83
4	0.27	6.90
6	1.28	48.63
8	0.24	12.12
12	0.27	20.40
16	0.30	30.19
24	0.40	60.35
36	0.37	83.71

Table 3: Resistance and Resistivity Measurements (Aguiar et al. 2009)

The earth stake/rod was modelled using the equivalent circuit in Figure 21:

a) Low frequency (kHz) earth rod;

b) Protection structures with inductive cable effects;

c) Very high frequency (MHz) displacement parallel conduction current is considered;

d) General cases for the rods characteristic inductance.

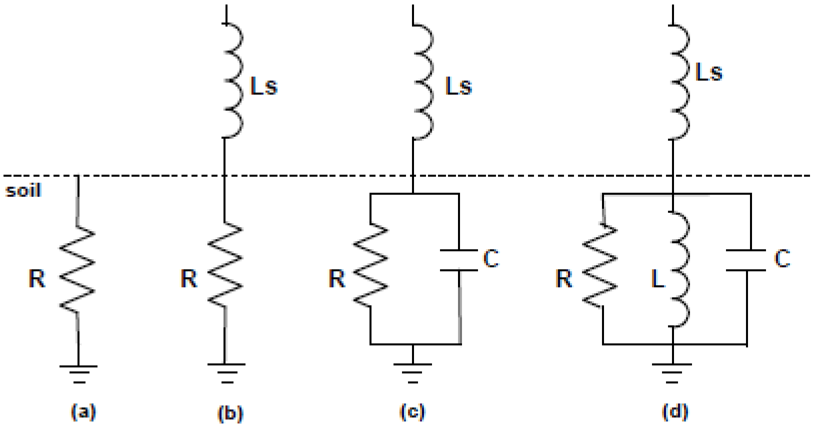


Figure 22: Equivalent Circuit of a Rod (Aguiar et al. 2009)

A single phase full bridge inverter was developed for the topology to represent a current source to perform soil injection. The variable square waveform current injection was through probes C1 and C2, as shown in Figure 23.

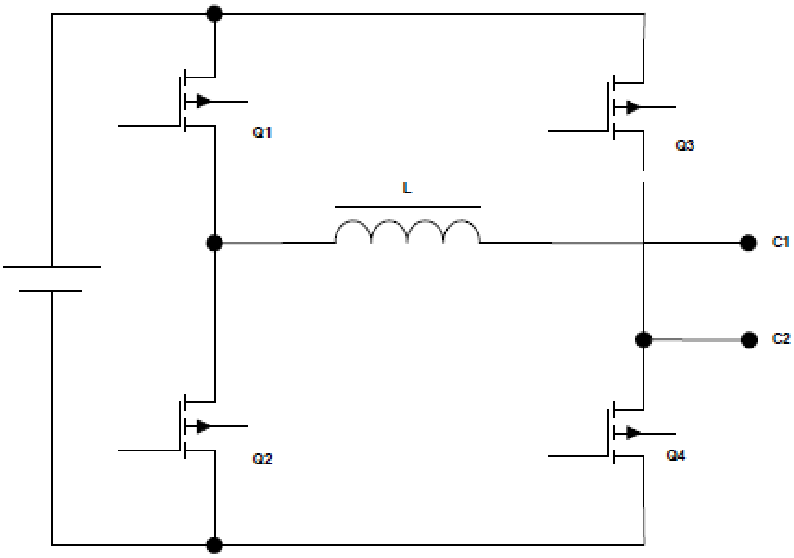


Figure 23: Electrical Model of a Rod (Aguiar et al. 2009)

The MATLAB simulations were performed using the impedance as a function of the frequency variation and with the addition of the inverter with the impedance measured via variable frequency. The paper concluded that the non-linear behaviour of soil is the main contributing factor to establishing accurate simulation results. The paper did not verify the results with any field trials.

2.7 Gap Analysis

Through the analysis of existing methods to measure and monitor earthing systems, researchers have recognized there is a definite need to monitor earth systems due to the non-homogeneous nature of soil and the subsequent variations in results. Studies have identified that the heterogeneous characteristics of soils play an essential role in electrical earthing behaviour and although the electrical parameters can be influenced to improve resistivity and conductance, in reality it is impractical and cost prohibitive to change the parameters on every site that returns a poor test result.

This dissertation has acknowledged that there is a knowledge gap in the real life design and application of remote monitoring of SWER earthing. The question remains: can remote earth monitoring of SWER distribution transformer HV and LV earthing be achieved accurately without changing the design or inhibiting the operational safety of the return earth path? Will the results be beneficial to the electrical supply industry to review current SWER earthing thresholds, practices and procedures and potentially introduce change with economic benefits?

It is the expectation that the results from this dissertation will provide a theoretically proven method to remote monitor SWER earthing. If the stretch target is achieved the field results will provide early data enabling further study into the relationship between geographical locations, climatic conditions and seasonal change, anthropogenic intervention, vegetation and network influences.

Chapter 3 - Why SWER and the emerging distributed network?

3.1 Overview

SWER originated from the need to supply sparsely populated rural areas with small individual load densities in a cost effective manner. The economic benefits of SWER are derived from its single conductor design which reduces the initial investment, maintains reliability and lowers ongoing maintenance costs. This chapter discusses the advantages and disadvantage of SWER systems, the different configurations and what is preferred as current industry practise.

Customer loads, generation injection options, expectations and behaviours have considerably changed over that past 40 years. The following chapter briefly discusses the introduction of new and emerging technologies in the electrical supply industry that aim to sustain economic benefit and customer satisfaction. Safety is paramount to all electrical designs and drives industry change, the challenges associated with maintaining safety on SWER systems is essential.

Energy Queensland’s SWER system voltages are 12.7kV and 19.1kV; these are the line to ground voltages of the standard 22kV and 33kV three phase distribution supply systems. The voltage was implemented to utilise standard insulator, surge diverters and switchgear (Taylor & Effeney 1988).

3.2 Advantages

Simplicity of design: By utilising one overhead conductor, the design of SWER is simpler than that of the single or three phase alternatives, the need for cross-arms and additional pole hardware is eliminated. One conductor reduces the pole tip loads, increases flexibility of deviation angles, increases the maximum span achievable, decreases the weight span and decreases the clearance to structure proximity. All of these previous mentioned factors also permit the use of reduced kN rated poles.

Statutory ground clearance elevations can still be achieved with a reduction in pole height due to the single overhead conductor located at the highest point of the structure. Phase to phase conductor clashing is also eliminated facilitating greater design sag and ultimately leading to longer span lengths.

Conductor Size: SWER systems are generally lightly loaded enabling the main conductor to be a smaller cross sectional area. Ergon Energy guidelines for SWER conductor size is listed in Table 4.

Conductor	Application	Recommended Stringing Tension	Area (mm^2)
3/2.75 SC/GZ Gal Steel	SWER maintenance where work practices are not available for SC/AC.	25%	3
3/2.75 SC/AC Alumoweld	New SWER construction	25%	5.9
3/4/2.5 ACSR Raisin	SWER Backbone for reconductoring	22%	17.9
4/3/3.0 ACSR Sultana	New SWER Backbone	22%	31.6

Table 4: Ergon Energy Conductors Guideline (Brooks 2006)

In the past galvanised steel was the main conductor used for SWER networks due to its high tensile strength enabling conductors to be strung over longer spans. Over time the introduction of aluminium alloys has brought about a lighter and more corrosion resistant alternative. The three main climate zones across Australia are arid, temperate and tropical, Ergon Energy's infrastructure in the state of Queensland covers all three of these zones therefore it is a good cross-section for equipment trials.

Less pole hardware: Cross-arms and transposition configurations are eliminated with the use of a single conductor.

Switching: Air or gas break switches are used for three phase systems to switch all phases simultaneously; this is not required for single wire systems. SWER systems are isolated using reclosers and/or pole fuses.

Lower capital and operational costs: The main advantage of using SWER construction is the low capital and maintenance costs in comparison to the three phase alternatives. For the electricity supplier it provides a higher yield to profit ratio than single or three phase systems. Narrower vegetation clearance profiles and less poles lead to reduced access track footprints and provide construction and maintenance cost savings. Metering units connected to the earth lead of the isolation or distribution transformer can be rated to lower voltages as the potential difference is lower than the HV supply voltage.

Typically a SWER line initial capital outlay is 50% less than that of a single phase (two wire) system and they can be 70% less than that of a three phase (three wire) system (Ergon Energy 2017).

Faster Construction: Less hardware, poles, single conductor design, smaller vegetation profiles and less access tracks to pole sites leads to a reduction in time to install. Conductor stringing is often one of the most difficult aspects of installing overhead lines over rural terrain, running one conductor saves one third of the time to install than a three phase system.

Bush fire reduction: Bush fire hazards associated with molten metal from conductor clashing and conductor ground contact from cross-arm failure is eliminated with the use of one overhead conductor. The risk of bushfires is still present from conductor to ground failures or earthing integrity failure.

3.3 Disadvantages

Earthing Integrity: The earth is used as a conductor to carry the return current, this necessitates a low resistance connection and path at all times. If a poor connection occurs, the voltage gradient can increase and electric shock to humans and livestock can occur.

Load Restrictions: The first SWER systems were relatively short and the earth return current was limited to 8 amperes to control interference with telecommunications infrastructure. The 8 ampere limit was lifted and modern SWER lines are load restricted due to the Electrical Safety Code of Practice 2010 – Works section 3.3.7 (Queensland Government 2010) which requires the maximum voltage on the SWER earth lead with respect to a remote earth under normal operating conditions does not exceed 20V.

Telephone interference: SAA HB88 refers to SWER as an unbalanced high voltage power line due to the difference of impedance between the overhead conductor and the earth as the other conductor. As a result of the unbalanced conductors, electromagnetic fields are produced which can induce interfering voltages on any unshielded paired conductive telecommunication lines within close proximity to the overhead line (Telecom Australia and Electricity Supply Association of Australia 1997). The resultant of induced nuisance voltages can range from excessive noise on the telecommunication system to hazardous voltages to people working on them. Unbalanced power lines can also produce electrostatic fields that can induce nuisance currents on a telecommunication system, a result of which is hazardous to people working on the line and can also induce minor noise.

Copper has been the preferred material for telecommunications systems for the last 60 years since the telegraph line was phased out in Australia between the years of 1959 to 1993. Technological developments in satellite communication, wireless communication and optical fibre have fundamentally changed data transmission and long parallel runs of conductive telecommunications systems are becoming obsolete. Telecommunications interference from SWER systems is becoming a rare occurrence but one that must always be considered in the concept and design phase.

Load balance issues on the backbone feeder: SWER systems are radial lines connected to two phases of the main distribution feeder through an isolating transformer. This applies an unbalanced load on the main three phase backbone feeder. Due to the dissimilarities of each SWER system with non-uniform customer distribution and usage patterns it is difficult to maintain proportional load uniformity between SWER systems. Main backbone long rural feeders can be 50km to 180km in length and SWER systems radiating from these can be 10km to 380km. As an addition to the imbalance caused by SWER system loads, the long backbone feeder can experience high energy losses from small conductors.

Charles Fortescue’s 1918 theory of symmetrical components discovered that any unbalanced phasor can be expressed as the sum of its sequence components (Fortescue 1918). Figure 24 shows the sequence components of a balanced and unbalanced three phase systems with the result of an unbalanced system causing considerable lack of phasor symmetry. Voltage unbalance is often expressed as a percentage of negative sequence voltage to the positive sequence voltage or simply V_2/V_1 as shown in equation (3-10). This can often be Line to Line (L-L), which can cause heating in three phase induction motors, or Line to Neutral (L-N), which can affect distribution feeder insulation levels and line charging current magnitudes in the supply system neutral (Loveday & Turner November 2003) .

$$Voltage\ Change = \frac{\Delta U_{dyn}}{U_N}\% \tag{3-10}$$

ΔU_{dyn} = Dynamic voltage change

U_N = Actual voltage

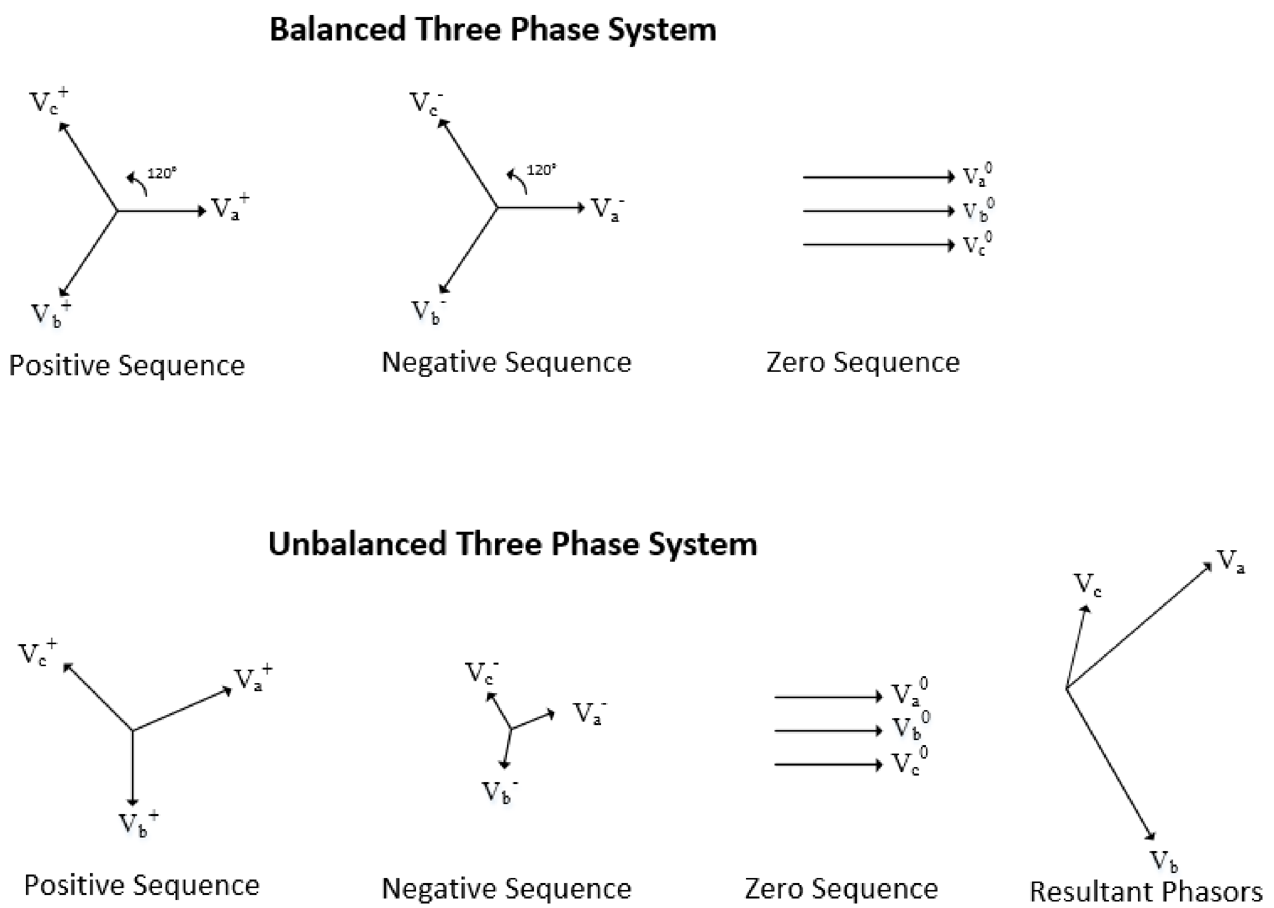


Figure 24: Three Phase Sequence Voltages Balanced and Unbalanced

SWER system loads are analysed and balanced during the network design planning process, unfortunately historical customer growth has proven difficult to predict and accumulative voltage drop effects can be significant at the extents of the three phase network. Software modelling requires correct load current magnitudes, phase angles and line transpositions to be entered. Line current balancing requires metering at critical points along the feeder which is expensive and maintenance-intensive. Detection of voltage unbalance can often be a result of a customer voltage complaint and can require urgent attention once recordings have been obtained. This is not ideal for Electricity Supply Entities and network control methods are usually implemented to reduce the magnitude of voltage unbalance.

A number of proposals to treat voltage unbalance have been recommended and implemented over the years, sometimes these can be complex due to customer load variations and the inability to balance the system at all times. Feeder efficiency can be improved by restructuring or augmenting the feeders to balance the load distribution, SVC's can be used for negative sequence control when the system is supplied from a generator.

Voltage regulators are often installed to control the magnitude-balance of the line to line voltages on long rural feeders. The unbalances can be limited to approximately 6% however the phase angle cannot be controlled resulting in power quality issues (Hossein-Zadeh et al. 2004). Open delta regulator arrangement uses two single phase voltage regulators that regulate two of the line-to-line voltages with the third being indirectly regulated. This method is not recommended for three phase feeders with SWER system loads as the indirectly regulated phase can reach unacceptable magnitudes and if one of the regulators fails the remaining regulator can inadvertently tap to the maximum position and remain there. To avoid this issue additional remote voltage sensors are required. Closed delta regulator arrangements are the preferred option for long rural three phase feeders supplying SWER systems as all three phases are regulated using three single 10% boost units that results in an accumulated 15% boost for each phase. Closed delta systems also provide operational redundancy in the case of one tank failing in service.

A substantial amount of modelling studies and hardware can be implemented yet outages can cause significant issues to voltage unbalance. A protracted outage from protection equipment operation on an isolated SWER system with seasonal access issues can cause a severe unbalance on the three phase network that cannot be rectified expediently.

Reduction to voltage control and power quality: An outcome of most SWER system schemes is voltage drop as a result of small conductors covering vast distances with characteristically high impedance. This produces disturbed voltage profiles and in extreme situations the susceptibility to voltage collapse. Problems are most prevalent during peak load times. The quality of supply is often jeopardised with voltage fluctuations, unbalances and harmonic disturbances.

Overvoltage occurs in lightly loaded conditions and is the side effect of the capacitive charging effects of the single conductor and earth; this is referred to the Ferranti effect and is not discussed in detail in this dissertation. Distributed shunt reactors are utilised to reduce the capacitive line charging effect and control any over-voltage situations (Ergon Energy 2017).

Limitations to Load density: A major limitation for SWER systems is the load carrying capability and flicker issues associated with motor starts. Rural customer behaviour, expectations and loads have changed considerably in the past forty years with domestic heating and air conditioning, agricultural pumping, production line handling, packing and refrigeration facilities. This has pushed the size of SWER distribution transformers from 5kVA to 10kVA, 25kVA and 50kVA and SWER isolation transformer from 100kVA to 200kVA units. Flicker is voltage fluctuation caused by changing loads such as motor starts and welding equipment. The maximum percentage voltage changes as a function of the number of changes per hour as set by the AS/NZS 61000.3.7:2001 Section 9 and the National Energy Regulator is 4%, as seen in Table 5 and Table 6.

r (hour^{-1})	$\Delta U_{dyn}/U_N$ (%)	
	MV	HV
r ≤ 1	4	3
1 < r ≤ 10	3	2.5
10 < r ≤ 100	2	1.5
100 < r ≤ 1000	1.25	1

Table 5: Emission Limits for Voltage Changes as a Function of the Number of Changes Per Hour (Australian Standards 2001)

Nominal Supply Voltage (kV)	Maximum negative sequence voltage (% of nominal)			
	Non contingency event	Credible contingency event	General	Once per hour
	30 minute average	30 minute average	10 minute average	1 minute average
more than 100	0.5	0.7	1.0	2.0
more than 10 but not more than 100	1.3	1.3	2.0	2.5
10 or less	2.0	2.0	2.5	3.0

Table 6: Sequence Levels (AEMC 2018)

Electrolytic Corrosion: Corrosion in an electromagnetic process that requires an electrolyte such as water to cause metal atoms to oxidise. The overhead conductor and electrodes can be subjected to two types of corrosion, atmospheric and galvanic (Naranpanawe, Ma & Saha 2018). The corrosion process of electrodes and conductive components can be accelerated in areas with high concentrates of moisture, salt, sulphur and chlorine. Galvanic corrosion (bimetallic corrosion) occurs when two metal with different electrical potentials are in contact with an electrolyte such as water, one metal becomes an anode, releasing electrons whilst the other a cathode. In this scenario cathodic protection can be installed via a sacrificial anode to prevent the corrosion of the earthing electrode.

3.3.1 Standard Configurations and Construction

SWER systems are grouped into three main configurations: isolated, hybrid and non-isolated. These variations are a result of years of engineering aiming to reduce costs, balance loads and increase capacity. Some of them have evolved directly from Mandeno's original SWER design or are a mixture with other system arrangements.

Isolated: Isolated SWER systems are the typical construction adopted by electricity distribution companies today. As seen in Figure 25, the primary winding of an isolation transformer is connected to two phases of the distribution feeder, one terminal of the secondary winding supplies the SWER system and the other is connected to the mass of earth. The isolation transformer provides a path for the return current of the distribution transformers and isolates these currents from the main feeder network. An isolation transformer allows for upstream protection devices to perceive SWER loads as normal single phase loads.

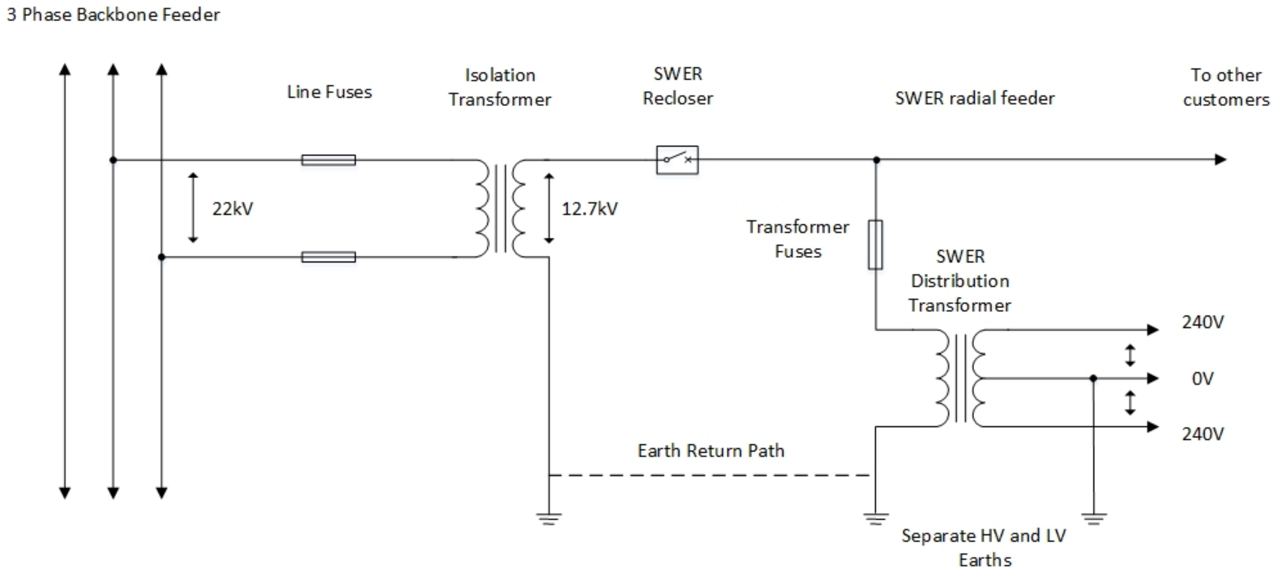


Figure 25: Isolated SWER System Diagram (The Electricity Authority of New South Wales 1978)

Hybrid Duplex: Two SWER lines, on the same poles, can be supplied from one isolation transformer with an earthed centre tap resulting in the phases being in two configurations depending on the limiting factor, as shown in Figure 26 and Figure 27. If the earth current is the limiting design factor then the system is built to reverse polarity, 180 degrees apart, alternatively if the balance of the supplying three phase feeder is the limiting factor then the feeder angle is used as the source and the system is configured to 120 degrees apart as shown in Table 7.

Duplex SWER - Design Limiting factor				
	Voltage (kV)			Phase Angle Degrees
Dist Fdr	L-G	12.7	19.1	
	L-L	22	33	120°
Earth current	L-G	12.7	19.1	
	L-L	25.4	38.1	180°
Distribution Feeder Balance	L-G	12.7	19.1	
	L-L	22	33	120°

Table 7: Duplex SWER Voltages

Duplex SWER system design is used for areas that require additional capacity without the need to install a new spur line and line route. If correctly load balanced, harmonics and fundamental ground currents can be cancelled. High magnetising metering current transformers must be used to avoid high line to line charging current interference.

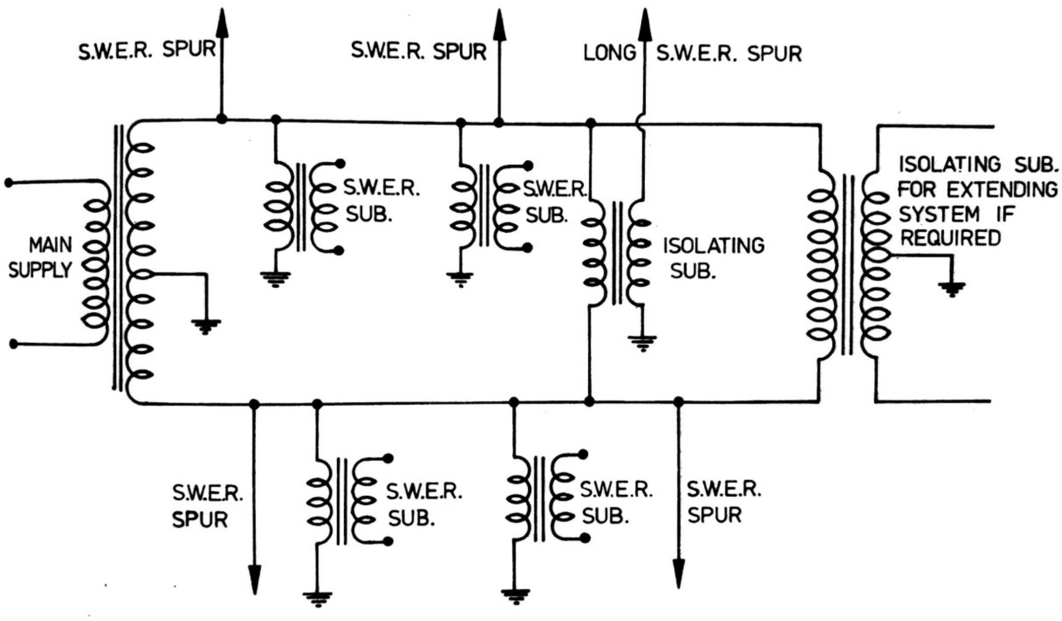


Figure 26: Duplex SWER System (The Electricity Authority of New South Wales 1978)

Figure 27: Duplex SWER System Configuration in Central Queensland

Hybrid Triplex: Triplex SWER systems are often referred to as an isolated three phase system. As seen in Figure 28, the three phase backbone feeder is connected to the isolation transformer and three SWER conductors are supplied from the secondary of the isolation transformer. The system is used for radial SWER lines that cover considerable distances is diverse directions. Triplex SWER systems enable improved feeder balancing with additional load capacity. The disadvantage of this system is that the size of the isolation transformer can be in the MVA ratings and this is a cost-prohibitive, non-standard construction. If correctly balanced, Triplex systems can cancel harmonics and fundamental ground currents.

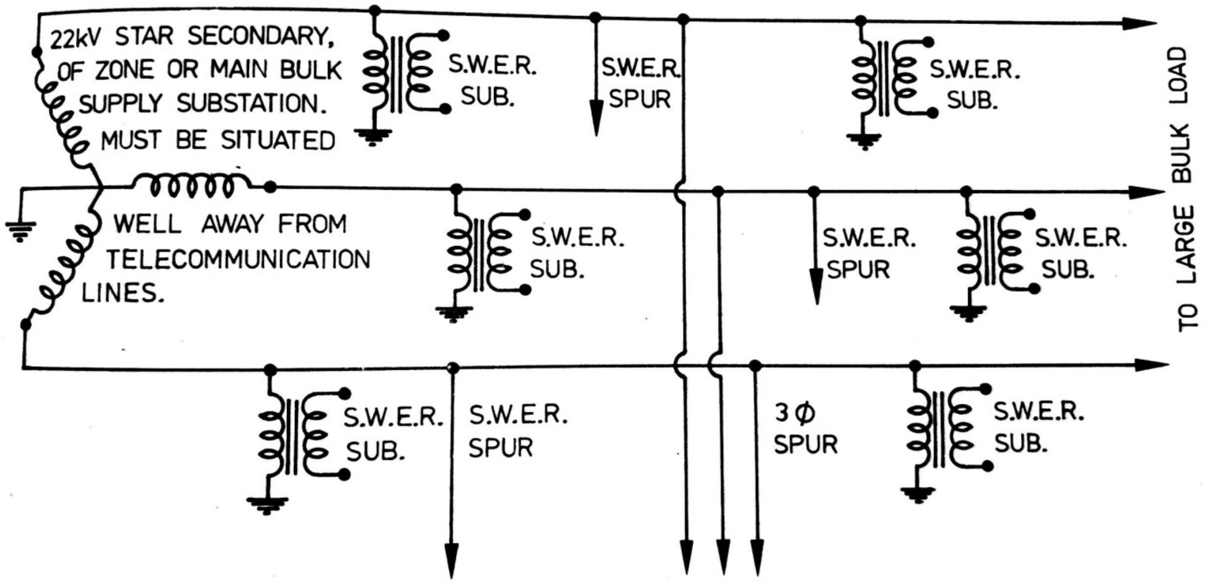


Figure 28: Triplex SWER System (The Electricity Authority of New South Wales 1978)

Integrated SWER: Due to the capacity constraints and performance of the network, a number of alternative and renewable energy solutions are being trialled and investigated. New technologies such as low voltage regulators (LVR's) have been deployed successfully on the Ergon Energy network, these units provide continuous filtered power to the customer to avoid voltage fluctuations. LVR's are single phase electronic 20kVA regulators connected in series with the customer's mains; the input voltage is continuously monitored with the output adjusted to maintain a constant output. Figure 29 shows LVR's fitted to SWER distribution transformers in 240V and 480V configuration.

Figure 29: LVR Units Fitted to SWER Distribution Transformers 240V and 480V Configuration

Grid Utility Support System (GUSS) is an Ergon Energy developed network connected autonomous energy storage unit that currently provides 2MWh of distributed energy storage across multiple SWER sites in regional Queensland, as shown in Figure 30. Ergon Energy currently owns 20 individual GUSS units which have been deployed and integrated on different SWER networks for 4.5 years and have provided significant voltage support/ stability and Var control at peak demand periods.

Figure 30: GUSS Units Installed on the Western Grid (Taylor 2015)

As shown in Figure 31 and Figure 32 the units are classified as an LV item of plant connected to the secondary winding of a 25kVA SWER distribution transformer. GUSS units consist of a 25kW single phase inverter, 240V grid interface unit, autonomous control system and a 100kWh energy storage in the form of 2 strings of lithium batteries. The batteries are charged from the grid at times of low demand and provide compensated energy at peak demand. A distribution transformer is used as a bidirectional grid voltage converter acting as a step down power supply when the GUSS unit is charging and a step up transformer to export to the network. GUSS units utilise a real time control system with 210µs sample time to determine the compensation characteristics of the resultant export signal waveform and the charge and discharge rate of the batteries.

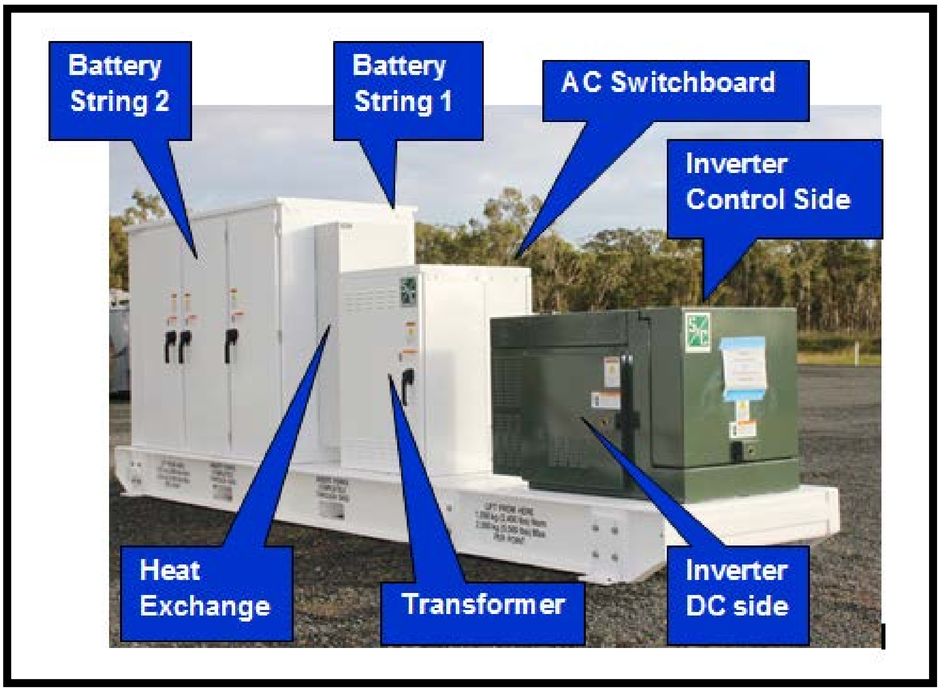


Figure 31: GUSS Unit Components (Ergon Energy 2019)

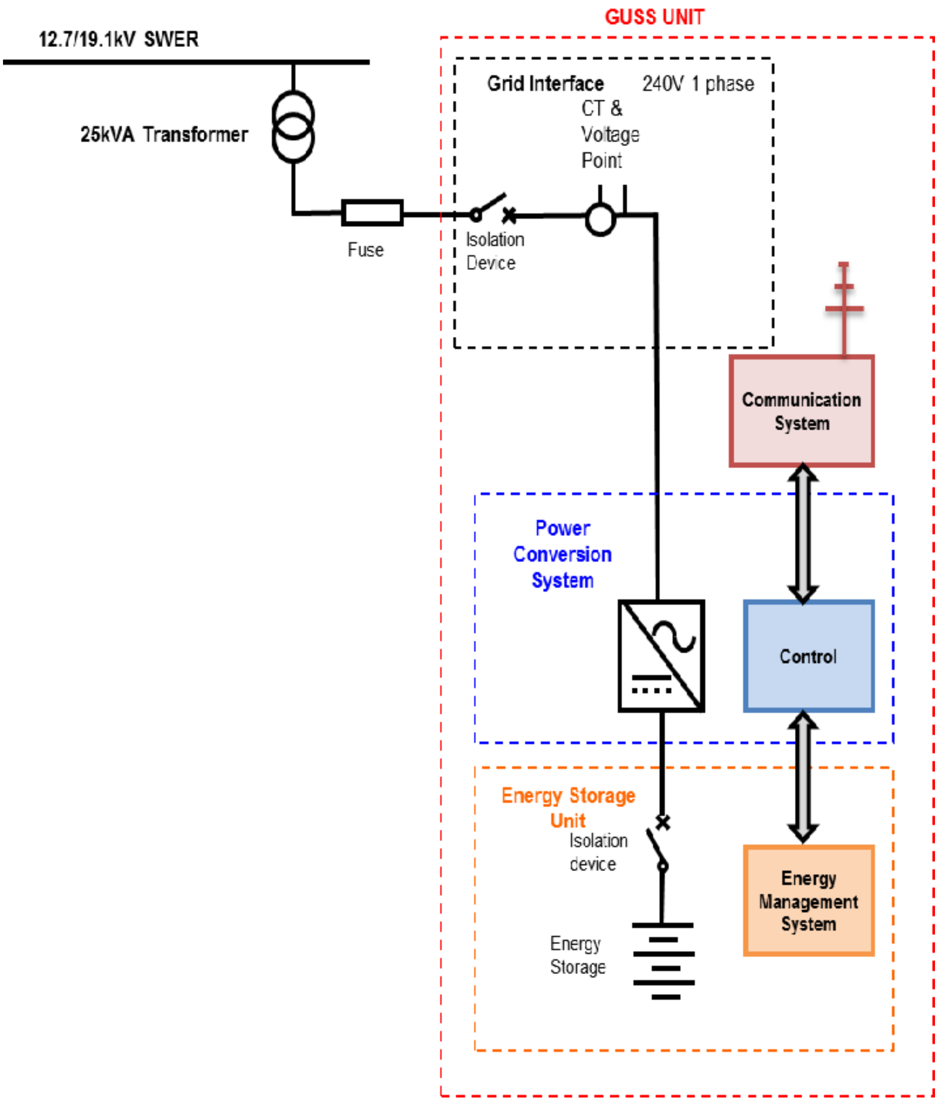


Figure 32: GUSS Unit Connected Configuration and Control (Taylor 2015)

To maintain electromagnetic compatibility, the standard resistance for GUSS site earthing is <4Ω as shown in the MEN configuration of Figure 33 (Ergon Energy 2015). Although GUSS units are successfully providing dynamic upstream and downstream network voltage control, steady state control is still required via regulators. Feedback from the initial field trials revealed the importance of maintaining reliable, low resistance earth connections with spurious control system values being experienced when a poor microcontroller earthing connection resulted in a floating earth.

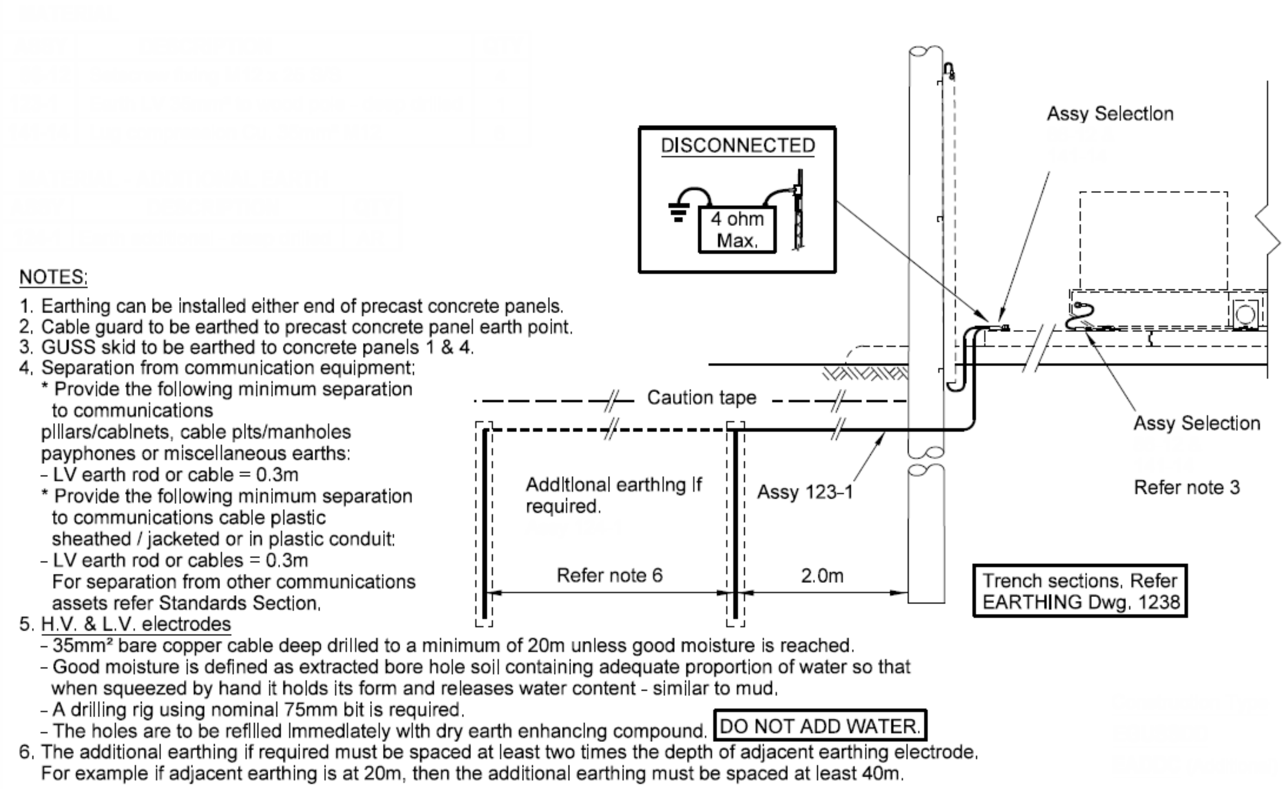


Figure 33: MEN Earth Configuration for GUSS Units – Deep Drilled (Distribution Network Standards 2018)

Un-isolated: Un-isolated SWER systems are an extension of one phase of the three phase backbone feeder with no isolating transformer. The line to ground voltage is still the same as an isolated system; the main difference is the return current travels to the neutral point on the zone substation power transformer. Un-isolated SWER configurations create a four wire HV distribution network which creates issues with sensitive earth fault protection discrimination at the zone substation. Un-isolated SWER systems are being phased out in most electrical networks within Australia with the installation of isolation transformers.

3.3.2 Network growth, reliability, loading and customer densities

Ergon Energy has 758 SWER systems spread over 6 legacy regions, Far North (FN), North Queensland (NQ), Mackay (MK), Central (CA), South West (SW) and Wide Bay (WB), as seen in Figure 34. Investigative modelling and data collection from 2012, has shown that 105 of these are overloaded (Figure 35), with 134 suffering voltage quality constraints (Figure 36). The study revealed that an annual average of 250 new distribution transformers are connected to the network with another 50 existing units being upgraded, introducing an additional 6MVA of load (Ergon Energy 2012). Customers supplied by SWER systems are predominantly very low density with growth of new customers, prior the millennium, being predictably low. The internet has provided a transparent educational platform for current customers, they are electricity savvy and their loads have increased in capacity with power quality and reliability expectations a priority. Load profiles are influenced by the penetration of domestic grid connected photovoltaic systems, air conditioning and larger commercial and industrial loads. Table 8 shows the asset status and indicators associated with Ergon Energy's SWER systems. A key indicator for increases in connected load is the decrease in customer density from 3.4 km/customer in 1992 to 2.53km/customer in 2012, a 25% increase.

A number of reliability management projects have been completed that address poorly performing SWER systems. Maintenance programs have assisted in detecting pole and conductor faults prior to catastrophic failure. Storm related outages have been reduced from the installation of electronic reclosers equipped with remote communication functionality, aerial line patrols following storms and initiatives to fit gapped bands to all new SWER intermediate poles.

Asset or Indicator	Description	Value	
Customers	Number	25,322	
	Density	2.53	km/customer
	Annual growth	3.8%	
SWER Network	Total Schemes	758	
	Unisolated	98	12.9%
Conductor	Length	64,000	km
	% of Network	43%	
Voltage	11kV	70	
	12.7kV	421	
	19.1kV	267	
Isolating Transformers	Number	651	
	Installed Capacity	96.4	MVA
	Utilisation	77.90%	
SWER Transformers	Number	24,973	
	Installed Capacity	249.9	MVA
	Annual growth	2.40%	
	Density	3.9	kVA/km

Table 8: Asset Status and Indicators (Ergon Energy 2012)

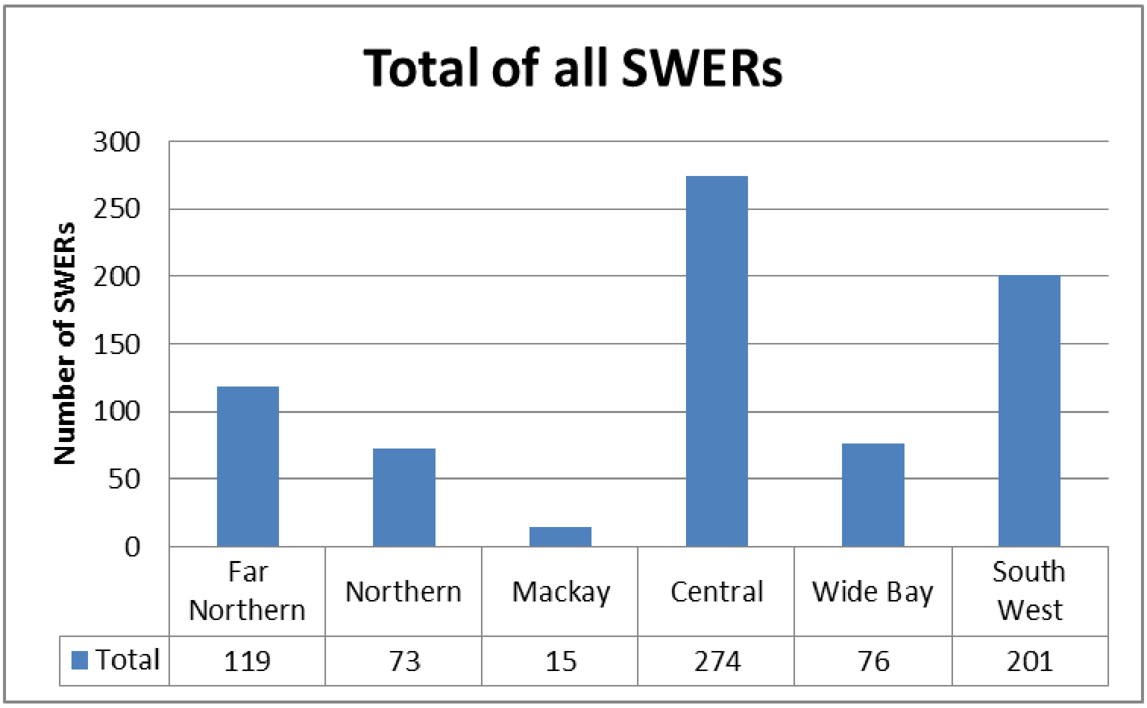


Figure 34: Number of SWER Systems Per Legacy Region (FN, NQ, MK, CA, SW, WB) (Ergon Energy 2012)

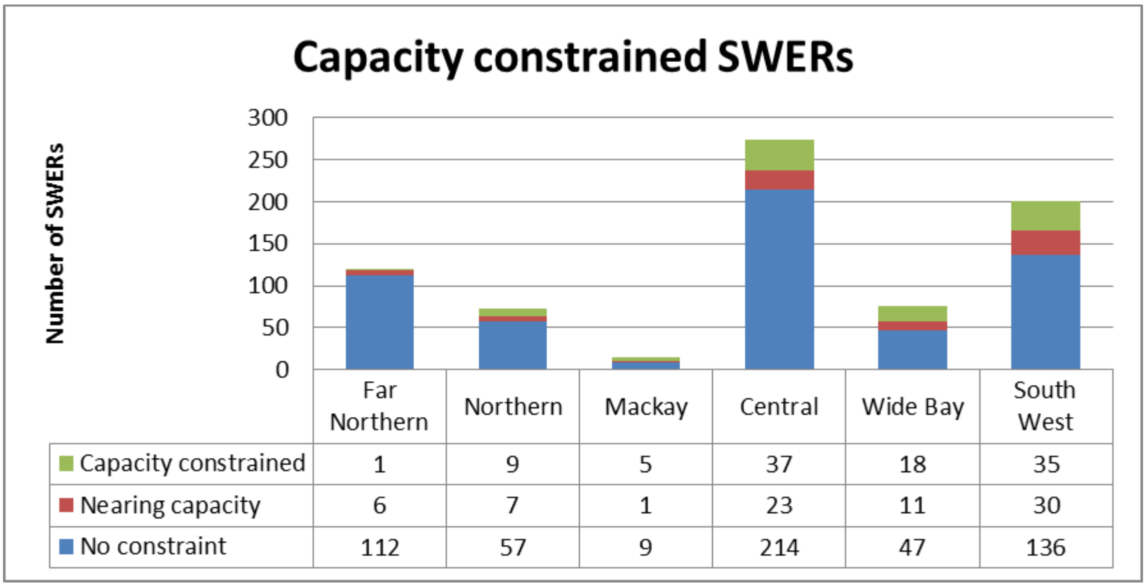
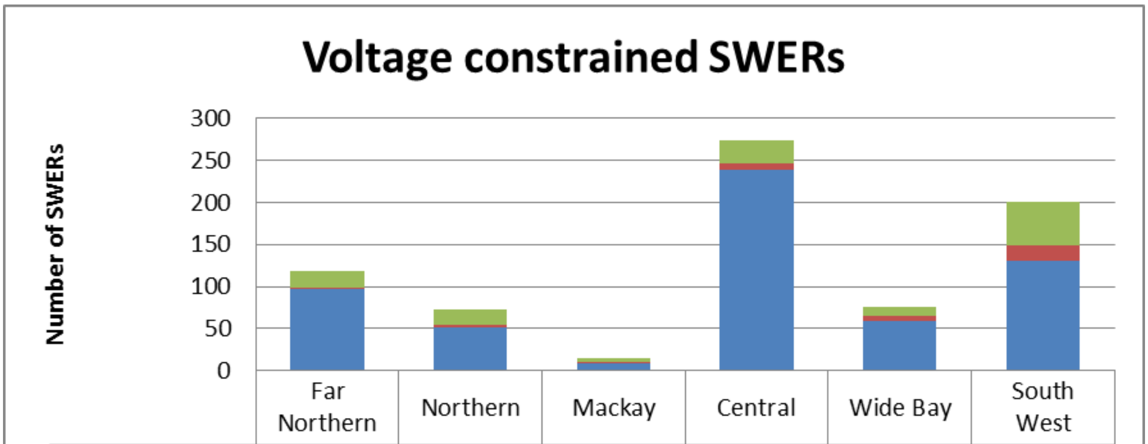


Figure 35: Number of Capacity Constrained SWER Systems Across All Regions (Ergon Energy 2012)



	Far Northern	Northern	Mackay	Central	Wide Bay	South West
Constrained	20	18	5	28	11	52
Near constraint	2	3	2	7	6	19
No constraint	97	52	8	239	59	130

Figure 36: Number of Voltage Constrained SWER Systems Across All Regions (Ergon Energy 2012)

3.3.3 Traditional SWER Earthing methods

In the early days of SWER systems in Queensland, the earthing systems for shunt reactors, isolation and distribution transformers consisted of earthing rods which often involved interconnected 1.2m galvanised star pickets being driven 2 to 4 metres into the soil. This form of shallow earthing system proved to be insufficient for electrode to soil conductivity in dry conditions. As seen in Table 9, from years 1979 to 1987, The Capricornia Electricity Board (CEB) experienced a number of isolation transformer poles failures. These failures were all attributed to poor earthing, operating at the then standard of up to 8 amperes, in drought conditions. Extensive engineering analysis, investigations and testing were undertaken with findings revealing severe thermal damage to the existing electrode systems from poor contact with the mass of earth.

Location	Size	Voltage	Mode of failure	Year of failure
Wilpeena Isolator	100kVA	12.7kV	Pole burnt down, repaired two more times over 7 years until the earthing was replaced.	1979
South Springsure Isolator	100kVA	12.7kV	Pole base caught fire.	1980
Fernless Isolator	50kVA	12.7kV	Voltage complaints	1980
Bombandy Isolator	150kVa	19.1kV	Pole fire after one year of service, failed following years until an extensive earthing system was installed.	1981
Kianga Isolator	100kVA	12.7kV	Pole burnt down.	1981
Yan Yan Isolator	50kVA	12.7kV	Earthing replaced.	1982
Montrose Isolator	50kVA	12.7kV	Pole burnt, voltage complaints	1982
Alpha East Isolator	150kVa	19.1kV	Burnt down.	1982
Stonehenge Isolator	150kVA	19.1kV	Burnt down twice in two years.	1983
Long Island Isolator	100kVA	12.7kV	Burnt down.	1984
Alton Downs South Isolator	100kVA	12.7kV	Isolator failed, earthing burnt up.	1984
Alton Downs West Isolator	100kVA	12.7kV	Isolator failed, earthing burnt up.	1984
Cedarvale Isolator	100kVA	12.7kV	Pole base caught fire.	1984
Roseberry Downs Isolator	100kVA	19.1kV	Burnt down.	1984
Wealwandangie Isolator	100kVA	12.7kV	Burnt down, and then failed again one year later.	1985
Isisford Stage 2 Isolator	150kVa	19.1kV	Burnt down.	1985
Rolleston North Isolator	150kVa	19.1kV	Burnt down.	1987
Jericho North Isolator	150kVa	19.1kV	Burnt down.	1987
Lawgi Isolator	100kVA	12.7kV	Pole smoking.	1987

Table 9: History of SWER Isolator Earthing Failures in the Capricornia Electricity Board Region (Transmission and Distribution Planning and Development Department 1987)

The outcome of the CEB SWER isolator failures allowed substantial changes to be made to Queensland SWER earthing systems to align with NSW Earthing Handbook guidelines. In Queensland the SWER isolation, reactor and transformer HV earthing standard was upgraded to consist of mandatory quantities of copper earth rods and configuration specifications. These standards have been engineered and adjusted over the years to form the current requirements set by Ergon Energy shown in section 4.2.1.

3.3.4 Climate

Energy Queensland's electricity network covers the entire state of Queensland and the climate is diverse from the highland areas in the South, the arid areas in the Western centre to the tropical coasts in the North.

The following section provides a brief description of each National Construction Code (NCC) climate zone (Australian Building Codes Board 2018), shown in Figure 37, with climatic figures taken from the Bureau of Meteorology (Bureau of Meteorology 2019).

- **Far North and The Gulf Region:**
    - **Climate zone 1 -** High humidity summer, warm winter.
    - This region experiences monsoonal seasons, the average annual temperatures on the coastal fringes range from 20°C to 29°C with an average rainfall of 1,987mm. The Gulf Region average temperatures range from 18.4°C to 32.7°C, with an average rainfall of 819mm.
- **Central and Southern East Coast Region:**
    - **Climate zone 2 -** Warm humid summer, mild winter.
    - The average annual temperatures on the Central Coastal fringes range from 18°C to 27.3°C with an average rainfall of 1,544mm. The Southern East Coast Region average temperatures range from 16.4°C to 28.4°C, with an average rainfall from 815mm to 1011mm.
- **Central and Southern Inland to West Region:**
    - **Climate zone 3 -** Hot dry summer, warm winter.
    - The average annual temperatures on the Central Inland West Region range from 15.9°C to 31.5°C with an average rainfall of 436mm. The Southern West Inland Region average temperatures range from 15.4°C to 29.2°C, with an average rainfall from 350mm.
- **Southern East Highlands Region:**
    - **Climate zone 5 -** Warm temperate
    - The South East Coastal Region has a temperate climate influenced by warm ocean water with warm summers and cold winters. Average annual temperatures range from 11°C to 25.5°C with an average rainfall of 618mm.

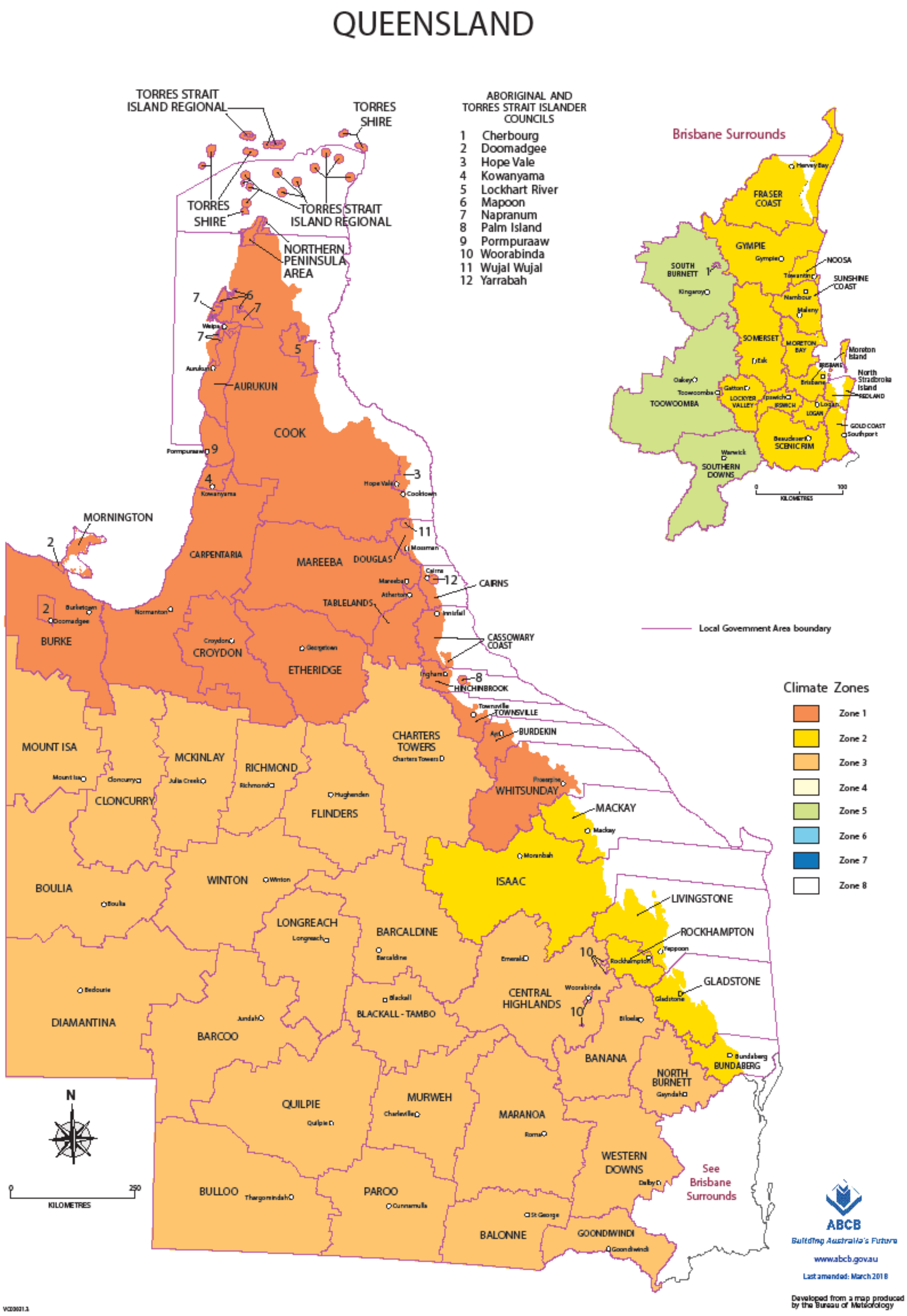


Figure 37: Climate Zone Map of Queensland (Australian Building Codes Board 2018)

3.3.5 Protection:

Protection of SWER systems is challenging due to the earth carrying the return current and the fault current. A protection system utilising an automatic circuit recloser (ACR) or circuit breaker (CB) for a three or single phase system can detect a fault current flowing to earth and operate to clear the fault. In a SWER system, a fallen conductor with a high impedance earth contact, may not trip and clear the fault if the ACR and CB don't have the capabilities of differentiating between the return current and the fault current. Reclosers provide primary protection to a SWER line with the HV fuse as the backup protection. Fuses can often restrict the settings of upstream devices.

Negative phase sequence protection is not effective on single wire lines and cannot be utilised.

Fusesaver units have been trialled as a cost effective replacement for SWER ACR's in South West in 2016. Installation cost of a single ACR is $80k; a Fusesaver with RCU (Remote Communications Unit) cost is approximately $35.5k. Although cost savings are gained with Fusesaver units, remote monitoring of voltage events is still only available with the ACR's.

3.4 SWER Earth Safety

3.4.1 Overview

SWER systems can present a danger to humans and animals from potential gradients in close proximity to the HV earth electrodes. This is due to the earth being used as a live conductor for the return current, any poor connection between the earth and the electrode will result in high voltage potentials in the proximity of the electrode.

3.4.2 Australian Standards and Work Practices:

3.4.2.1 Maximum earth voltage:

SWER currents through the ground are limited by the Electrical Safety Code of Practice 2010 – Works which states the 'maximum voltage on the earth lead with respect to remote earth under operating conditions resulting in maximum continuous earth current, should not exceed 20 Volts' (Queensland Government 2010).

3.4.2.2 HV, LV earthing separation, integrity and insulation:

Electrical Safety Code of Practice 2010 – Works require the following: the HV and LV earthing systems should be separated to avoid voltages being superimposed on the LV Multiple Earthed Neutral (MEN) earthing system. HV earthing must consist of two separate earthing conductors to allow for duplicate paths in the case of one being damaged. The HV earthing system must consist of a minimum of three interconnected earthing electrodes at least three metres apart.

3.4.2.3 Separation (Telecommunications equipment and 3rd party assets, fences and other conductive paths)

AS/ACIF S009:2006 states that earth potential rise (EPR) hazard from electrostatic coupling requires a zone of 15 metres between telecommunications assets and SWER transformers (Australian Communications Industry Forum 2006).

3.4.2.4 Mechanical protection (earth electrodes, cables, joints)

The earthing systems must be insulated, with 0.6/1.1kV grade insulation, where personal contact can be made. All earth joints must not be disconnectable. Any exposed conductive parts within 2.4 metres above the ground associated with the HV in a SWER system must be insulated.

3.4.2.5 Maintenance

Ergon Energy's current Standard for Testing SWER Earths, STNW0553, specifies the approved earth test units are Geo-X and AEMC 6471. SWER earth testing is scheduled to be completed every 6 years or less. Defects discovered during maintenance testing are classified as per Ergon Energy's Defect Classification Manual and are repaired within time frames set by Ergon Energy's Asset Identification and Defect Management (AIDM) Guidelines.

SWER systems safety risks:

- **Step potentials and touch potentials** are the highest probability risk that can occur with SWER systems. This scenario occurs when the connection between the soil and earthing conductors fail and high voltage potentials can occur in the vicinity of the pole. Overloaded SWER systems can also pose the risk of the return earth voltage at the transformer pole rising above the 20V standard.
- **Low conductors:** Often timber poles can fail from white ant damage, rot or bushfires, there have been instances when the SWER conductor does not make contact with the ground and can remain below statutory clearances without the protection operating. This poses a risk of contact to humans and livestock. Regular maintenance and feeder patrols following severe weather conditions reduce the risk of incidents occurring.
- **Failure of protective devices** to detect faults can occur due to protection settings not allowing for typical safety margins from high conductor impedance.
- **Bushfires:** Poor earthing connections can results in arcing between the soil and the conductor; this has led to pole fires in previous years as mentioned in section 3.3.3. Fallen conductors from failed poles, insulators or conductor ties can result in arcing leading to ground fires. Ergon Energy's Bushfire Mitigation Strategy details processes to assess and mitigate the risk of Ergon Energy's assets sparking a bushfire (Ergon Energy 2012). The 2009 Victorian Bushfires, which resulted in the deaths of 173 people, were found to be caused by a broken SWER conductor contacting the ground with the upstream recloser on a 20A minimum operating, two shot trip. The failed conductor was 3/2.75 steel and on a 1.05km span length across a gully, there were no known defects from inspections carried out in 2008. One of the recommendations from the 2009 Victorian Bushfires Royal Commission was to disable the reclose function on SWER ACR's for six weeks of greatest risk in every fire season (2009 Victorian Bushfires Royal Commission 2010).

Chapter 4 - Chapter 4: SWER Earth Construction

4.1 Overview

SWER systems use the body of the earth as a live HV conductor for the return earth current, it is important to understand the characteristics of soil and the method and integrity of connecting to the earth. The following chapter explores the resistivity of soil and effects of type, moisture, temperature and chemical content. The theory and summarised calculations relating to the return earth current path are described to enable a complete understanding of the behaviour of earth as a conductor. An understanding of the common use of earth electrodes to connect to the soil, their combined resistive values and importance to the integrity of the system is established. The assumptions surrounding uniform resistivity and resistance values to achieve relatable and consistent test results are explained.

4.2 General construction characteristics

Soil resistivity or the specific resistance of the soil is measured in Ohm metres (Ωm). This is explained in section 2.4.1. Ideally earthing resistivity readings and predictions could easily be established for each site if soil was homogenous. Unfortunately this is not the case and considerable investigation is required for SWER line and transformer site design.

Soil types: Queensland has a diverse range of soil types with varying resistivity values.

Rock: Areas of poor resistivity often consist of shallow soil cover over rock foundation. Natural igneous rocks with high resistivity are types containing a minor component of pore water being of common types: basalt, granite and quartz. Medium resistivity types with hydrous minerals and fabrics are metamorphic rock of common types: slate, marble and schist. Lower resistivity types with abundant pore space and fluids are sedimentary rocks of common types: chalk, gravel, limestone, shale, sand, sandstone and clay.

Figure 38 maps the common soils of Queensland.

Vertosols or black brigalow clay soils occur in the Darling Downs and Central Highlands; they exhibits high swelling characteristics when saturated and high withdrawal characteristics upon dry-out. This can result in air pockets and surface cracking which can extend up to 5 metres in extreme conditions (Taylor & Effeney 1988). Clays are often acidic in nature and can have a natural pH of 4.5.

Ferrosols are a form of clay-loam to clay, basaltic soil that is strongly aggregated making it more permeable, with very little expansion or contraction, causing the resistivity to vary seasonally. These soil types are associated with volcanic activity and can be found along the Great Dividing Range with large areas occurring around Kingaroy and Atherton.

Dermosols are another form of soil with loam to clay texture occurring in the higher rainfall coastal and sub-coastal regions as well as the Burdekin delta, Lockyer and Fassifern valleys; these soils exhibit varying seasonal resistivity characteristics similar to the Ferrosols (Queensland Government 2016).

Chromosols are found in Western Downs and Maranoa districts, west of the Great Dividing Range, they consist of peaty to silty clay loamy textures.

Kurosols occur along the southern Queensland coast and are strongly acidic with a pH below 5.5; they have a low water-holding capability. These soils can cause corrosion of earthing conductors and should have neutral pH materials placed around the conductors as a transitional medium for conduction.

Kandosols are sandy to loamy surface soils, with porous sandy-clay subsoils, they are often found in mulga vegetation areas. They are permeable and are found around SWER lines in Charleville.

Podosols are sandy soils with large soil particles making them very permeable. These soils exhibit moderate resistivity when damp and exceptionally poor resistivity when dry. This type of soil occupies less than 1% of the state soils.

Sodosols are very common in large areas of inland Queensland; they contain concentrations of sodium which leads to them being impermeable subsoils having a highly dispersive nature when wet. These soils have a pH above 5.5, have poor structure, low permeability and are vulnerable to erosion and salinity.

Calcarolsols are sandy or loamy soils, which are rich with lime, usually located above calcium rich sedimentary rocks of limestone and windborne. They occur in arid and semi-arid areas of western Queensland with low rainfall and cover less than 0.5% of the state. They are highly permeable, having high salinity, alkalinity and resistivity.

Rudosols and Tenosols are generally shallow, sandy and stony and are commonly found in areas inland from Cairns. They exhibit exceptionally poor resistivity characteristics due to the air pockets dispersed through the soil texture.

Hydrosols are soils that have been saturated by water for prolonged periods; they are mainly found in coastal areas, inland wetlands and other areas with tidal influences. These soils can often contain high levels of salt and can be magnesic at depth. Depending on the chemical composition, these soils can exhibit medium resistivity characteristics.

Organosols are commonly referred to as peats with their main texture being made up of organic materials. They occur in small pockets in the wet and humid coastal areas of Queensland, mainly in the Wet Tropics. These soils can exhibit low to medium resistivity characteristics depending on the moisture content.

It is important to understand the requirement for adequate soil conductivity which necessitates deep layers of soil coverage over rock, a ready supply of mobile ions in the soil structure, the presence of moisture (ionic conduction cannot occur without moisture) and continuous soil structure.

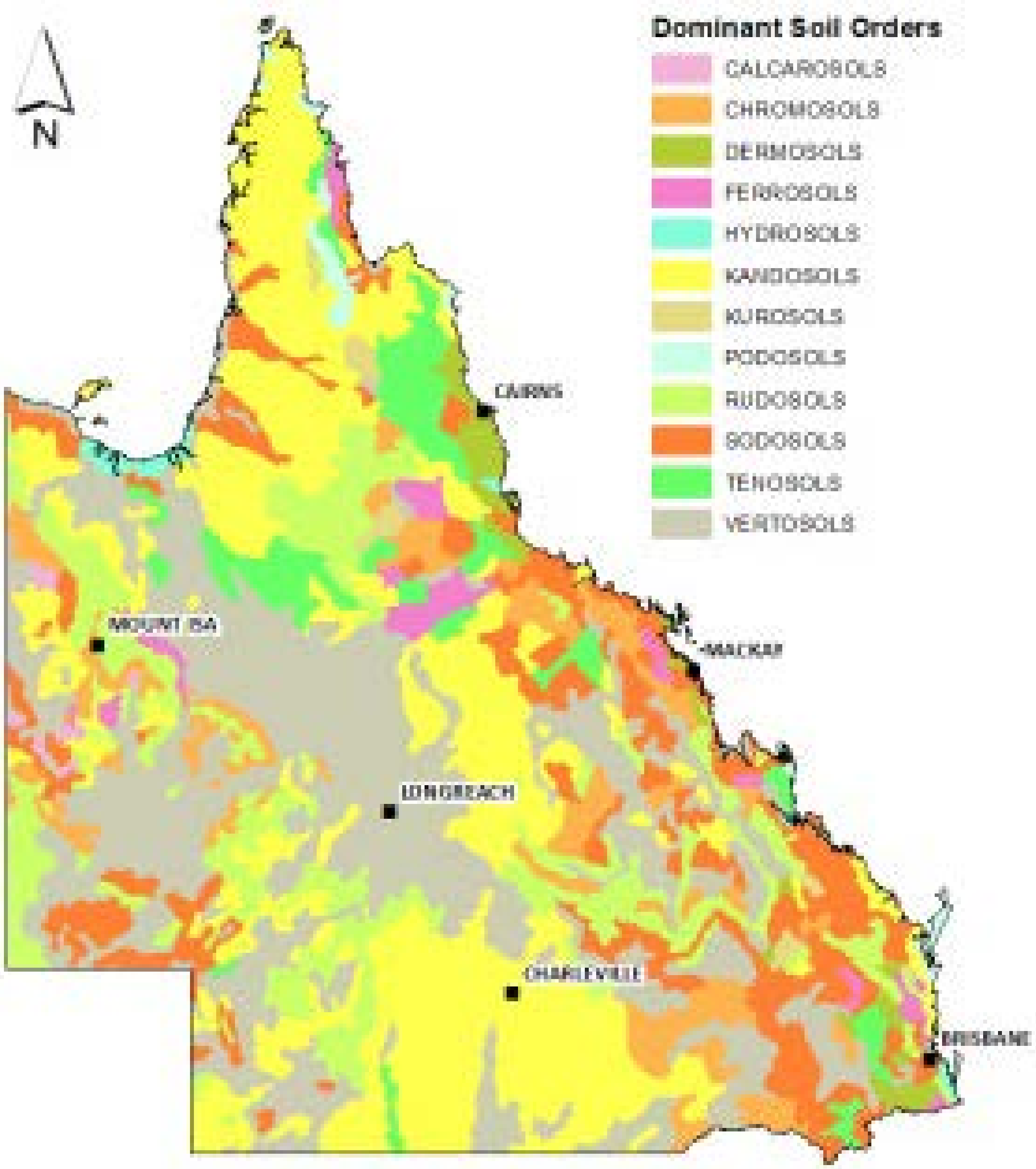


Figure 38: Common Soil Types of Queensland (Queensland Government 2016)

Earth resistance or the resistance of the earth path is determined by the resistivity of the soil surrounding the earthing electrode, the integrity of the contact between the electrode and the soil and the quality of the earthing conductors and connections from the electrode to the terminal of the primary transformer winding.

Earth return current path is the path of the HV earth return current and is the most fascinating and ingenious part of a SWER system. Rudenberg explains the transition of current from electrode to soil as streamlines of current radiating in space from the electrode (Rudenberg 1945). Rudenberg's initial calculations were based on direct current which disperses radially to great distances. He explains that with alternating current the self-inductive effect of the return current magnetic field is preponderant and travels in closer proximity to the overhead line. The earth is being used as a conductor and behaves in the same manner, therefore the return current depth is determined by the skin effect or inductive mechanism related to the rate of change of the magnetic field. In high frequency applications the skin effect causes the current to travel on the surface of the conductor, with low frequency applications such as 50Hz, the depth of the return earth current can be calculated with approximations for soil permeability. Figure 39 shows the Bessel function of zero order Ho, determining the current density (up to 5 kHz) against distance in calculations using equation (4-11).

i = current density

ρ = resistivity

$\mu = \mu_0.\mu_r$ Permeability (10^{-7} nonmagnetic material)

$\varepsilon_g = \varepsilon_{rg}.\varepsilon_0$ Permittivity of homogeneous earth

$\omega = 2\pi f$ Angular velocity

$$i = 2\pi\mu\frac{\omega}{\rho}.\mathrm{I}.\mathrm{H_o}\sqrt{j}.\sqrt{2\pi\mu\frac{\omega}{\rho}}.y \tag{4-11}$$

The field strength in the ground is derived from equation (4-12):

$$e = \rho i = \pi\mu\omega l \mathrm{H_o}\sqrt{j}.y\sqrt{2\pi\mu\frac{\omega}{\rho}} \tag{4-12}$$

The surface level voltage directly under the powerline over a distance l is calculated using equation (4-13)*:*

$$E = \pi\mu\omega I l \mathrm{H_o}\sqrt{j}.h\sqrt{2\pi\mu\frac{\omega}{\rho}} \approx \omega I l\left[\frac{\pi}{2} + j2.log_{\mathrm{e}}\left(\frac{1.12}{\sqrt{2\pi\mu\frac{\omega}{\rho}h}}\right)\right]10^{-7} \tag{4-13}$$

The surface level voltage is complex and can be represented as the resistive (real) and inductive (imaginary) parts using equations (4-14) and (4-15):

$$R = \frac{\pi}{2}\mu\omega l = \pi^2 f l.10^{-7} \tag{4-14}$$

$$L = 2l.log_{\mathrm{e}}\left(\frac{0.178}{\mathrm{h}}\sqrt{\frac{\rho}{f}}\right).10^{-7} \tag{4-15}$$

f=supply frequency (Hz)

l=length of ground current path (m)

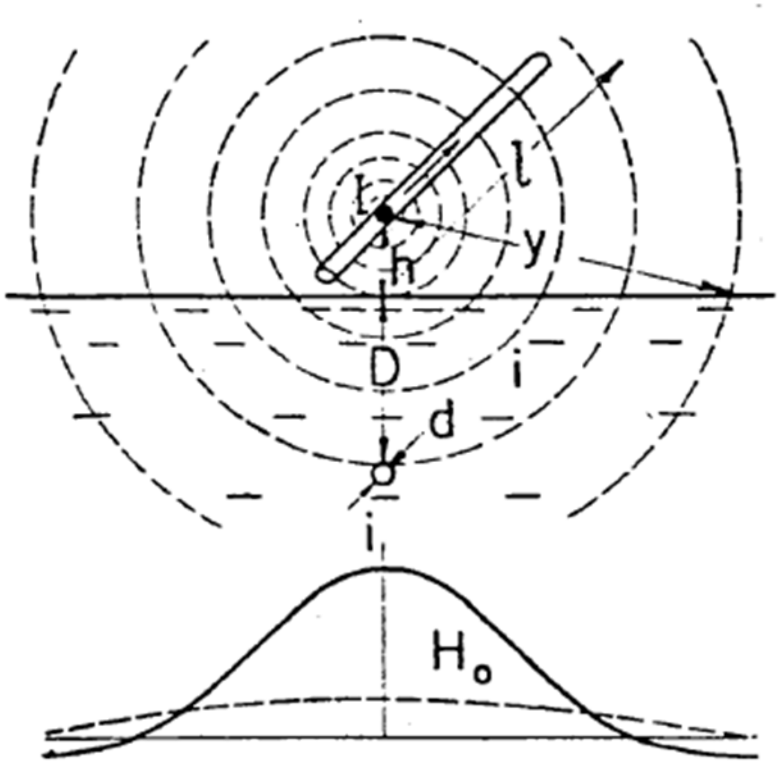


Figure 39: Distribution of Ground-Return Currents Under AC Transmission Lines (Rudenberg 1945)

According to Rudenberg the resistance of the return earth current is proportional to the length of the current path and the supply frequency. The self-inductance is proportional to length, slightly affected by the height of the overhead conductor, resistivity and frequency. For a large range of data, Rudenberg deduced that the self-inductance is close to L=0.9mH/km or ωL=0.34Ω/km. With the resistivity approximation from Table 10, the permittivity of homogeneous earth at unity and the relative permeability of the nonmagnetic ground considered to be equal to 10^{-7}, it is possible to calculate the average depth of the return earth current. The skin depth effect that determines the depth of the return current can be assumed as per equation (4-16):

$$\delta_s = \sqrt{\frac{\rho}{\pi f \mu \varepsilon_g}} m \qquad (4\text{-}16)$$

δ_s = Skin Depth (m)

ρ = Resistivity (Ωm) (common clays = 10)

$\mu = \mu_0 . \mu_r$ Permeability (10^{-7} nonmagnetic material)

$\varepsilon_g = \varepsilon_{rg} . \varepsilon_0$ Permittivity of homogeneous earth (unity)

f = 50 Hz Frequency

$$\delta_s = \sqrt{\frac{10}{\pi * 50 * 1 * 10^{\wedge} - 7}} = 797.88\, m \qquad (4\text{-}17)$$

As per the result from equation (4-17), for a 50Hz SWER distribution line, the return current travels at approximately 800 metres below the surface. An understanding of the depth and path of the return current highlights the importance of the electrical characteristics of the Earth's soils and how they can be utilised as good conductors. Figure 40 shows approximations of different types of soil and moisture and the behaviour between the skin effect depth and the supply frequency. It is deduced that the earth can be used as an adequate conductor for low frequency transmission. High frequency transmission through the earth would result in hazardous high voltage potentials at the surface.

Resistivity values of common rock types	
Material	**Resistivity (Ωm)**
Air	∞
Pyrite	0.3
Galena	0.002
Quartz	$4x10^{10}$ - $2x10^{14}$
Calcite	$1x10^{12}$ - $1x10^{13}$
Rock Salt	30 - $1x10^{13}$
Mica	$9x10^{12}$ - $1x10^{14}$
Granite	100 - $1x10^{6}$
Gabbro	$1x10^{3}$ - $1x10^{6}$
Basalt	10 - $1x10^{7}$
Limestones	50 - $1x10^{7}$
Sandstones	1 - $1x10^{8}$
Dolomite	10 - 10000
Sand	1 - 1000
Clay	1 - 100
Ground Water	0.5 - 300
Sea Water	0.2

Table 10: Approximate Resistivity Values of Common Rock Type (Baggini 2008)

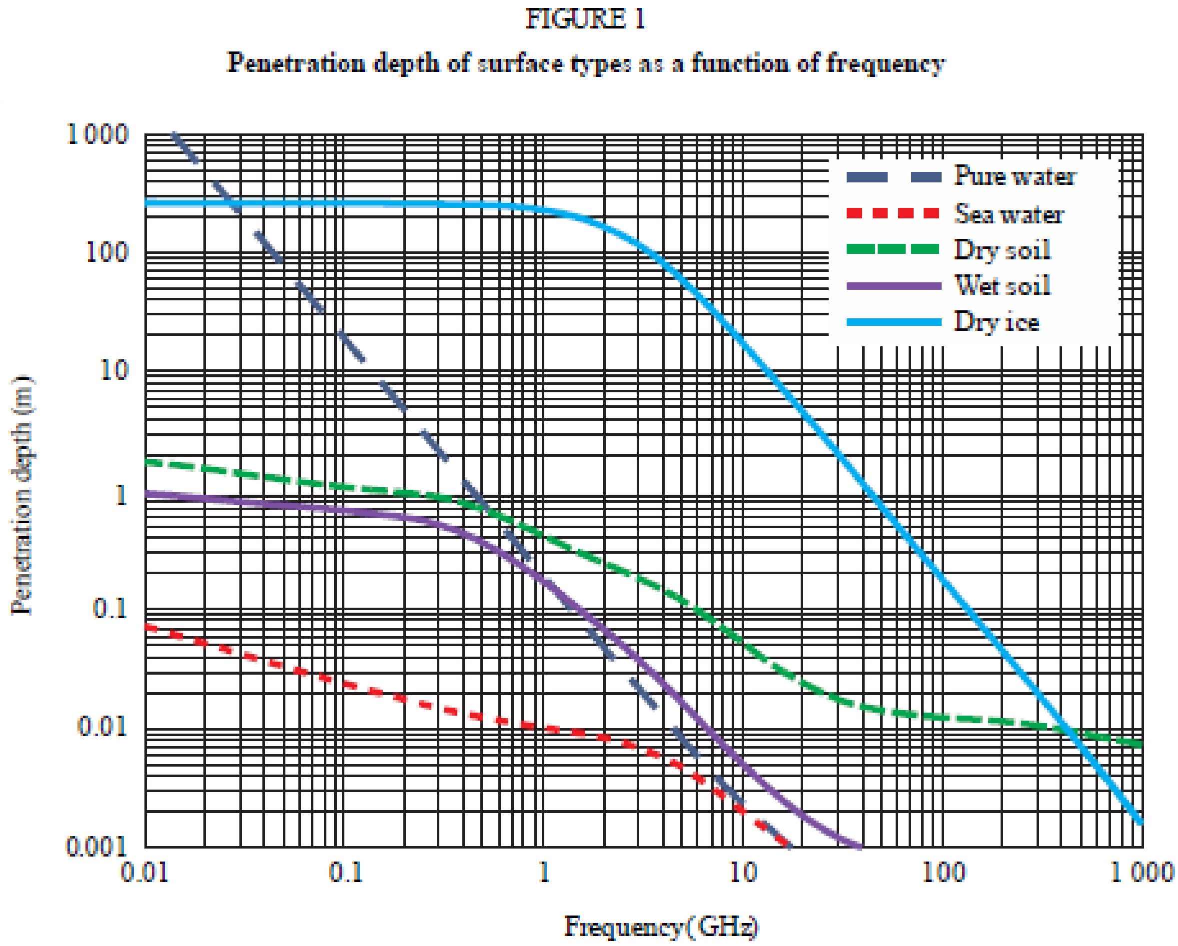


Figure 40: Electrical Characteristics of the Surface of the Earth (Radiocommunication Sector of ITU 2017)

A point of interest is that the inductive influence of the alternating current magnetic field has very little effect on the current distribution in close proximity to the electrode due to the dominance of the local resistivity of the soil (Samra 1972). Basically the electrical current passes through the main earth electrodes into the soil, traversing from a low resistance medium to an area of high resistance. This area of high resistance surrounding the earthing electrode is referred to as a series of sheaths of ever-increasing diameters or concentric rings. Generally current passing from a low resistance medium to a high resistance medium, without an alternative path, results in heating of the immediate area, similar to that of an incandescent light bulb. The beauty of the relationship between earthing electrodes and soil is that the series of sheaths surrounding the electrode are increasing in cross-sectional area thus decreasing in resistance, creating a natural transitional medium for current to be dissipated and dispersed. It is important there is consistent soil in the sheath immediately adjacent to the electrode and all successive sheaths up to a distance of at least three metres (Rudenberg 1945). Rudenberg discovered that the density of current along an electrode, surrounded by uniform soil, is double at the end compared to that at the centre plane. This is referred to as the point effect of the electrode. Due to the spherical sheath current distribution effect, the resistance of the electrode is determined by the largest dimension; therefore it is advantageous to increase the length of an electrode rather than to increase the radius. This is shown in Figure 41 and reflected in the resistance as a quotient of voltage and current equation (4-18) (ANSI/IEEE 1984):

$$R = \frac{E}{I} = \frac{\rho}{2\pi L} log_{e}\left(\frac{8L}{d} - 1\right)\ \Omega \tag{4-18}$$

ρ=resistivity of soil (Ωm)

L=buried length of electrode (m)

d=electrode diameter (m)

R=resistance (Ω)

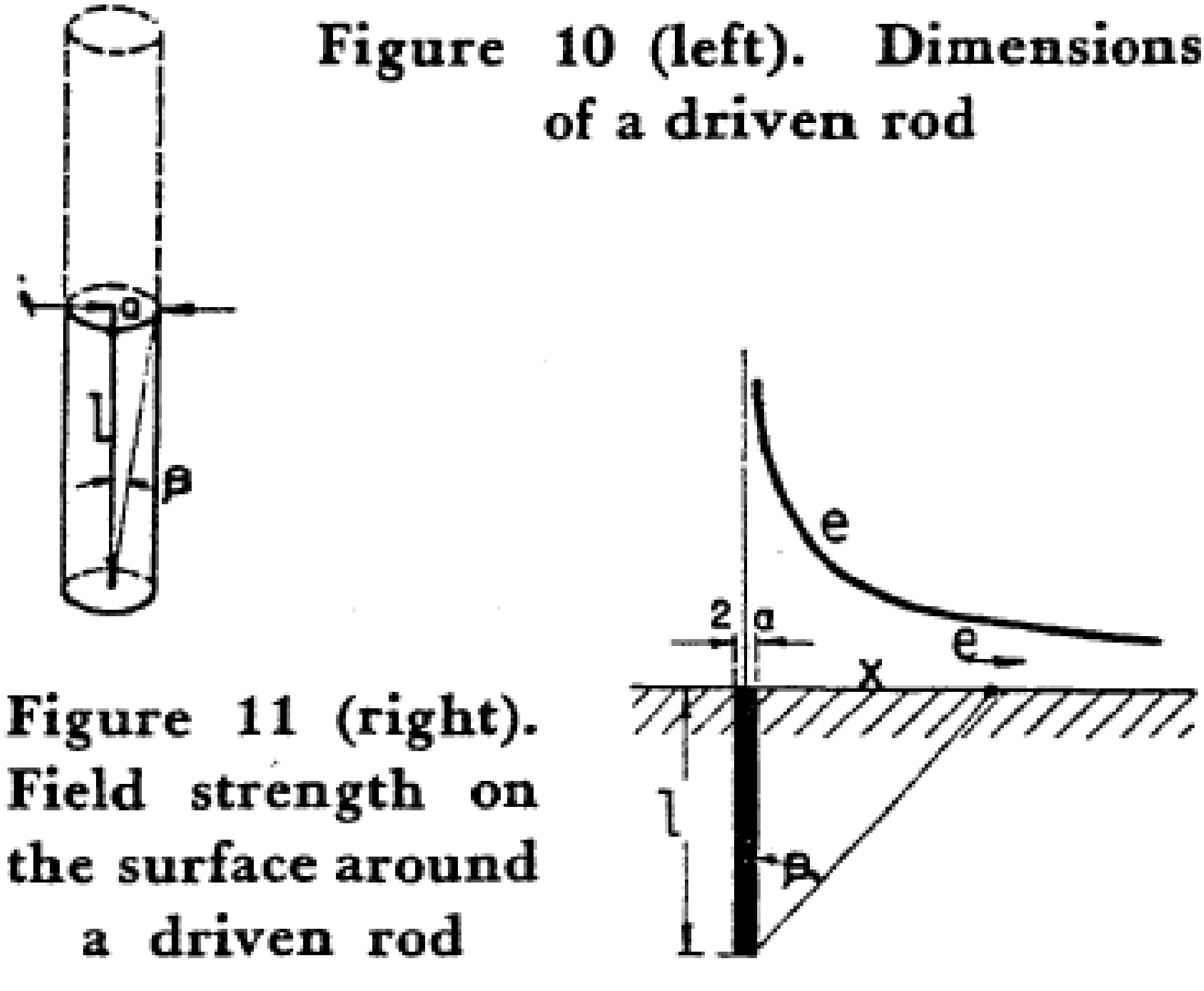


Figure 41: Dimensions of a Driven Rod and the Field Strength on the Surrounding Surface (Rudenberg 1945)

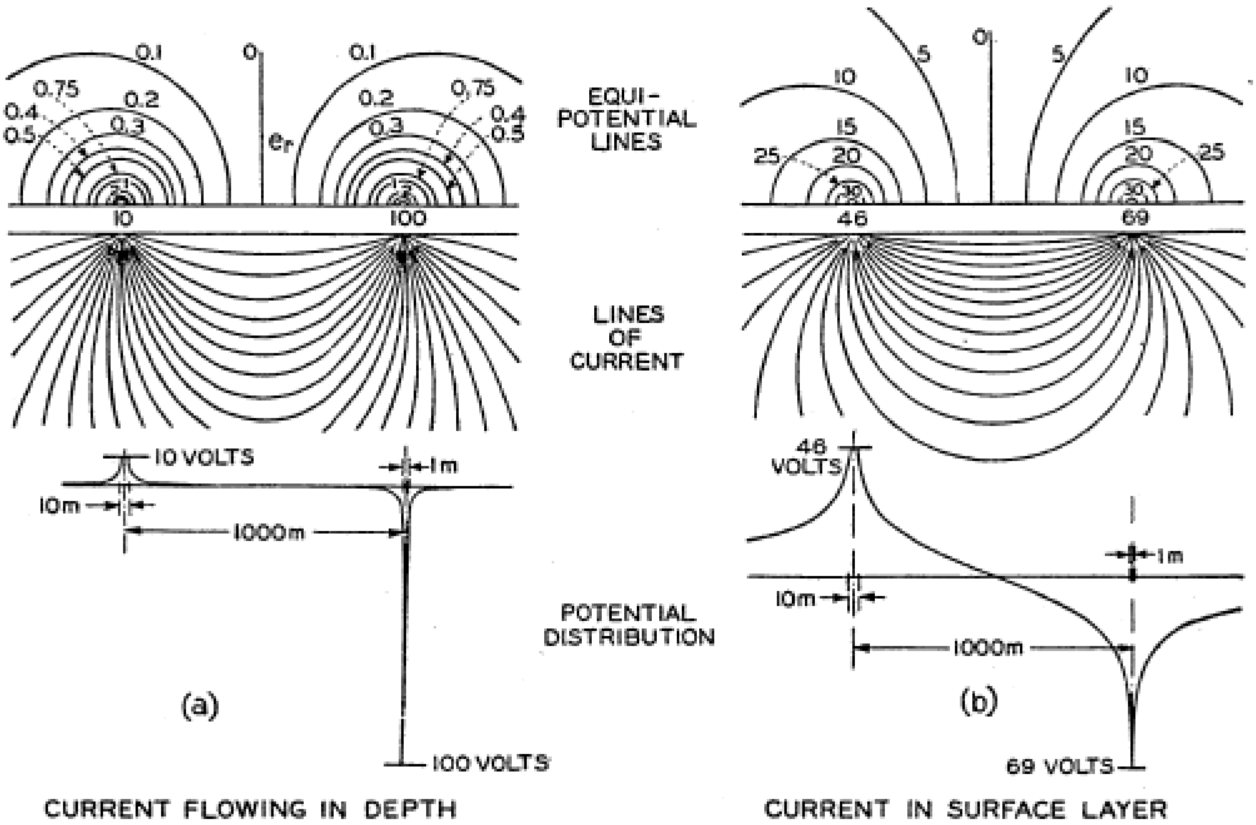


Figure 42: Current Streamlines around Spherical Electrodes (Rudenberg 1945)

Figure 42 shows the current streamlines around spherical electrodes close to the earth surface. The potential on the soil surface surrounding the electrode can be calculated using ground plane theory as represented in Figure 43. A point lies on a ground plane, x is the horizontal distance from the centre of the electrode and h is the height of the ground plane or length of the electrode. Figure 44 shows that extending the electrode reduces the surface potential. The potential (V_p) along the ground plane is given by equation (4-19).

$$V_P = \frac{\rho I}{4\pi}\left[\frac{2}{\sqrt{x^2 + h^2}}\right] \tag{4-19}$$

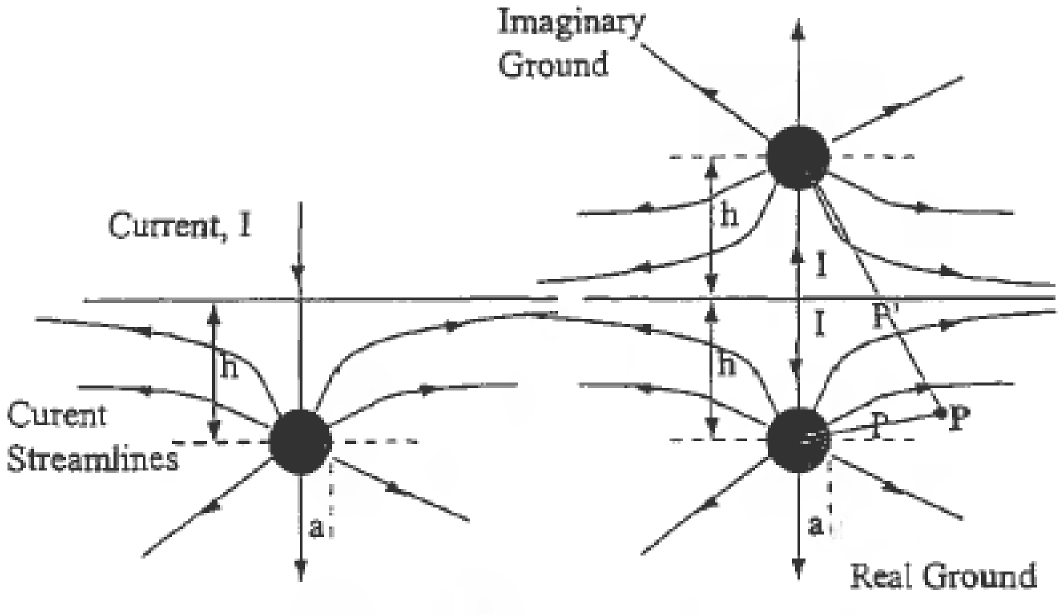


Figure 43: Current Streamline Using Ground Plane Theory (Birtwhistle & Pearl 1997)

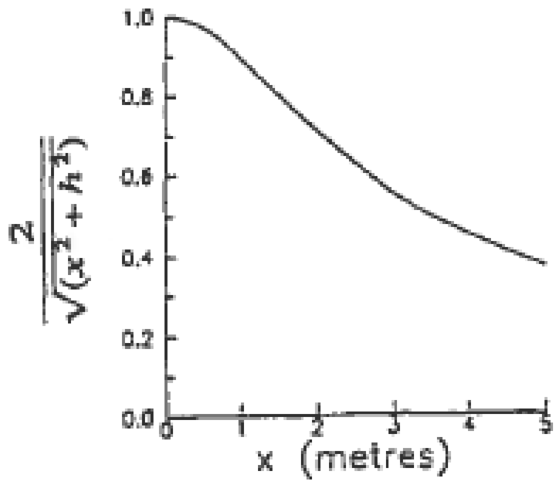


Figure 44: Normalised Surface Potential above a Spherical Electrode (Birtwhistle & Pearl 1997)

As shown in Figure 44, it is essential that the soil beyond three metres still allows current flow but at this point the current dissipation into the main body of earth has occurred.

The standard configuration for SWER HV earthing is a triangular pattern with two HV earthing down leads; this creates a ring around the pole on the HV side that reduces the probability of high potential voltages occurring from one of the electrodes failing. It is a system with built-in redundancy in the case of a component failure.

The three electrodes become the vertices of the interconnected triangle and the overall resistance can be calculated as per equation (4-20):

$$R_N = \frac{1}{3}(2\left[log_e\left(\frac{8L_1}{d}\right) - 1\right] - 1 + 2L_1 s)\ \Omega \tag{4-20}$$

L_1 = length of the electrode (m)

D = diameter of the electrode (m)

S = length of one side of the equilateral triangle (m)

If an array of electrodes is evenly spaced apart then the combined resistance can be calculated using equation (4-21):

$$R_N = \frac{\rho}{2\pi L_1}[log_e\left(\frac{8L_1}{d} - 1\right) + \frac{2K_s L_1}{\sqrt{A}}\left(\sqrt{N} - 1\right)^2]\ \Omega \tag{4-21}$$

K_s = the resistance constant obtained from the expression for the resistance of a horizontal plate on ground surface with the depth of the electrode the determining factor.

N = number of electrodes within the area A

A = area electrodes are configured in (m^2)

For the purpose of this dissertation, the standard construction practice of a delta earthing pattern at the base of the pole and radial extensions has been considered. Grid earthing can be used but is costly and impractical for SWER earthing due to the remote rural locations allowing for radial earthing to be easily installed.

4.2.1 Standard earthing configuration

The current requirements set by Ergon Energy are shown in Table 11.

SWER Substation HV Connected (Ω)				
kVA	**11kV**	**12.7kV**	**19.1kV**	**LV**
10	13	15	22	10
25	6	7	10	10
50	3.3	3.5	5	10
100	2	2.3	3.4	10
SWER Substation Deep Drilled HV Connected (Ω)				
10	14	16	25	10
25	6	7.5	11	10
50	3.5	4	6	10
100	2	2.3	3.4	10
SWER Isolator Deep Drilled HV Connected (Ω)				
100	2	2.3	3.4	10
200	1	1.2	1.9	10
SWER Reactor HV Connected (Ω)				
25	6	7	10	n/a
50	3.3	3.5	5	n/a

SWER Reactor Deep Drilled HV Connected (Ω)				
25	6	7.5	11	n/a
50	3.5	4	6	n/a
SWER Regulator HV Connected (Ω)				
50	3.5	3.5	3.5	n/a
SWER Regulator Deep Drilled HV Connected (Ω)				
50	4	4	4	n/a

Table 11: Distribution Earth Resistance Standards for Ergon Energy (Distribution Network Standards 2018)

Figure 45 and Figure 46 represent Ergon Energy HV standard earthing with the following requirements:

- Minimum of three copper earth rods, 1.44m in length, 13mm diameter.
- Two HV earthing down leads connected to the HV earth bushing and tank.
- Two HV electrodes installed perpendicular to the line route, on each side of the pole, located 2.5m from the centre of the pole.
- The third electrode installed 2.5 metres from the centre of the pole under the HV line.
- All earthing electrodes connected with 35mm^2 or 70mm^2 hard drawn copper conductors, with allowance to extend the system radially from the apex.

Figure 47 and Figure 48 represent the deep drilled HV earthing system arrangement with the following differences:

- Main earth electrode uses 35mm^2 or 70mm^2 bare copper cable drilled to a minimum of 20m into the soil using a 75mm drilling bit.
- All deep drilled electrodes to be installed at the same depth.
- All holes to be refilled immediately with dry earth enhancing compound.
- The third apex electrode is to be located 5m from the centre of the pole.

The LV earthing is installed separately to the HV earthing, radially under the LV supply conductors, with at least one copper earth electrode of length 1.44m installed 2.5m from the centre of the pole for normal HV earthing and a deep drilled earthing electrode located 5m from the centre of the pole for deep drilled configurations. Both configurations have allowance to extend radially if required.

Ergon Energy requires all Isolation transformers to have deep drilled earth configurations.

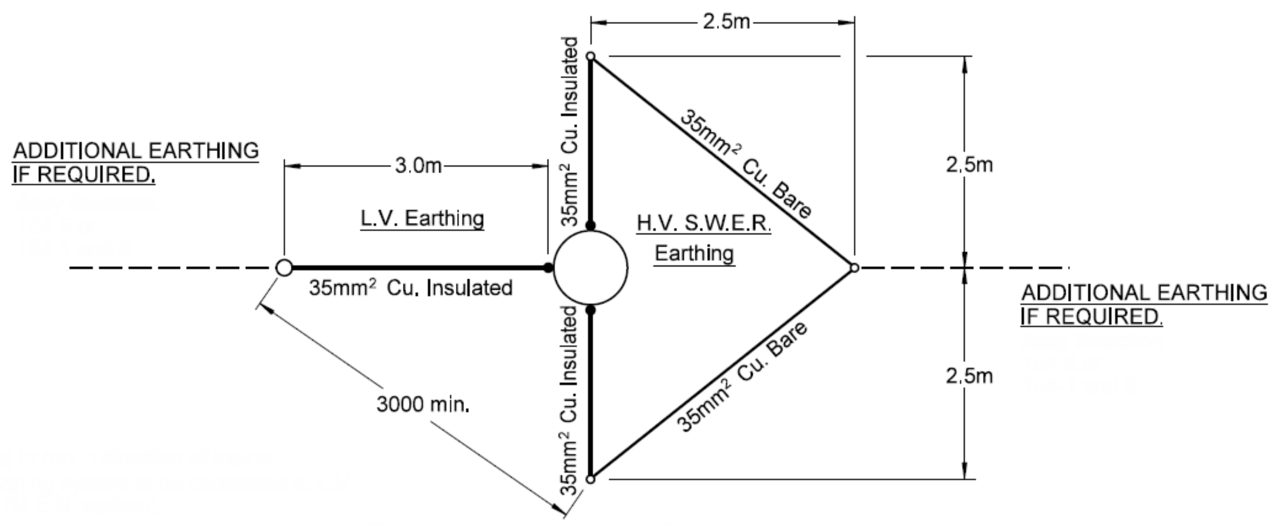


Figure 45: SWER Transformer Earth on Wood Pole (Distribution Network Standards 2018)

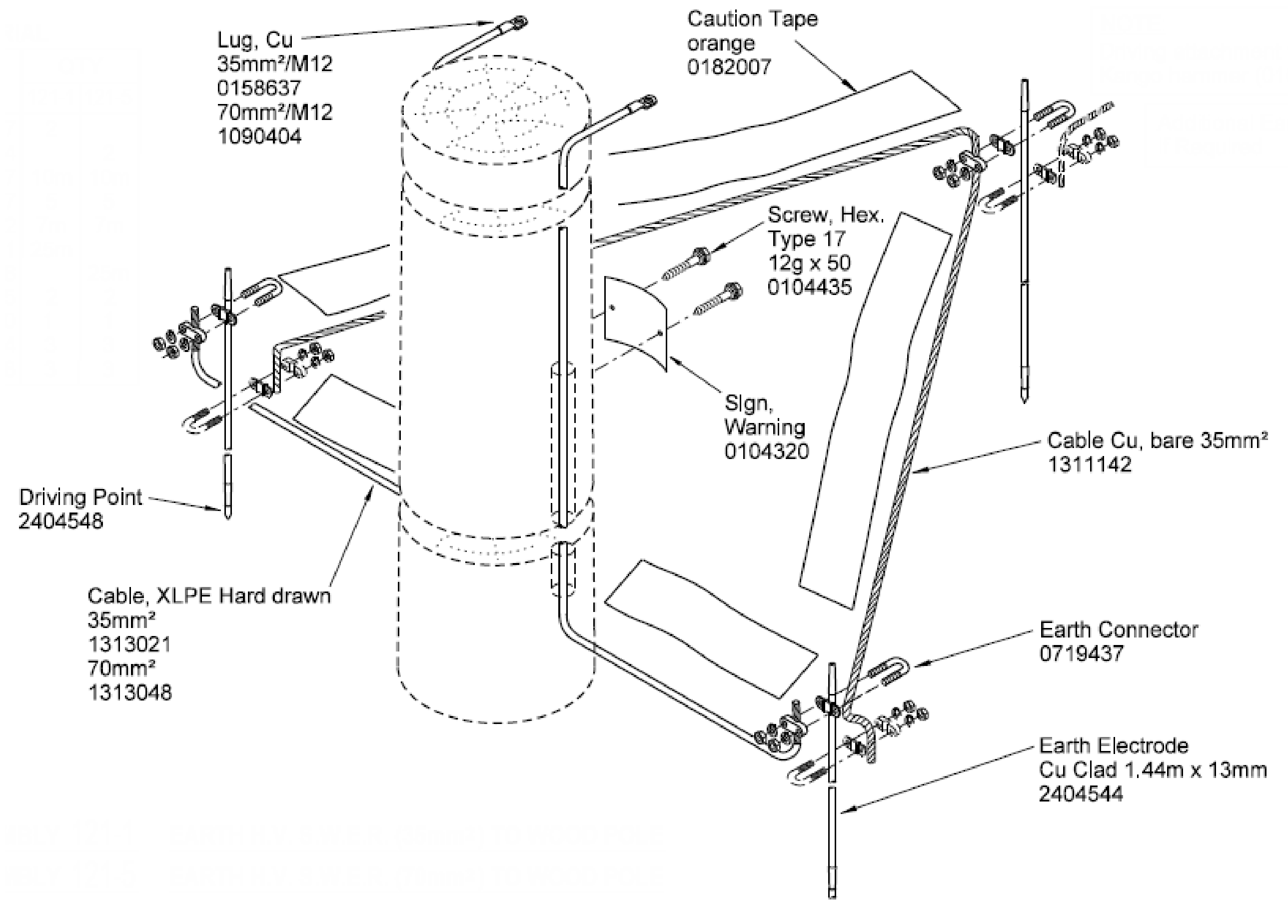


Figure 46: HV SWER Earth to Wood Pole (Distribution Network Standards 2018)

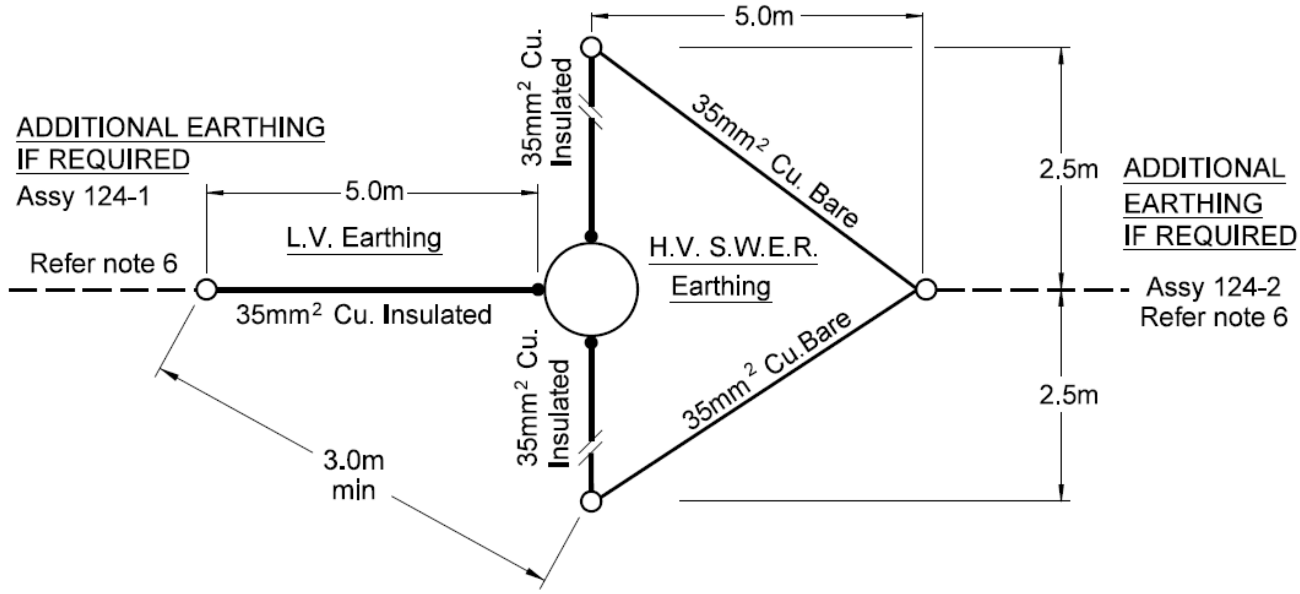


Figure 47: SWER Isolator/Transformer Earth on a Wood Pole, Deep Drilled (Distribution Network Standards 2018)

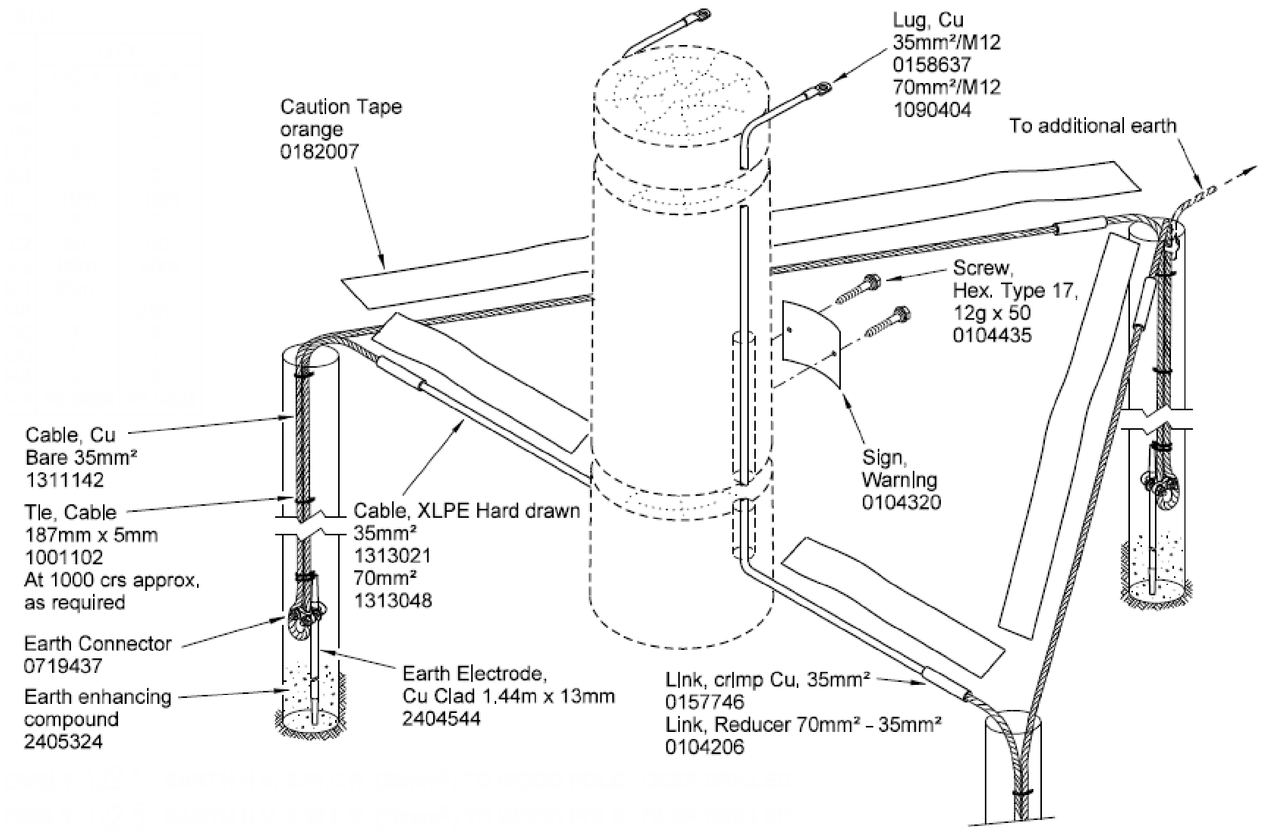


Figure 48: HV SWER Earth to Wood Pole – Deep Drilled (Distribution Network Standards 2018)

Underslung earth conductors are used in areas with exceptionally poor soil resistivity, this dissertation recognises this method can be used in extreme cases but it is not discussed due to the method resembling a single phase HV system rather than a return earth system.

4.2.2 Heating Effects

SWER system earth return paths require earthing electrodes to maintain a continuous low resistance connection to the surrounding soil. Poor transfer of current between the electrode and surrounding soil can result in local heating combined with loss of soil moisture and in the worst case scenarios catastrophic thermal failure. A journal article written in 2016 analysed previous investigations relating to the temperature rise in continuously loaded electrodes. The journal concluded electrodes subjected to acceptable voltage rises have modest temperature rises; excessive current and poor connections are the main cause of heating and loss of soil moisture that ultimately leads to electrode failure (Noorudheen, Wolfs & Alahakoon 2016). Figure 49 is a data plot of variations of resistance and current for an overloaded pipe, strip and plate electrode of 1m^2 surface area, buried in loamy soil. The plot shows a steady rise in resistance for a current overload scenario with a steep exponential increase in resistance as system failure occurs. Figure 50 represents the behaviour of the resistance of soil with an increase in current density for moist, dry and saturated soil.

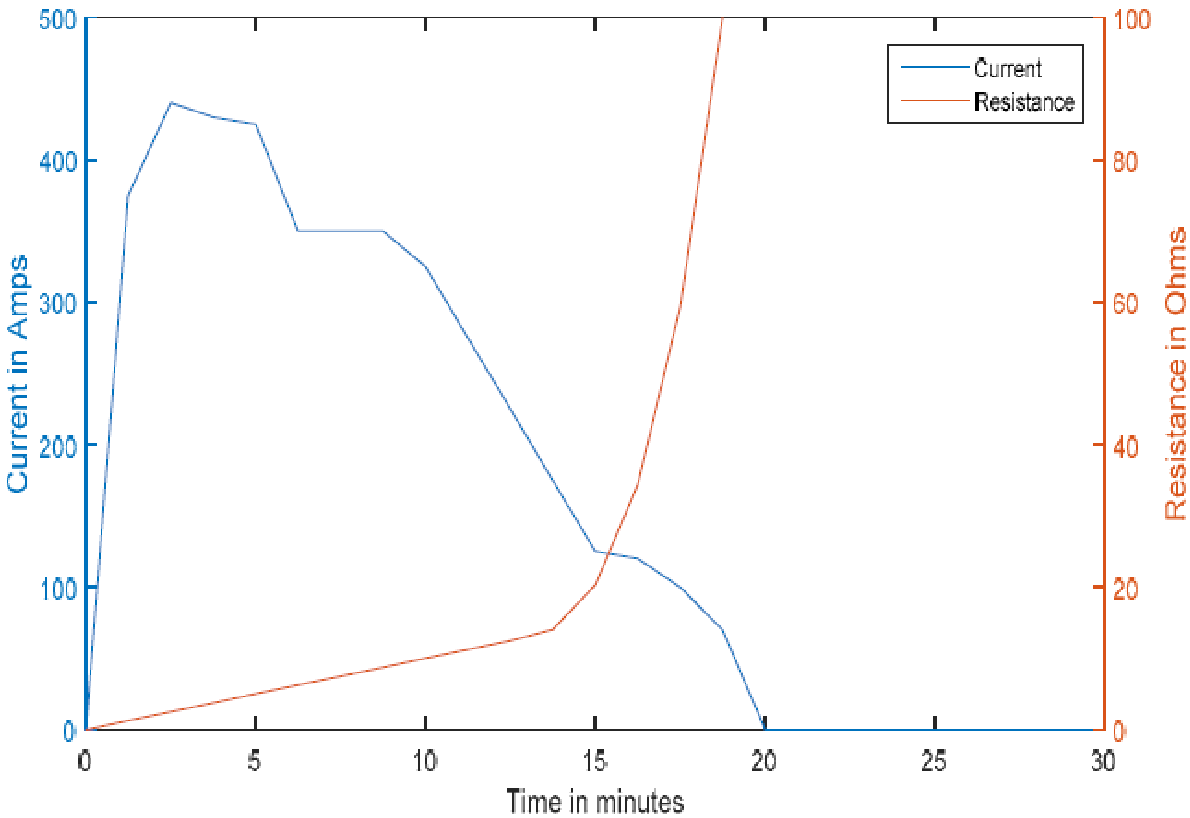


Figure 49: Variation of Resistance and Current with time in Overloaded Electrodes (Noorudheen, Wolfs & Alahakoon 2016) (Taylor 1935)

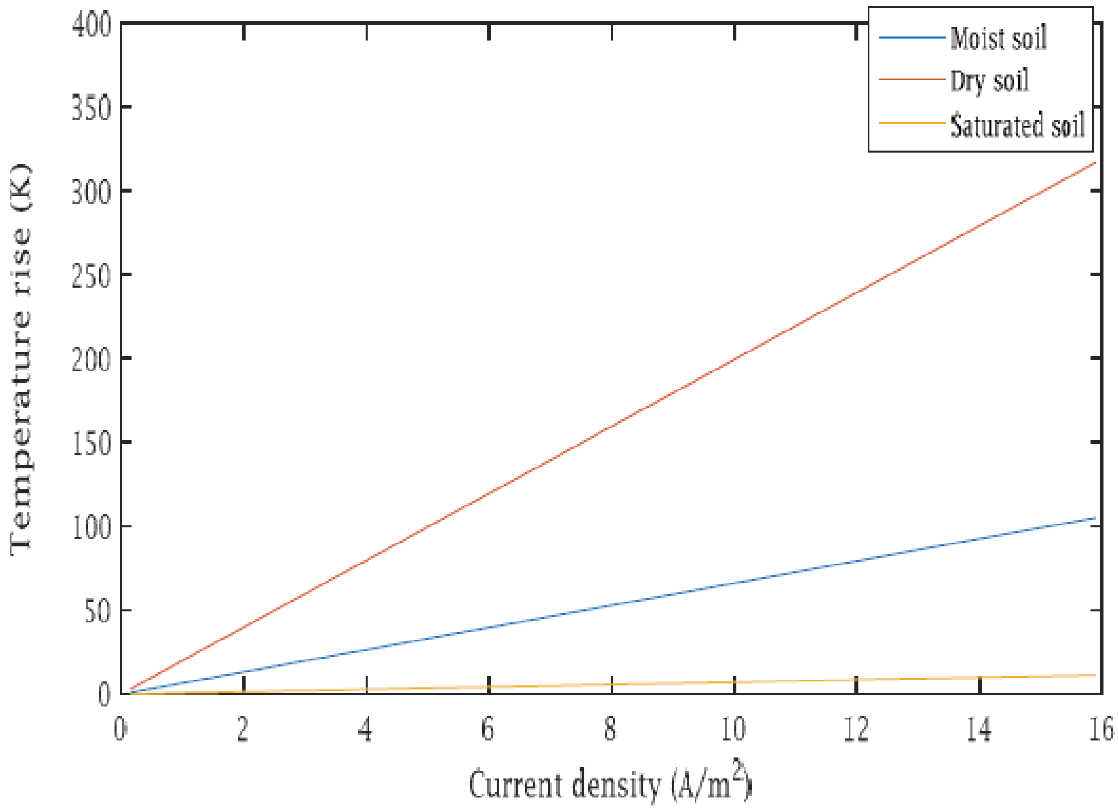


Figure 50: Current Density vs Temperature Rise (Noorudheen, Wolfs & Alahakoon 2016)

Previous investigations carried out by the Capricornia Electricity Board (CEB) showed the electrode surface temperature is proportional to the square of the electrode voltage rise when carrying current (Transmission and Distribution Planning and Development Department 1987). H.G. Taylor's study 'Current-loading capacity of Earth Electrodes', determined that, neglecting any small change in soil thermal resistivity, the electrode voltage rise is proportional to the square root of the soil resistivity. The maximum resistance can be established from equation (4-22):

$$R(max.allowable) = \sqrt{\frac{\rho}{I}} \;\; \Omega \qquad (4\text{-}22)$$

The above correlation is a reflection of the influence soil resistivity has on the required HV earth safety standard maximum of 20V, for normal operating conditions. It was evident from failures in Central Queensland in the 1980's that in dry conditions, soils can contract and only moist soil and clay in physical contact with the electrode will conduct the return earth current. The I^2R losses associated with the localised contact points result in soil heating through current channels. Eventually the current channels reach temperatures above 100°C, boiling any surrounding soil moisture and once the moisture is evaporated via steam a spark discharge will occur. The consequence of spark discharge is glass formation around some of the conductors and the earth system. This eventuates in severing the connection between the soil and the conductors, high step potentials and touch potentials can occur at the base of the pole resulting in charring and potentially a pole fire. Professor Peter Wolfs stated that investigations into the CEB SWER Isolator failures revealed potato sized vitrified glassy nodules had formed along the bare copper conductor that severed the conductor in multiple sections until eventually the arcing at the base of the pole resulted in fire (Wolfs 2013).

4.2.3 Electrode installation in medium

The integrity of the earthing systems is directly related to the medium surrounding the electrode that develops the electrolytic mechanism for continuous current flow. These mechanism characteristics consist of the chemical composition, soil ionisation, homogenous grain size, medium distribution soil moisture retention and packing density. Soils with a pH of less than 6 or greater than 10 can cause copper electrode corrosion; neutral backfill surrounding the conductor and electrode is required (Substation Standards 2007).

4.2.3.1 Earthing compounds

Earthing compounds are soil enhancement materials that play an essential role in maintaining consistent connections between the soil and the earthing electrode, assisting with electrode heat dissipation and reducing electrode corrosion from acidic and alkaline soils. Ergon Energy requires all deep drilled earths to be backfilled with soil enhancement materials; the recommendation has been a dry bentonite-gypsum mix.

Soil enhancement materials can be mixed with existing soils to improve texture, moisture retention and resistivity or can be used as a substitute for voids in drill holes and trenches.

Bentonite is a commonly used soil enhancement material that was first discovered in 1890 in Montana USA. It is a naturally occurring sodium activated montmorillonite clay compound with a typical resistivity level of 3Ωm. It is non-corrosive and inherently stable, hygroscopic and absorbs moisture from the surrounding environment. It is important to understand the physical properties of Bentonite, when mixed with water it can absorb up to 5 times its weight in water and can swell to 13 times its dry volume. Bentonite is supplied in granular form for use in cable trenches or powdered form for pouring into bore holes (EnviroTronics 2013).

In 2012 an isolation transformer deep drilled earth bore hole on the Atherton Tablelands collapsed resulting in a 13.5 metre, 6 inch hole in the ground. Investigations revealed the dry bentonite used to backfill had bridged part way down the bore hole. Following a substantial wet season the bridge collapsed causing the ground to subside. Geotechnical engineers were engaged and a recommended cementitious grout/bentonite mix was pumped via a trammie tube from the surface (Ford 2012).

Gypsum is the chemical compound calcium sulphate dehydrate; it is insoluble in water and has very little volume change with moisture. It is commonly combined with bentonite to improve the engineering properties by stabilising the expansive nature of bentonite. It is also used to stabilise the sodic nature of clay to assist layer cohesion.

Earthrite is a soil enhancement material that is a combination of bentonite, gypsum and sodium sulphate.

CEB experimented with combinations of backfill comprising 70% Bentonite clay and 30% agricultural gypsum in replacement of Earthrite.

Erico GEM is another soil enhancement material that has been developed to provide a reduced resistivity of less than 1Ω. It is a combination of hydrous aluminium silicates, carbon, hydraulic cements and mineral dusts.

Ergon Energy does not recommend slurry mixtures for deep drilled earth due to the risk of contraction upon drying causing air pockets to form.

4.2.3.2 Earth Darverters and Gapped Bands

Darverters and Gapped Bands are two forms of lightning protectors for timber poles. Darverters are an arc-quenching device that utilises two pieces of timber to extinguish a flashover path. Gapped bands are two metal bands, approximately 900mm apart; the gap helps discharge high transient voltages and lightning strikes, as illustrated in Figure 51.

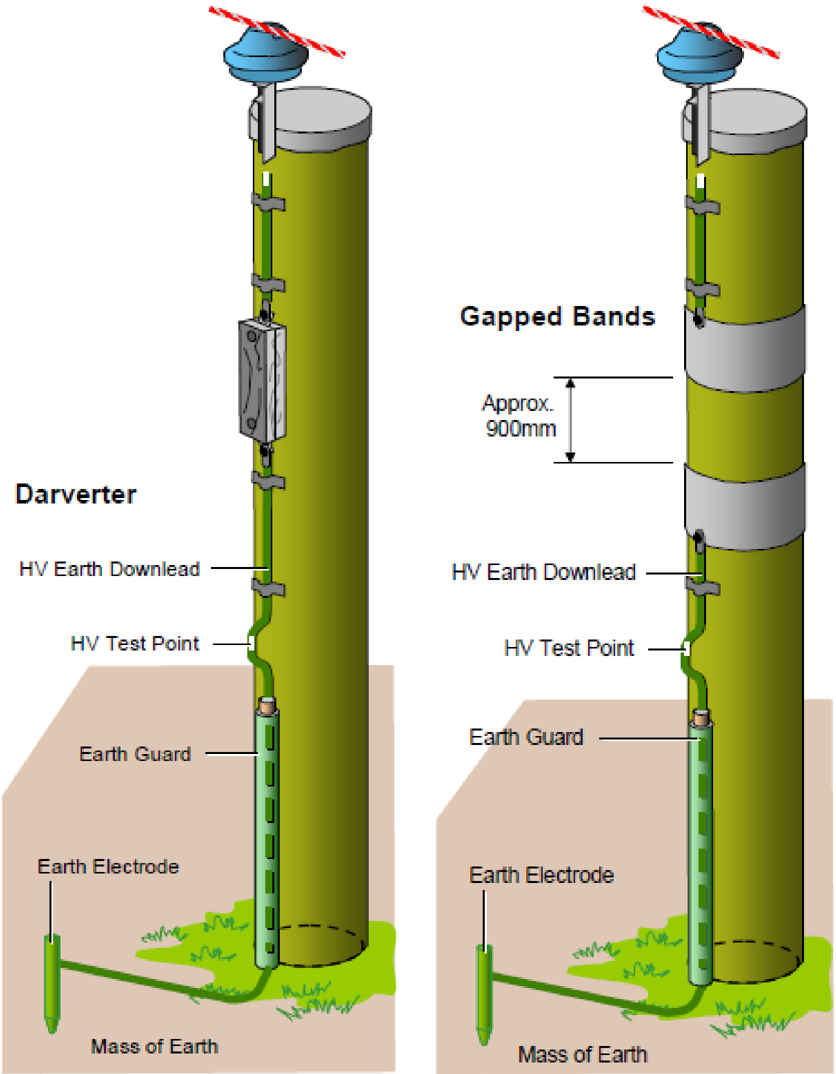


Figure 51: Darverters and Gapped Bands (Ergon Energy 2017)

Chapter 5 - SWER Earth Testing – Theory and Standards

5.1 Overview – EE test practices

The earth constitutes a major part of the SWER system circuit by acting as the conductor for the return current path. When the earth system is tested there are two significant factors; the resistance of the connection between the electrode and the soil and the resistivity of the soil. Table 12 is an extract from Ergon Energy's earth test reference document that outlines the different earth tests applied to SWER assets (Energy 2018).

SWER Asset to be Earth Tested		HV Earth (A)		LV Earth (B)	HV Continuity (C)	Grid Neutral (D)
Catalogue Profile	**Object Group**	**R1 Test**	**R2 Test**			
Substation	SWER Distribution Sub Earth	Selective	Selective	Selective	Loop	Selective
	SWER Isolator Earth	Selective	Selective	Selective (If connected)	Loop	Selective (If connected)
	SWER Reactor Earth	Selective	Selective		Loop	
	SWER Regulator Earth	Selective	Selective		Loop	
Switch	SWER Recloser Earth Nulec	Selective	Selective		Loop	
	SWER Recloser Earth Non Nulec	Selective				
Pole	Operator Earth	Selective				
	Overhead Earth	Selective or Stakeless	This earth shall not be tested until advised.			
	Darverter Earth	Selective				
	Gapped Bands Earth	Selective				

Note: All tests are **Mandatory**, with the exception of Pole Overhead Earths, which are not to be tested unless otherwise advised.

Table 12: Ergon Energy Earth Test Selection Table (Energy 2018)

Ergon Energy's standard for the testing of SWER earths specifies the following requirements for test staff:

- Only trained staff are to complete the testing;
- Testing is to be completed by an electrical tradesperson and competent offsider;
- Earth Tests are to be performed using an approved and calibrated Geo-X Tester or AEMC 6471;
- SWER Earth Testing is required for all active earths and passive earths (note: passive earths are operator earths which provide primary earth protection when staff are working on a switch, as shown in Figure 52);
- SWER Earth Testing is to be carried out immediately before asset inspection to ensure that it is safe to excavate around the pole;
- Immediately following the earth test on an active SWER earth, the electrical tradesperson shall either perform, or supervise, the excavation around the pole for the timber pole asset inspection;
- All results are to be recorded through an approved handheld device, including defects, P1 (worst case) defects to be rung through immediately to trigger isolation if required.
- **IMPORTANT: A voltage reading at 1 metre is mandatory for all tests. This reading is to be taken immediately after the Safe to Approach has been performed and prior to any other test being undertaken. Testing is not to proceed if the voltage is larger than 20 volts.**

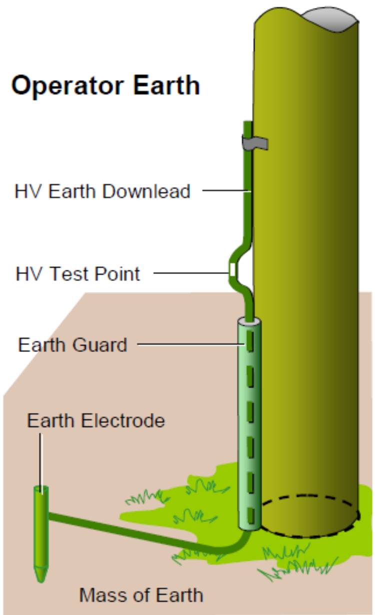


Figure 52: Diagram of Passive or Operator Earth (Ergon Energy 2017)

Initial visual inspections must confirm the following:

1. Identification and inspection of the Earth Return Terminal, shown in Figure 53, on the SWER transformer or reactor tank, to ensure it is mechanically sound and has adequate connectivity.

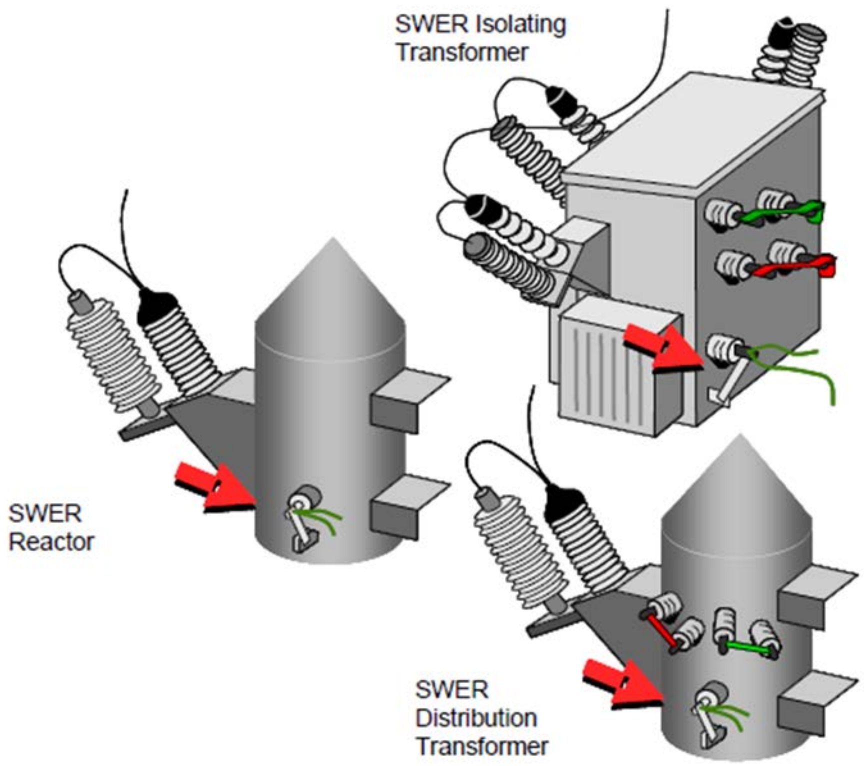


Figure 53: Earth Return Terminal on SWER Transformers and Reactors (Ergon Energy 2017)

2. Ensure any joint in the HV SWER earthing conductors, between the transformer terminals and the earth electrodes, should not be disconnectable (Ergon Energy 2017).
3. All earthing conductors within 2.4 metres of the ground are to be insulated with 0.6/1.1kV grade insulation and are mechanically protected.
4. The LV earthing system should be bonded to the LV neutral terminal on the transformer and any earth leads of LV surge protection devices at the transformer.
5. All SWER transformer HV and LV earth electrodes are to be kept at a minimum of three metres apart to reduce the possibility of injecting HV current into the LV system.
6. IN SERVICE earth testing requires a minimum of Class '00' insulating gloves to be worn at all times.

Customer MEN earthing can vary depending on the number of customers connected to a transformer and the number of electrodes installed at their premises. Often a number of sub-boards at one premises can result is additional electrodes and lowering the overall earthing resistance. A customer's earth electrode must comply with AS/NZS 3000:2018, as shown in Table 13 (Standards Australia 2018). It is important to note there is no specific value of resistance to earth that is required by this Standard. The resistance of the customer's main earthing conductor, measured between the main earthing terminal/connection or bar and the earth electrode, including connection to the earth electrode, shall be no more than 0.5Ω. With the above information it is not recommended for an electrical entity to be reliant upon the customer to provide an earth connection of low resistance.

TABLE 5.2
ACCEPTABLE EARTH ELECTRODES

Material	Surface treatment	Minimum dimensions	Minimum surface treatment thickness
Vertical electrodes			
Steel	Copper clad	∅12 mm circular rod	250 µm
	Copper plated	∅12 mm circular rod	250 µm
	Stainless (including clad with stainless)	∅12 mm circular rod	500 µm
	Hot dipped galvanized	∅16 mm circular rod	63 µm
	Hot dipped galvanized	Section with minimum cross-sectional area of 200 mm² and with no part less than 3 mm thick	63 µm
Non-ferrous (excluding aluminium)	Solid	12 mm	N/A
Horizontal (strip) electrodes			
Copper rod	Solid	∅7 mm circular	N/A
Copper strip	Solid	25 mm × 1.6 mm	N/A
Copper pipe	Bare	∅15 mm circular × 2.45 mm wall thickness	N/A
Copper cable	Bare	25 mm²	N/A
Steel pipe	Hot dipped galvanized	∅20 mm circular × 3 mm wall thickness	63 µm
Steel strip	Hot dipped galvanized	40 mm × 3 mm	63 µm

Table 13: Acceptable Earth Electrodes AS/NZS 3000:2018 (Standards Australia 2018)

5.1.1 Fall of Potential – 4 Pole Selective – SWER HV Equipment Earth Test

The 4 pole selective test is carried out to test the resistance of the HV earth to the ground. This test injects a known current through a test stake driven at 100m and measures the resultant drop in voltage through the insulation piercing test clamp (IPTC) on the HV down lead earth and the test stake driven at 50m. The use of a CT clamp on the HV earth down lead measures the current flowing through the HV earth electrode, this measurement is used to apply Ohm’s Law to calculate the resultant HV resistance. The selective clamp method provides improved resolution and test lead compensation. This method must be carried out twice, once on each SWER HV earth down lead to ensure both conductors connecting to the earth delta configuration are tested. The two measurement configurations are shown in Figure 54, it is important to note only the clamp is moved to the second HV down lead in the second test, the IPTC remains in place.

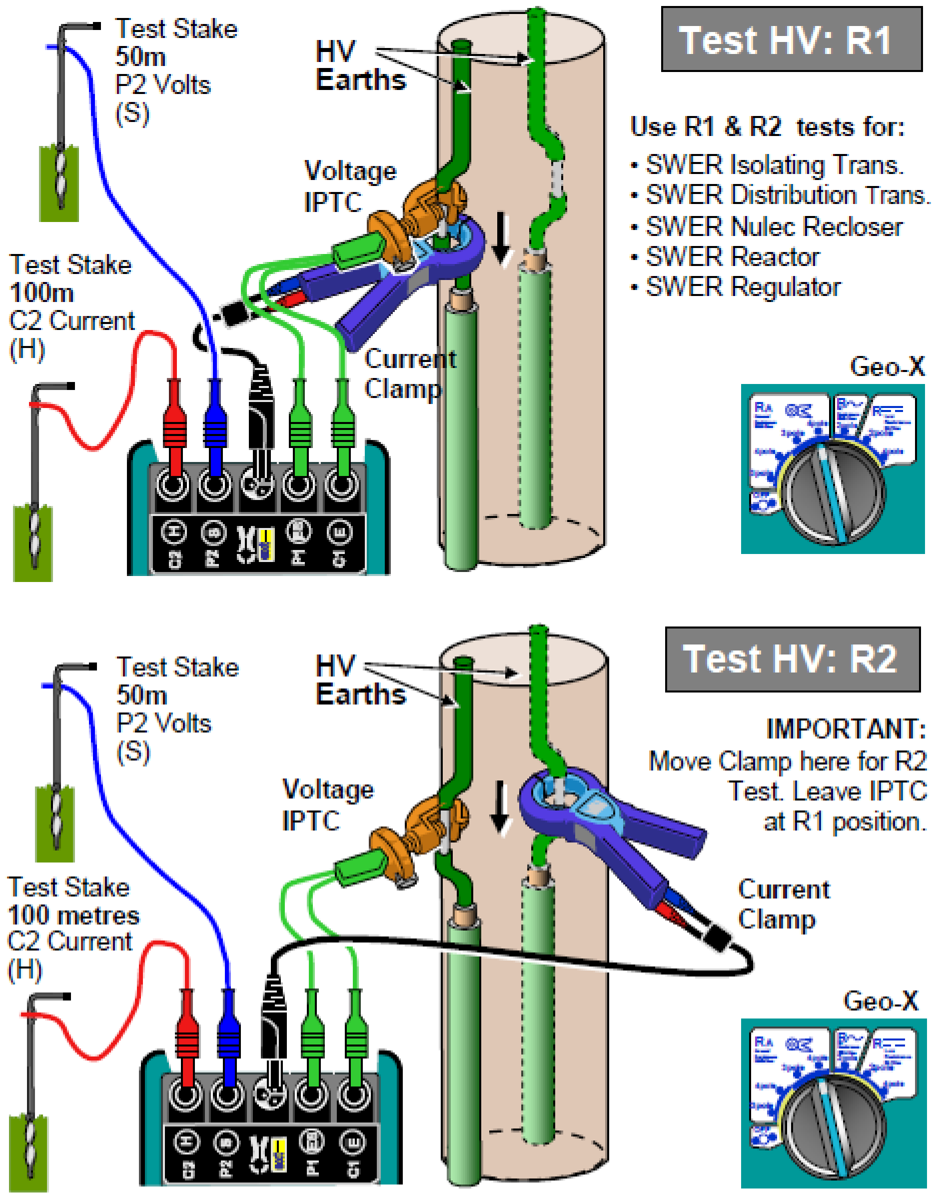


Figure 54: 4 Pole Selective SWER HV Earth Test Method (Ergon Energy 2017)

5.1.2 Stakeless – 2 Clamp Loop Resistance - SWER HV Earth Continuity

The 2 clamp loop resistance measures the continuity of the HV earth loop from the connection to the tank, through the earth down leads and through the delta under the ground, as shown in Figure 55. When using a AEMC 6471, the current clamp induces a 1611Hz voltage on the conductor and the second current clamp measures the current flowing through the loop. The resultant resistance is calculated by the device using Ohm's Law. To avoid electromagnetic interference between the clamps, a minimum separation is specified, by the manufacturer, as per Table 14.

Value measured (Ω)	Minimum separation	
	MN82	SR182
0 to 1	0.1m (4")	0m (0")
1 to 5	0.4m (1' 04")	0.1m (4")
5 to 10	0.5m (1' 08")	0.2m (8")
10 to 50	0.7m (2' 04")	0.3m (1')
50 to 100	0.9m (3')	0.5m (1' 08")
100 to 500	1.2m (4')	0.5m (1' 08")

Table 14: Minimum Clamp Separation for the AEMC 6471 Digital Ground Resistance Tester (AEMC Instruments 2018)

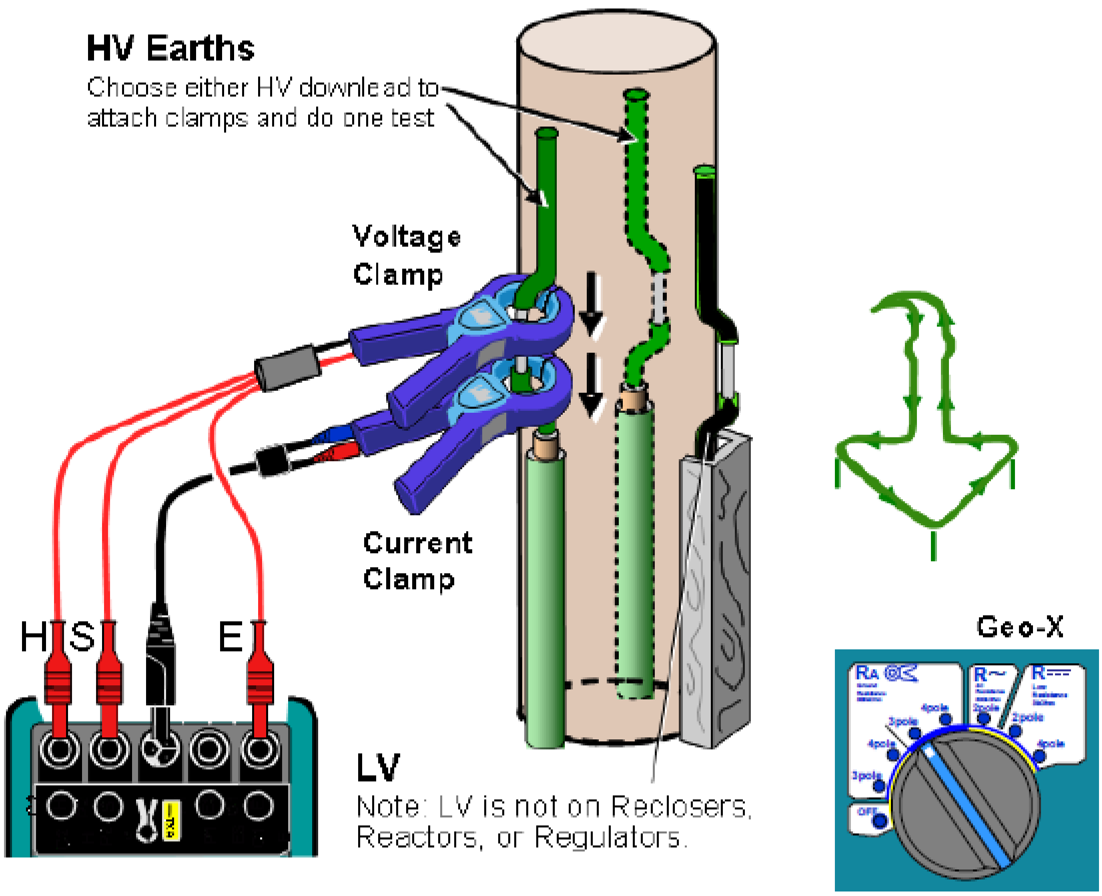


Figure 55: 2 Clamp Loop Resistance HV SWER Earth Continuity Test (Ergon Energy 2017)

5.1.3 Fall of Potential – 4 Pole Selective – SWER LV Equipment Earth Test

The 4 pole selective test is carried out to test the resistance of the LV earth to the ground. This test injects a known current through a test stake driven at 100m and measures the resultant drop in voltage through the insulation piercing test clamp (IPTC) on the LV down lead earth and the test stake driven at 50m. The use of a CT clamp on the LV earth down lead measures the current flowing down through the earth electrode to the ground; this measurement is used with Ohm's Law to calculate the resultant resistance. The selective clamp method provides improved resolution and test lead compensation. This method is carried out once as there is only one LV earth lead. The test device configuration is shown in Figure 56.

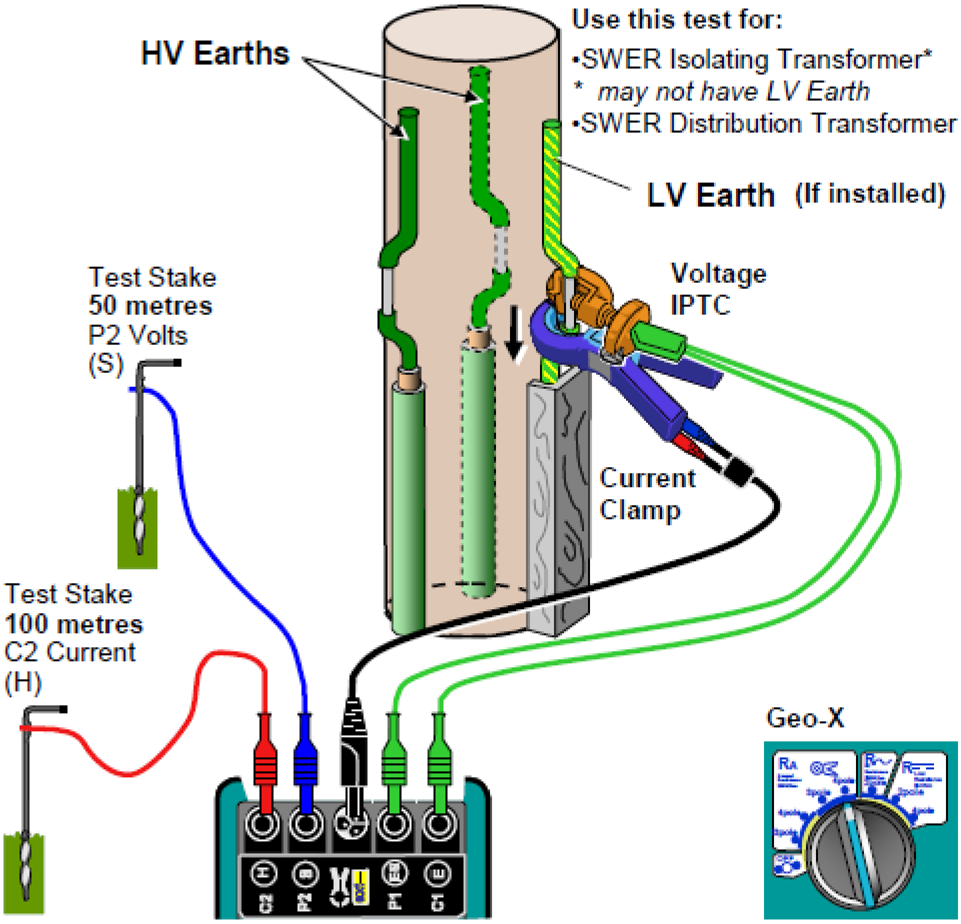


Figure 56: 4 Pole Selective LV SWER Earth Test Method (Ergon Energy 2017)

5.1.4 Fall of Potential – 4 Pole Selective - Grid Neutral SWER LV Earth

The grid neutral earth test measures the resistance to ground of the grid neutral. The configuration is the same as the 4 pole selective LV SWER earth test method; the difference being the current clamp is reversed to above the voltage IPTC. This test injects a known current through a test stake driven at 100m and measures the resultant drop in voltage through the insulation piercing test clamp (IPTC) on the LV down lead earth and the test stake driven at 50m. The use of a CT clamp on the LV earth down lead measures the current flowing up through the earth electrode to the grid neutral, this measurement is used with Ohm's Law to calculate the resultant resistance. The selective clamp method provides improved resolution and test lead compensation. This method is carried out once as there is only one LV earth lead. The test device configuration is shown in Figure 57.

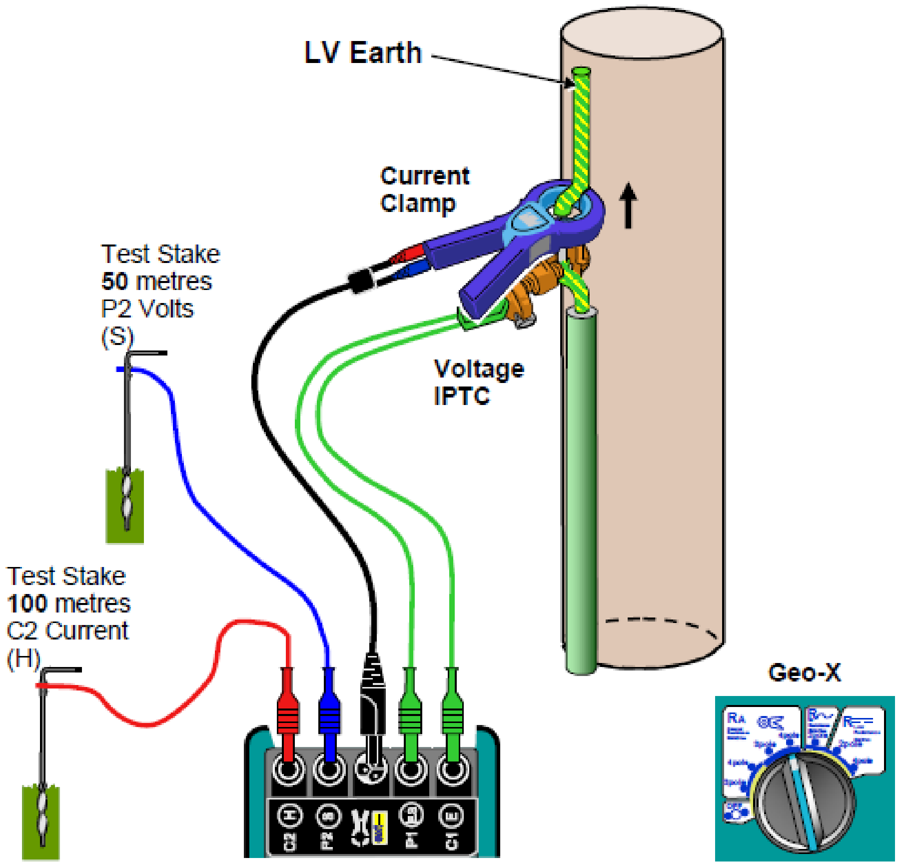


Figure 57: Grid Neutral LV SWER Earth Test Method (Ergon Energy 2017)

5.1.5 Soil Resistivity Test Method – Wenner

The recommended soil resistivity test method is using the Wenner method. This configuration uses four small electrodes, driven to a depth (d) which cannot exceed 5% of their separation distance, spaced evenly apart (s) in a straight line. A test current is injected between the two out electrodes and the potential between the two inner electrodes is measured. Ohm's Law is used to calculate the resistance; the resistivity equation (5-23) is used to calculate the final result (Substation Standards 2007).

$$\rho = \frac{4\pi sR}{1 + \frac{2s}{\sqrt{s^2 + d^2}} - \frac{2s}{\sqrt{4s^2 + 4d^2}}} \tag{5-23}$$

R = calculated resistance, Ω

s = electrode spacing, m

d = electrode depth, m

For cases when $d < s/20$ then we can assume $d \approx 0$, equation (5-24) is used.

$$\rho = 2\pi sR \tag{5-24}$$

The test device configuration is shown in Figure 58.

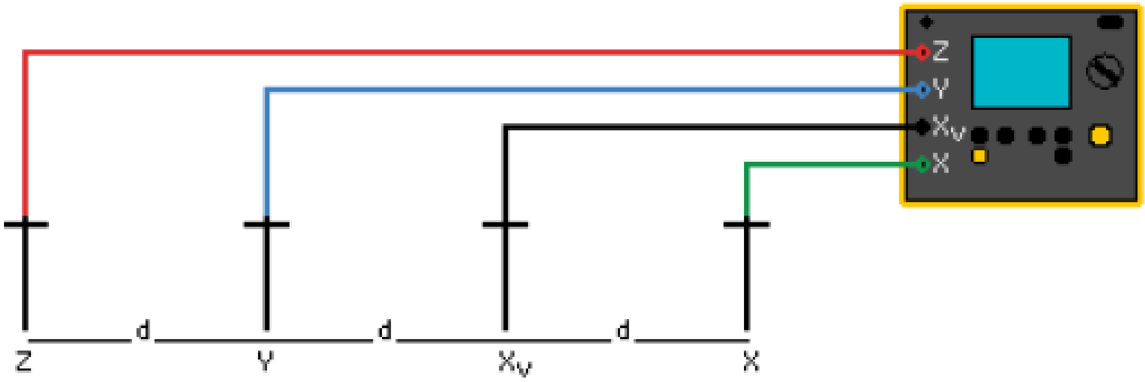


Figure 58: Wenner Soil Resistivity Test Method (Ergon Energy 2017)

Chapter 6 - SWER Earth Testing – Field Testing and Results

6.1 Field Testing

Field testing was carried out to understand the true behaviour and characteristics of SWER distribution transformers and the return earth current. The following chapter lists the requirements deemed appropriate for a test site, the network configuration, hardware specifications, method of testing and results.

6.1.1 Test Site Requirements

The following test site criteria were deemed necessary to establish trending data from a typically loaded SWER transformer:

- Located in close proximity to an Ergon Energy depot;
- Beside a bitumen road, base of the pole to be easily accessed by vehicles in all weather conditions;
- Located within a wide accessible road reserve to allow for test electrodes to be laid out in different configurations;
- High number of consumers to allow for diverse load profiling;
- Surrounding houses and property entrances not to be hindered by test electrodes;
- Known original transformer earthing layout;
- Diversity of consumers with solar array injection;
- Consumer premise configuration such that the earthing electrodes can be run without the consumer MEN's affecting the test electrode sphere of influence.

6.1.2 Test Site Selection

A SWER transformer site was identified that fitted the above requirements; the site transformer reference number was SS4631 with the following details:

- **Address**: 451 Glen Allyn Road, Malanda, Queensland 4885
- **GPS location**: Latitude 17°21'45.89"S and Longitude 145°38'14.86"E.
- **Site establishment date**: The site was originally built in October 1984.
- **SWER distribution transformer details**: Tyree 25kVA 12.7/0.240kV SWER distribution transformer. The transformer was replaced in 2005 with an ABB 25kVA 12.7/0.5/0.25kV SWER distribution transformer.
- **Pole details**: Site Label: 5002220; Legacy Label: GA28. The original 1984 timber pole was replaced with a 14m, 12kN White Stringybark CCA (Copper, Chromium and Arsenic) salt impregnated timber pole in 2009. The last pole inspection was May 2017.

6.1.3 Test Site Existing Earthing – SS4631

The original earthing has not changed since installation in 1984, and consists of 22 metres length of HV earthing with 18 earth electrodes running in a South East direction directly under the incoming SWER line. The LV earthing consists of 30 metres with 16 earth electrodes running directly under the outgoing SWER line to pole DW4 (5002220) GA28. The earthing configuration is shown in Figure 59 with the original transformer installation card shown in Figure 60. The commissioning earth readings in 1984 were HV Earth = 16Ω and the LV earth = 15Ω. There are three historical records of earth testing for site SS4631 as shown in Figure 61, the plot reveals the fluctuations in LV and HV recordings that create difficulty in identifying a true defect from one being influenced by weather conditions or variances in testing methods.

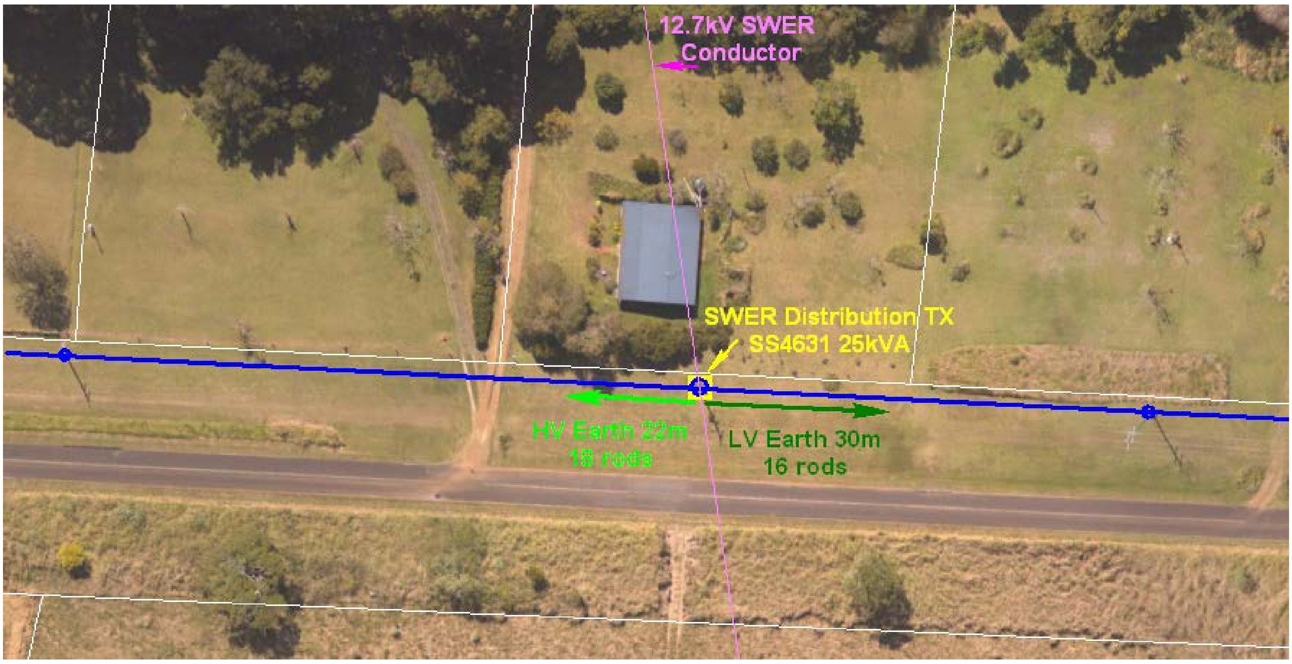
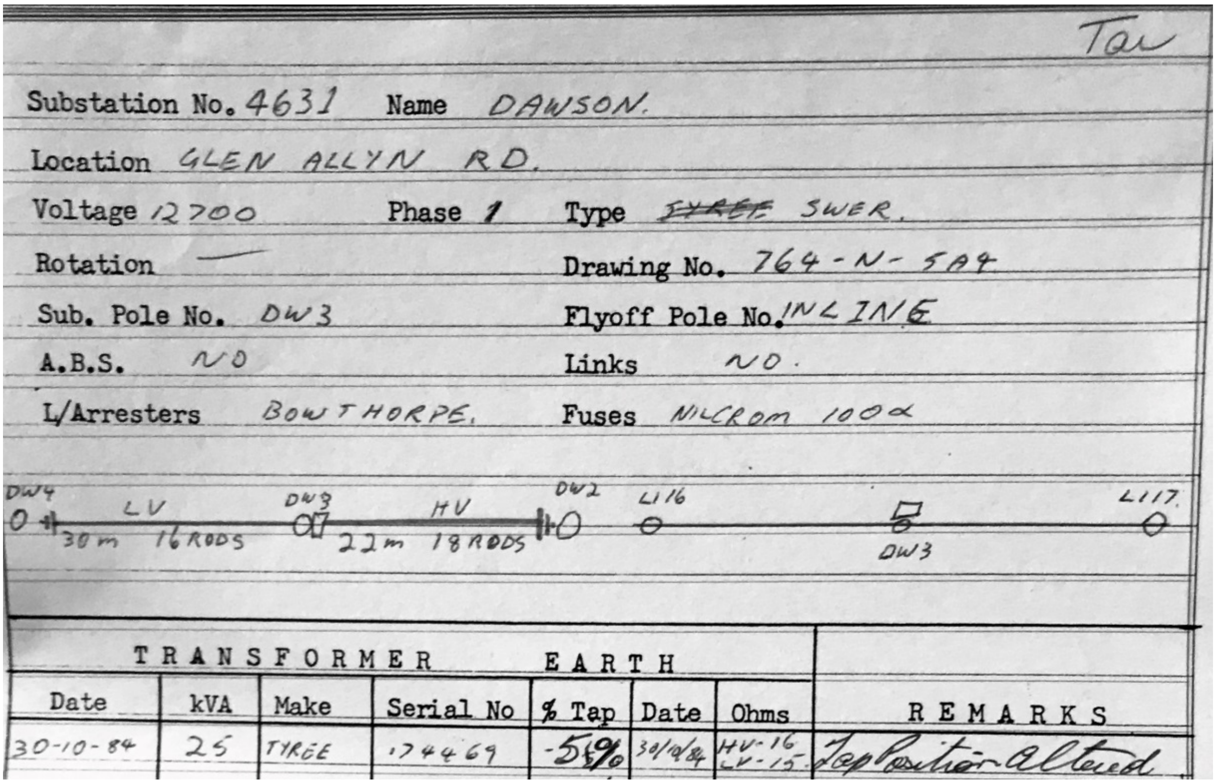


Figure 59: Aerial View of Earthing Configuration for SWER Distribution Transformer SS4631



Substation No. 4631 Name DAWSON.

Location GLEN ALLYN RD.

Voltage 12700 Phase 1 Type ~~TYREE~~ SWER.

Rotation — Drawing No. 764-N-5A4

Sub. Pole No. DW3 Flyoff Pole No. INLINE

A.B.S. NO Links NO.

L/Arresters BOWTHORPE. Fuses NICROM 100α

TRANSFORMER				EARTH			REMARKS
Date	kVA	Make	Serial No	% Tap	Date	Ohms	
30-10-84	25	TYREE	174469	-5%	30/10/84	HV-16 LV-15	Tap Position Altered

Figure 60: Original Transformer Installation Card for SS4631

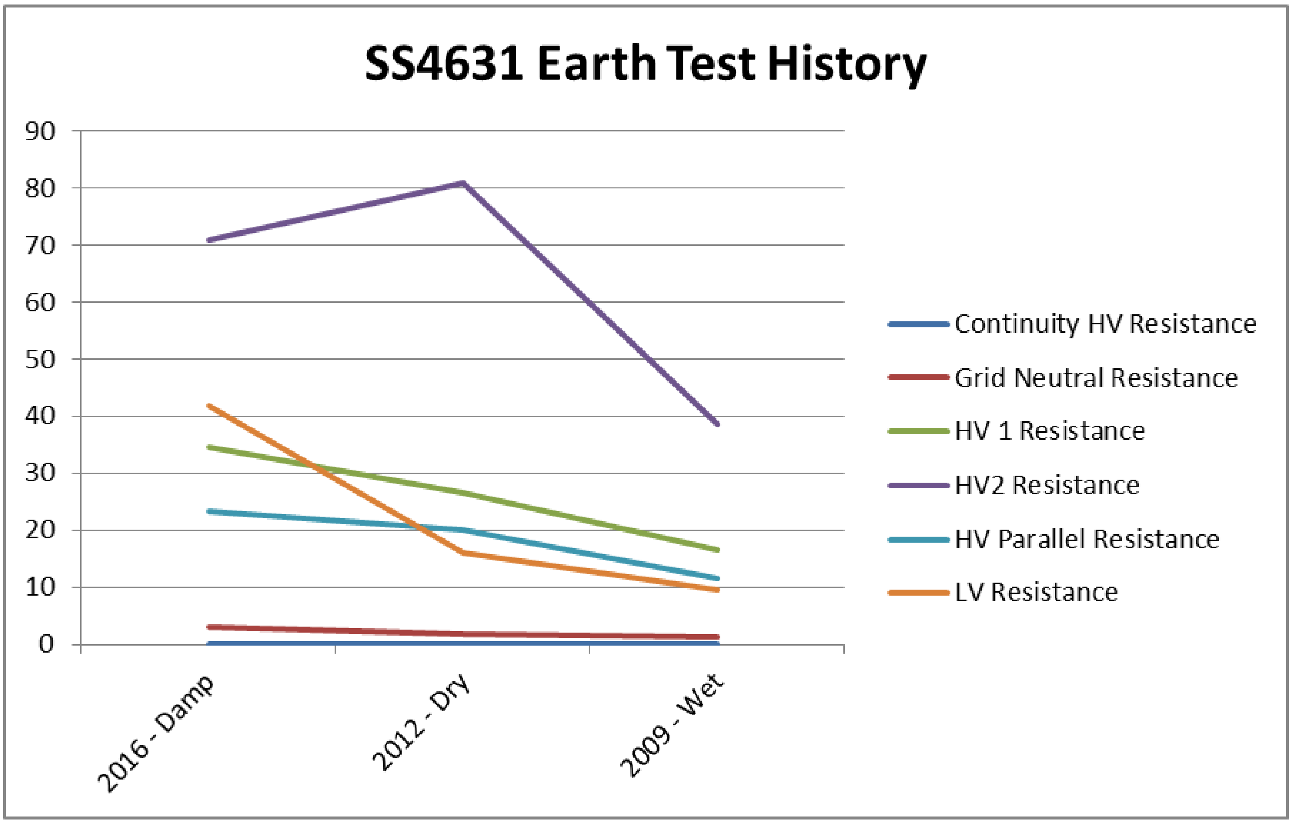


Figure 61: Earth Test History from 2009 to 2016 for SWER Distribution Transformer SS4631

Other distribution transformer historical earth test results within a 1km radius of SS4631 were graphically represented to reveal considerable fluctuations in the HV parallel resistance and grid neutral resistance over a period from 2009 to 2016. The entered values that are high are either genuine earthing defects or issues with the accuracy of the testing method. This is a standard example of the inaccuracies generated from current testing methods.

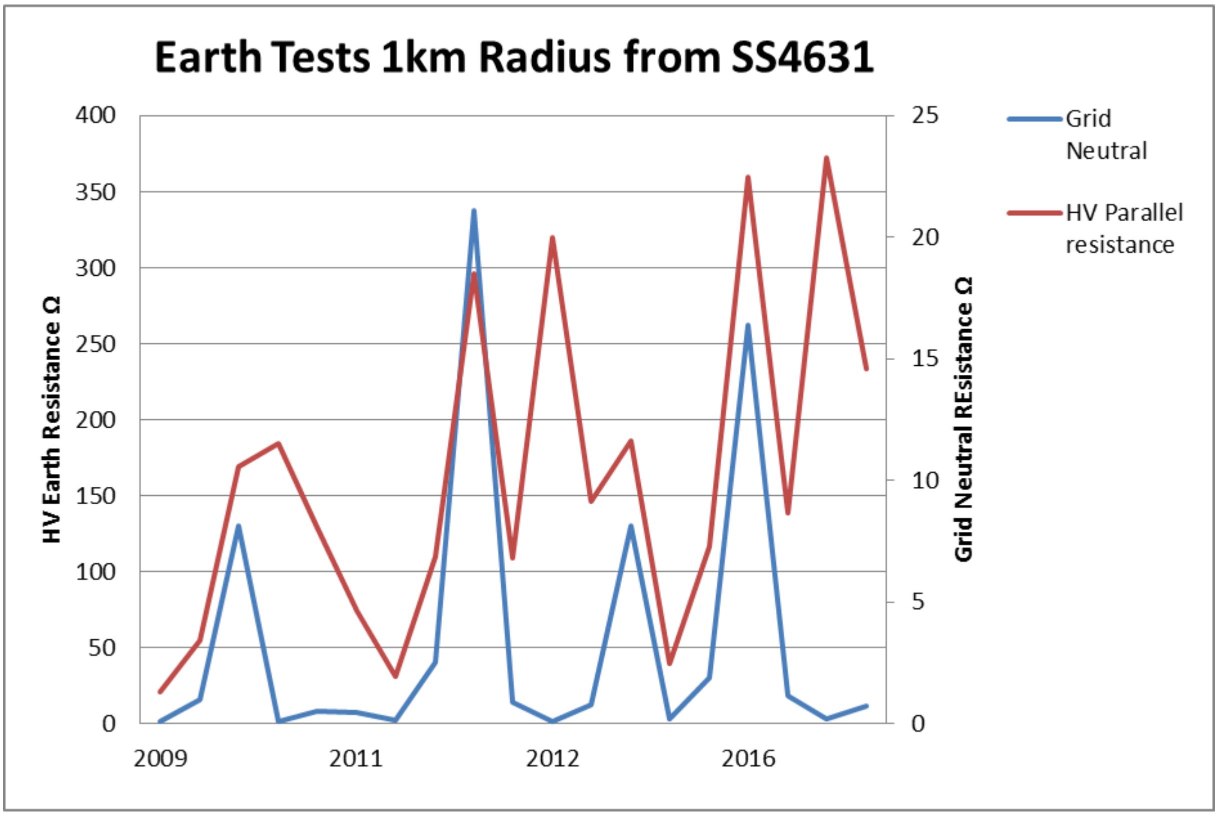


Figure 62: Earth Test History from 2009 to 2016 for SWER Distribution Transformers in a 1km Radius from SS4631

6.1.4 Test Site Distribution Transformer – SS4631

Nameplate: The 12.7kV 25kVA ABB SWER transformer nameplate rating is listed in Table 15, the current tap setting is on 'buck' or '4' as seen in Figure 63 and Figure 64.

Rated kVA	25
Phase	1
Frequency	50 Hz
HV amperes	1.97 A
Impedance % at 25kVA 75°C	3.3%
HV no load volts	13018V
LV no load amperes	100A (250V) 50A (500V)

Table 15: SS4631 Nameplate Details

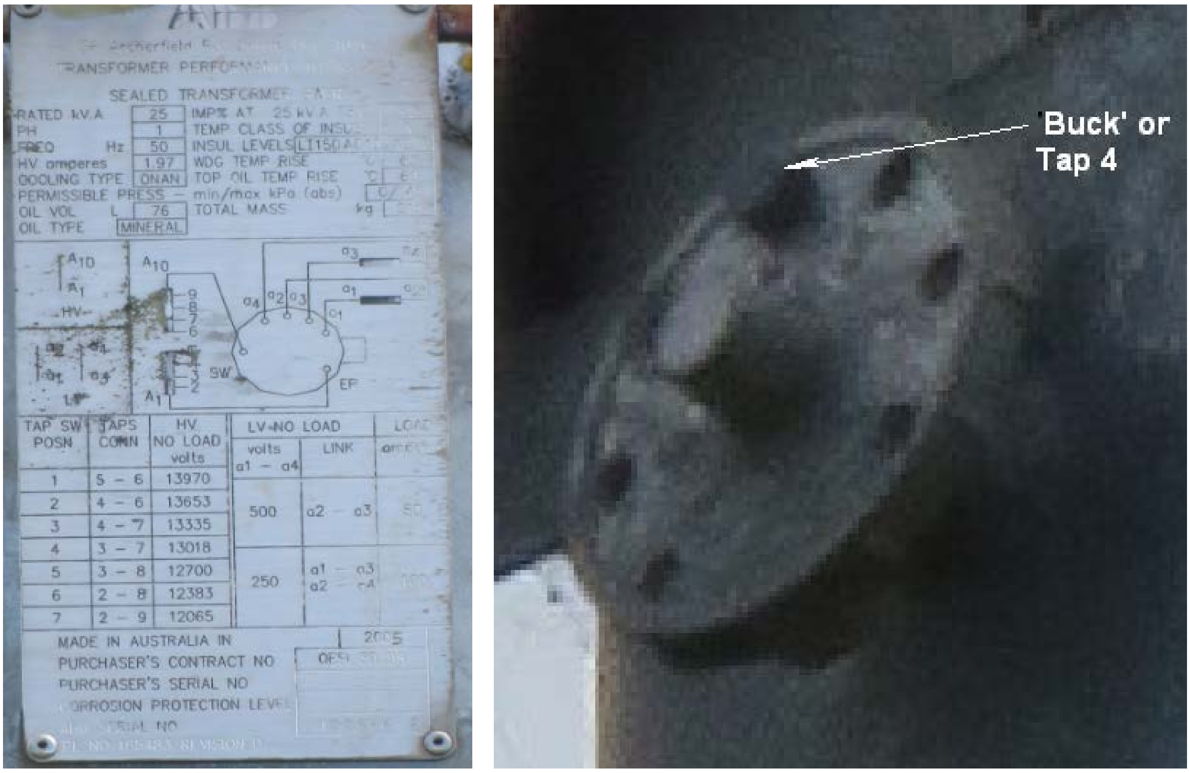


Figure 63: SS4631 Transformer Nameplate and Tap Setting

Figure 64: SS4631 Site Photograph

Consumers: SS4631 has a total of 10 connected residential/rural consumers, 6 of whom have photovoltaic (PV) systems with export capabilities amounting to a total of 12.8kW, as shown in Table 16.

Customer	Substation Name	Substation Desc	Substation Rating Kva	Pv Panel Kw	Pv Capacity Kw	Install Date
1	SS4631	DAWSON	25	4.0	3.5	10/02/2012
2	SS4631	DAWSON	25	3.6	3.4	18/10/2012
3	SS4631	DAWSON	25	1.4	1.3	27/11/2012
4	SS4631	DAWSON	25	5.5	4.6	06/04/2016
5	SS4631	DAWSON	25	2.5	3.8	04/11/2011
6	SS4631	DAWSON	25	6.48	5.0	27/07/2017
			Total	**14.5**	**12.8**	

Table 16: Consumers with PV Connected to SS4631

Legacy maximum demand customer data from 2014 to 2017 is shown in Figure 65, current data is difficult to obtain due to 'ring fencing' between Ergon Energy Network and Ergon Energy Retail and for the purpose of this dissertation, legacy data was deemed adequate. The monthly maximum demand data is calculated via an algorithm from consumer billing meter read data and can be assumed to be accurate. The plot in Figure 65 illustrates the transformer maximum demand has an average value of 17.29kVA which is under the maximum demand of 25kVA rating of the transformer. Therefore it is assumed the transformer is moderately loaded for the designed capacity.

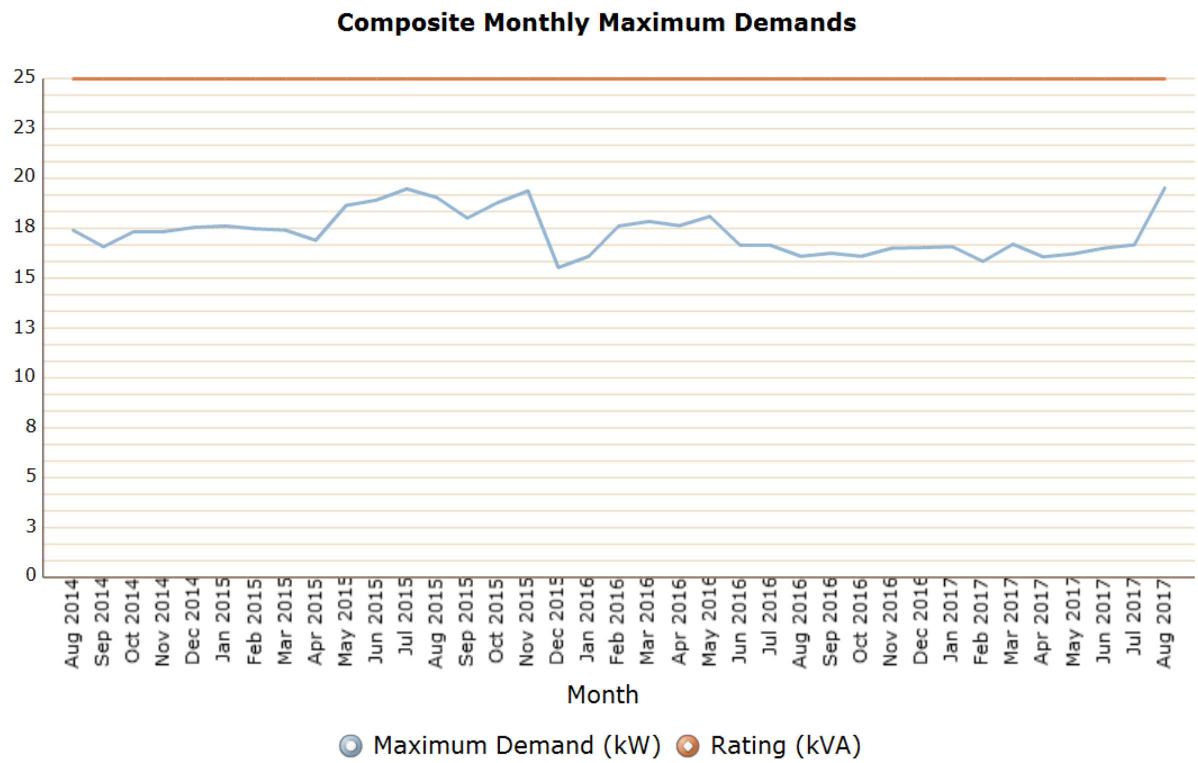


Figure 65: SS4631 Legacy Composite Monthly Maximum Demand

Figure 66 represents the monthly percentage utilisation for SS4631 which has an average of 69.16% utilisation over a period of 3 years.

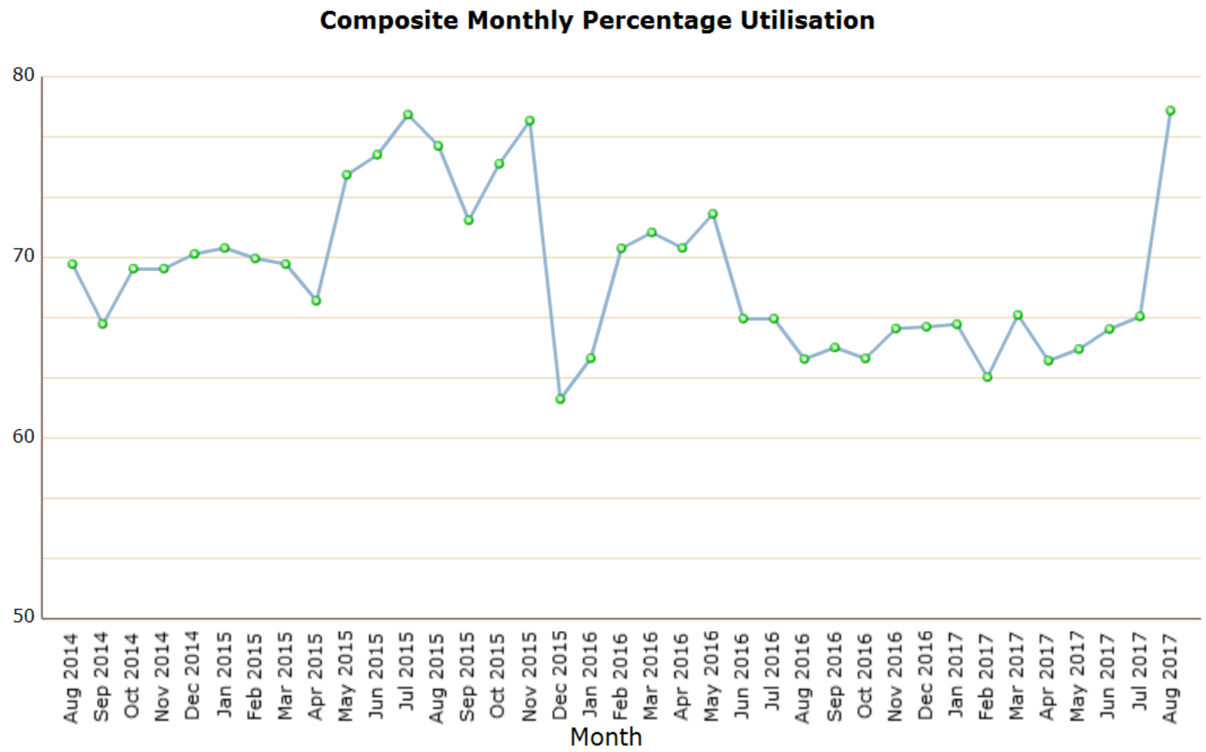


Figure 66: SS4631 Legacy Composite Monthly Percentage Utilisation

It is to be noted that on this particular site a new three phase feeder was constructed above the LV and perpendicular to the SWER line in 2011; the SWER distribution transformer was left under the new three phase line. Due to restraints on the isolation transformer, SS4631 was upgraded to a single phase transformer in June 2019.

6.1.5 Upstream Assets

The distribution SWER transformer SS4631 is supplied from the 12.7kV Clarks Track SWER line as shown in Figure 67. SS4631 is located 6.1 km via aluminium clad (3/2.75 SC/AC), aluminium clad steel reinforced (Raisin 3/4/2.5 ACSR/GZ) and galvanised steel (3/2.75 SCGZ) conductor from the 200kVA SWER isolation transformer SS10620. Figure 68 shows an aerial view of the isolating transformer SS10620 which is supplied from the three phase Tarzali Feeder out of Atherton Zone Substation via 31.9km of backbone feeder consisting of a combination of 7/0.104 HDBC, Mink 6/1/0.144 ACSR/GZ and Banana 6/1/3.75 ACSR/GZ.

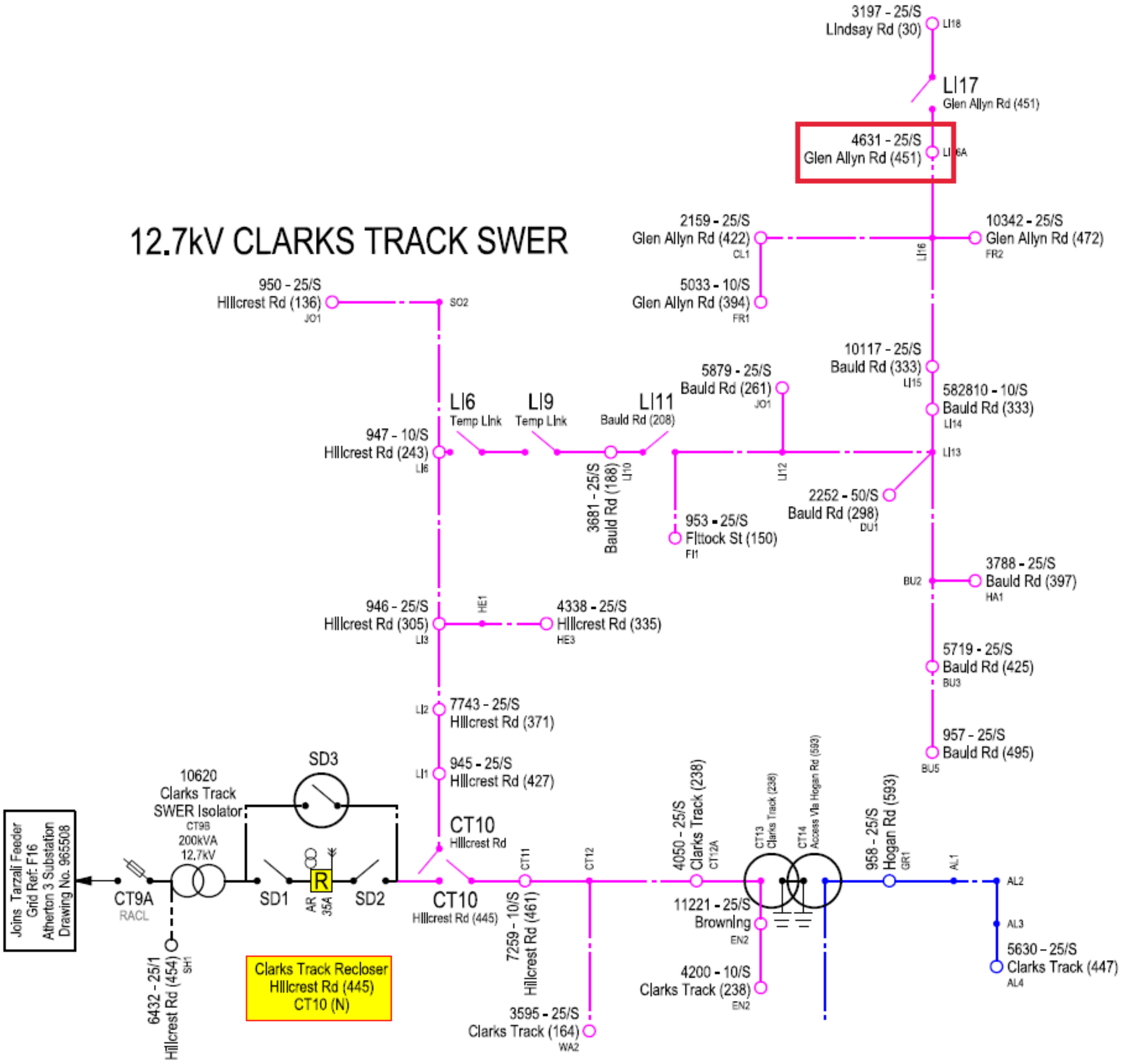


Figure 67: Schematic for Clarks Track SWER

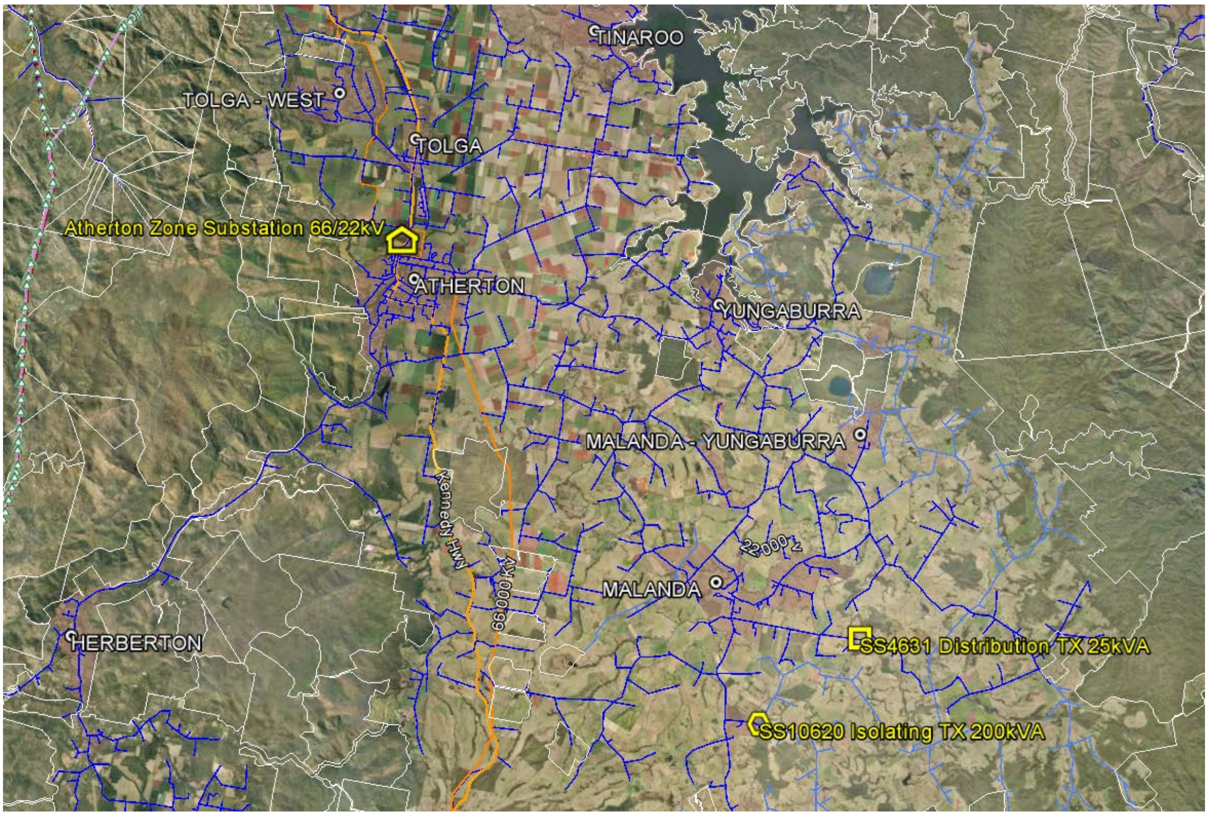


Figure 68: Aerial View of SS4631 in Relation to the SWER Isolating Transformer and Main Zone Substation

SWER isolation transformer SS10620 has the following site details:

- **Address**: 454 Hillcrest Road, Jaggan, Queensland 4885.
- **GPS location**: Latitude 17°23'28.66"S and Longitude 145°36'24.62"E.
- **Site establishment date**: The SWER scheme installation date is from the 1980’s, the isolation transformer site was established in 2011.
- **SWER isolation transformer details**: ABB 200kVA 22/12.7kV SWER isolation transformer.
- **Pole details**: Site Label: 2145077; Legacy Label: CT9B. The original 1980’s timber pole was replaced with a 14m, 12kN broad leaf ironbark CCA (Copper, Chromium and Arsenic) salt impregnated timber pole in 2011 when the isolating transformer was installed. The last pole inspection was December 2016.

The earthing was installed in 2011 and is a combination of electrodes and deep drilled earths traversing 450 metres of HV earthing to the South of the pole site and 70 metres to the North. The LV earthing consists of 30 metres with deep drilled earth electrodes. There are three historical records of earth testing for site SS10620 as seen in Figure 69. The plot reveals the fluctuations in LV and HV recordings. The isolating transformer is current set on tap ‘3’, as shown in Figure 70 and Figure 71.

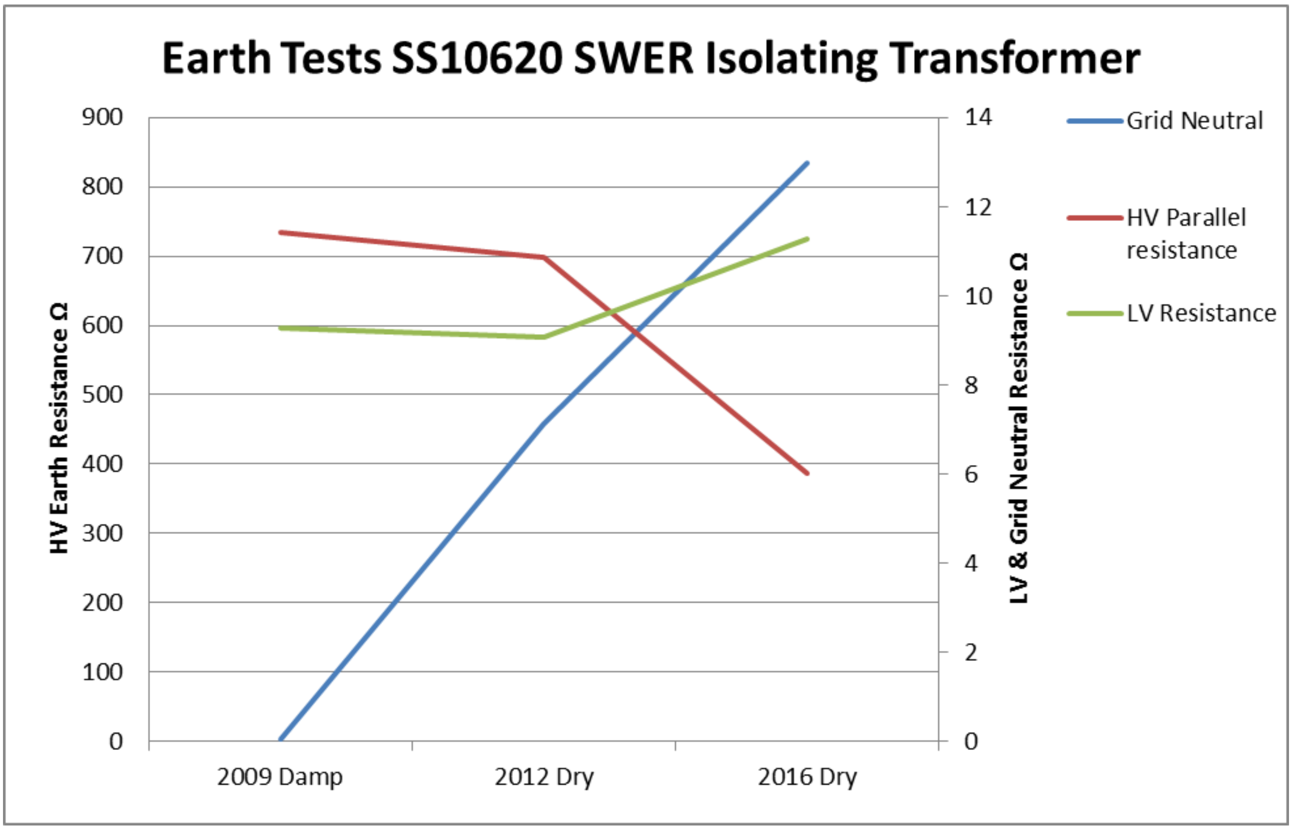


Figure 69: SS10620 SWER Isolating Transformer Historical Earth Tests

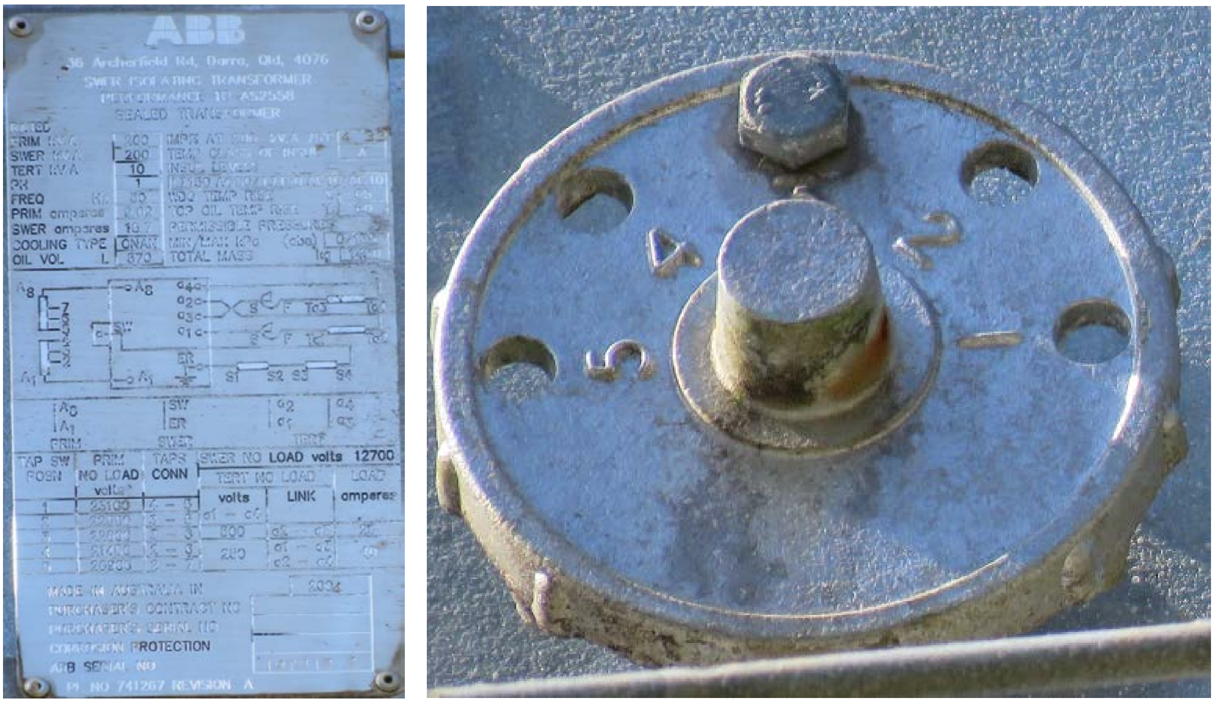


Figure 70: SS10620 SWER Isolating Transformer Nameplate and Tap Setting

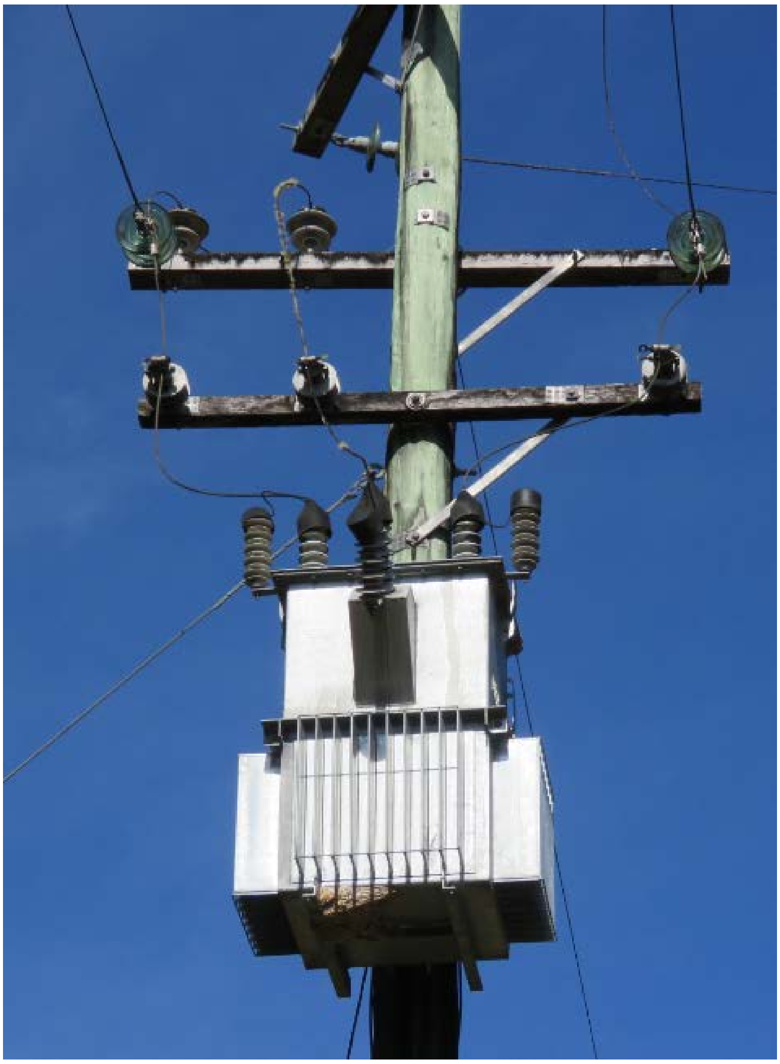


Figure 71: SS10621 Site Photograph

6.1.6 SS4631 Earth Site Testing prior to Test Monitoring Equipment Installation

Earth resistance testing was completed on the 7th of January 2019 to ensure that the HV and LV earth resistance values were under Ergon Energy's mandatory requirement of HV Earth Resistance ≤ 7Ω and LV Earthing Resistance ≤ 10Ω for a 12.7kV 25kVA SWER distribution transformer. An Ergon Energy standard AEMC 6471 Ground Tester unit was used to complete the onsite benchmark tests. The test probes were run perpendicular to the existing earthing arrangement to maintain exclusion from the sphere of influence of the existing earthing and customer MEN's, as shown in Figure 72. As a safety precaution traffic control was required to run the test leads across the road and complete the tests, an example of the difficulties required for regular earth tests.

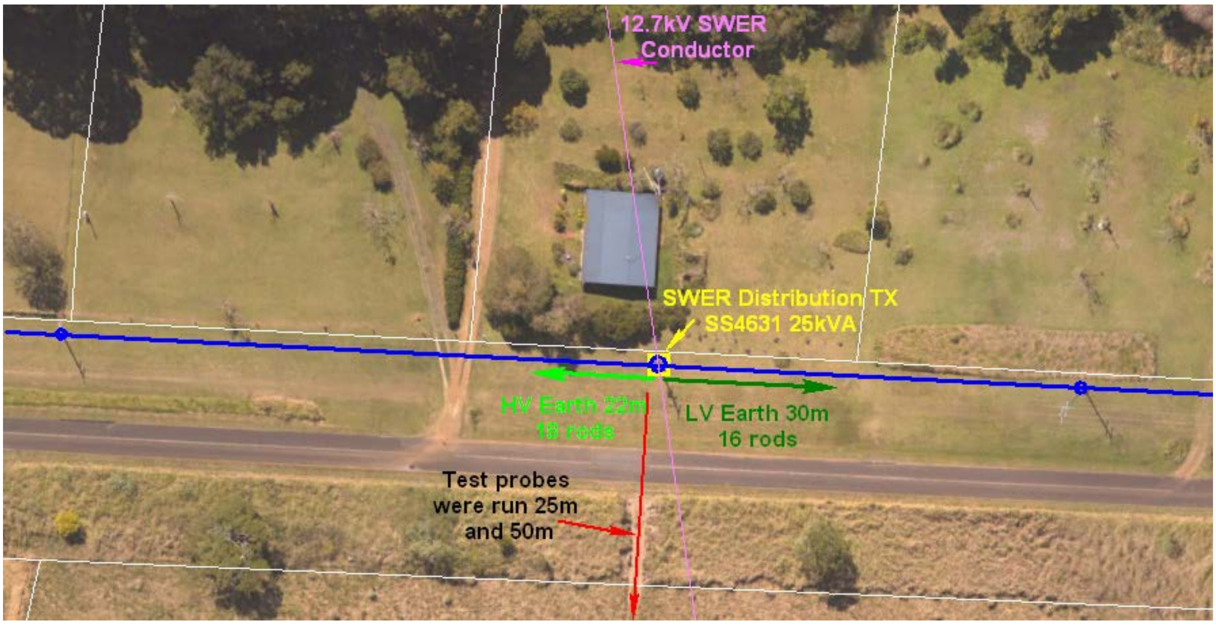


Figure 72: SS4631 Earth Test Probes Arrangement

The weather conditions were recorded as dry with the test probes moistened to enable a solid connection to the ground/soil. The earthing test results were deemed compliant, as per Table 17 and Figure 73, with acceptably low HV loop impedance. Spot tests on the voltage on the HV earth leads was measured at a fluctuating 3.09V and the LV earth lead a solid 0.56V. Both of these values were considered good as the HV was expected to be fluctuating in accordance with the load on the distribution transformer and the measurement on the LV was a float voltage due to the reference earth being close to the fluctuation HV earth. The tests were repeated with 50m and 100m test leads to verify the accuracy of the results, the outcome was identical. These results were taken to be accurate benchmark test results for the monitoring and modelling calculations in the following chapters.

SS4631 Pole: 5002220 GA28			
Date	**Test Type**	**Resistance (ohms)**	
		LV Earth (≤ 10Ω)	**HV Earth (≤ 7Ω)**
7th January 2019	**4 pole**	3.842	6.339
	3 pole	3.87	6.39
	Loop		0.2

Table 17: SS4631 Earth Test Results 7th January 2019

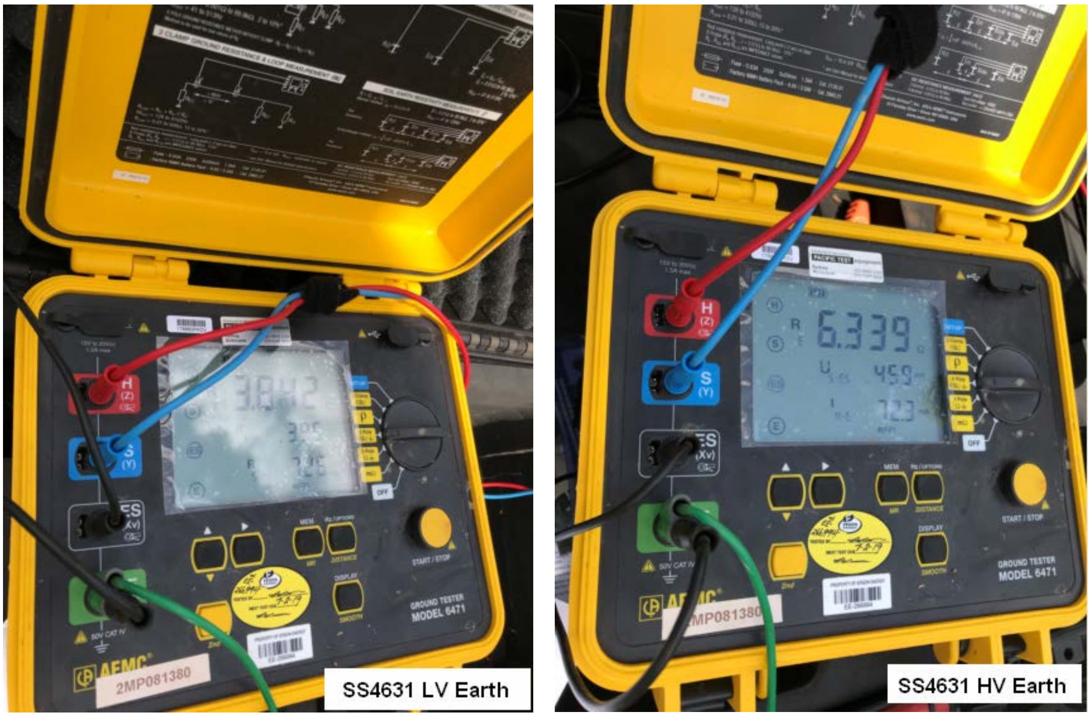


Figure 73: SS4631 Earth Test Readings 7th January 2019

The earth resistivity tests were carried out on the 17th of January 2019 using the Wenner method with four earth test probes. Tests in two positions were completed to establish the soil layers, the first position was perpendicular to the existing SWER line and the second parallel to the existing SWER line. Figure 74 shows the calculated apparent resistivity against the electrode spacing. The dip in the plot at 8m and 12m indicates a three layer soil structure. Figure 75 uses the inverse slope method as a simple interpretation technique to establish the ‘breakpoints’ or changes in resistivity layering. The inverse slope plot provides graphical evidence that there are three identifiable resistivity layers to a depth of 20m. The perpendicular and parallel to the SWER line results have ‘breakpoints’ at 8, 12 and 16 metres. This verifies the existence of three resistivity layers with varying values, the upper layer has a resistivity of 113.11Ωm; the middle layer has a resistivity of 15.93Ωm and the lower layer has a resistivity of 4.73Ωm. Onsite visual inspection of the soil indicated it is predominantly clay loam, this is also verified by the calculated resistivity values which suggest the lower layers are predominantly clay. The field tests reveal the non-homogenous structure of the soil at the site with the variance in resistivity and they verified the necessity to measure the earth resistance rather than make assumptions from resistivity values.

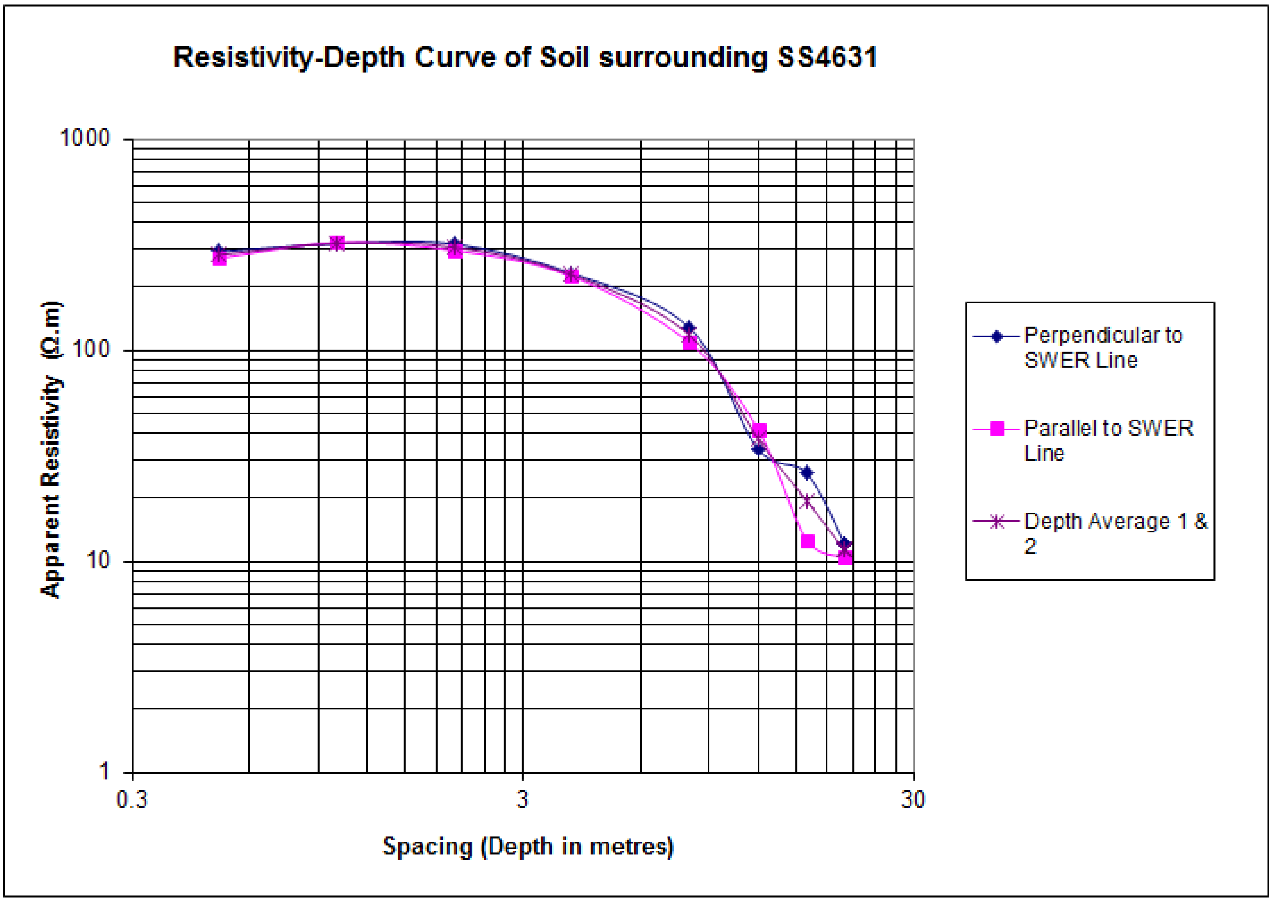


Figure 74: SS4631 Soil Resistivity-Depth Curve Results 17th January 2019

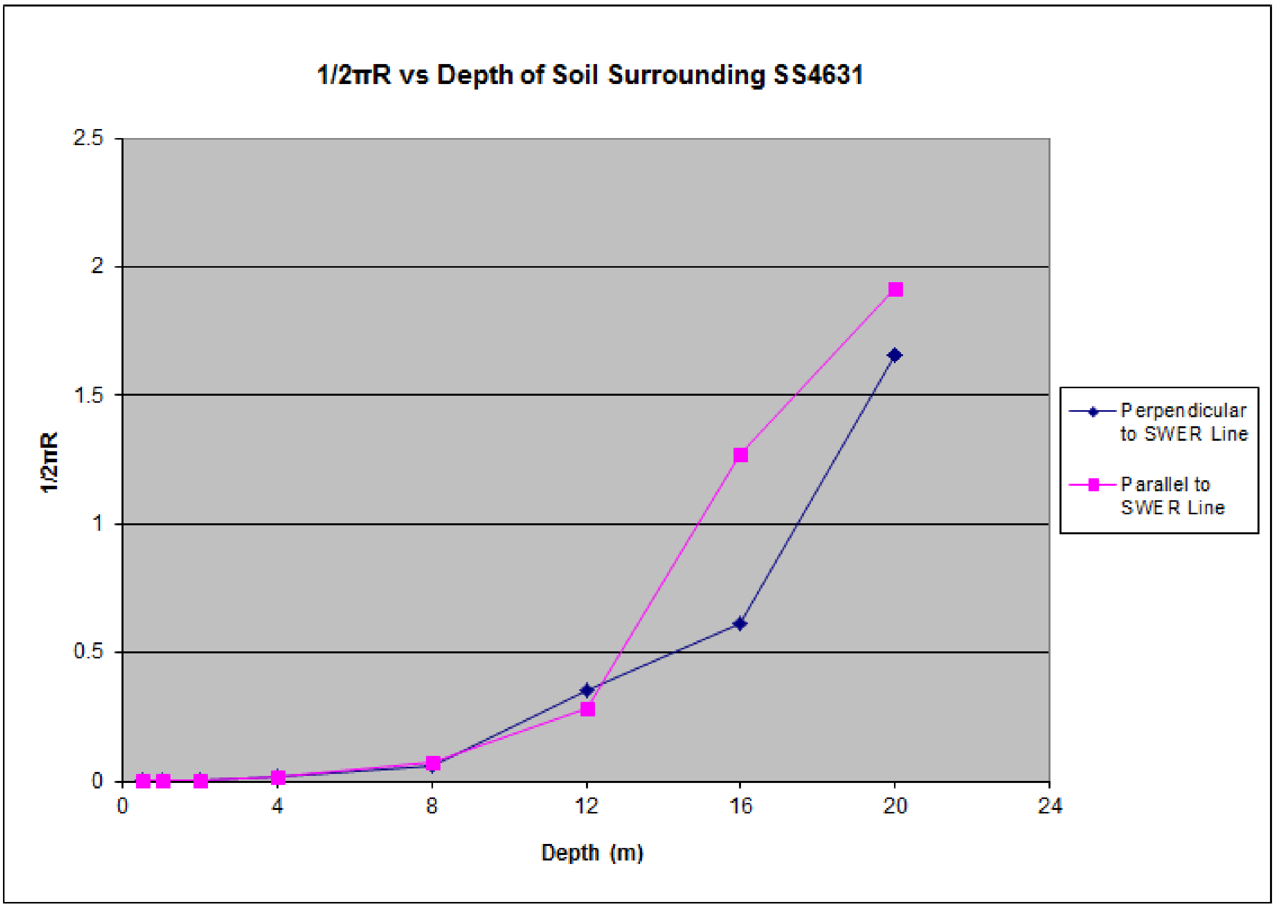


Figure 75: SS4631 Soil Resistivity Inverse Slope Results 17th January 2019

6.1.7 Test Monitoring Equipment Installation

A GridSense PowerMonic PM45 three phase power and disturbance analyser, shown in Figure 76, was installed on the 17th of January 2019. The PM45 was programmed to capture the current, voltage, 2nd harmonic, 3rd harmonic and 4th harmonic waveform measurements with all other power measurements de-activated to enable 11 days of recordings, as shown on the configuration summary page in Figure 77. The log intervals were set at 60 seconds to capture consumer and system fluctuations. The unit CT clamps and VT probes were used to monitor the main LV current and HV earth current with the LV earth as the reference.

To ensure the test configuration was safe the earth was first tested to establish a benchmark low voltage of below 3V. 4 pole and 3 pole earth resistance tests were carried out on site and these were found to match the values obtained on the 7th of January with 6.33Ω for the HV earth electrodes and 3.85Ω for the LV earth electrodes. The tests proved that the earth connections had not fluctuated in 10 days and were in good condition whilst meeting statutory and Ergon Energy Standard requirements. The PowerMonic PM45 unit was rated at Cat IV 600V, the VT leads are rated at 600V with a 0.2A current limiting fuse; therefore, any abnormally high voltage imposed on the HV transformer earth return leads could potentially be isolated via the fuse operating, isolating any excessive voltage to the PM45 unit and the possibility of a high voltage being imposed on the consumer's installations connected to the transformer LV network. The HV earth down lead cover strips were inspected and deemed in good order therefore the likelihood of any break in the earth leads was identified as having a very low risk of occurrence. Additional control measures by means of barricades were installed around the base of the pole to ensure both HV earth down leads were not inadvertently damaged by wildlife or the public. The site was inspected daily for the testing period of 11 days to ensure the integrity of the HV earth was maintained.

Figure 76: PowerMonic PM45 Analyser Unit and Installation for Test Monitoring

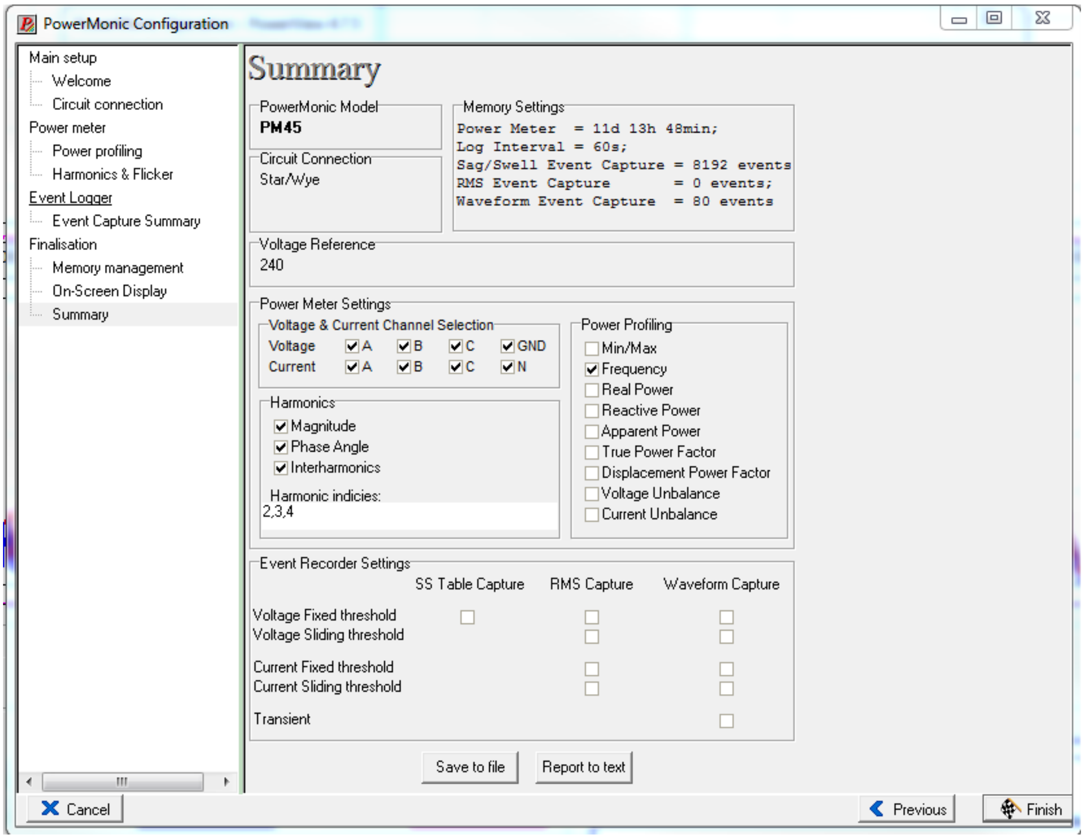


Figure 77: PowerMonic PM45 Analyser Configuration Prior to Installation

6.1.8 Test Monitoring Equipment Results

The data was extracted from the PM45 once it was disconnected and removed from the field. The data range was from Thursday 17th January to Monday 28th January 2019. The PowerMonic Analyser performed as per the pre-set requirements; logged exactly 11 days, 13 hours of data before the memory reached capacity. Figure 78 represents the raw current data extract for the four CT clamps with the HV earth current scaled to the secondary axis. As expected the secondary HV Earth current is a scaled correlation of the primary LV current.

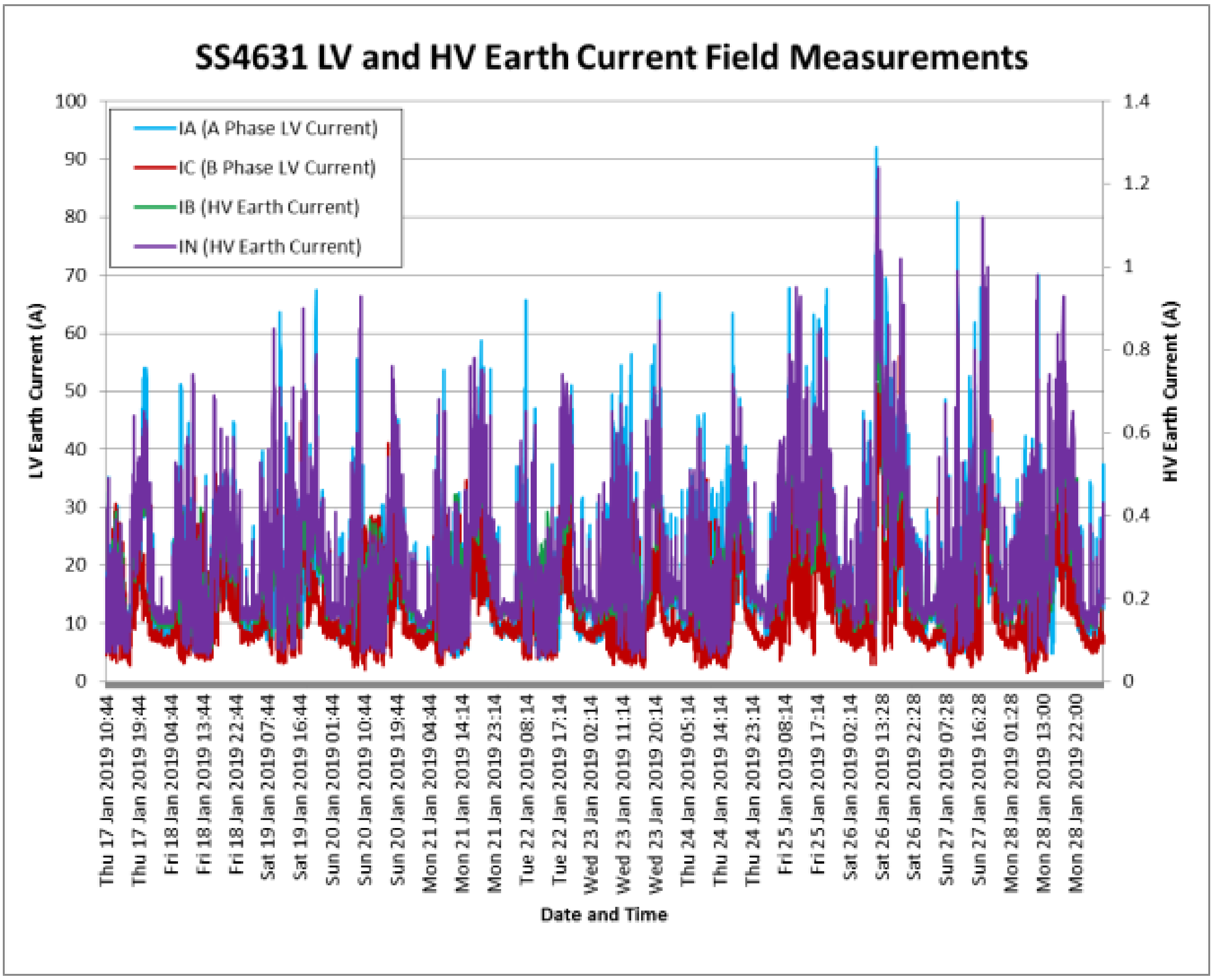


Figure 78: PowerMonic PM45 Analyser Raw Current Data for SS4631

Figure 79 represents the raw voltage data extract for the four VT probes with the HV voltage scaled to the secondary axis. It is interesting to note the secondary HV earth voltage does not correlate to the primary LV voltage and is actually a scaled reflection of the HV earth current.

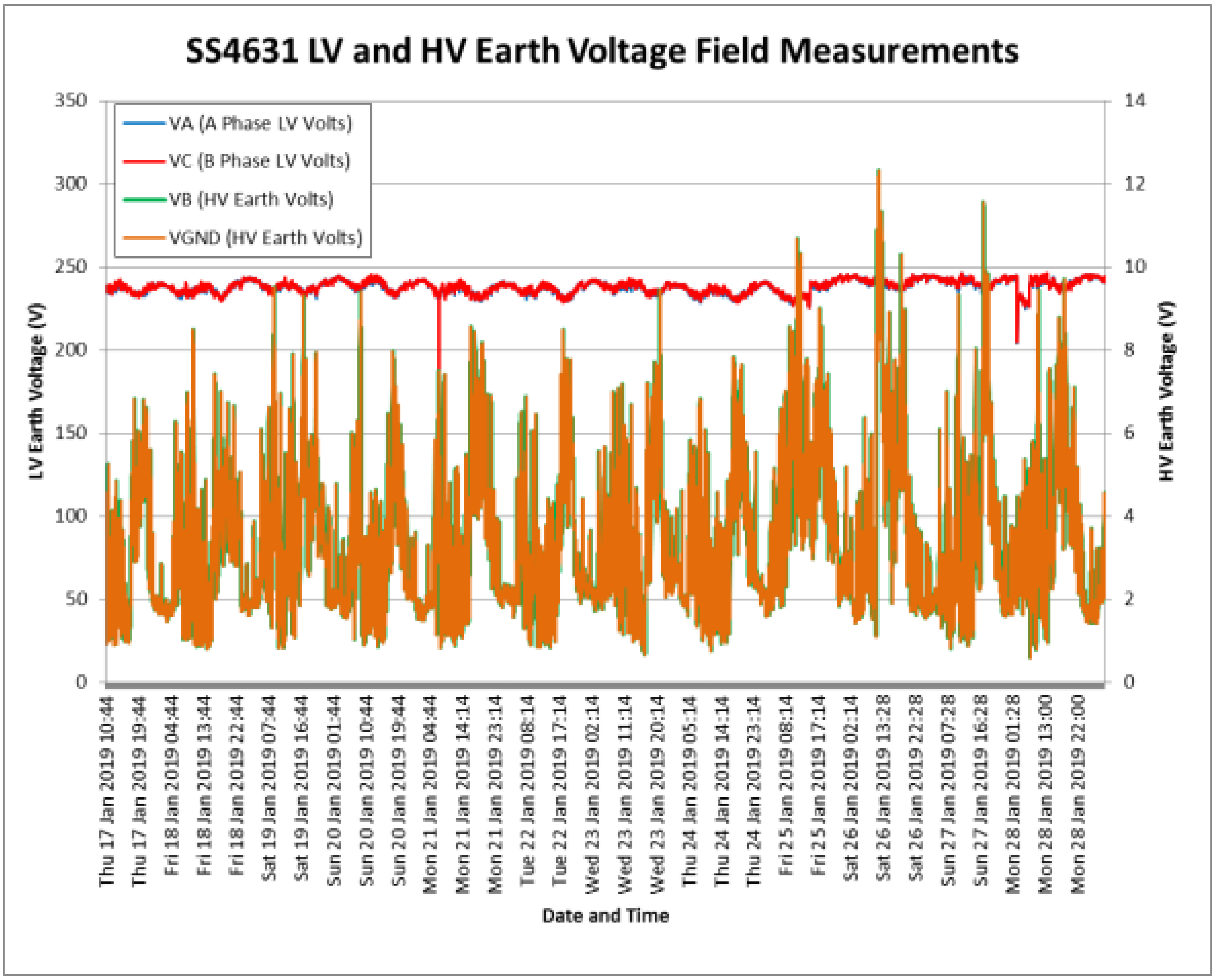


Figure 79: PowerMonic PM45 Analyser Raw Voltage Data for SS4631

Figure 80 represents the correlation between the HV earth current and the LV earth voltage. With this relationship it can be deduced from the raw data that the HV earth current, HV earth voltage and the primary LV earth current are all scaled correlations of each other. With this in mind a direct relationship between the HV earth voltage and the LV earth current can be formed as shown in Figure 81. The reason the HV earth voltage is chosen as the component to monitor is that it is very easy to install test probes to the two HV earth down leads in comparison to CT clamps; therefore less hardware is required. A VT test probe can be connected to a HV rated relay that could be operated for test pulses and not continuously connected to avoid any operational issues associated with the high voltages. If an abnormally high voltage is detected, the relay could be opened and the monitoring device could send an alarm.

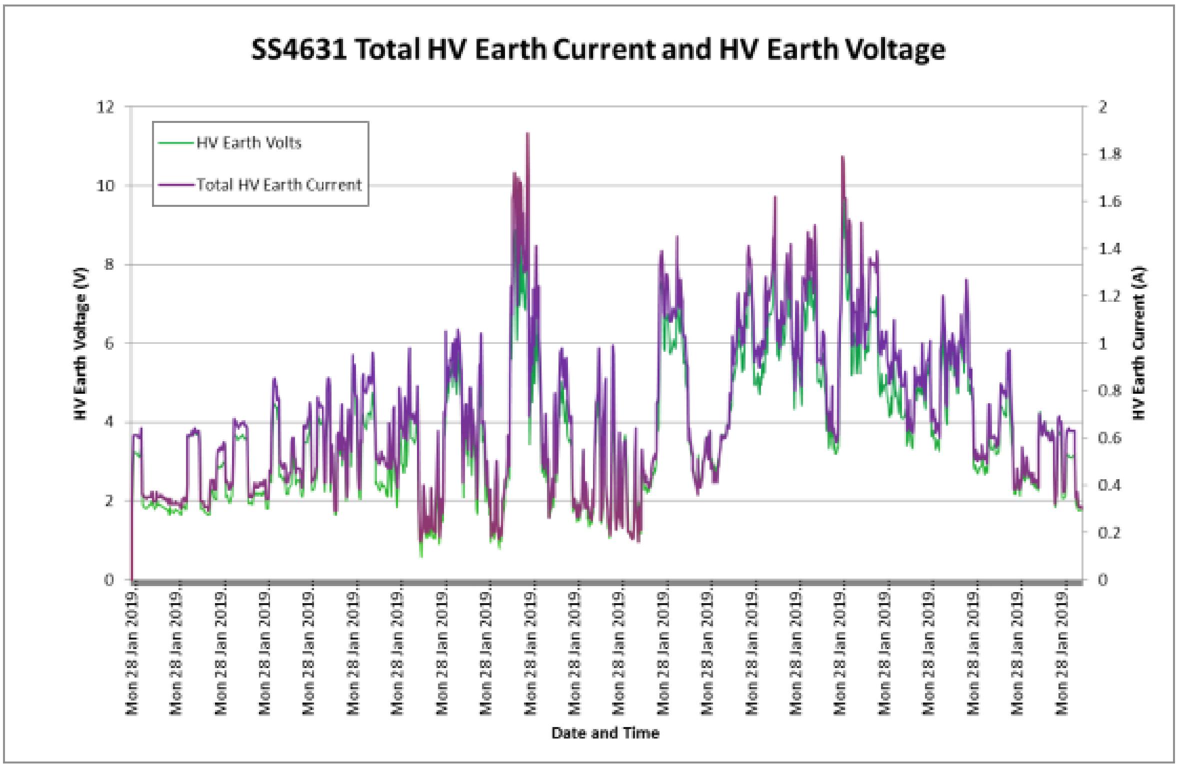


Figure 80: PowerMonic PM45 Analyser HV Earth Current and HV Earth Voltage SS4631

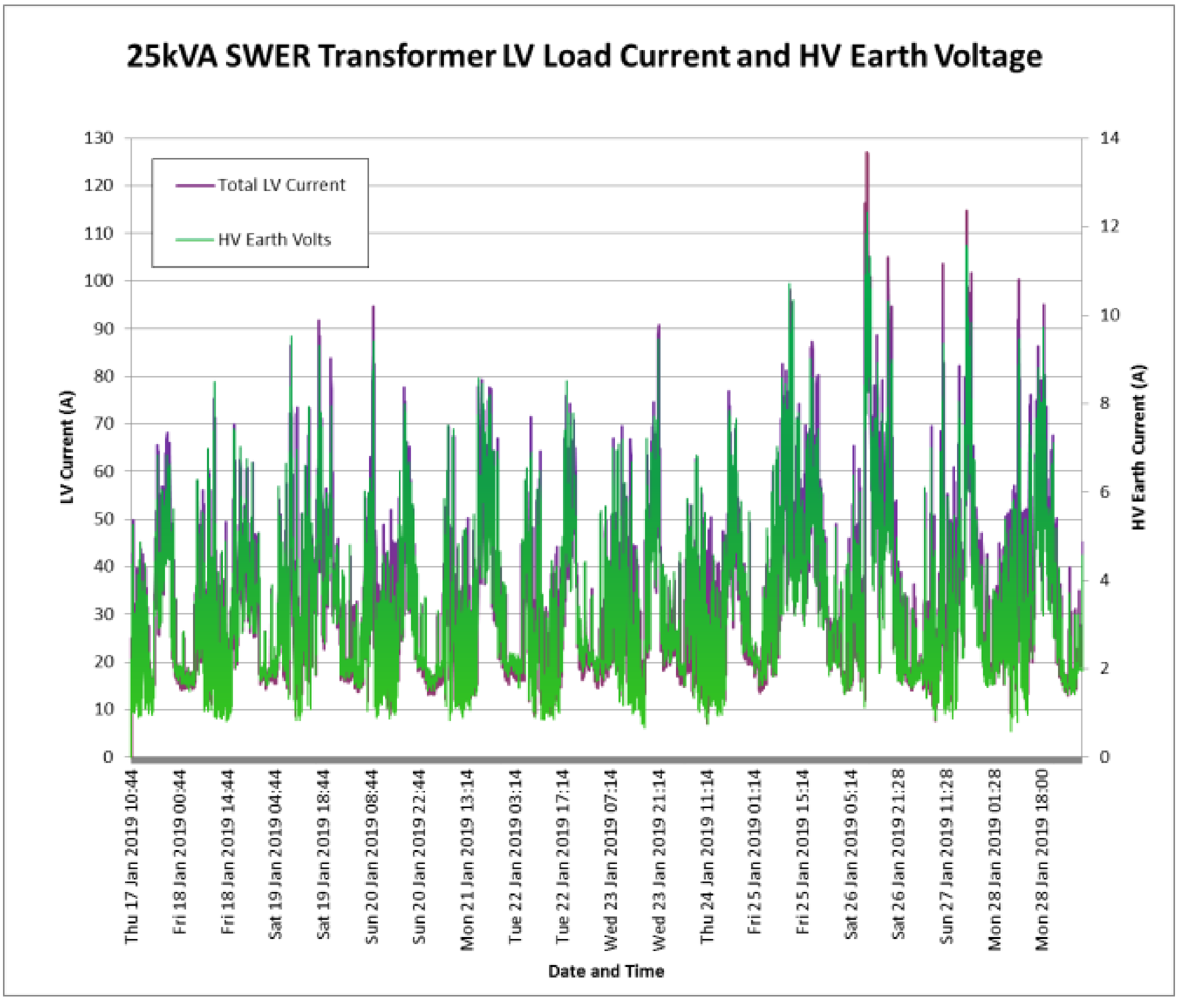


Figure 81: PowerMonic PM45 Analyser Total LV Load Current vs HV Earth Voltage for SS4631

The correlation of the LV load current and HV earth voltage can be theoretically explained with the use of the Ampere Turns Ratio formula. The transformer nameplate ratios are represented in equations 4-25 and 4-26, with values taken directly from the transformer nameplate as highlighted in Figure 82.

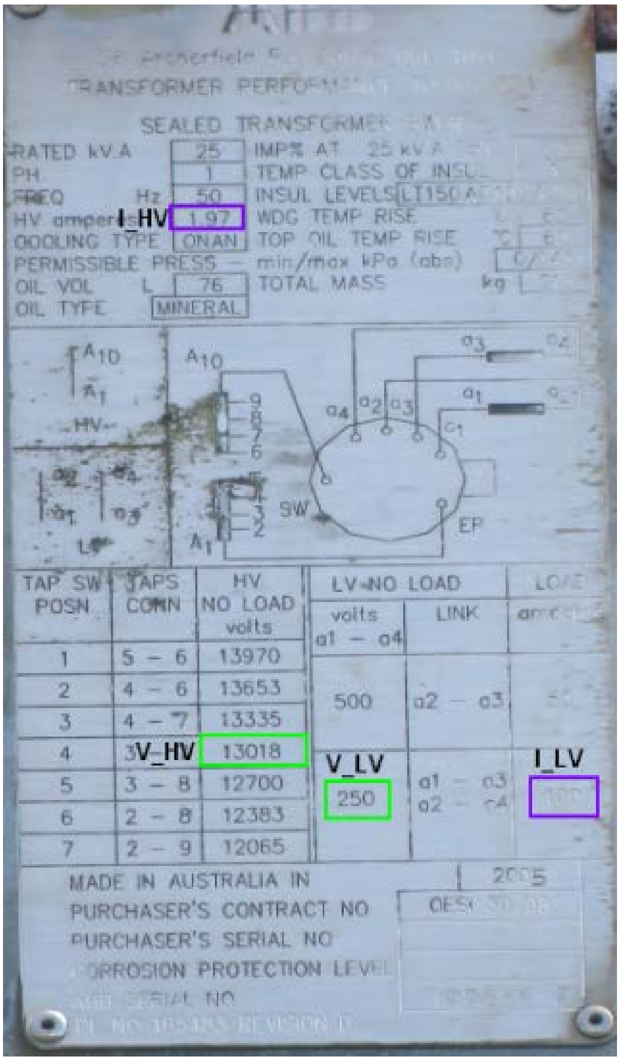


Figure 82: SS4631 Nameplate Ratings with HV and LV Values Highlighted

Voltage:

$$Ratio_{Voltage\ Nameplate} = \frac{V_{HV}}{V_{LV}} = \frac{13018}{250} = 52.072 \tag{4-25}$$

Current:

$$Ratio_{Current\ Nameplate} = \frac{I_{LV}}{I_{HV}} = \frac{100}{1.97} = 50.76 \tag{4-26}$$

Assumptions have been made for minimal transformer losses and thus these have been assumed zero and excluded from the calculations. These assumptions have been proven to be accurate through the analysis of the test data accumulated by the PM45 unit. The ampere-turns ratio can be applied as per equation 4-27 then simplified to equation 4-28 with the final equation 4-29.

$$\frac{V_{HV\ Nameplate}}{V_{LV}} \approx \frac{I_{LV}}{I_{HV}} \tag{4-27}$$

$$I_{HV} \approx \frac{I_{LV} * V_{LV}}{V_{HV\ Nameplate}} \tag{4-28}$$

$$R_{HV} \approx \frac{V_{HV}}{I_{HV}} \tag{4-29}$$

Substitute I_{HV}:

$$R_{HV} \approx \frac{V_{HV\ Earth\ field} * V_{HVnameplate}}{I_{LV} * V_{LV}} \approx \frac{V_{HV\ Earth\ field} * Ratio_{Voltage\ Nameplate}}{I_{LV}} \tag{4-30}$$

$$R_{HV} \approx \frac{V_{HV\ Earth\ field} * Ratio_{Voltage\ Nameplate}}{I_{LV}} \tag{4-31}$$

Field Test Data:

$$R_{HV} \approx \frac{V_{HVEarth\ field} * V_{HVnameplate}}{I_{LV} * V_{LV}} \approx \frac{V_{HV\ Earth\ field} * 13018}{I_{LV} * 250} \approx \frac{V_{HV\ Earth\ field} * 52.072}{I_{LV}} \tag{4-32}$$

$$R_{HV} \approx \frac{V_{HV\ Earth\ field} * 52.072}{I_{LV}} \tag{4-33}$$

Equation 4-30 is simplified to equation 4-31, which represents a general equation that can be used for the calculation of the SWER HV earth resistance using real field data for the HV earth voltage and the total LV primary current. Equation 4-31 which is simplified to equation 4-33 is the test site specific formula that was applied to the field data to calculate the final resistance values as shown in Figure 83. The true resistance value in the plot below was calculated using the field data for the HV earth voltage and the total HV earth current and applying Ohm's Law. The calculated resistance was determined by using the field data HV earth voltage and the total LV secondary current and applying equation 4-33. One of the anomalies with the data, which is evident in Figure 83, was found to be in the daylight period and prevalent on days of high solar exposure. It was deduced that these errors were due to the photovoltaic exports from the 6 consumers with a rated maximum total of 12.8kW of PV injection. The reason for the anomaly in the data is explained in the next two paragraphs. Harmonic data was captured for the 2nd, 3rd and 4th indices; this was found to be extremely small and has been considered negligible for this investigation.

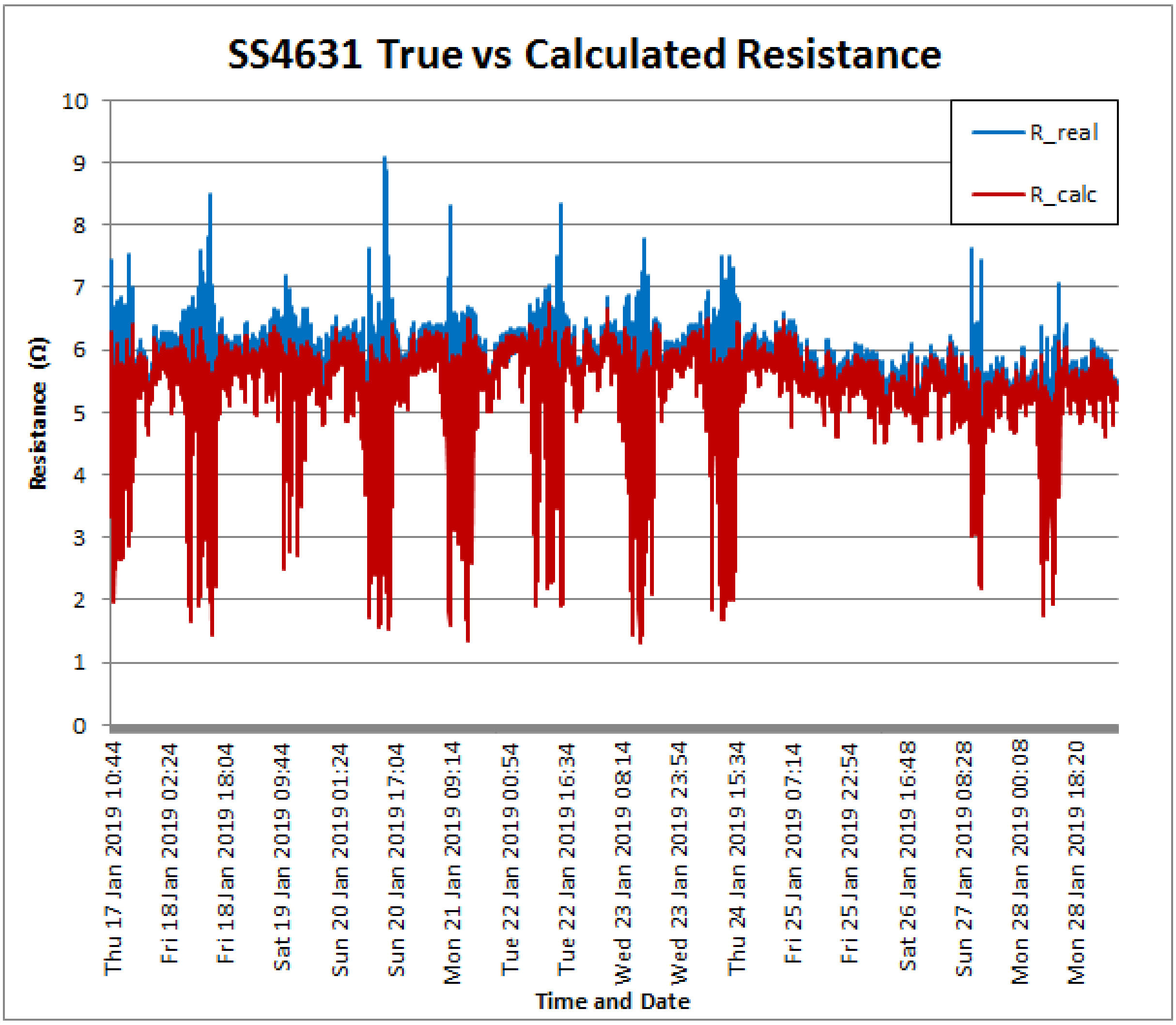


Figure 83: SS4631 True HV Earth Resistance vs Calculated HV Earth Resistance over 11 days

To investigate the anomaly in the data, the Bureau of Meteorology solar exposure index was analysed as per Figure 84. It became evident that the solar index was extremely low on January 25th and very high on January 20th. With this information the two days of HV earth voltage and LV current plots and true and calculated resistance plots were analysed.

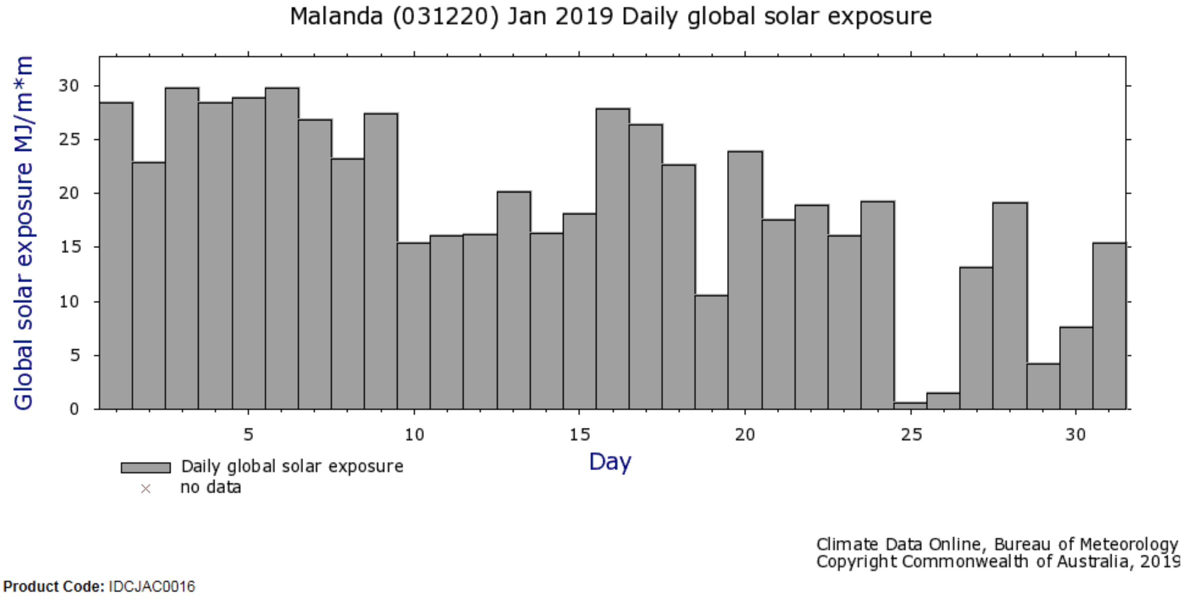


Figure 84: Malanda Solar Exposure Bureau of Meteorology Data for January 2019

Figure 85 shows the discrepancies in the HV resistance calculations for a high solar exposure day occurring on the 20th January 2019. It can be seen that the differences occur between the hours of 9am to 5pm which aligns with when the photovoltaic export power would be occurring. Figure 86 shows a near perfect correlation between the true and calculated resistance values for a very low solar exposure day occurring on the 25th January 2019.

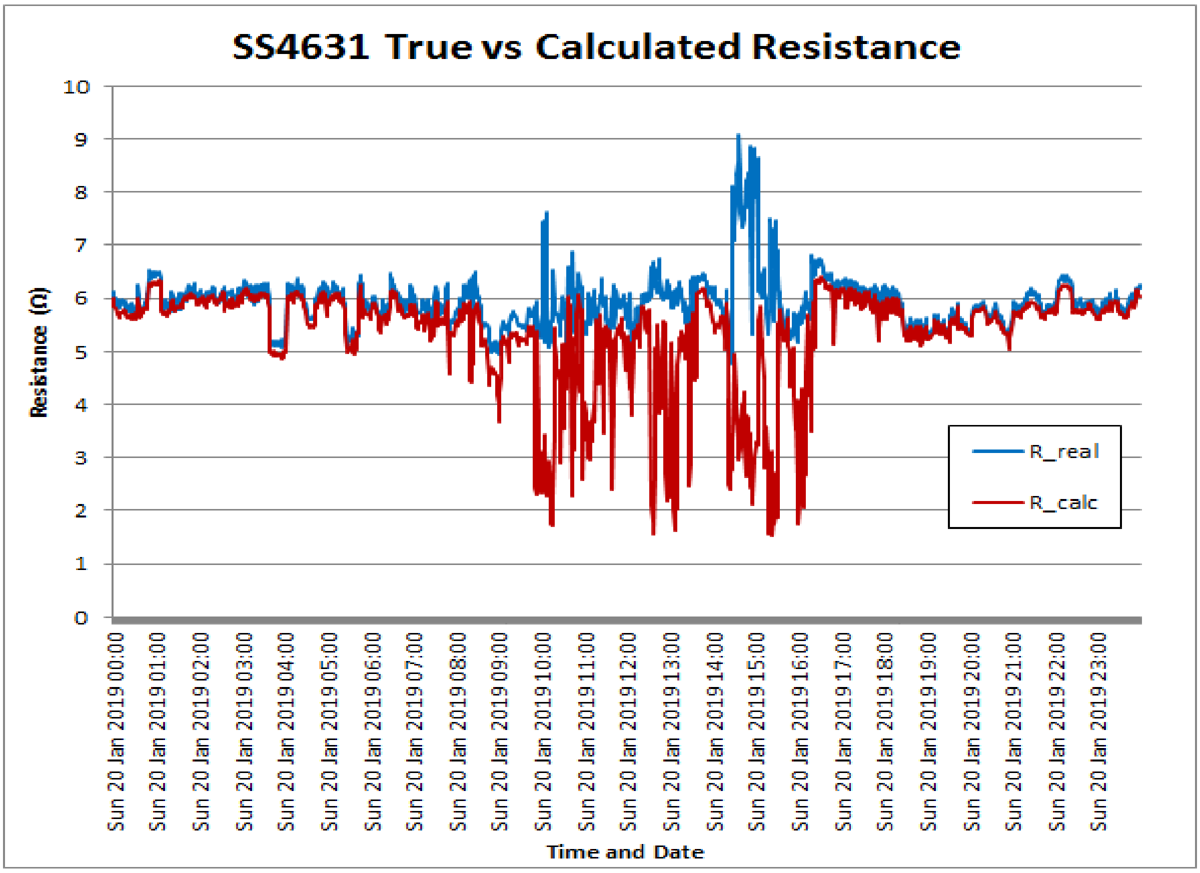


Figure 85: SS4631 True HV Earth Resistance vs Calculated HV Earth Resistance for 20th January 2019

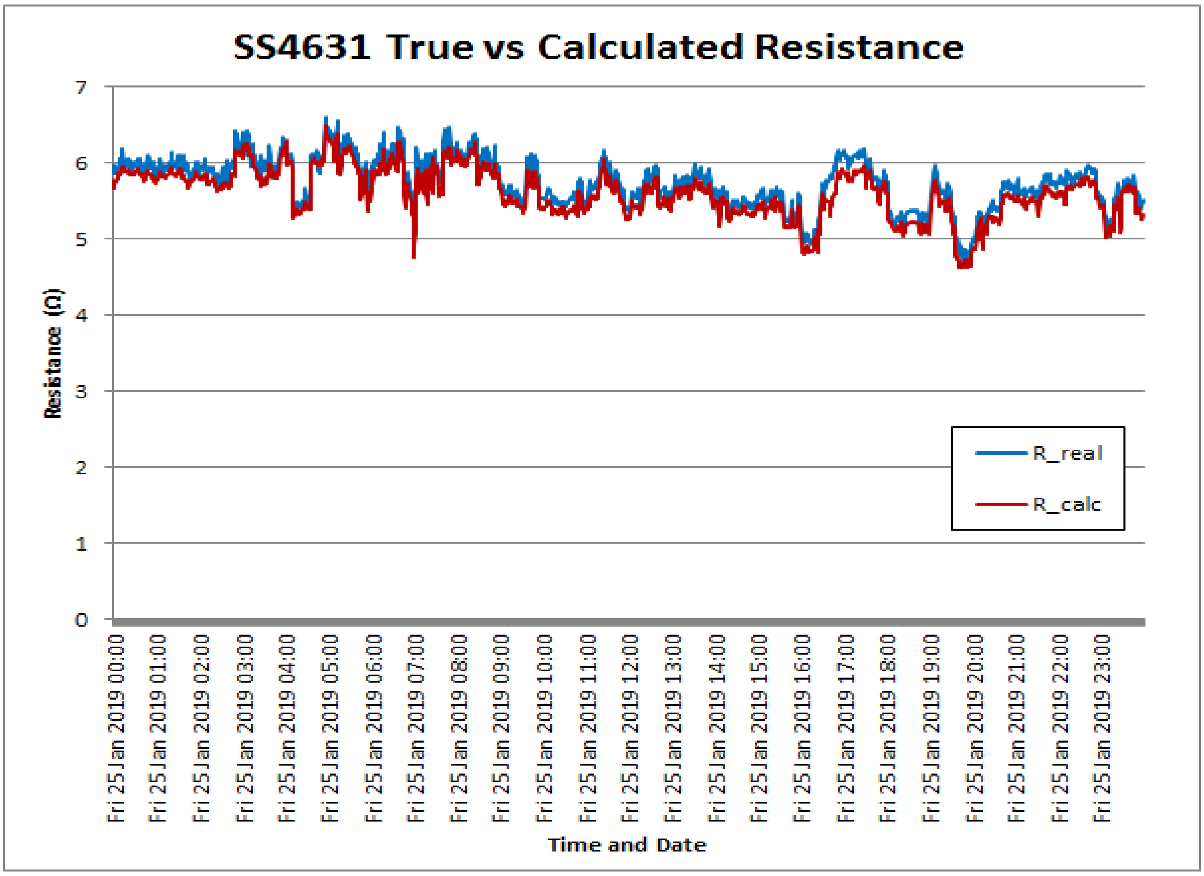


Figure 86: SS4631 True HV Earth Resistance vs Calculated HV Earth Resistance for 25th January 2019

The fundamental waveform angle for the LV currents for each winding was extracted from the PowerMonic PM45 analyser harmonic data tables. Figure 88 shows the phase angle of the LV current for the two transformer secondary windings; the two windings are referred to as winding A and winding C to align with the test configuration of the PowerMonic analyser's CT test clamps.

The two secondary windings on a SWER transformer are separated by180 degrees for a theoretically unity power factor load. Figure 87 shows the ideal voltage and current vectors and a resultant current vector from the test site data whilst PV injection was occurring. The C phase winding polarity has been reversed or made absolute in Figure 88 to show the vector angle correlation between the two windings. It is evident that during the periods of high solar exposure that result in PV injection, the vector angles on both windings exhibit considerable change, in some cases close to 180 degree phase shift. Figure 89 and Figure 90 show the difference in current phase angles for a high PV injection period occurring on the 20th January and a low PV injection period occurring on the 25th January 2019.

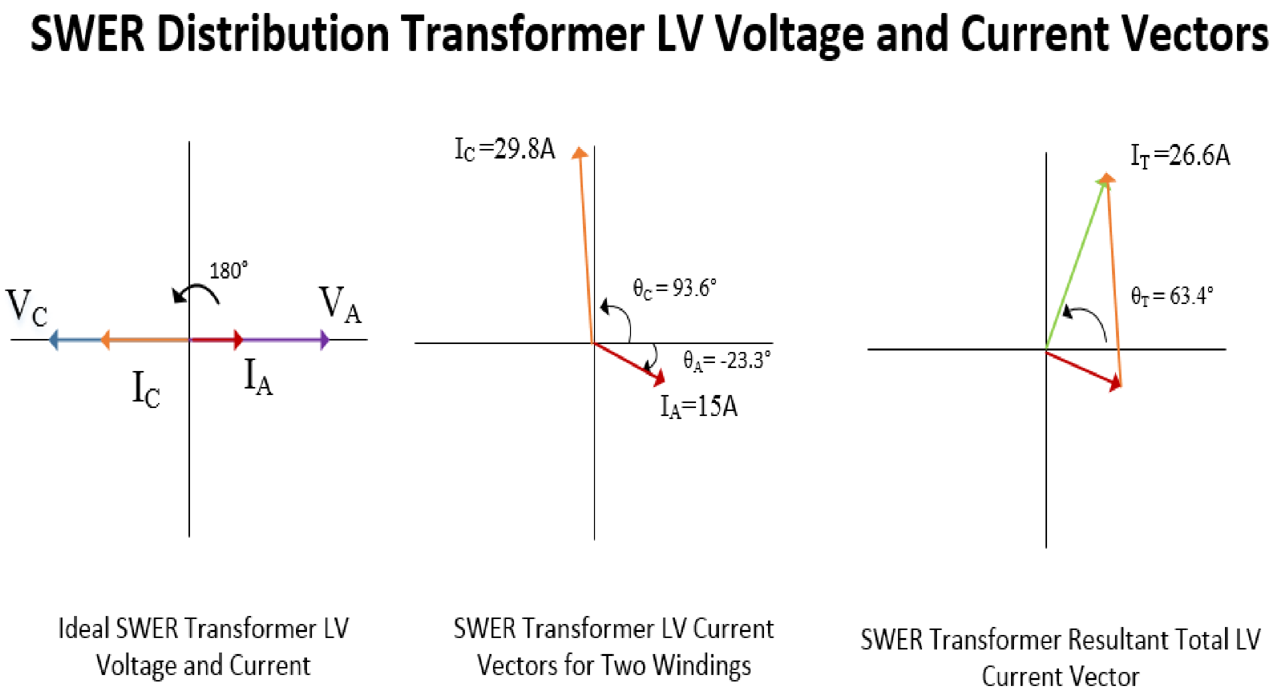


Figure 87: SWER Distribution Transformer LV Voltage and Current Vectors

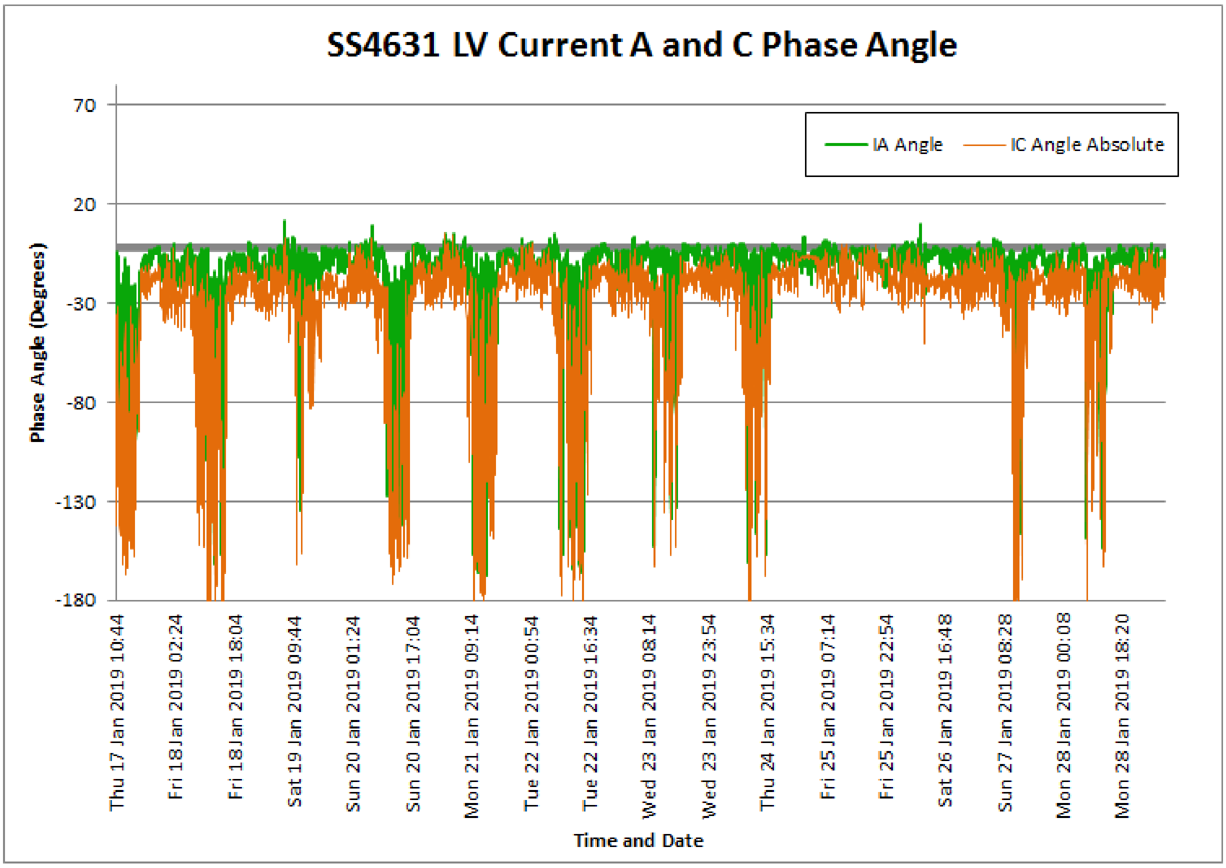


Figure 88: SS4631 Phase Angle of the LV Current for Two Windings

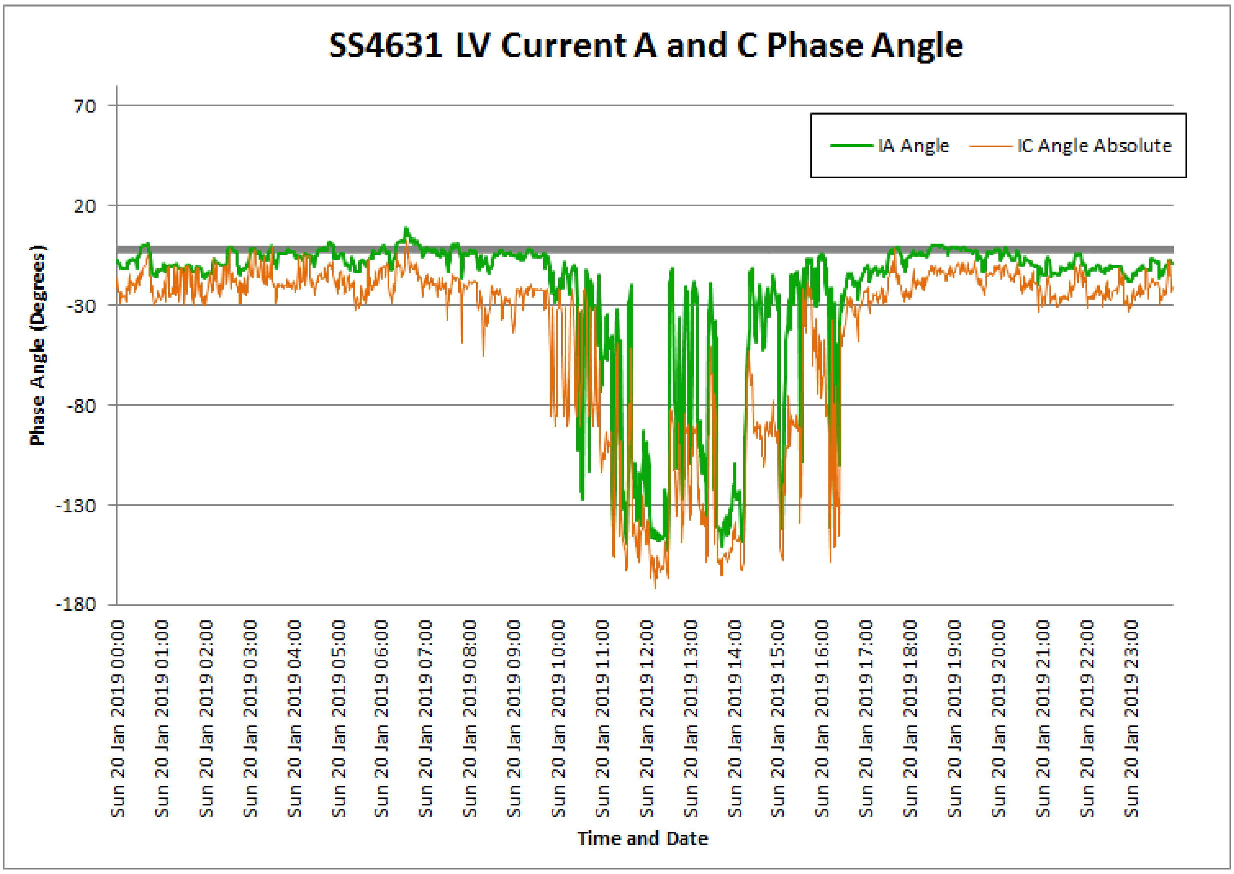


Figure 89: SS4631 Phase Angle of the LV Current for Two Windings for the 20th January 2019

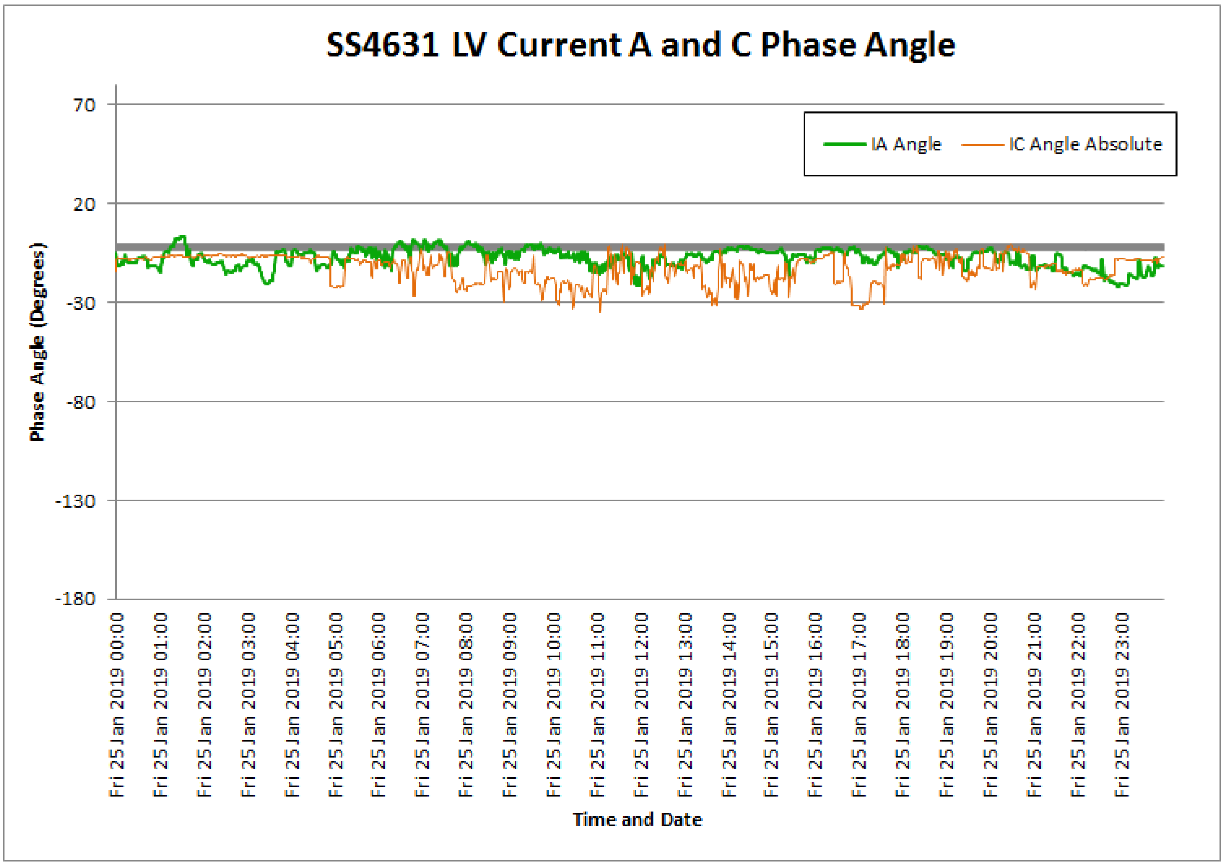


Figure 90: SS4631 Phase Angle of the LV Current for Two Windings for the 25th January 2019

The current phase angle was incorporated into equations 4-31 and 4-33 to accurately calculate the HV earth resistance under the influence of PV injection and consumer inductive and capacitive loads. Equation 4-34 is the final equation to calculate the HV earth resistance with equation 4-35 altered for the calculation of the test SWER transformer with two secondary windings.

θ = Fundamental phase angle for the total LV current

θ_A = Fundamental phase angle for current winding A

θ_C = Fundamental phase angle for current winding C

Equation to Calculate the HV Earth Resistance:

$$R_{HV} \approx \frac{V_{HV\ Earth\ field} * Ratio_{Voltage\ Nameplate}}{I_{LV} * cos\ \theta} \tag{4-34}$$

Field Test Data Equation to Calculate the HV Earth Resistance:

$$R_{HV} \approx \frac{V_{HV\ Earth\ field} * 52.072}{\left(I_{LV_A} * cos\ \theta_A\right) + \left(I_{LV_C} * cos\ \theta_C\right)} \tag{4-35}$$

Equation 4-35 was applied to the PowerMonic PM45 test dataset obtained from SS4631 with successful results, as shown in Figure 91. Figure 92 and Figure 93 show the HV earth resistance calculation for the 20th of January and 25th of January 2019 respectively. The addition of the LV current phase angle to the equation results in an accurate HV earth resistance calculation. Figure 94 shows a maximum error of 23% between the calculated real HV earth resistance and the new equation calculated HV earth resistance. The noticeable errors mainly occur during the periods of high PV injection, this is believed to be from PV inverter harmonic distortion. With the maximum error across the 11 day test period being 23%, the newly formed equation is considered accurate for the purpose of measuring remote SWER transformer sites and the method is deemed acceptable to use for the purpose of proof of theory for this dissertation.

It is important to ensure the specifications for the final monitoring unit and CT’s are capable of measuring and calculating the vector angle of the LV current and HV earth voltage.

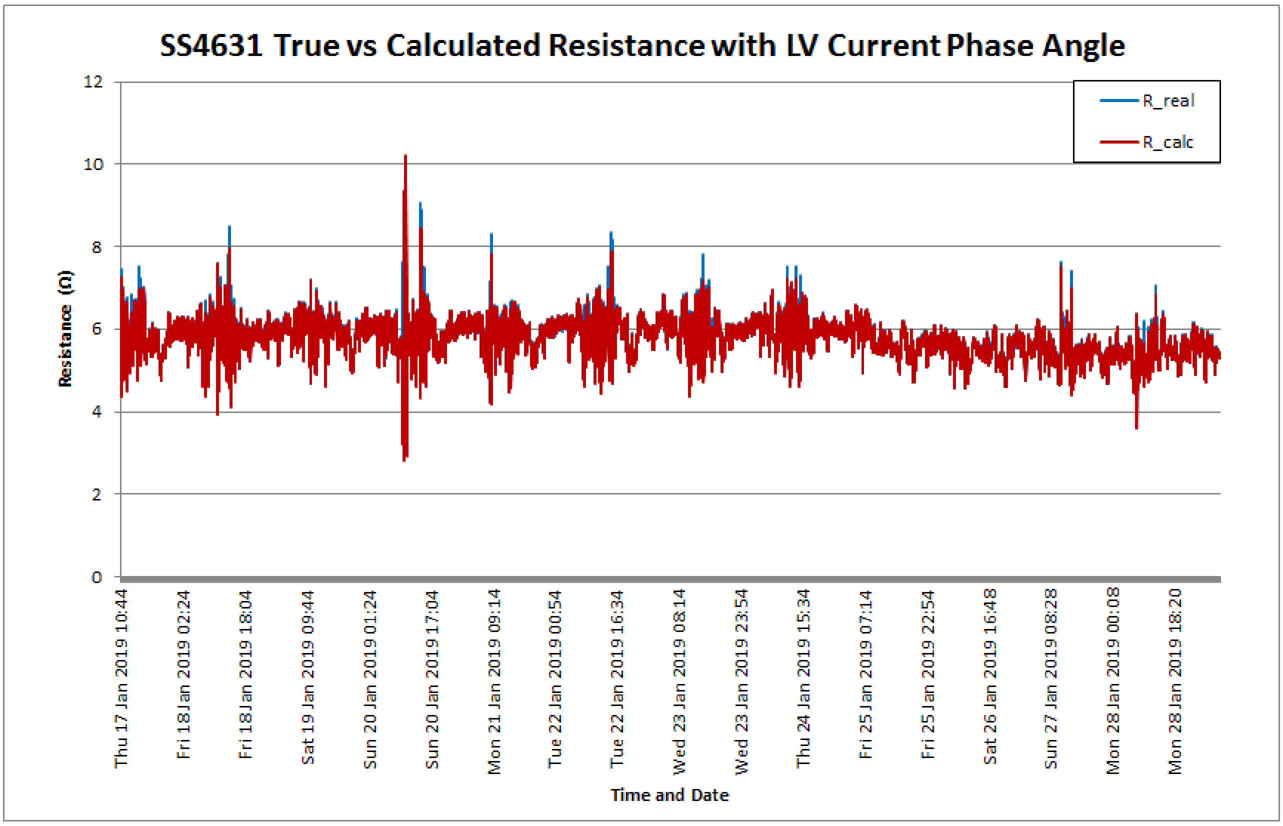


Figure 91: SS4631 True HV Earth Resistance vs Calculated HV Earth Resistance over 11 days with Phase Angle

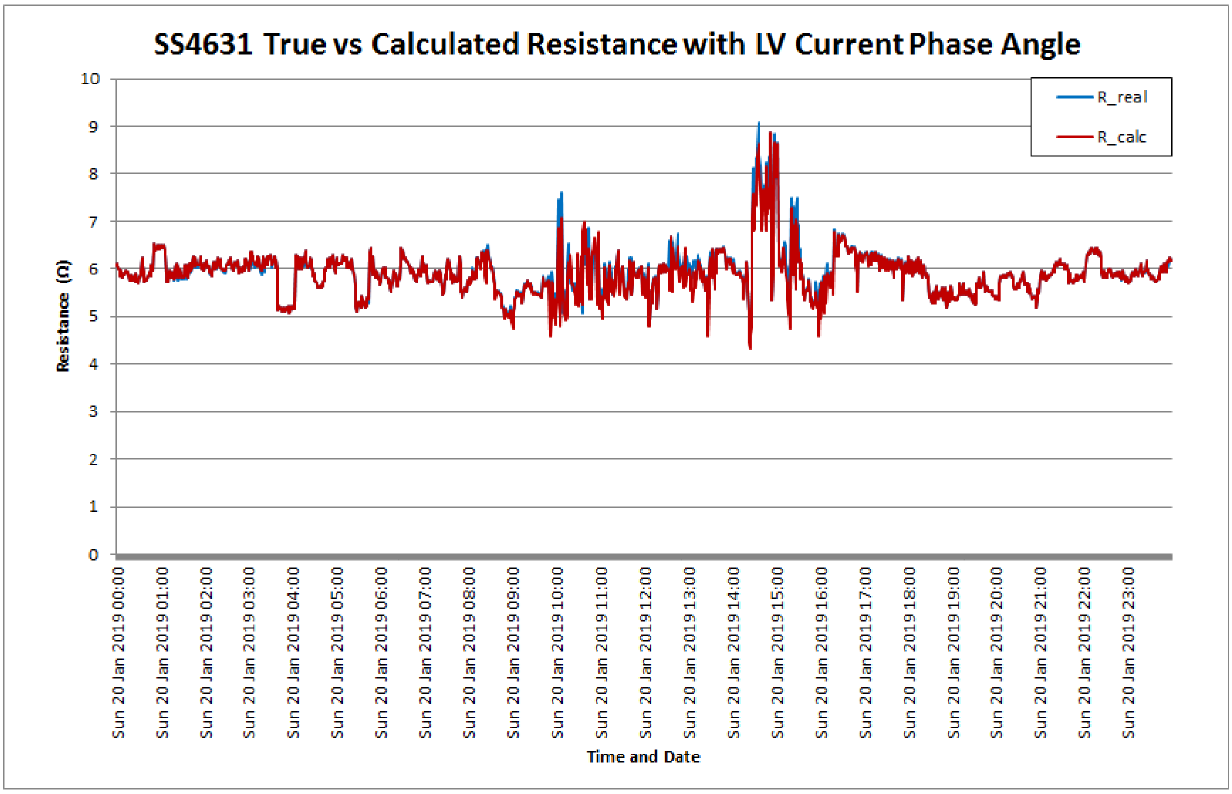


Figure 92: SS4631 True HV Earth Resistance vs Calculated HV Earth Resistance for 20th January 2019 with Current Phase Angle

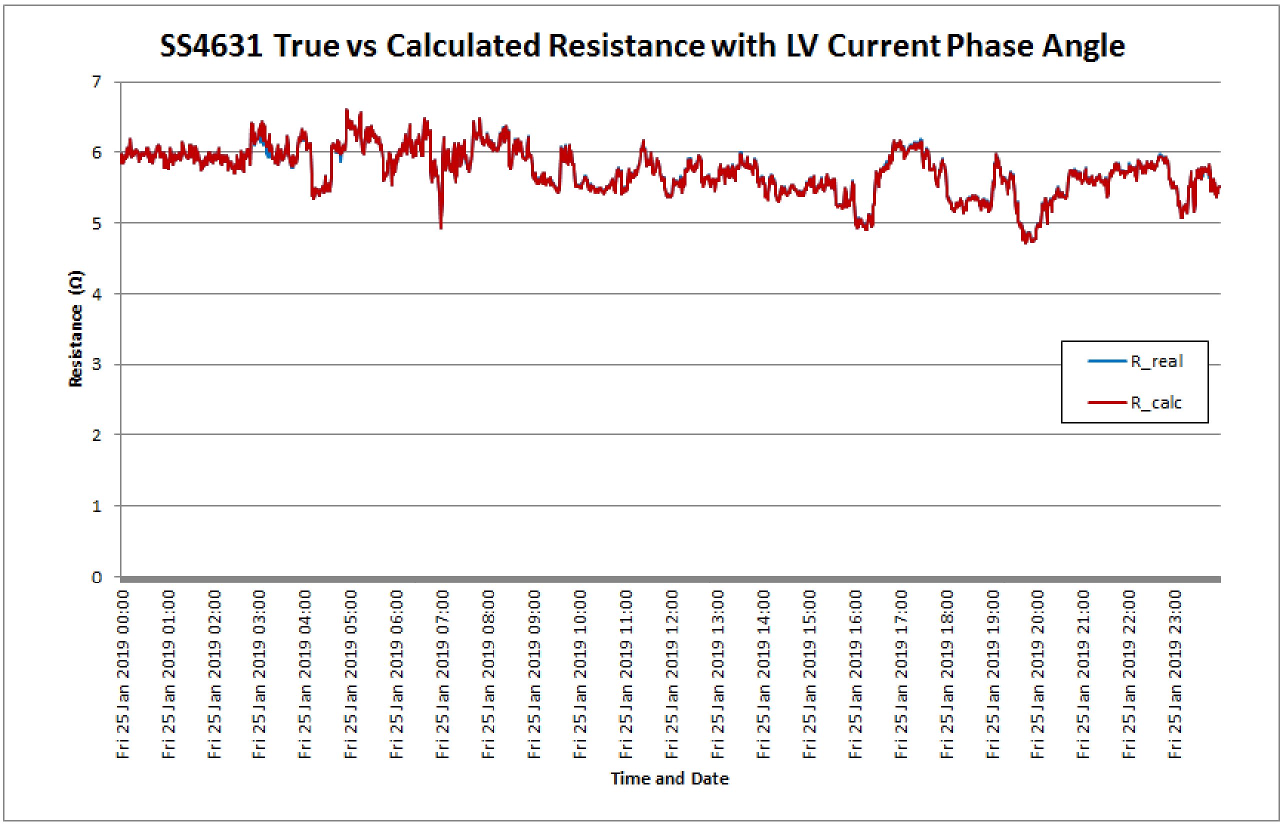


Figure 93: SS4631 True HV Earth Resistance vs Calculated HV Earth Resistance for 25th January 2019 with Current Phase Angle

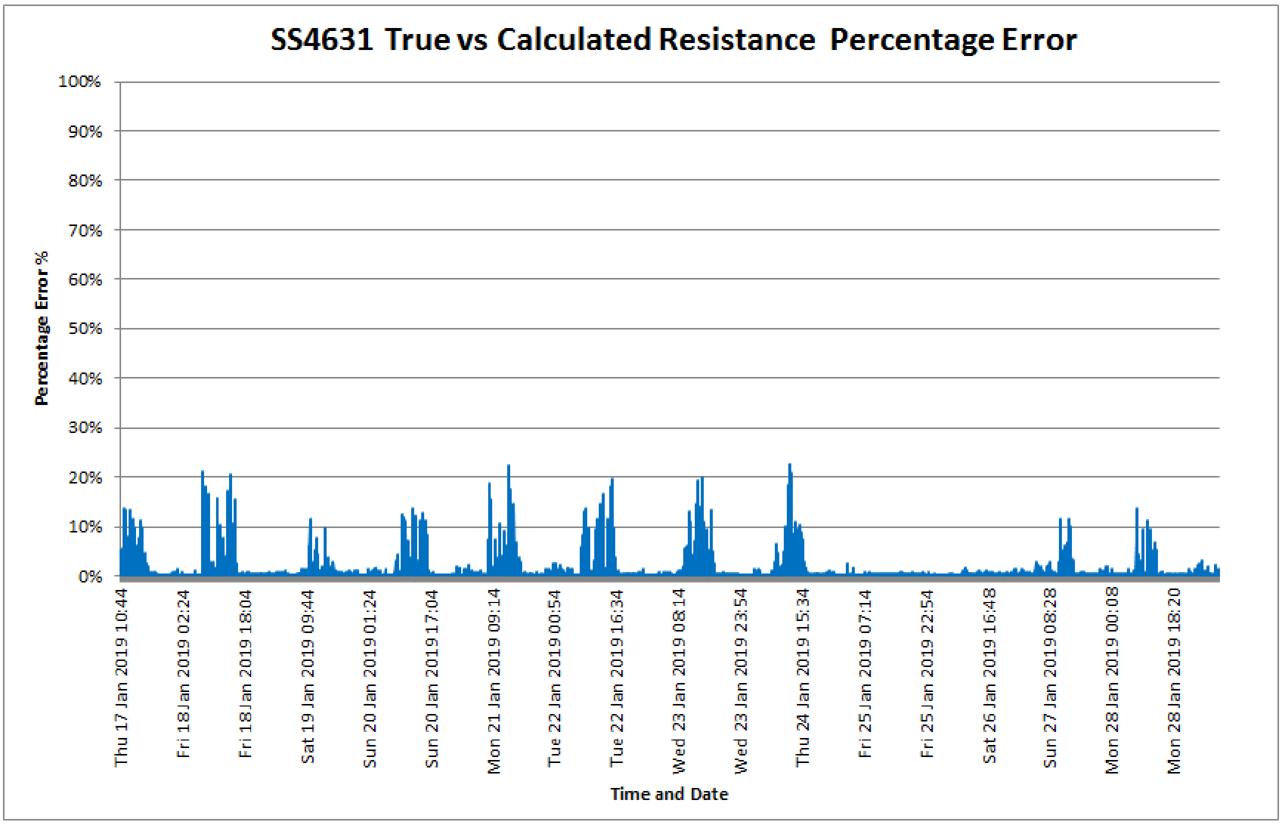


Figure 94: SS4631 True HV Earth Resistance vs Calculated HV Earth Resistance Error Plot for 20th January 2019

The apparent power was calculated from the field test data, as shown in Figure 95, this data will also contain anomalies during the period of PV injection. Excluding the data anomalies, the distribution transformer SS4631 is operating within its nameplate rating of 25kVA. It is important to understand a distribution transformers operating range as transformer losses will increase if the transformer is operating for a prolonged period of time above its nameplate rating. If this occurs and is identified, it is the obligation of the electrical entity to investigate, potentially upgrade the asset or advise the consumer/s to reduce the peak load.

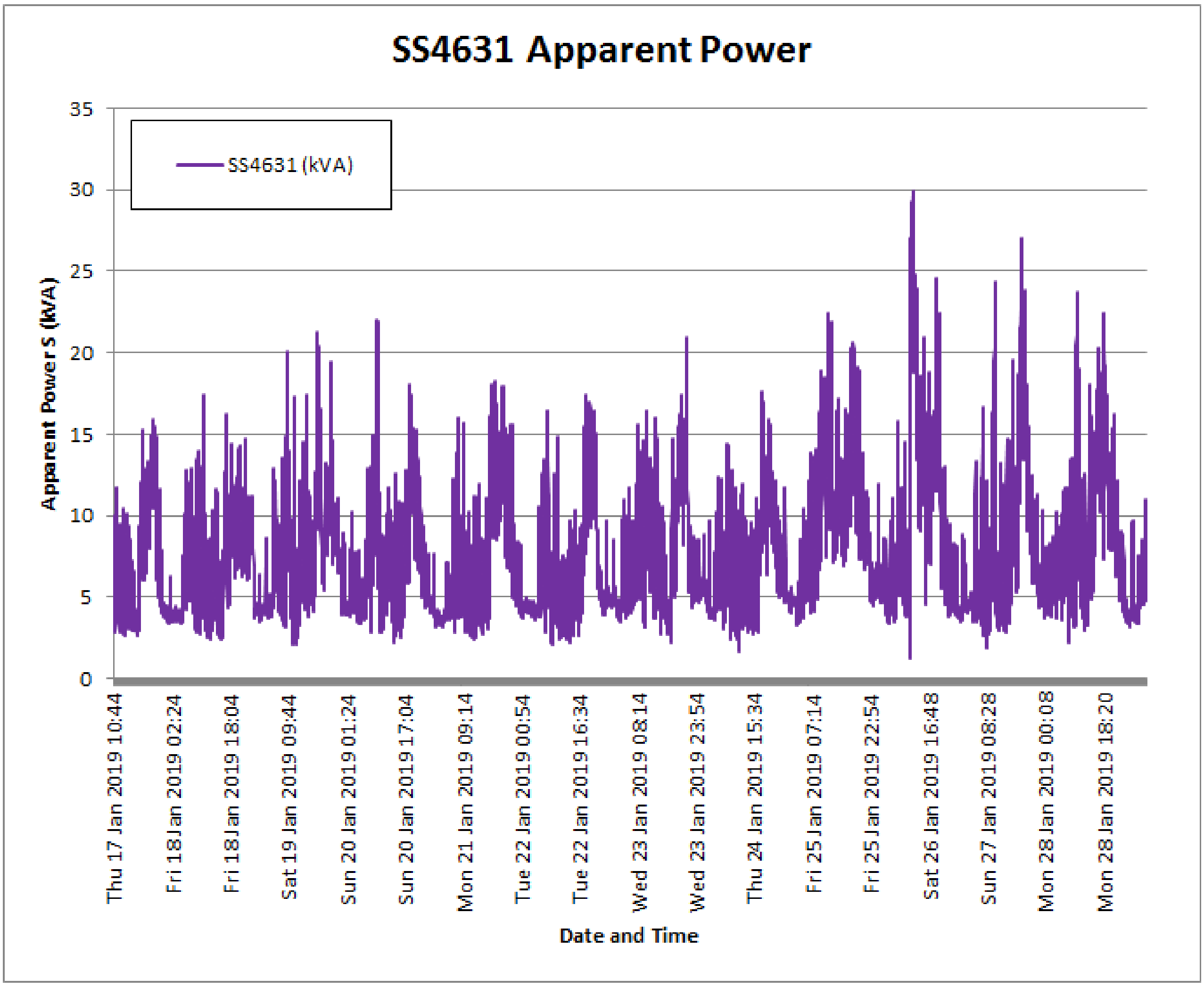


Figure 95: Apparent Power Calculations for SS4631 Field Test Data

Chapter 7 - SWER Earth Modelling

7.1 Overview

This chapter develops a basic model to simulate a SWER distribution system using the MATLAB Simulink environment. Once the basic model is established and verified against the field test data then two earth resistance test methods are developed. The first test method is based on the existing two clamp, stakeless, earth resistance method which involves a high frequency, fixed current injection signal with additional voltage monitoring to calculate the earth stake resistance. The second is developed from the new method, theoretically proven in the results section 6.1.8; this method involves continuous monitoring of the total LV current and HV earth voltage, with a calculation to produce the HV earth resistance. Initially Simscape was proposed to use for dynamic response of a changing earth resistance over time. Due to restrictions with the student software licensing and the success of the Simulink simulations, with accurate correlation to the field data results, the Simulink modelling was chosen as the suitable modelling tool. Rather than dynamic response, the change in resistance was manually entered for different values to verify calculation accuracy.

7.2 SWER transformer Model – Simulink Configuration

The test model was built to simulate the field test site SS4631 using the known specifications and upstream characteristics. The base model was constructed in the Simulink environment with the following properties taken from the nameplate data and conductor properties matching the field test site:

- The **Three Phase Voltage Source** was built using a three-phase programmable voltage source element:
  - Vrms Ph-Ph Amplitude = 22kV
  - Frequency = 50Hz
- The **SWER Isolating Transformer** was modelled using the standard two winding linear transformer element. The Electricity Supply Association of Australia (ESAA) Guide to the Specification of Distribution Transformers, (ESAA 1998), was used for the transformer winding specifications, shown in Table 18. The standard has been superseded by ENA DOC 007—2006, unfortunately the new standard does not specify the resistance and impedance ratings for the transformer windings and the manufacturers are only obliged to provide a percentage impedance rating, hence the use of the older standard specification guidelines.

ESAA Transformer Specifications		
TX Style	Pole	Pole
Rated (kVA)	25	200
HV Voltage (kV)	-	22
SWER Voltage (kV)	12.7	12.7
Impedance (%)	3.3	4
Number of Phases	1	1
Winding Resistance R (%)	1.54	0.83
Winding Impedance X (%)	2.92	3.91
Calculated Winding Resistance R (pu)	0.0154	0.0083
Calculated Winding Impedance X (pu)	0.0292	0.0391

Table 18: ESAA Transformer Specifications

- Nominal Power = 200kVA
- Frequency = 50Hz
- Winding 1 Parameters V1rms = 22kV; R1(pu) = 0.083; L1(pu) = 0.0391
- Winding 2 Parameters V2rms = 12.7kV; R2(pu) = 0.083; L2(pu) = 0.0391

- The **SWER Line Segment** was built using a Pi section line element. The SWER line conductor properties where taken as worst case scenario using the smallest of the three conductors that supply the Clarks Track SWER, aluminium clad (3/2.75 SC/AC). The resistance, inductive reactance and capacitive reactance were acquired from Ergon Energy distribution design conductor data programs, as shown in Table 19.

• **Conductor Aluminium Clad 3/2.75 SC/AC**		
MECHANICAL PROPERTIES		
Stranding	3 / 2.75	
Metric (Y / N)	Y	
Total Sectional Area	17.8	mm^2
Overall Diameter	5.9	mm
Calculated Breaking Load	22.7	kN
Unit Mass	118	kg / km
Modulus of Elasticity	162	GPa
Coefficient of Linear Expansion	13	x E -6 / C
ELECTRICAL PROPERTIES		
DC Resistance @ 20^{o}C	9.7	Ω / km
AC Resistance @ 75^{o}C	6.03	Ω/ km
Temperature Coefficient Resistance @ 20^{o}C	0.0036	/ deg C
Inductive Reactance @ 1m spacing	0.39	Ω / km
Capacitive Reactance @ 1m spacing	0.334	MΩ / km

Table 19: SWER Line Conductor Properties

- Frequency = 50Hz
- Resistance per unit length = 6.03 Ω/km
- Inductance per unit length = 0.39 H/km

- Capacitance per unit length = 1.063×10^{-9} F/km
- Line Length = 6.1 km
- Number of Pi sections = 1

- The **SWER Distribution Transformer** was modelled using the standard two winding linear transformer element with one primary winding and two secondary windings. The transformer properties were acquired from Table 18:
  - Nominal Power = 25kVA
  - Frequency = 50Hz
  - Primary Winding 1 Parameters V1rms = 12.7kV; R1(pu) = 0.0154; L1(pu) = 0.0292
  - Secondary Winding 2 Parameters V2rms = 250V; R2(pu) = 0.0154; L2(pu) = 0.0292
  - Secondary Winding 3 Parameters V3rms = 250V; R3(pu) = 0.0154; L3(pu) = 0.0292
- The **Consumer Loads** were modelled using load elements for three consumers. For the purpose of this investigation it was chosen to use purely resistive loads which were set to match a point in the field test data that occurred at 12:00am on the 25th January 2019 with the data values: HV Earth Voltage = 4.9V; HV Earth Current = 0.82A; LV Voltage = 236.59V; LV Current = 44.21A. To achieve the desired current and voltage, the consumer loads for SS4631 were set at:
  - Consumer 1 = 4kW
  - Consumer 2 = 4kW
  - Consumer 3 = 3.7kW

  The resulting values were: Earth Voltage = 5.24V; HV Earth Current = 0.88A; LV Voltage = 236.1V; LV Current = 44.19A; these were deemed as close as possible to the true field test values and adequate to complete the modelling.
- The **PV Injection** was modelled using an AC Current Source connected in parallel with the consumer loads, injecting into the incoming active supply.
  - Peak Amplitude = 30A
  - Phase = 0°
  - Frequency = 50Hz
- The **Earth to Electrode Connection Resistance** was modelled using resistance elements set as per field tests. The consumer neutral point was connected to the second secondary winding connection to the distribution transformer; this was then connected to ground through resistances as per a standard MEN connection.
  - HV Earth Resistance = 5.9Ω
  - LV Earth Resistance = 3.87Ω
  - Consumer Earths (estimated value) = 2Ω
- The **Downstream SWER Line Segment** was built using a Pi section line element. The SWER line conductor properties where the same as the first Pi segment except the distance was set at 30km. The SWER distribution transformer was set with the same properties as the previous unit specified above. The consumer load was set at 14kW.

7.2.1 SWER Base Model Simulation

Figure 96 represents the base SWER system model with the use of voltage and current measuring devices to display the modelled RMS values. Figure 97 shows a plot of the HV earth and LV output voltage and current waveforms using MATLAB code and Figure 98 shows the waveforms via the Simulink scope. The MATLAB code for the waveform plot is listed in Appendix D: MATLAB Codes.

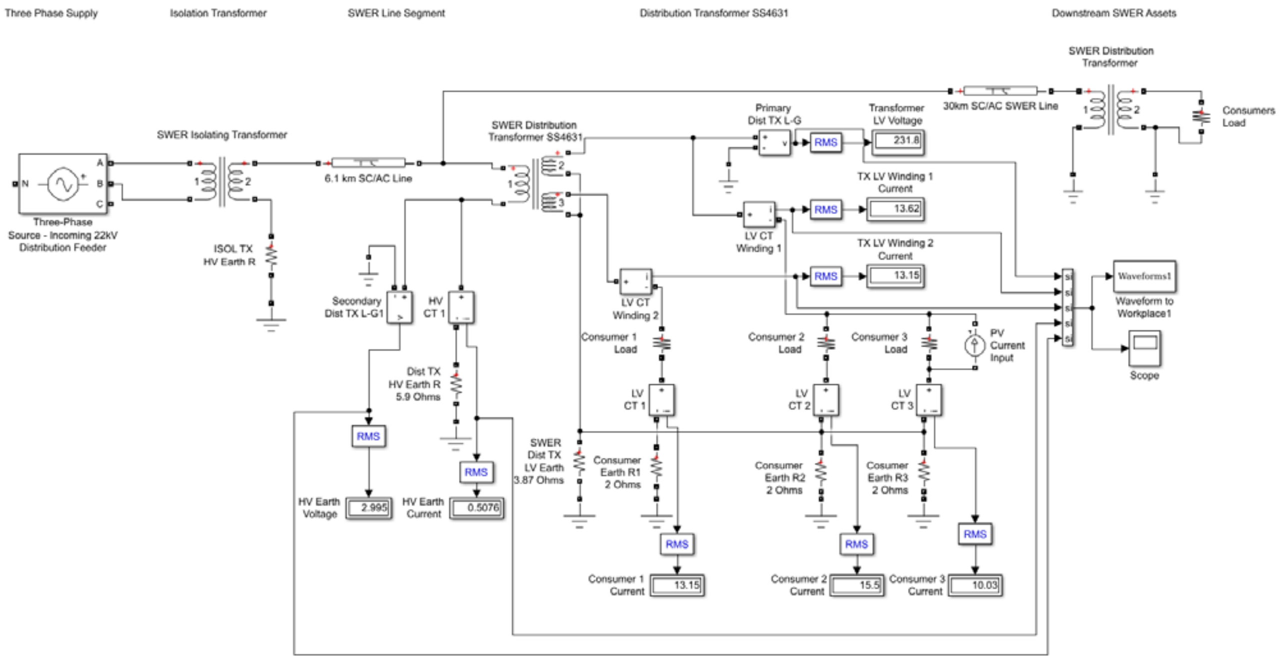


Figure 96: Simulink Base SWER Network Model

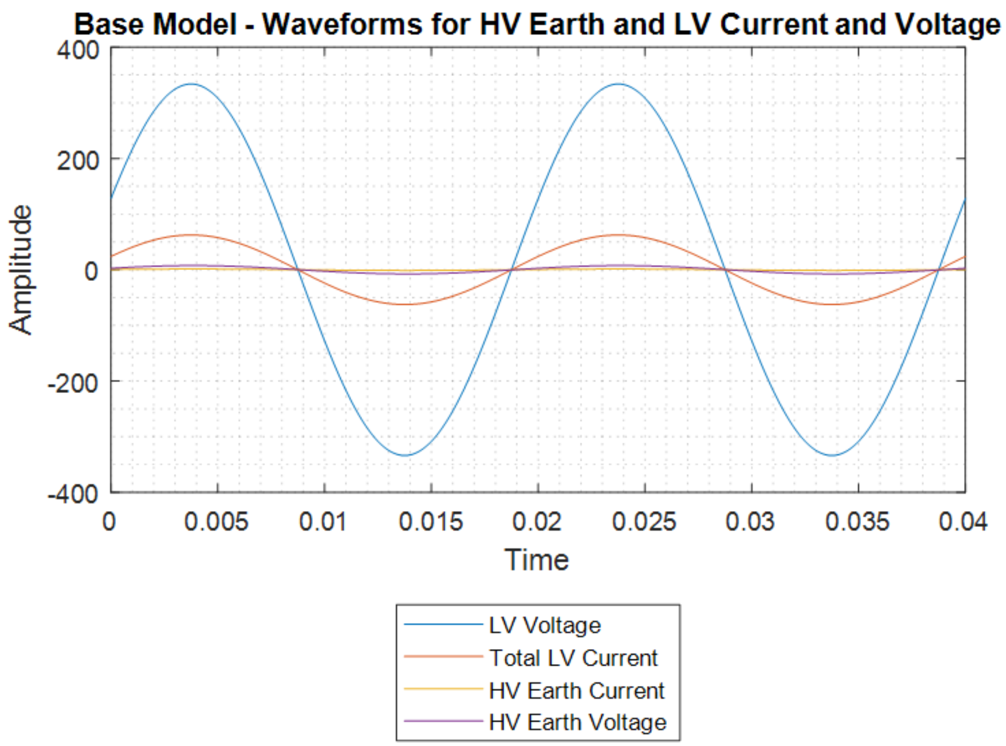


Figure 97: Simulink Base SWER Network Model Output Waveforms

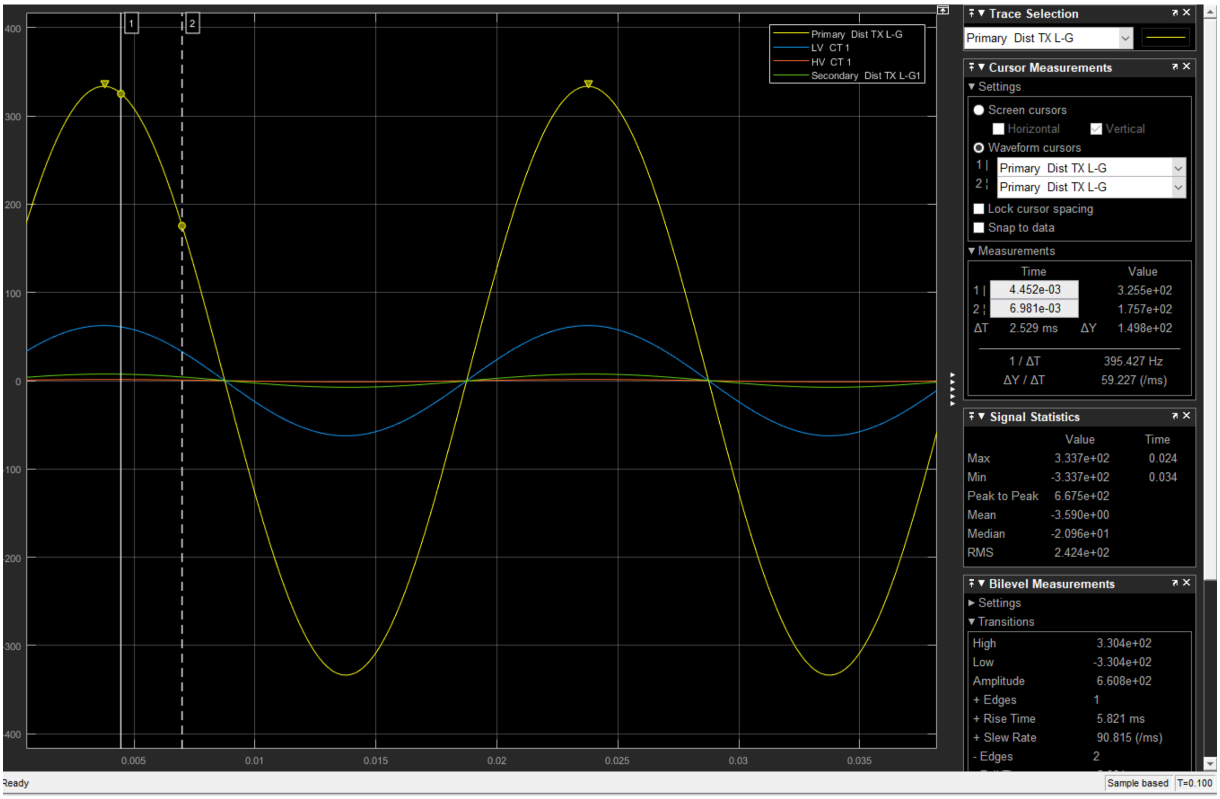


Figure 98: Simulink Base SWER Network Model Scope Output Waveforms

7.2.2 LV Two Clamp Stakeless Model Simulation

The first test equipment model was based on the two clamp stakeless test method; this was achieved by using an AC current source element to simulate the 1611 Hz test frequency as per the specifications for the AEMC 6471 ground test unit. Current and voltage elements were used for the two clamps. All of the elements for the two clamp method were combined to create a subsystem as shown in Figure 99.

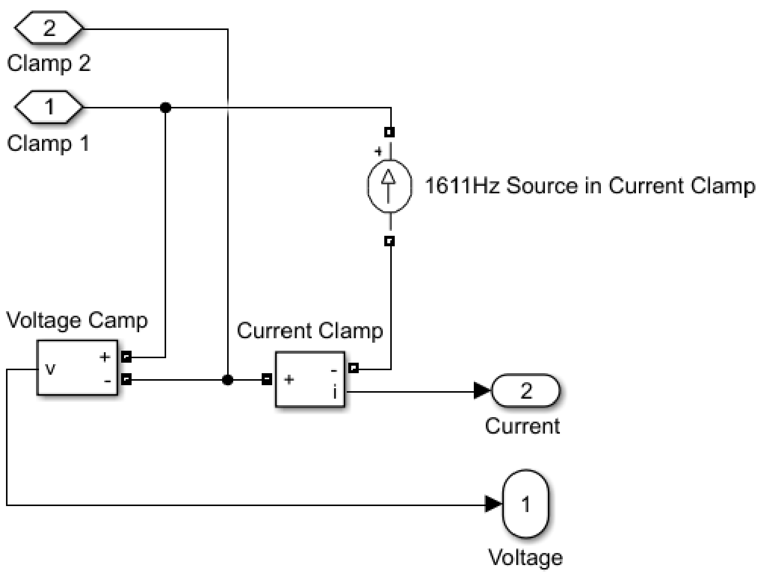


Figure 99: Two Clamp Test Method Subsystem

A high pass filter was created to monitor the 1611Hz test injection signal and separate the high frequency component from that of the 50Hz base system frequency. The values were displayed on the Simulink screen and also sent to the MATLAB Workplace for graphical analysis with standard MATLAB coding. A Simulink MATLAB function block was used to apply Ohm's Law to the outputs to calculate the earthing resistance as shown in Figure 100.

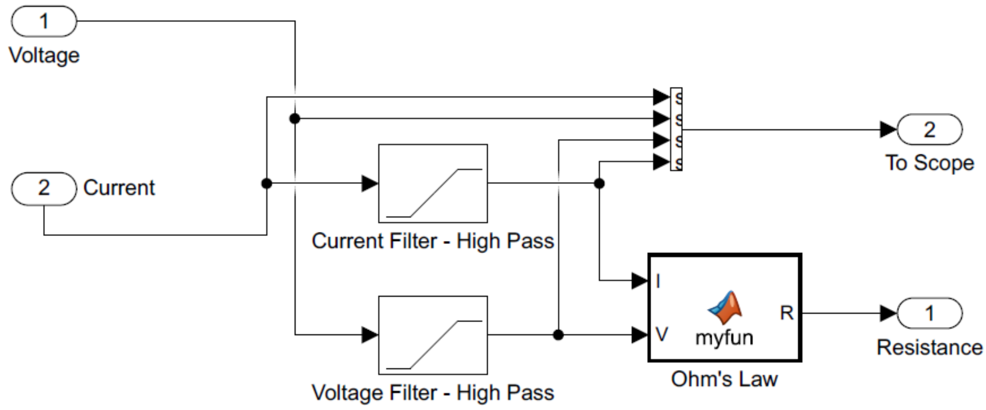


Figure 100: Two Clamp Model High Pass Filter and Ohm's Law Function

The injection and measurement subsystems with filter system were combined, as shown in Figure 101 with the total connected model shown in Figure 102; the graphical representation of the output to workplace was then plotted as shown in Figure 103; the scope output is shown in Figure 104.

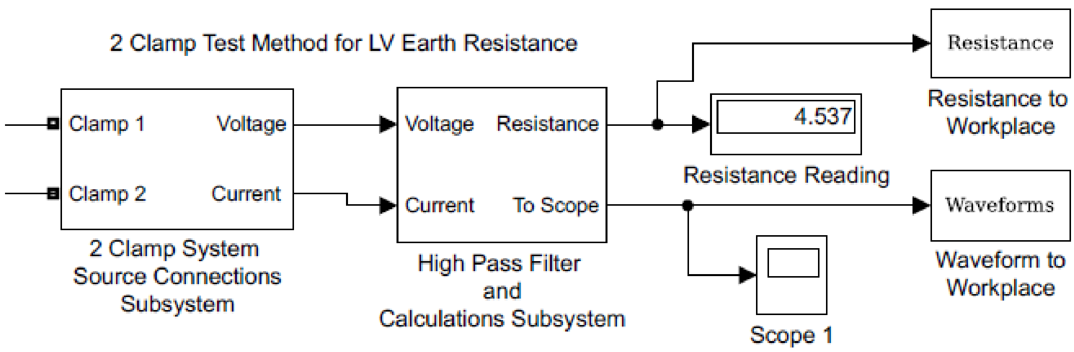


Figure 101: Two Clamp LV Earth Test Model

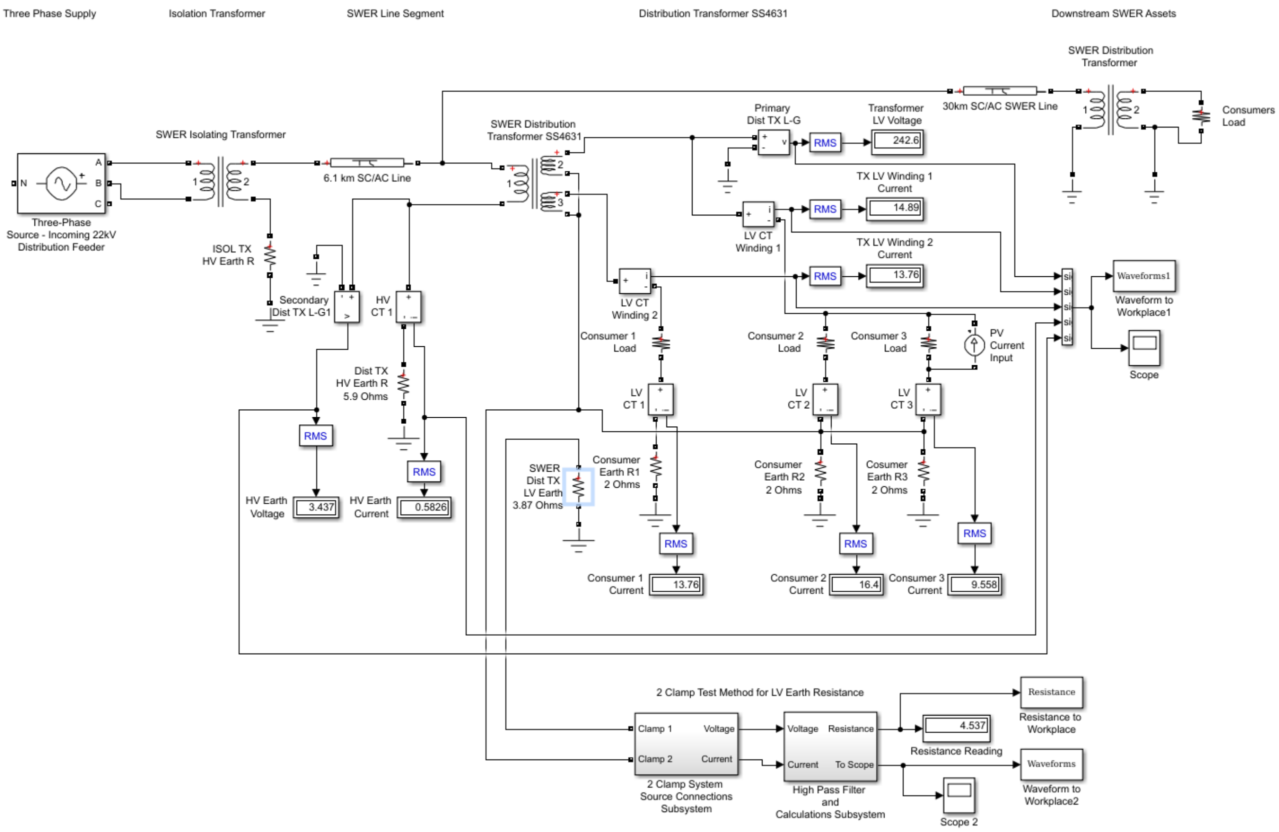


Figure 102: Two Clamp Test Model Connected to the Base SWER Model

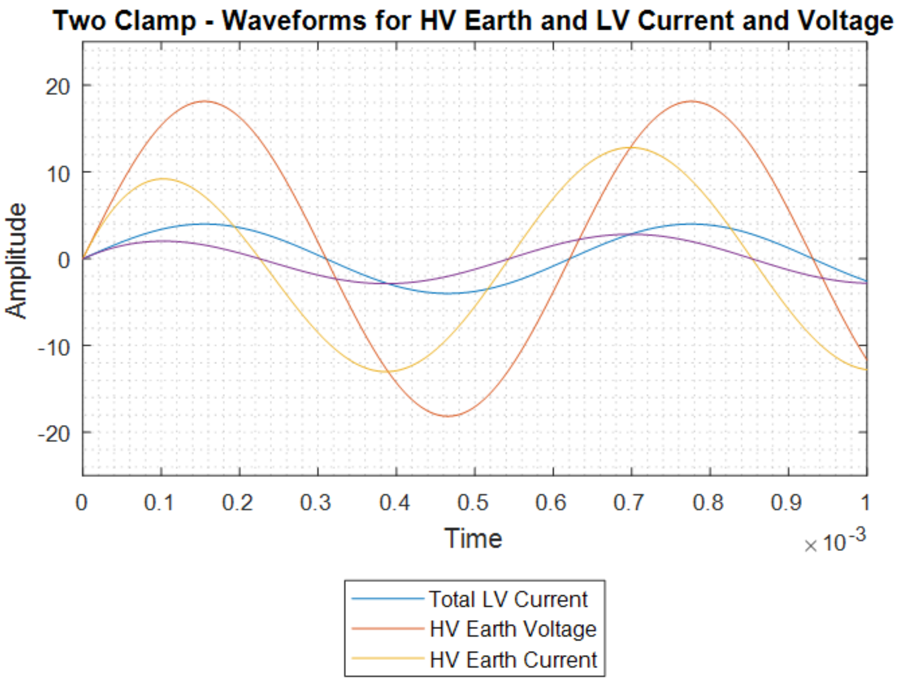


Figure 103: Waveform for Earth Current and Voltage from the Two Clamp Test Method

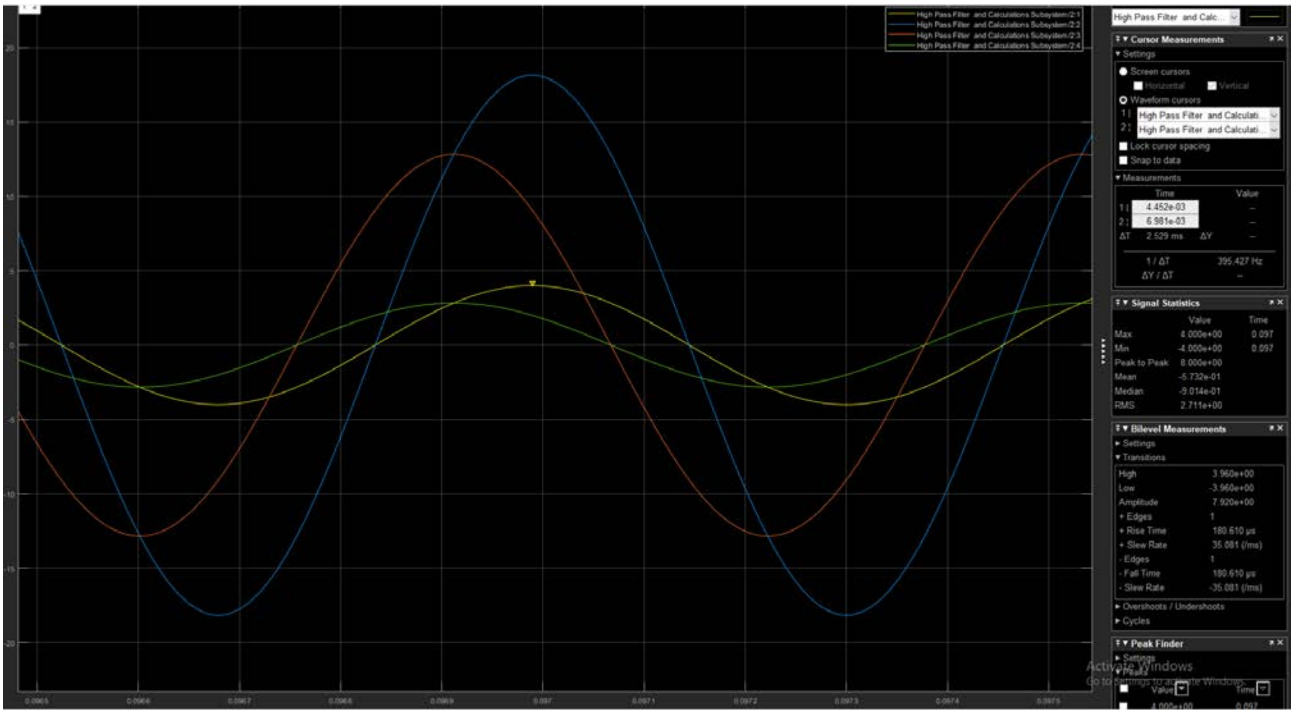


Figure 104: Simulink Two Clamp Test Method SWER Network Model Scope Output Waveforms

To install this type of system it would be appropriate to use it to monitor the LV earth as it is not an active conductor and doesn't have continually fluctuating values to monitor. Figure 102 shows the two clamp test system connected to the LV earth, for the purpose of the model, the system had to be connected in series to enable the current to be monitored. The test model worked as predicted with the LV earth measured with the addition of all the consumer earths in parallel. Therefore for a 3.87Ω LV distribution transformer earth and three 2Ω consumer earths the total value is 4.537 Ω as per equations 4-34, 4-35 and 4-38:

$$R_T = R_{LV} + \frac{1}{\frac{1}{R_{C1}} + \frac{1}{R_{C2}} + \frac{1}{R_{C3}}}\ \Omega \tag{4-36}$$

$$R_T = 3.87 + \frac{1}{\frac{1}{2} + \frac{1}{2} + \frac{1}{2}}\ \Omega \tag{4-37}$$

$$R_T = 4.537\ \Omega \tag{4-38}$$

7.2.3 HV Earth Monitoring Model Simulation

Keeping in mind the above comments relating to using the two clamp high frequency injection test method for measuring the integrity of the LV earth, a simple method of testing the HV earth voltage and total LV current was created. This HV earth monitoring subsystem model was based on the outcomes from the investigations into the field data results. The model, shown in Figure 105 and the subsystem in Figure 106, also incorporated the HV earth current to enable an additional calculation to ensure the model outputs would match the true field data outputs. A function called MATLAB Function R_True received inputs from the Total HV Current and HV Earth Voltage and used Ohm's Law to calculate the True Resistance, this value was for verification purposes only. A second function called MATLAB Function R_Calc received inputs from the two secondary winding LV Currents and the HV Earth Voltage and used the combined Ampere-turns-Ohm's Law equation 4-33 to calculate the HV earth resistance. It is noted that equations 4-34 and 4-35 were not required as the MATLAB functions calculated the resistance result directly from the waveform values and not peak or RMS values. The two functions were grouped in a subsystem, shown in Figure 106, with inputs to enable ease of connection to different network models.

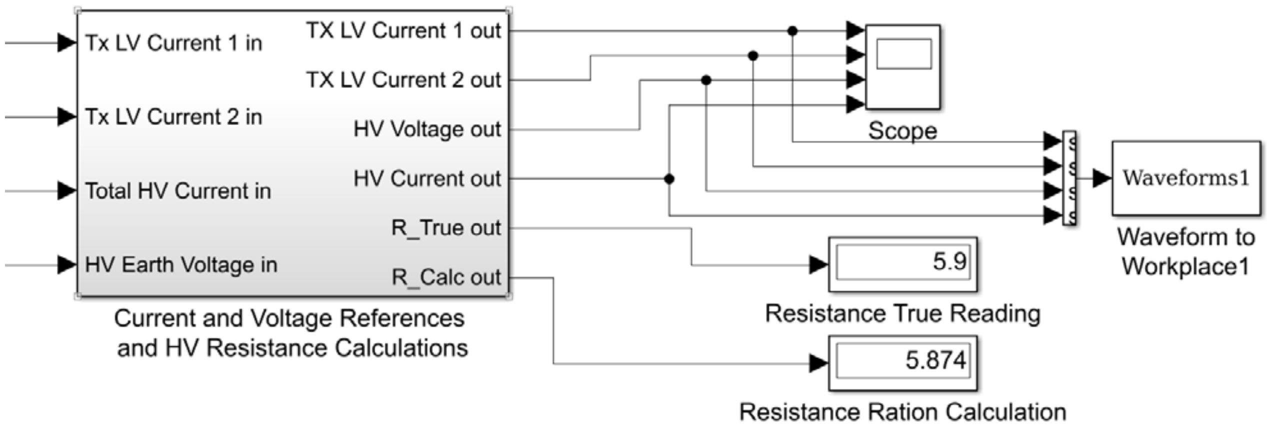


Figure 105: HV Earth Monitoring Model

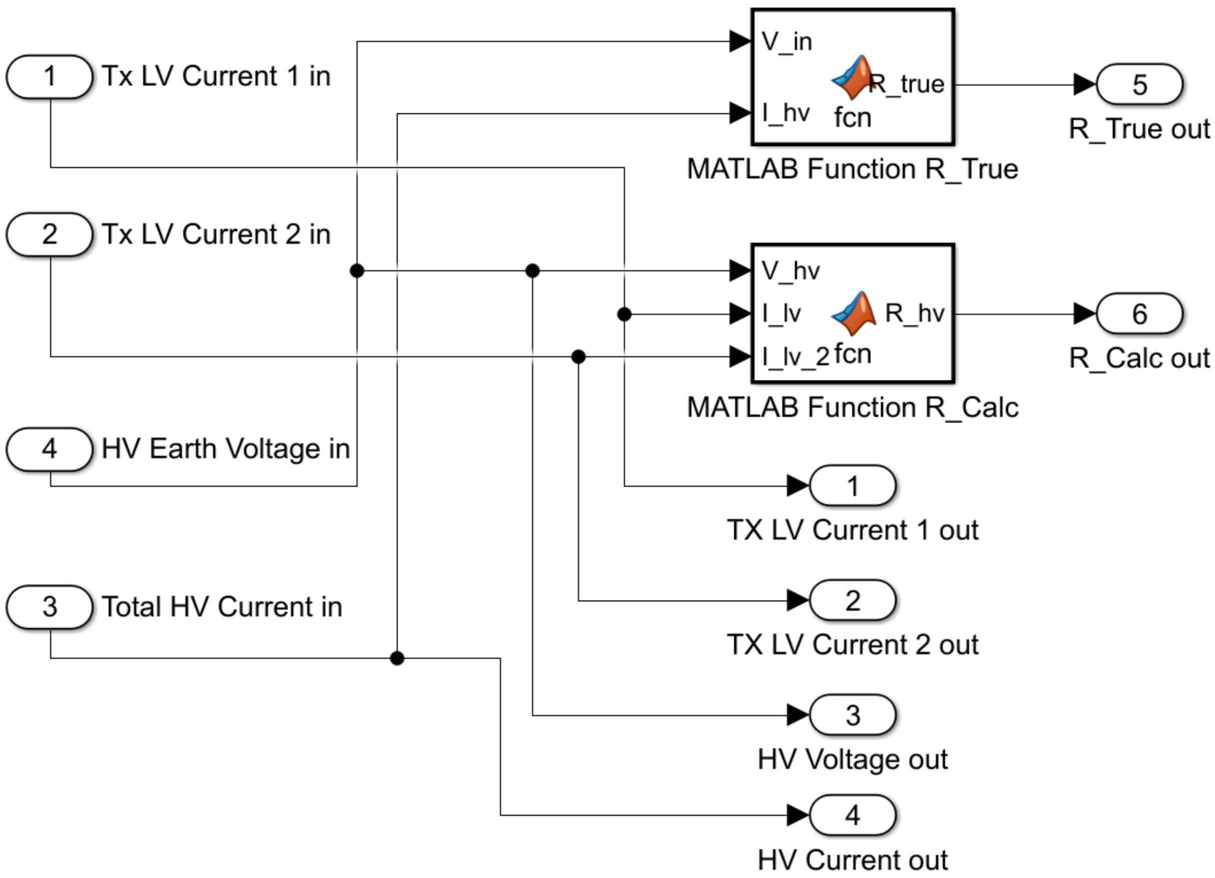


Figure 106: HV Earth Monitoring Subsystem Model

The HV earth monitoring subsystem was connected to the base SWER distribution system with outputs to a scope for waveform verification, Workplace and display values to verify the final values matched the field data values. Figure 107 shows the HV earth monitoring subsystem connected to the main SWER distribution base model, the results were accurate and matched those calculated from the true field test data. The model proved that the method of testing the total LV current and HV earth voltage would return an accurate calculated value for the HV earth resistance between the HV earth electrodes and the mass of earth. Figure 108 shows the MATLAB waveform output for the HV earth resistance monitoring system calculations.

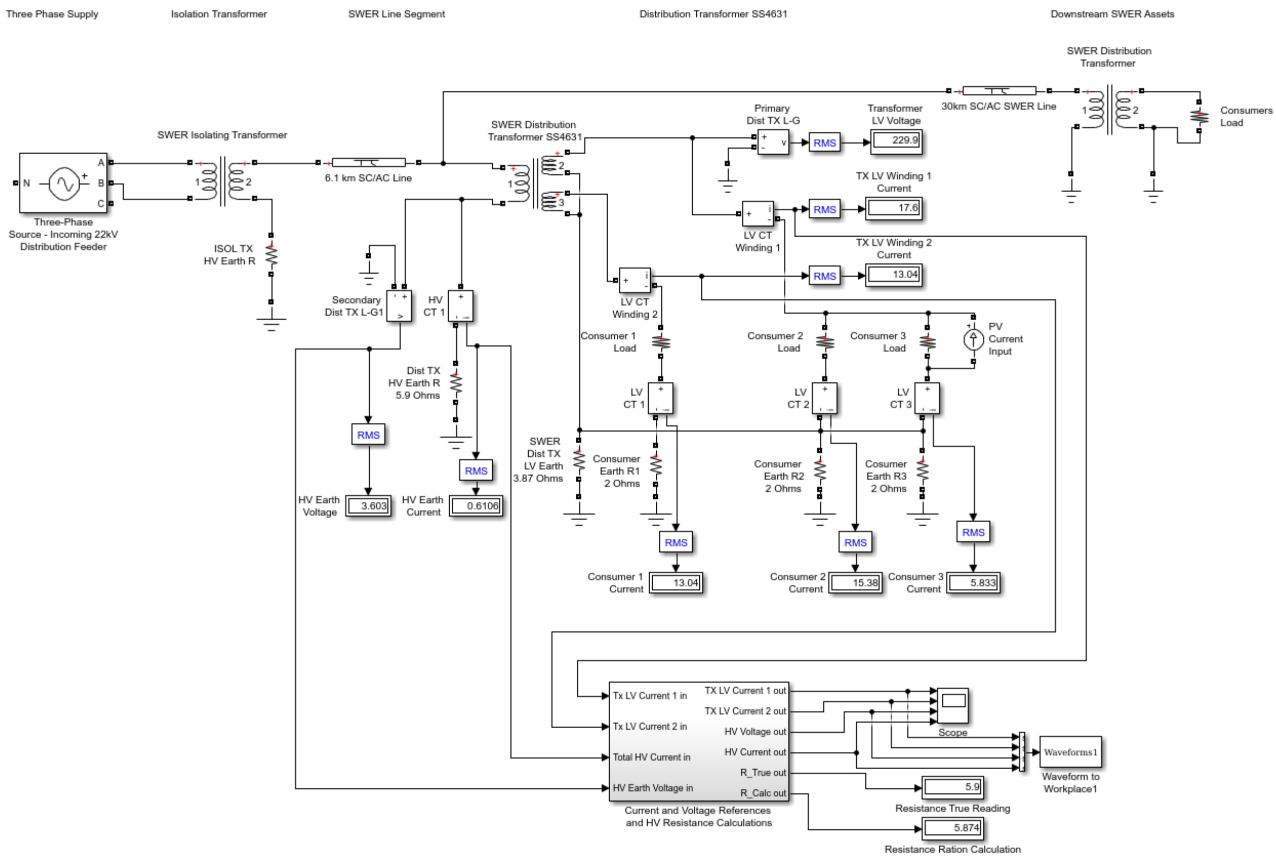


Figure 107: SWER Base Model with HV Earth Monitoring Subsystem

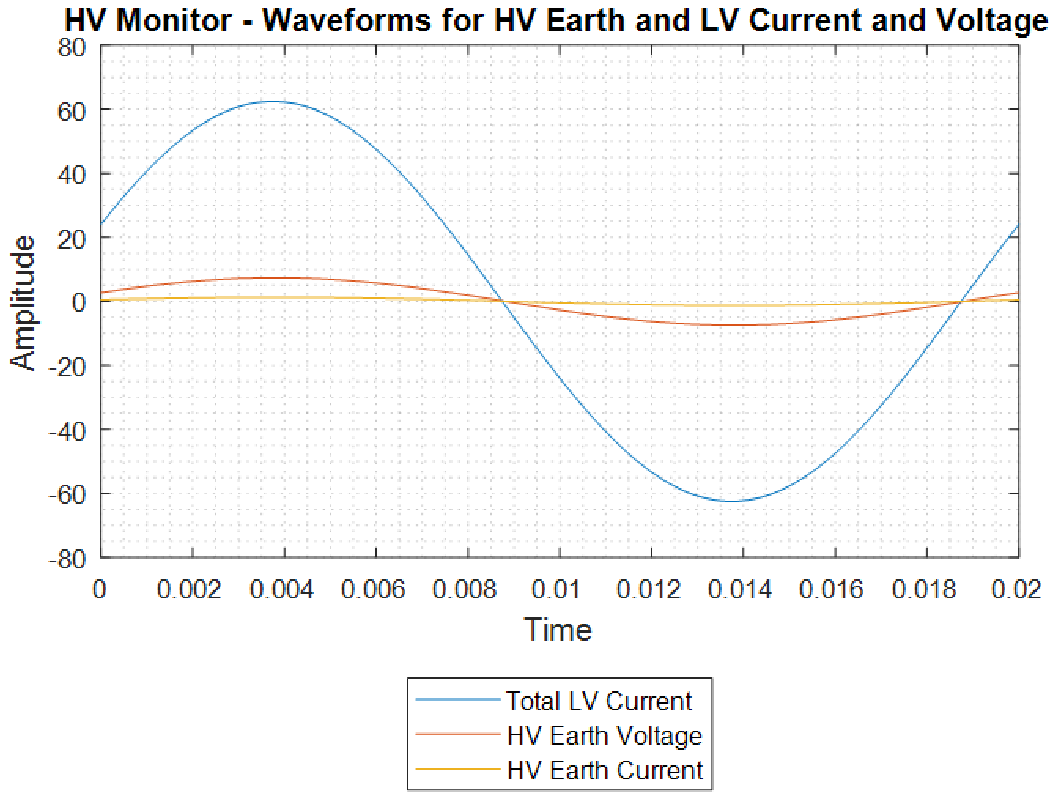


Figure 108: HV Earth Monitoring Subsystem MATLAB Waveform Output Plot

Chapter 8 - Functional Specification

8.1 Overview

This specification outlines the function requirements for the manufacture, supply and delivery for a real time continuous SWER HV earth resistance monitoring system.

8.2 Applicable Standards

The electrical measurement device shall comply with all relevant requirements specified by the Standards Association of Australia, in particular the following standards:

STANDARD	TITLE
AS 61010.1 IEC 61010.1	Safety requirements for electrical equipment for measurement, control and laboratory use – General requirements (IEC 61010-1 MOD).
AS 61010.031 IEC 61010.031	Safety requirements for electrical equipment for measurement, control and laboratory use - Part 031: Safety requirements for hand-held probe assemblies for electrical measurement and test.
AS 61010.2-032 IEC 61010.2-032	Safety requirements for electrical equipment for measurement, control and laboratory use – Part 2-032: Particular requirements for hand-held and hand-manipulated current sensors for electrical test and measurement.
IEC 61243-1	Live Working - Voltage Detectors - Part 1: Capacitive Type to Be Used for Voltages Exceeding 1 kV A.C.
IEC 61243-2	Live working - Voltage detectors - Part 2: Resistive type to be used for voltages of 1 kV to 36 kV a.c.
IEC 61243-3	Live working – Voltage detectors- Part 3: Two-pole low-voltage type.
IEC 61557-1	Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - Part 1: General requirements
IEC 61557-2	Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - Part 2: Insulation resistance
IEC 61557-3	Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - Part 3: Loop impedance
IEC 61557-4	Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - Part 4: Resistance of earth connection and equipotential bonding
IEC 61557-5	Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - Part 5: Resistance to earth
IEC 61557-6	Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - Part 6: Effectiveness of residual current devices (RCD) in TT, TN and IT systems
IEC 61557-7	Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures - Part 7: Phase sequence
IEC 61000-4 Series	Electromagnetic compatibility (EMC) - Part 4-1: Testing and measurement techniques
	Work Health and Safety Queensland - Managing Risks of Plant in the Workplace Code of Practice 2013

8.3 Hardware Requirements

8.3.1 Service Conditions

The item will be subject to continuous exposure to the following environmental conditions:

Temperature	Average Range –10º C to +55º C.
Precipitation	Annual rainfall up to 3200 mm average per annum.
Humidity	Extended periods of relative humidity in excess of 90% above 31ºC.
Solar exposure	Mounted in an outdoor environment with up to 11 hours of daily solar exposure.
Vermin and Dust	The equipment will be mounted outdoors in extreme environmental conditions, vermin proofing for insects and larger intrusive species is required. Sealing against fine dust particle intrusion is required.

8.3.2 Duties

The electrical measuring item will be subjected to following:

- Nominal LV working voltage (L-N) – 230V +10% to -6%.
- Overcurrent protection is required, SWER transformer secondary LV supplies can be protected by a maximum drop-out fuse size of 100A (500V configuration) or 160A (250V configuration).
- An HV earth voltage has the potential to rise to 12.7kV in the event of severed connection. The HV earth voltage reference must be connected through a >15kV rated relay for operational separation in the event of a sudden voltage rise in the earth.
- Overcurrent protection is required for the HV earth voltage connection to maintain protection in the event of an extreme event.

8.3.3 Design and Construction

- Manufacturers operating instructions shall be supplied for all items in this specification. The supplied instructions shall be written in clear concise English.
- Insulation Category - All electrical measurement equipment shall be rated and marked according to AS 61010.1 or IEC 61010-1. The lead ratings are to be rated as per the voltages outlined in section 8.3.2.
- Mechanical Protection - Mechanical Protection shall comply with AS 61010.1 or IEC 61010-1 for measurement equipment and IEC 61243-1 for HV detectors, protection against mechanical hazards.
- Voltage Measurement –
    - Range 0 to 15kV through a relay and voltage divider
    - Resolution 0.1mV

    - Accuracy ± (1.0%)
    - Response 50-2000 Hz
    - Piercing probe for conductors up to $70mm^2$
- Current Measurement –
    - Range 0 to 200A
    - Resolution 0.01mA
    - Accuracy ± (1.0%)
    - CT clamp with minimum diameter of 45mm
- Resistance Measurement –
    - Range 0 to 50MΩ
    - Resolution 0.01Ω
    - Accuracy ± (1.0%)
- Memory battery backup must be installed with a warranty life of >10 years.
- Total overall unit mass must not exceed 10kg.
- Additional removable storage device data capture capabilities must be available.
- Communications capabilities –
    - Modem with minimum of 4G with capabilities of 5G for data transfer and receiving within the Australian communications network.
    - Bluetooth for local data downloading and uploading of configuration changes and firmware updates.
- Graphical user interface – unit to be provided with a GUI to enable current values to be displayed.

8.3.4 System Architectural Overview – Block Diagram

The new system must provide online monitoring in real time with connectivity to Energy Queensland condition monitoring software packages. Capabilities for remote and local system input and editing must be available to enable individual site nameplate attributes to be programmed. Figure 109 shows a conceptual overview of the system architecture major components.

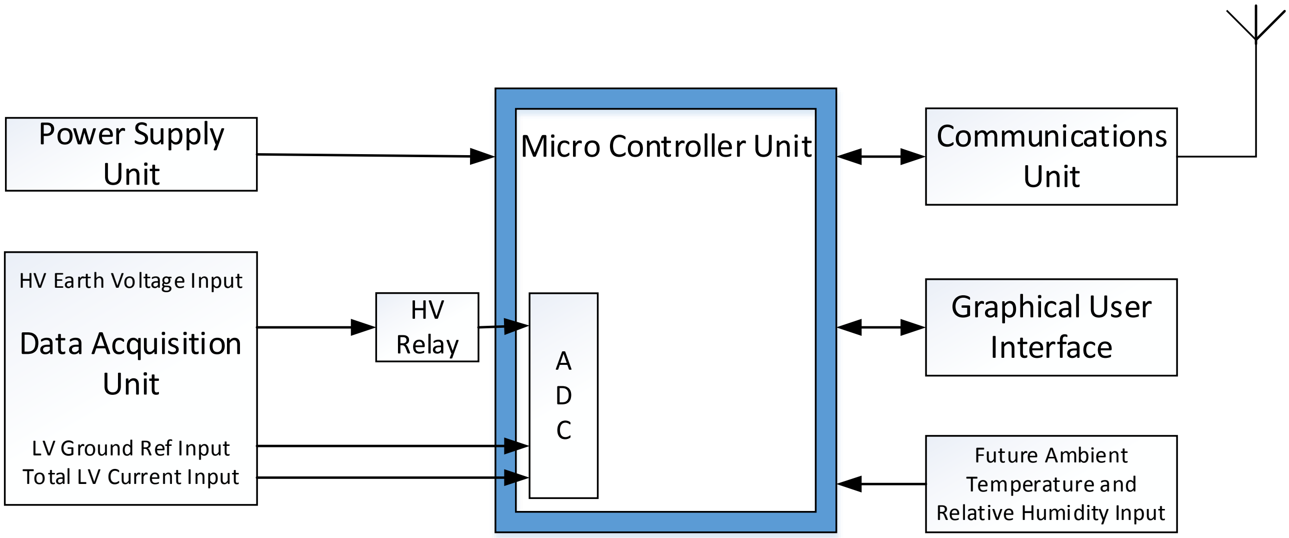


Figure 109: System Architectural Overview for SWER Earth Monitoring Device

8.4 Software Requirements

The software provides a method to collect, analyse and communicate via real time for the measured voltage and current values and calculated resistance values on site. The software environment must be capable of integrating with Energy Queensland condition monitoring software packages, GIS systems and other existing environments.

- Ability to interface with Windows with a supplied application for Android and Apple mobile device platforms.
- Software must include a web-based application for Energy Queensland to view, monitor, manage, control, configure and report on remote earthing activities.
- Software must be capable of safe and autonomous operation in the event of loss of communications.
- Ability to represent the output data in a variety of textual formats (e.g. .txt, .csv).
- Ability to change data transfer rates and periods.
- Ability to support read/write mobile applications.
- Ability to change calculation parameter for site specific nameplate data.
- Ability to erase and reset stored data.
- Ability to capture and store specific site information:
    - Substation/transformer site identification number;
    - Pole identification number;
    - Legacy pole number;
    - Site physical address;
    - Site GIS location (latitude and longitude);
    - Earthing configuration LV and HV (direction, length);

- Earthing onsite tests (using 3 pole method if needed);
- Number of consumers;
- Number of PV arrays;
- Access status (e.g. beside road, within private property);
- Ambient temperature;
- Independent weather and soil condition (e.g. raining and wet, sunny and dry).

- Ability to auto alarm to the web-based system and the option of an SMS facility for threshold value breaches. Ability to enter and edit alarm threshold values for current, voltage and resistance.
- All values are to be metric.
- Compliance with Australian privacy laws for managing Host Customer data.

8.4.1 Software System Flow Diagram

Figure 110 represents the software system flow.

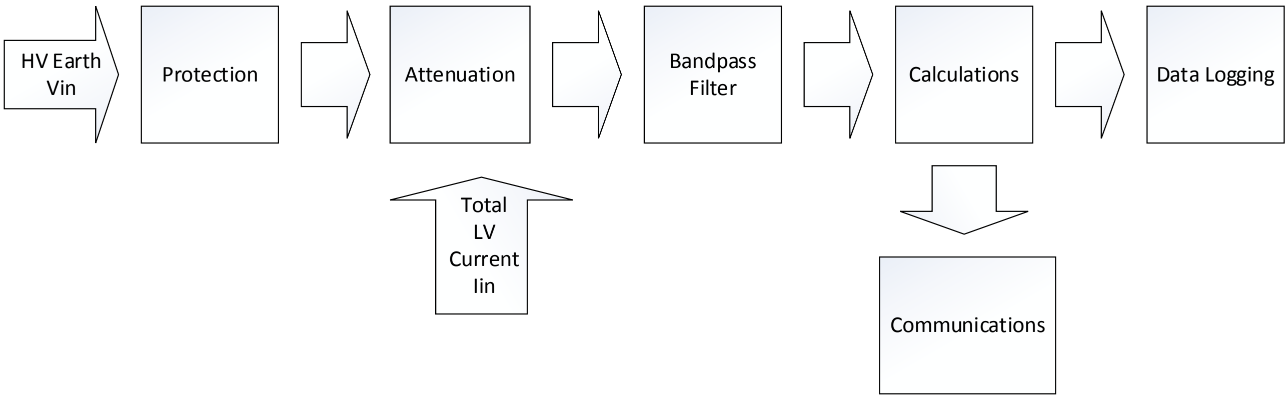


Figure 110: Software System Flow Diagram for SWER Earth Monitoring Device

8.4.2 Program Flowchart

Figure 111 provides the program flowchart outlining the framework for the application component decisions required to maintain a dynamic monitoring and communication of the received and calculated data.

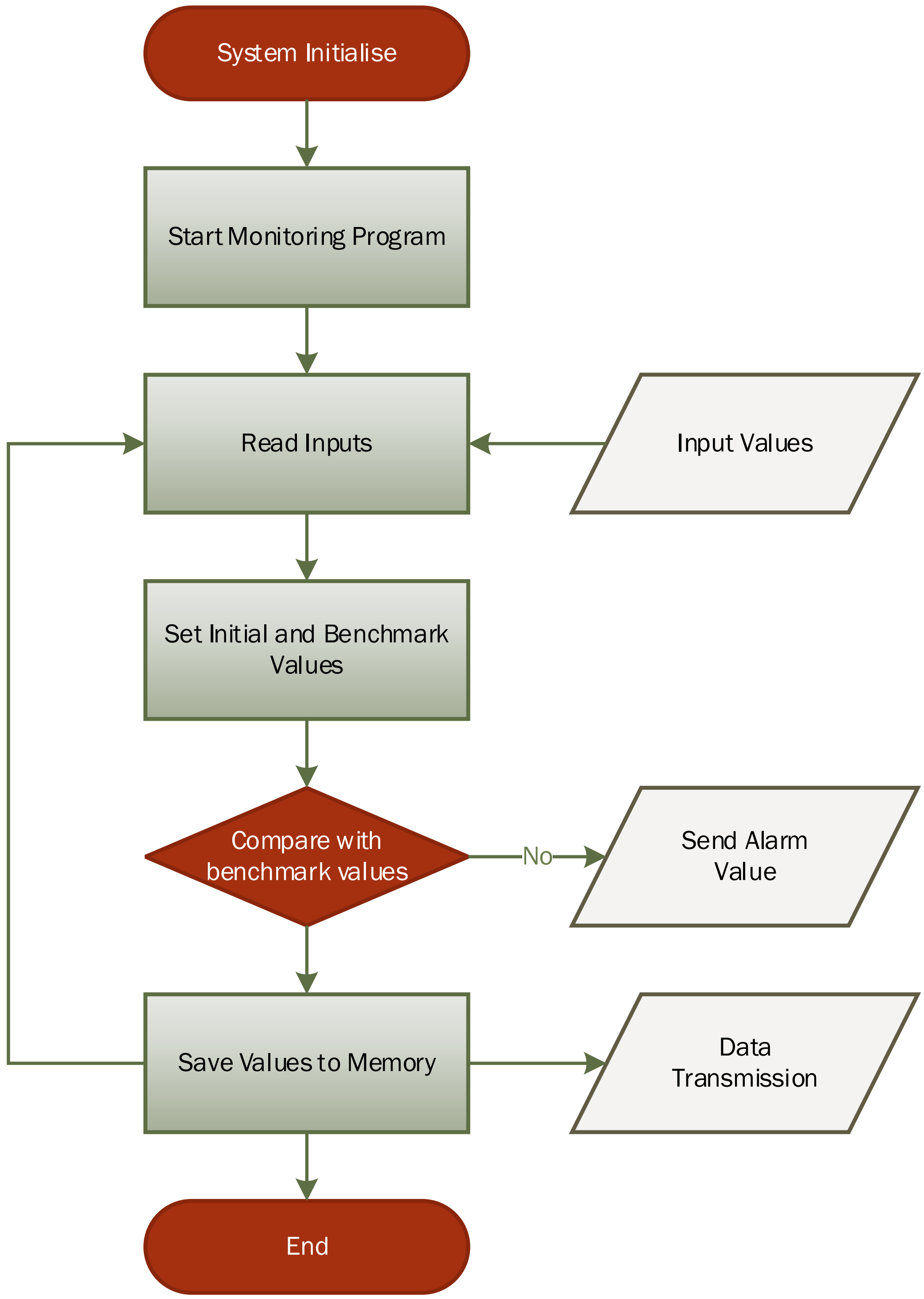


Figure 111: Program Flowchart for SWER Earth Monitoring Device

Chapter 9 - Test Site Requirements and Construction

A test site to carry out trials of the proposed new remote SWER HV earth monitoring unit was required that would resemble a “laboratory like” environment. Due to the operational safety constraints with SWER distribution systems and the live nature of the HV earth a decision was made to test the unit on a SWER pole with no consumers and a site that was not accessible to the public. As this site was not available in the current network a test site was built to accommodate the necessary safety precautions for the first test trail to ensure the equipment could be rigorously tested for all scenarios and conditions.

9.1.1 Test Site Requirements

The following test site criteria were deemed necessary to establish a typical SWER distribution transformer site:

- Located in close proximity to a major Energy Queensland Regional Centre;
- Beside a bitumen road easily accessed by vehicles in all weather conditions;
- Located on an Energy Queensland owned greenfield site with no services above or below the surface;
- Located within a fenced compound with no public access;
- Located on flat, traversable land, greater than 1000m^2, to allow for test electrodes to be installed in different configurations;
- Located in close proximity to a 22kV or 33kV three phase distribution line to allow for a SWER connection;
- Located away from any consumers MEN or other distribution earthing connections;
- Located within a 4G coverage area.

The following site, shown in Figure 112, was chosen as a “laboratory like” test environment based on the criteria listed above.

Site Details:

- **Site Address:** Lot 41 SP202665 Swallow Road, Edmonton QLD 4869.
- **Site Owner:** Ergon Energy as a subsidiary Energy Queensland.
- **Site Area:** 7 Hectares.
- **Security:** Full security fence around the perimeter with Ergon Energy locks on the gates.
- **Supply Availability:** Multiple supply termination poles on one boundary (22kV).
- **Current Usage:** Site is not utilised at present, previously it was used for Pegasus unit trails, and it is reserved for the future Ergon Energy Stores Depot.
- **Proximity to Regional Centre:** 15 minutes from Cairns Bunda Street Office (shown in Figure 113) with all-weather access.

- **Trial Scenarios:** Potential to set up multiple earthing scenarios with different aggregate materials to simulate poor earthing conditions in controlled conditions.

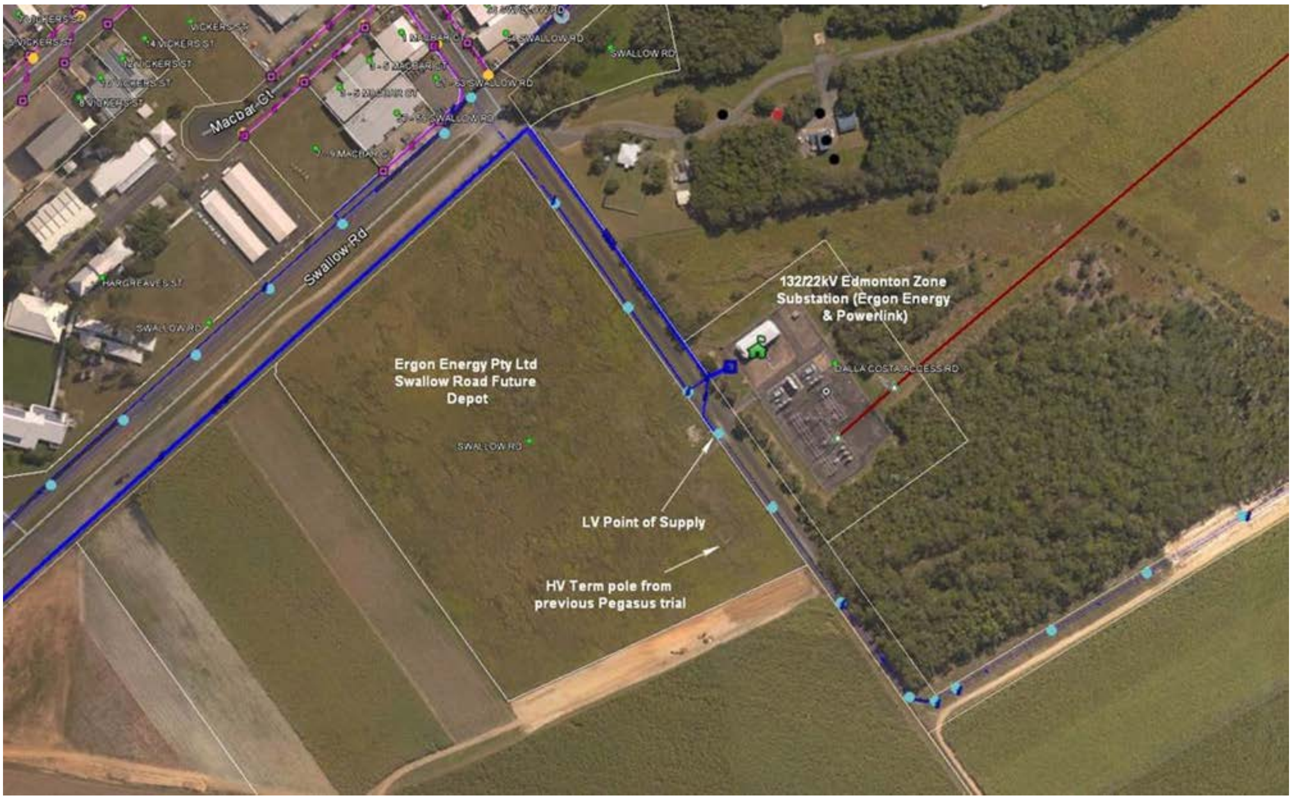


Figure 112: Site map and proximity to Edmonton Zone Substation

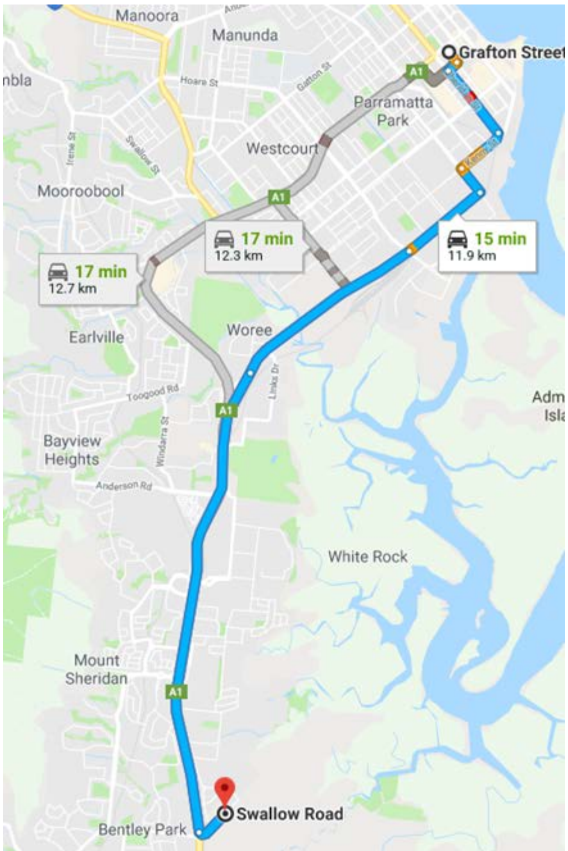


Figure 113: Distance via Road from Energy Queensland Major Regional Centre

Identified potential issues with obtained solutions:

- **Network Restrictions:** Edmonton Zone Substation is across the road – maybe a potential issue with high fault currents. Energy Queensland protection group were engaged and they deemed the test site to have no issues from the close proximity to the zone substation although all standard risk assessments should be completed and adhered to.
- **Approvals:** Energy Queensland property group provided approval to use the site for trail purposes only with all equipment to be removed from the site once the trial is completed. Temporary internal fencing may be required if other business units use the site whilst the trials are taking place.
- **Access:** The access road is already covered with aggregate rock from previous Pegasus unit trials and is adequate for standard line trucks and lifter/borer access.
- **Vermin:** Yellow Crazy Ants have been identified at Edmonton Zone Substation. Standard inspection and wash down procedures to be adhered to with signage on the site gates and notes on all drawings.
- **Financial:** Costs will be incurred for the installation of a SWER distribution transformer, pole and associated hardware – these could be returned to the stores and material costs reimbursed after the trial is finished.
- **Milestone Impacts:** Time delays may be incurred as line installation works will need to be approved in the works plan. Funding approval was granted in January 2019, a Works Request and associated Works Orders were raised in February 2019, design was completed in May 2019 and construction completed in July 2019.

9.2 Cost Analysis and Summary

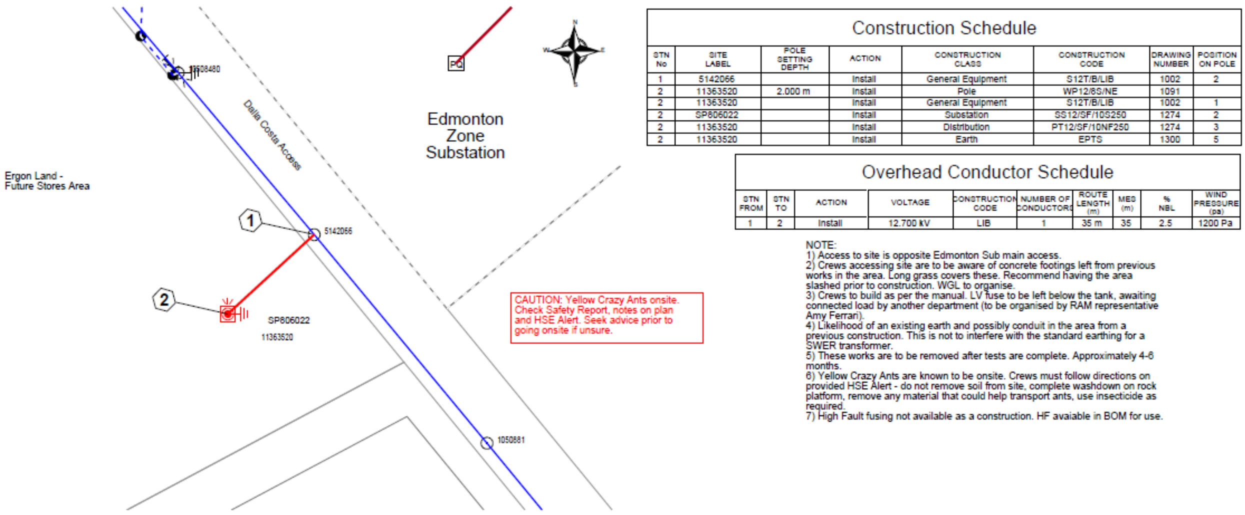
The estimated and actual costs are listed in Table 20, the total comparison of estimated versus actual is unknown as the supplier has not delivered the initial test equipment to date. The construction of the trial site was delivered under the estimate cost and was delivered prior to the delivery of the test unit.

Cost Description	**Estimated Cost (excluding overheads)**	**Actual Cost (excluding overheads)**
Construction of a 12.7kV SWER Substation	$17,500	$16,948
Additional Remote Earth Monitoring Equipment	$11,770	Waiting on supplier
Miscellaneous	$2,000	
Total	**$31,270**	

Table 20: Estimated and Actual Costs to Date for Swallow Road Trial Site and Equipment

9.3 Test Site Design and Construction

Figure 114 shows the design portion of the test site construction plan for Swallow Road SWER earth monitoring trial site. To reduce costs and the overall trial site footprint, a SWER isolating transformer and recloser were not installed. This was deemed appropriate as the site was built to specifically test the installation and operation of the new remote SWER earth monitoring unit. If the unit is successful then it will be removed from the trial site and tested on network connected SWER distribution transformers within 4G network coverage areas. The HV single conductor used was AAC 7/3.0 Libra; it was strung at 2.5% NBL (nominal breaking load) over a 35m single span from the three phase 22kV Gordonvale 1 (2GO1) distribution feeder to the new transformer pole located within the compound. A 12 metre 8kN pole (site label 11363520) was installed with a 10kVA SWER distribution transformer (site identification number SP806022). Standard SWER earthing was installed with a single earth for the LV, 3m from the base of the pole, and three interconnected earths for the HV in a triangular formation, 2.5m from the base of the pole as per Figure 115.



Construction Schedule

STN No	SITE LABEL	POLE SETTING DEPTH	ACTION	CONSTRUCTION CLASS	CONSTRUCTION CODE	DRAWING NUMBER	POSITION ON POLE
1	5142066		Install	General Equipment	S12T/B/LIB	1002	2
2	11363520	2.000 m	Install	Pole	WP12/8S/NE	1091	
2	11363520		Install	General Equipment	S12T/B/LIB	1002	1
2	SP806022		Install	Substation	SS12/SF/10S250	1274	2
2	11363520		Install	Distribution	PT12/SF/10NF250	1274	3
2	11363520		Install	Earth	EPTS	1300	5

Overhead Conductor Schedule

STN FROM	STN TO	ACTION	VOLTAGE	CONSTRUCTION CODE	NUMBER OF CONDUCTORS	ROUTE LENGTH (m)	MES (m)	% NBL	WIND PRESSURE (pa)
1	2	Install	12.700 kV	LIB	1	35 m	35	2.5	1200 Pa

NOTE:
1) Access to site is opposite Edmonton Sub main access.
2) Crews accessing site are to be aware of concrete footings left from previous works in the area. Long grass covers these. Recommend having the area slashed prior to construction. WGL to organise.
3) Crews to build as per the manual. LV fuse to be left below the tank, awaiting connected load by another department (to be organised by RAM representative Amy Ferrari).
4) Likelihood of an existing earth and possibly conduit in the area from a previous construction. This is not to interfere with the standard earthing for a SWER transformer.
5) These works are to be removed after tests are complete. Approximately 4-6 months.
6) Yellow Crazy Ants are known to be onsite. Crews must follow directions on provided HSE Alert - do not remove soil from site, complete washdown on rock platform, remove any material that could help transport ants, use insecticide as required.
7) High Fault fusing not available as a construction. HF avaiable in BOM for use.

Figure 114: Swallow Road SWER Test Site Construction Plan

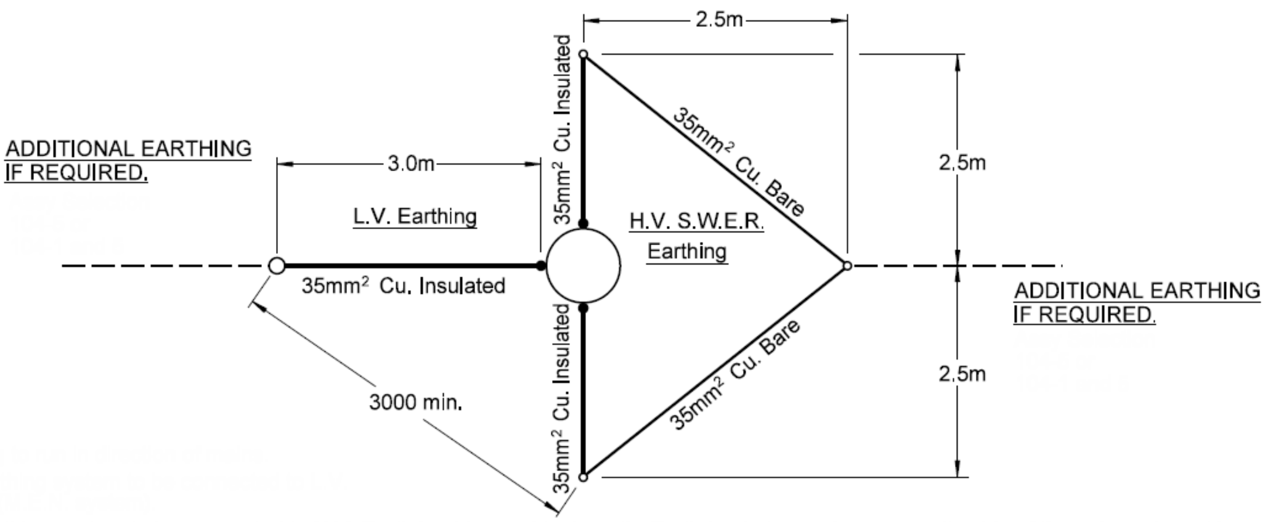


Figure 115: Standard SWER Distribution Earth Configuration

9.3.1 Test Site Consumer and Soil Replications

To replicate consumer loading on the transformer a 10kVA load bank will be used. This will enable the total LV current to be adjusted as per the incremental changes of 0.5kVA on the load bank. To replicate changes in soil to electrode conditions additional earth electrodes in different mediums will be installed onsite. These will individually be monitored over a period of days to establish dynamic changes in the measured resistance in different medium. De-energisation of the distribution transformer will be required for each change in HV earth electrode connection to ensure onsite safety to personal. Initially the change in earth can be simulated by connected the monitoring devices to a low voltage variac to establish the equipment measuring is accurate and alarms will be triggered when thresholds are met.

9.4 Test Site on-site testing

Following the commissioning of the SWER transformer SP806022, on site earth resistivity tests were completed on the 25th July 2019 and again on the 7th of August 2019 using an AEMC 6471 Ground Tester unit. Temporary earth stakes were installed perpendicular to the existing transformer LV and HV earths over a distance of 47.5m. The temporary stakes were spaced 5m apart, with the end stakes at 2.5m spacing. The quantity of 11 stakes consisted of 12mm copper clad steel, 725mm long with 500mm driven into the ground. The soil was moist on both test days with fine weather conditions on the 25th of July and weather conditions being of scattered light showers on the 7th of August.

The final results were graphically represented in Figure 116 and Figure 117 using the individual stakes to represent the earth resistance curves for the LV and HV earths. The final values taken at the 62% point or approximately 30m for the fall of potential method were:

LV Earth Resistance Test: 5.35Ω (Ergon Energy requirement of <10 Ω)

HV Earth Resistance Test: 3.75Ω (Ergon Energy requirement of <15Ω)

Both earth resistance values were considerably under the Ergon Energy standard requirement values and consistent with the clay soil type on site which has a predominantly low and consistent resistivity value. Figure 118, Figure 119 and Figure 120 show the Swallow Road trial site and the test stake layout.

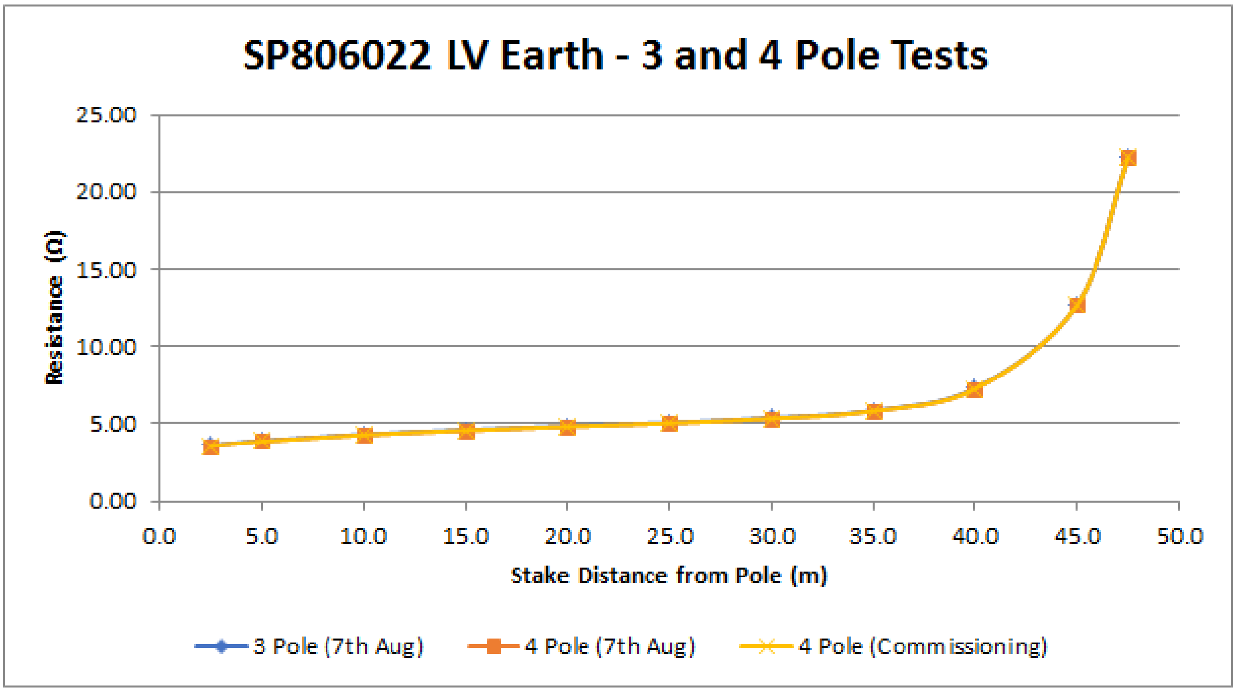


Figure 116: SP806022 LV Earth – 3 and 4 Pole Tests

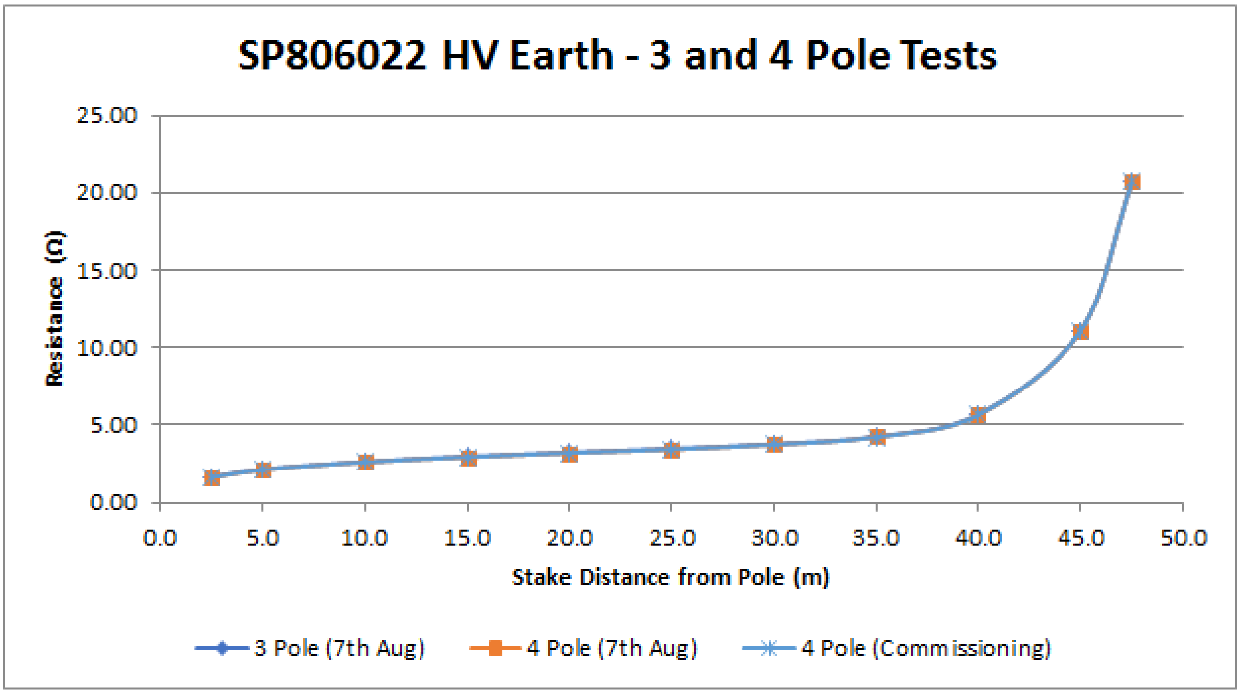


Figure 117: SP806022 HV Earth – 3 and 4 Pole Tests

Figure 118: Swallow Road Trial Site Onsite Testing with AEMC 6471 Ground Tester Unit

Figure 119: Swallow Road Trial Site Test Stake Layout

Figure 120: Swallow Road Trial Site SWER Distribution Transformer SP806022

9.5 Purchase of online monitoring equipment

A monitoring device has been ordered for testing at the trial site. The unit is a combination of a newly developed remote earth resistance monitoring unit with an additional isolation relay. The unit was ordered prior to the completion of the results section of this dissertation and it is believed improvements and simplification can be made to the overall design. For the preliminary trial purpose, the initial unit will be tested at the trial site with recommendations for changes and improvements to be made to the supplier and manufacturer for future versions.

Chapter 10 - Conclusion

The objective of this dissertation was to investigate and develop a method to remotely monitor and report the resistance of a SWER earthing system at the distribution substation level in real time. This was successfully achieved theoretically and proven through model simulations against field test results. The dissertation has proven that the HV SWER earth resistance can be monitored using two field inputs, the HV earth voltage and the total LV current, and using the fixed ratio of the HV and LV voltage from the transformer nameplate. A simplified formula combining the ampere-turn relationship of the transformer and Ohm's Law has been derived to calculate the HV earth resistance. The results from this dissertation have provided evidence and a functional specification to construct a simplified earth monitoring unit that can be remotely mounted to a SWER distribution transformer to monitor the HV and LV earth resistance in real time. An online monitoring device will provide an additional level of safety to existing SWER earthing systems with immediate alarm notifications when threshold resistances are breached.

A trial test site has been successfully constructed, commissioned and energised and is awaiting the installation of a prototype remote SWER earth monitoring device.

The outcome from this dissertation bridges a gap in engineering knowledge in relation to a simplified online method for condition monitoring of SWER earth resistances. The significance of this research will increase public and network safety with accurate real time values allowing critical engineering decisions in the event of a high resistance connection occurring.

Single Wire Earth Return is an example of engineering brilliance which is elegant in its simplicity. The derived formula and the method to online monitor contained in this dissertation is a reflection of this.

10.1 Further Research/work

A monitoring unit has been ordered and is due for delivery in November 2019. It is believed improvements will be made to this unit from the results of this dissertation. Once the online unit has been tested at the trial site under various conditions and the results have been proven to be accurate then deployment out to multiple SWER sites will be implemented. The results from the onsite trials will provide a fundamental understanding of the behaviour of SWER earthing and will potentially influence business behaviour and decision making. It is believed that knowledge from the trials will be shared within industry engineering groups to help understand the dynamic behaviour of SWER earthing and the influence of location and climatic conditions. Learnings will hopefully improve the current condition monitoring requirements, cyclic inspection periods, benchmark resistance requirements of individual electrical entities and network improvements.

The possibility of integrating the remote SWER earth monitoring device with the GUSS system locations in the South-West and remote regions of Queensland will provide enhanced information into the behaviour of the SWER system earthing.

It is believed a comprehensive knowledge of SWER earthing behaviour will improve safety to the general public and electrical entity personnel and will ultimately provide cost savings to earth remediation projects and forced work from pole failures.

Appendix A: Project Specification

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/4112 Research Project

Project Specification

For: Amy Ferrari

Title: Feasibility of remote earth monitoring for SWER systems

Major: Electrical and Electronic Engineering

Supervisors: Associate Professor Tony Ahfock
Mr David Bell, Energy Queensland Pty Ltd

Enrolment: ENG4111 – EXT S1, 2019
ENG4112 – EXT S2, 2019

Project Aim: This project investigates the development of a method to online monitor and report the resistance of a SWER earthing system at the distribution substation level. Recommendations for SWER earth online monitoring devices will be developed from theoretical and real life analysis of baseline conventional earth testing methods and clamp-on injection methods.

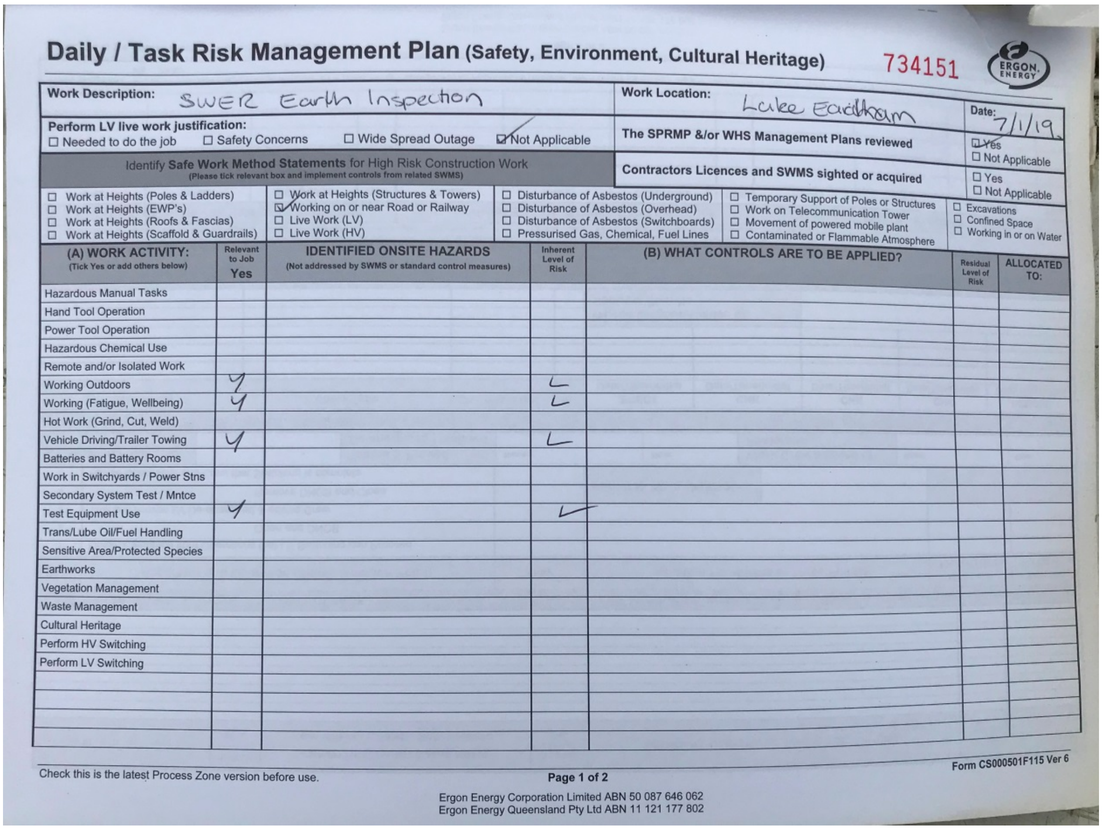
Programme: Version 1, 18th March 2019

1. Research existing SWER earth testing methods with comparison between the traditional combination of 4 pole Wenner earth resistivity method and 3 pole fall of potential method and the more recent stake-less/ clamp-on method.
2. Conduct onsite monitoring of an existing energised SWER distribution transformer and LV system using a PowerMonic meter and onsite testing using the traditional 3 pole fall of potential test method.
3. Collate test results, review and analyse. Evaluate the advantage/disadvantage of current test methods.
4. Develop a system model using Simscape Electrical to theoretically verify a test method for online SWER earth testing and monitoring.
5. Develop and provide functional specification to manufacturer in relation to requirements for online SWER earth test equipment.
6. Develop recommendations for test site location, test site construction requirements, cost analysis, cost summary and risk assessment.

If time and resources permit:

7. Purchase online monitoring equipment.
8. Build test site.
9. Complete onsite testing.
10. Analyse results.

Appendix B: Completed DTRMPs



Daily / Task Risk Management Plan (Safety, Environment, Cultural Heritage) 734151 ERGON ENERGY

Work Description: SWER Earth Inspection
Work Location: Lake Eacham
Date: 7/1/19.

Perform LV live work justification: ☐ Needed to do the job ☐ Safety Concerns ☐ Wide Spread Outage ☑ Not Applicable

The SPRMP &/or WHS Management Plans reviewed ☑ Yes ☐ Not Applicable

Identify **Safe Work Method Statements** for High Risk Construction Work (Please tick relevant box and implement controls from related SWMS)

Contractors Licences and SWMS sighted or acquired ☐ Yes ☐ Not Applicable

☐ Work at Heights (Poles & Ladders)
☐ Work at Heights (EWP's)
☐ Work at Heights (Roofs & Fascias)
☐ Work at Heights (Scaffold & Guardrails)
☐ Work at Heights (Structures & Towers)
☑ Working on or near Road or Railway
☐ Live Work (LV)
☐ Live Work (HV)
☐ Disturbance of Asbestos (Underground)
☐ Disturbance of Asbestos (Overhead)
☐ Disturbance of Asbestos (Switchboards)
☐ Pressurised Gas, Chemical, Fuel Lines
☐ Temporary Support of Poles or Structures
☐ Work on Telecommunication Tower
☐ Movement of powered mobile plant
☐ Contaminated or Flammable Atmosphere
☐ Excavations
☐ Confined Space
☐ Working in or on Water

(A) WORK ACTIVITY: (Tick Yes or add others below)	Relevant to Job Yes	IDENTIFIED ONSITE HAZARDS (Not addressed by SWMS or standard control measures)	Inherent Level of Risk	(B) WHAT CONTROLS ARE TO BE APPLIED?	Residual Level of Risk	ALLOCATED TO:
Hazardous Manual Tasks						
Hand Tool Operation						
Power Tool Operation						
Hazardous Chemical Use						
Remote and/or Isolated Work						
Working Outdoors	Y		L			
Working (Fatigue, Wellbeing)	Y		L			
Hot Work (Grind, Cut, Weld)						
Vehicle Driving/Trailer Towing	Y		L			
Batteries and Battery Rooms						
Work in Switchyards / Power Stns						
Secondary System Test / Mntce						
Test Equipment Use	Y		L			
Trans/Lube Oil/Fuel Handling						
Sensitive Area/Protected Species						
Earthworks						
Vegetation Management						
Waste Management						
Cultural Heritage						
Perform HV Switching						
Perform LV Switching						

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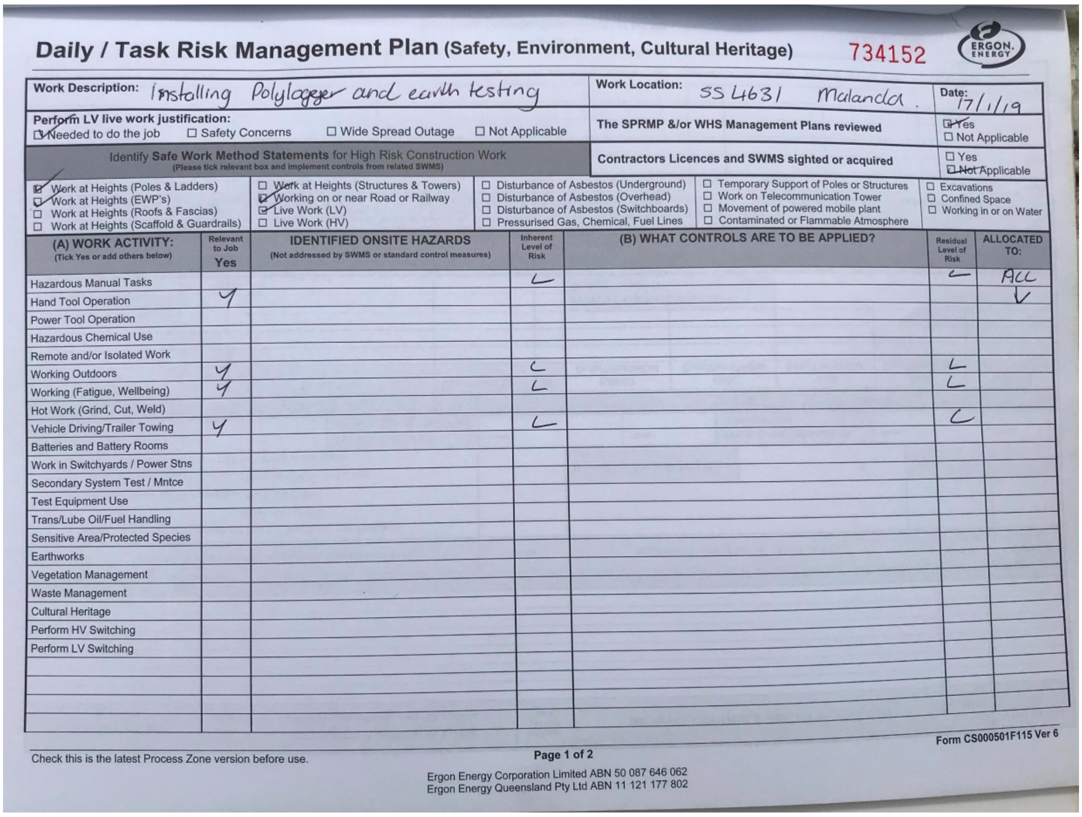
Ergon Energy Corporation Limited ABN 50 087 646 062
Ergon Energy Queensland Pty Ltd ABN 11 121 177 802

Figure 121: DTRMP Earth Test 07/01/2019



Daily / Task Risk Management Plan (Safety, Environment, Cultural Heritage) 734152 ERGON ENERGY

Work Description: Installing Polylogger and earth testing
Work Location: SS 4631 Malanda.
Date: 17/1/19

Perform LV live work justification: ☑ Needed to do the job ☐ Safety Concerns ☐ Wide Spread Outage ☐ Not Applicable

The SPRMP &/or WHS Management Plans reviewed ☑ Yes ☐ Not Applicable

Identify **Safe Work Method Statements** for High Risk Construction Work (Please tick relevant box and implement controls from related SWMS)

Contractors Licences and SWMS sighted or acquired ☐ Yes ☑ Not Applicable

☑ Work at Heights (Poles & Ladders)
☑ Work at Heights (EWP's)
☐ Work at Heights (Roofs & Fascias)
☐ Work at Heights (Scaffold & Guardrails)
☐ Work at Heights (Structures & Towers)
☑ Working on or near Road or Railway
☑ Live Work (LV)
☐ Live Work (HV)
☐ Disturbance of Asbestos (Underground)
☐ Disturbance of Asbestos (Overhead)
☐ Disturbance of Asbestos (Switchboards)
☐ Pressurised Gas, Chemical, Fuel Lines
☐ Temporary Support of Poles or Structures
☐ Work on Telecommunication Tower
☐ Movement of powered mobile plant
☐ Contaminated or Flammable Atmosphere
☐ Excavations
☐ Confined Space
☐ Working in or on Water

(A) WORK ACTIVITY: (Tick Yes or add others below)	Relevant to Job Yes	IDENTIFIED ONSITE HAZARDS (Not addressed by SWMS or standard control measures)	Inherent Level of Risk	(B) WHAT CONTROLS ARE TO BE APPLIED?	Residual Level of Risk	ALLOCATED TO:
Hazardous Manual Tasks			L		L	ALL
Hand Tool Operation	Y					✓
Power Tool Operation						
Hazardous Chemical Use						
Remote and/or Isolated Work						
Working Outdoors	Y		L		L	
Working (Fatigue, Wellbeing)	Y		L		L	
Hot Work (Grind, Cut, Weld)						
Vehicle Driving/Trailer Towing	Y		L		L	
Batteries and Battery Rooms						
Work in Switchyards / Power Stns						
Secondary System Test / Mntce						
Test Equipment Use						
Trans/Lube Oil/Fuel Handling						
Sensitive Area/Protected Species						
Earthworks						
Vegetation Management						
Waste Management						
Cultural Heritage						
Perform HV Switching						
Perform LV Switching						

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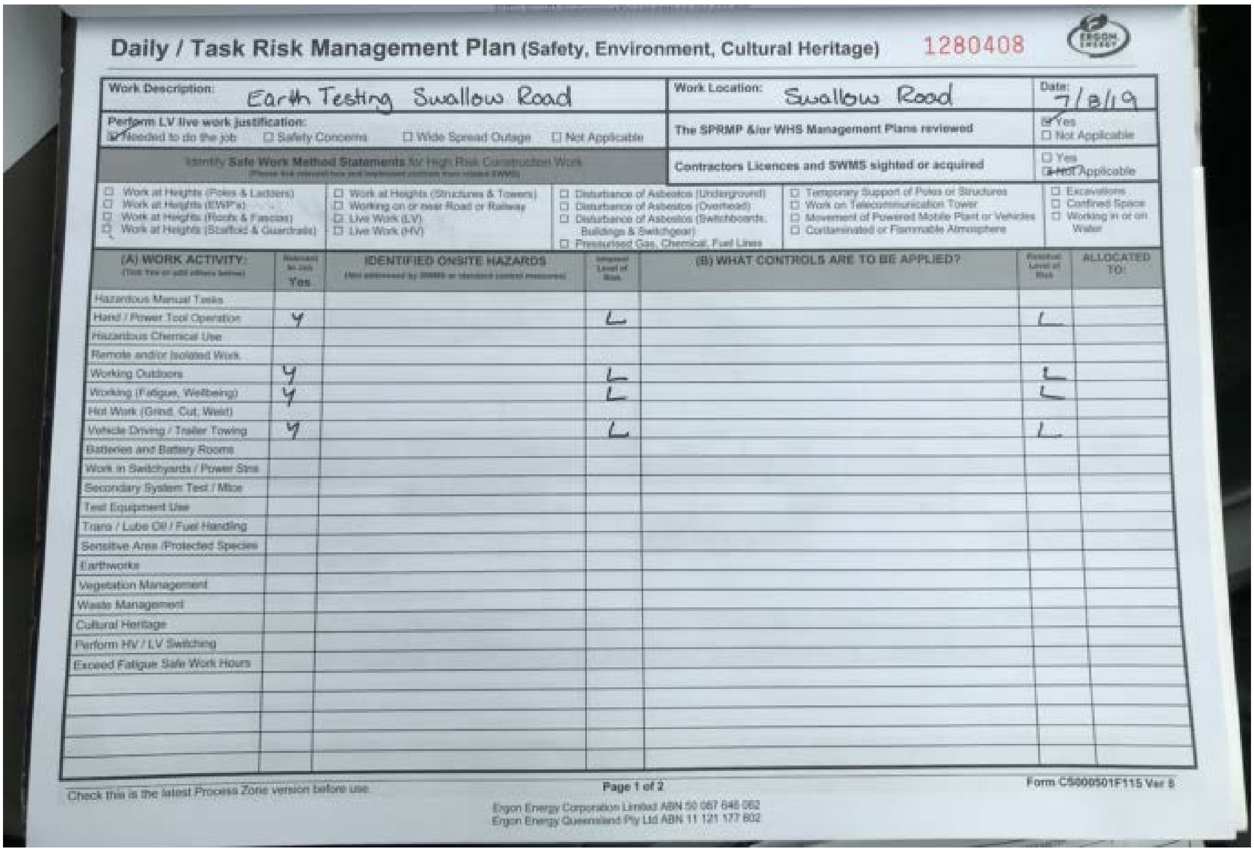
Ergon Energy Corporation Limited ABN 50 087 646 062
Ergon Energy Queensland Pty Ltd ABN 11 121 177 802

Figure 122: DTRMP Install Polylogger 17/01/2019


Daily / Task Risk Management Plan (Safety, Environment, Cultural Heritage) 1280408

Work Description: Earth Testing Swallow Road	Work Location: Swallow Road	Date: 7/8/19
Perform LV live work justification: ☑ Needed to do the job ☐ Safety Concerns ☐ Wide Spread Outage ☐ Not Applicable	The SPRMP &/or WHS Management Plans reviewed	☑ Yes ☐ Not Applicable
Identify Safe Work Method Statements for High Risk Construction Work	Contractors Licences and SWMS sighted or acquired	☐ Yes ☑ Not Applicable

☐ Work at Heights (Poles & Ladders) ☐ Work at Heights (EWP's) ☐ Work at Heights (Roofs & Fascias) ☐ Work at Heights (Scaffold & Guardrails)	☐ Work at Heights (Structures & Towers) ☐ Working on or near Road or Railway ☐ Live Work (LV) ☐ Live Work (HV)	☐ Disturbance of Asbestos (Underground) ☐ Disturbance of Asbestos (Overhead) ☐ Disturbance of Asbestos (Switchboards, Buildings & Switchgear) ☐ Pressurised Gas, Chemical, Fuel Lines	☐ Temporary Support of Poles or Structures ☐ Work on Telecommunication Tower ☐ Movement of Powered Mobile Plant or Vehicles ☐ Contaminated or Flammable Atmosphere	☐ Excavations ☐ Confined Space ☐ Working in or on Water

(A) WORK ACTIVITY:	Yes	IDENTIFIED ONSITE HAZARDS	Level of Risk	(B) WHAT CONTROLS ARE TO BE APPLIED?	Residual Level of Risk	ALLOCATED TO:
Hazardous Manual Tasks						
Hand / Power Tool Operation	Y		L		L	
Hazardous Chemical Use						
Remote and/or Isolated Work						
Working Outdoors	Y		L		L	
Working (Fatigue, Wellbeing)	Y		L		L	
Hot Work (Grind, Cut, Weld)						
Vehicle Driving / Trailer Towing	Y		L		L	
Batteries and Battery Rooms						
Work in Switchyards / Power Stns						
Secondary System Test / Mtce						
Test Equipment Use						
Trans / Lube Oil / Fuel Handling						
Sensitive Area /Protected Species						
Earthworks						
Vegetation Management						
Waste Management						
Cultural Heritage						
Perform HV / LV Switching						
Exceed Fatigue Safe Work Hours						

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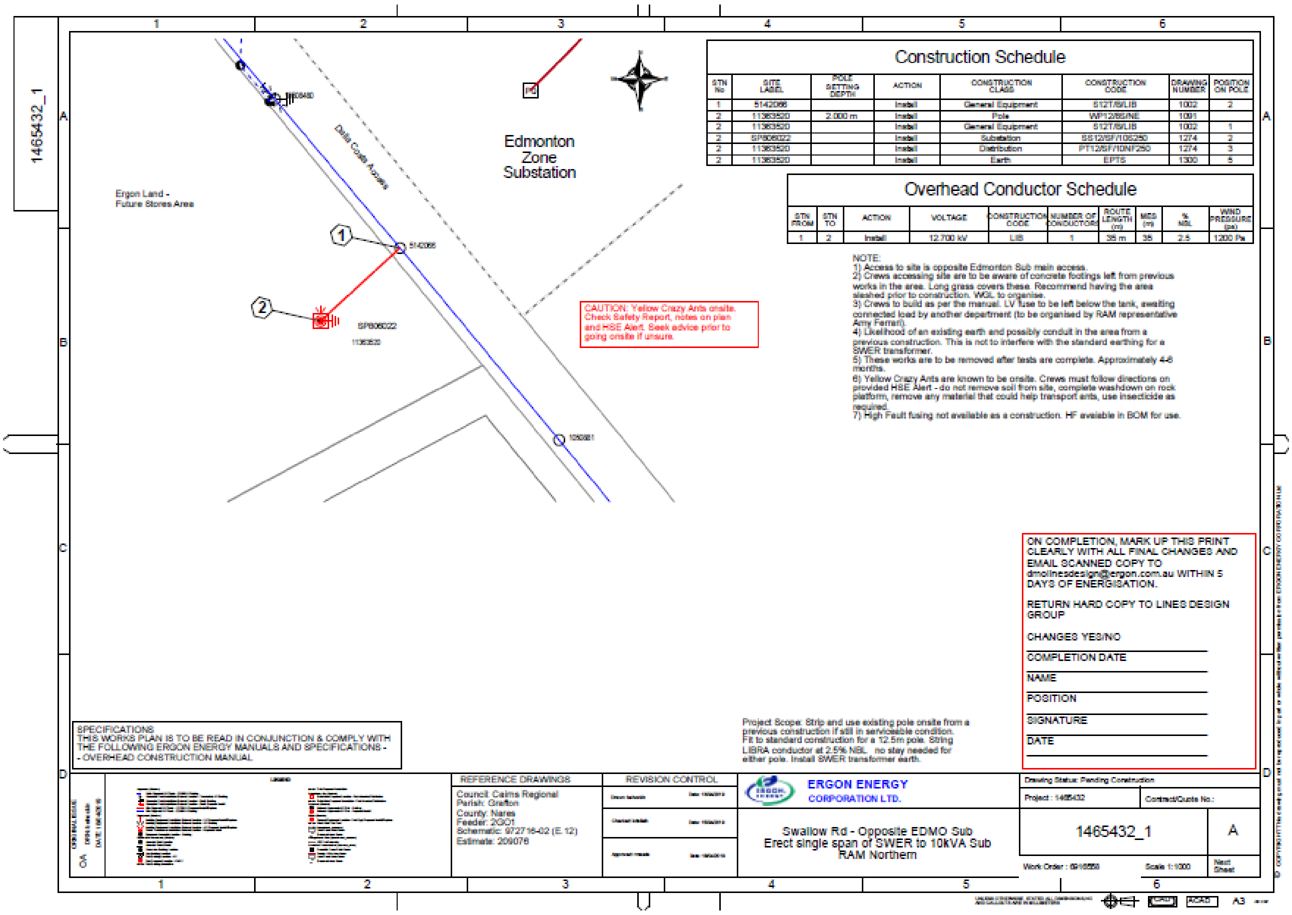
Ergon Energy Corporation Limited ABN 50 087 646 062
Ergon Energy Queensland Pty Ltd ABN 11 121 177 802

Figure 123: Risk Assessment from Earth Testing on the 7th August 2019

Appendix C: Trial Site Construction Plan



Appendix D: MATLAB Codes

BASIC SWER MODEL CODE:

```
%{
Dissertation model for ENG4111 and 4112 S2 2019 Student 19820762
This code runs the Simulink model for a basic SWER model. The
outputs from the simulation are plotted to analyse the current
and voltage waveforms.
%}

clear vars; %clear all variables before the code commences
close all; %close all previous plots
clear all; %clear all

sim('SWER_basic_model',0.1) %run Simulink model
figure (1) %Open new plot window
plot(Waveforms.time,Waveforms.signals(1,1).values) %Create plot from Simulink
Waveforms output
title(['Base Model - Waveforms for HV Earth and LV Current and Voltage']) %Place
a Title on plot
ylabel('Amplitude') %Place a label for the y axis
xlabel('Time') %Place a label for the x axis
legend({'LV Voltage','Total LV Current','HV Earth Current','HV Earth
Voltage'},'location','southoutside') %Place a legend on the plot
%legend('boxoff') %Turn the legend outline off
%hline = refline([0 0]); %Place a line at 0
%hline.Color = 'k'; %Make the line black
grid minor %Place a grid on the plot
xlim([0 0.04]); %Set the x-axis limits
print('C:\Users\Owner\Desktop\Uni\Thesis Model\SWER Basic Model Plot','-
dmeta');%Save plot image to file
```

LV TWO CLAMP CODE:

```
%{
Dissertation model for ENG4111 and 4112 S2 2019 Student 19820762
This code runs the Simulink model for a basic SWER model with a two
clamp LV resistance monitoring unit. The outputs from the simulation
are plotted to analyse the current and voltage waveforms. The final
measured resistance value is displayed in the Command Window.
%}

clear vars; %clear all variables before the code commences
close all; %close all previous plots

sim('SWER_basic_model_twoclamp',0.1); %run Simulink model
figure (1) %Open new plot window
plot(Waveforms.time,Waveforms.signals(1,1).values) %Create plot from Simulink
Waveforms output
title(['Two Clamp - Waveforms for HV Earth and LV Current and Voltage']) %Place
a Title on plot
ylabel('Amplitude') %Place a label for the y axis
xlabel('Time') %Place a label for the x axis
legend({'Total LV Current','HV Earth Voltage','HV Earth
Current'},'location','southoutside') %Place a legend on the plot
%legend('boxoff') %Turn the legend outline off
%hline = refline([0 0]); %Place a line at 0
%hline.Color = 'k'; %Make the line black
grid minor %Place a grid on the plot
xlim([0 0.001]); %Set the x-axis limits
ylim([-25 25]); %Set the y-axis limits
```

```
print('C:\Users\Owner\Desktop\Uni\Thesis Model\SWER Two Clamp Plot','-dmeta');%Save plot image to file
R=Resistance.signals.values(2); %Extract the resistance from the Simulink Model outputs
ohm=char(hex2dec('03A9')); %Set the omega character
fprintf('True HV Earth Resistance = %0.3f %s\n',R,ohm);%display value to command window
```

LV TWO CLAMP CODE - SIMULINK FUNCTION:

```
function R  = myfun(I,V)
R=V/I;
```

HV EARTH MONITOR CODE:

```
%{
Dissertation model for ENG4111 and 4112 S2 2019 Student 19820762
This code runs the Simulink model for a basic SWER model with a
HV resistance monitoring unit. The outputs from the simulation
are plotted to analyse the current and voltage waveforms. The final
measured resistance value is displayed in the Command Window.
%}

clear vars; %clear all variables before the code commences
close all; %close all previous plots

sim('SWER_basic_model_HV_resistance',0.1); %run Simulink model
figure (1) %Open new plot window
plot(Waveforms.time,Waveforms.signals(1,1).values) %Create plot from Simulink Waveforms output
title(['HV Monitor - Waveforms for HV Earth and LV Current and Voltage']) %Place a Title on plot
ylabel('Amplitude') %Place a label for the y axis
xlabel('Time') %Place a label for the x axis
legend({'Total LV Current','HV Earth Voltage','HV Earth Current'},'location','southoutside') %Place a legend on the plot
%legend('boxoff') %Turn the legend outline off
%hline = refline([0 0]); %Place a line at 0
%hline.Color = 'k'; %Make the line black
grid minor %Place a grid on the plot
xlim([0 0.02]); %Set the x-axis limits
%ylim([-25 25]); %Set the y-axis limits
print('C:\Users\Owner\Desktop\Uni\Thesis Model\SWER HV Monitor','-dmeta');%Save plot image to file
R=Resistance.signals.values(2); %Extract the resistance from the Simulink Model outputs
ohm=char(hex2dec('03A9')); %Set the omega character
fprintf('True HV Earth Resistance = %0.3f %s\n',R,ohm);%display value to command window
```

HV EARTH MONITOR CODE - SIMULINK FUNCTIONS:

```
function R_true = fcn(V_in,I_hv)
R_true= V_in/I_hv;

function R_hv = fcn(V_hv,I_lv)
R_hv = V_hv*52.072/I_lv;
```

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