University of Southern Queensland

Faculty of Health, Engineering & Sciences

Effectiveness of earth mat when jointing high voltage underground cables (33 kV and above).

A dissertation submitted by

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Abstract

It should never be assumed that when undergoing jointing or sheath repairs on underground high voltage (HV) cables, that they are at ground potential. Induced voltages and currents may be present from nearby cables and require engineering controls to be applied in order to reduce the risk of shock, by way of working earthed, insulated or isolated. Further, since all HV cables are sheath bonded to at least one substation, hazardous voltages will transfer to the remote joint bay site whenever a fault is present at the substation. Risk of ventricular fibrillation of the heart through step and touch potential is possible depending on many factors such as, protection timing, soil conditions, body weight and application of working earths. While the application of earthing is better than none, questions arise as to how much is adequate. Under certain conditions a sheath connection to earth rod is enough however a worst case fault scenario at the source substation requires more attention.

Uncertainty around the effectiveness of an earth mat within a 33 kV cable joint bay in order to mitigate unsafe situations has presented a topic that was realised through this project. Modelling of three scenarios with the use of the Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) software package has provided insight for a worst case substation fault situation. The results demonstrate that the application of an earth mat is effective in reducing both step and touch potentials for primary and backup protection timings. Analysis of results from remote earth injection testing indicated that only a portion of the fault current returns through the earth grid creating the transfer potential hazard. Further modelling with the reduced fault level has indicated that there may be situations that may not be hazardous without the use of earth mat.

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Limitations of Use

Certification 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.

Ryan Siddans

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This thesis was typeset using $\LaTeX\,2_\varepsilon$.

RYAN SIDDANS

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Glossary of Terms

Cable: A conductor that is insulated. It may be constructed as single cores or three cores. For 33 kV installations it will have protective coverings which may include a metallic sheath.

Cable Termination: The end of a cable which has a an insulated outlet installed for connection to other conductors.

CDEGS: Current Distribution Electromagnetic fields Grounding and Soil structure analysis.

Cigre: Collaborative global community committed to the world's leading knowledge development programme for the creation and sharing of power system expertise.

Circuit Breaker (CB): A mechanical switch that is enclosed found within a substation. A CB can break and make satisfactorily a circuit that is under the load it is rated and will automatically trip under a fault condition.

Conductor: An electric current capable object. Typically a cable, wire or metal form object.

Disconnected: Where parts of an electrical source are no longer connected. This can be achieved by separation, de-energisation, isolation or all of these.

Earthed: Phases that are short circuited so that they are connected electrically by means of a conductor to earth's general mass to effectively maintain electrical energy dissipation.

Earthing (Protective Earths): The connection of electrical equipment or apparatus that are part of the electricity supply network to ground (earth). This is so that dangerous voltages do not occur on electrical apparatus while being contacted by workers.

High Voltage (HV): A voltage that is in excess of 1000 V AC nominally or in excess of 1500 V DC.

Hot Spot: A point on a cable where local heating occurs.

Insulating Glove: Specific glove type that is used to protect through insulation, a person using it from electric shock.

Isolated: Disconnected from any energy source.

Lethal Current: Current in excess of 40 mA alternating current or 150 mA direct current through the human body. (Standards Australia 2010)

Live: An object that is energised or that is subjected to induced or capacitive voltages that are hazardous.

Low Voltage (LV): A nominal voltage above 50 V alternating current (AC) that is not in excess of 1000 V. It also applies when voltages are above 120 V for direct current (DC).

Network: A term describing the HV and LV distribution system.

Neutral: A circuit conductor that normally completes the circuit back to the source.

Operating Time: Relating to a devices protective time to operate.

Operator Earths: Approved earthing and short circuiting equipment applied to electrical apparatus, to ensure the electrical apparatus is effectively earthed as a requirement for the issue of an access/test permit. (Energex 2011)

Protection: See “Protection System”.

Protection System: Designed protection equipment used for the disconnection of electrical equipment within a power network under fault conditions.

Substation: Switchyards, terminal stations, or other places where HV is changed, converted, or transformed.

Supply: Supply of electricity.

Switchyard: A securely fenced area that holds electrical plant that is live and exposed.

Transformer: A piece of plant that is able to transform alternating current and voltage to different values at the same frequency.

Underground HV Network: A collective term used for electrical equipment such as underground cables and ring main units.

Voltage: The electrical potential difference between two conductors or between earth and a conductor.

WHS: Workplace Health and Safety

Work Practice: A set of detailed instructions to be used for particular work areas or particular pieces of electrical equipment.

Working Earths: Approved earthing equipment, additional to operator earths, applied to electrical apparatus following the issue of an access authority. Working earths are applied to limit the rise in potential difference at the work area. (Energex 2011)

Zone Substation: An intermediate substation that contains switchgear controlled by multiple relays and is used for transforming voltage and/or switching a higher voltage to a distribution voltage for example 33 kV to 11 kV.

Chapter 1

Introduction

This introductory chapter presents the necessary background information relating to underground cables, their construction, jointing, types of bonding and their importance in the electricity network; justify the need to undergo the study; state the project objectives; and describe the formation of the dissertation.

Energex is a subsidiary of Energy Queensland Limited, which is a Queensland State government-owned corporation. It's primary purpose is to build, operate and maintain the electricity distribution network for the South East Queensland region. The electricity distribution area is contained from the New South Wales border west to the base of the great dividing range and north to Gympie. It includes much of the urban areas of Brisbane, Sunshine Coast and Gold Coast. As such they provide distribution services to more than 1.4 million domestic and business connections with a population base of around 3.4 million people. Its power is supplied through more than 54000 km of underground cables and overhead lines, 288 zone substations and 50000 distribution transformers covering an area of 25000 km^2. (Energex 2021)

Due to the density of the urban areas within the Energex network, much of the high voltage (HV) network is delivered through underground cables.

Cables within the network undergo many phases throughout their life. Some of these phases include installation, maintenance, testing, repair and removal and it is during these times that work may be required to be performed where induced voltages or induced currents are involved. (Cigré 2020*a*)

1.1 Motivation

The motivation for this project came jointly from Transmission Services and Transmission Design within Energex. In considering their duty of care, as required under the Work Health and Safety Act 2011, it was suggested there was a need in looking at the effectiveness of the earth grid in joint pits.

Most issues with cables that require repair in the Energex network are from when there is a breakdown in the sheath of the cable. This causes a leakage to ground at this point and a fault occurs. The sheath fault is then located typically where the area is dug exposing the cable. A typical joint bay can be seen in Figure 1.1. The repair is conducted according to work practices, however, there is little documented regarding the earthing protection when conducting this work.

Figure 1.1: 33 kV cable joint bay (Source: Energex).

Current work practice for Energex when jointing states "that the earthing in the work area is to be sufficient" (Energex 2011) without adding any additional information to support how this is to be done. Typically galvanised chicken mesh laid in the area and is used as the working earth in the area. This presents a number of questions including "is it sufficient to protect in the event of induced voltages or currents being present?" In addition to this is working surface of the mesh grid providing a stable, trip free and safe work area that is not creating a different set of risks to the worker.

1.2 Aim and Objectives

The aim of this project is to primarily provide sufficient detail regarding the earthing requirements whilst working on underground cables, for the safety of the workers, in order to prevent injury or fatality.

The objectives of this project have been broken down into the points below. These have been developed from the *Project Specification* located in Appendix A.

- Document current practices and work procedures,
- Identification and review of relevant national and international standards,
- Review of current mathematical modelling and simulation potentially in conjunction with field tests, and
- Present recommendations aimed at improving work practices for cable jointing from a safety view point.

1.3 Overview of the Dissertation

This dissertation is organised as follows:

Chapter 2 - Literature Review presents the Literature Review including the gap in literature.

Chapter 3 - Methodology provides a statement of the planned approach taken to achieve the required project objectives for the modelling development, application and analysis.

Chapter 4 - Modelling development and their application for the purpose of defining and calculating of the earth grid within joint bays.

Chapter 5 - Results and Analysis which demonstrates the results with an analysis of these findings.

Chapter 6 - Conclusion and Futher Work concludes the dissertation providing a summary of the findings and suggests further work in the area of earthing in underground cable jointing bays.

1.4 Limitations

The following limitations and restrictions have been applied to this work:

- Cable joints for voltages 33kV and above.
- Cable joint bays that are not concrete.
- Exclusion of submarine cables.

To comply with Energy Queensland (EQL) ring fencing, confidentiality and security, when referring to EQL assets, exact locations, identification markings and substation names are not to be revealed. In their place, an alphabetical place-holder will be given.

1.5 Chapter Summary

This chapter has provided the background and introduction to this work. It delivers the aim of this dissertation which is to prevent injury or fatality when working on cables and sheaths that may be connected to a substation earth grid. The research into the relevant documentation is anticipated to give clear indication as to the approach and basis for the modelling component of this work. In addition, this will be able to used for the development and betterment of work practices by Energex.

Chapter 2

Literature Review

2.1 Introduction

The following literature review will establish the first two objectives from Section 1.2. The current practices and work procedures will be documented relative to the work for this project. In addition, a detailed approach will be provided into how a worker is exposed to induced voltages and transferred earth potential rise whilst performing work around 33 kV cables requiring repair, maintenance or additional attention.

A brief look at the relevant construction of features of high voltage (HV) cables, in particular, 33 kV will be required with related explanations and definitions of some of the principles, elements and attributes associated with working on HV cables and earthing. The properties of induced voltage and currents will also be discussed. Common cable connections will be shown within and between substations, as well as the various types of sheath bonding, focusing on single point and solid bonding.

An overview of earth potential rise and its effect on the worker at various locations will be taken, in particular step, touch and transferred potentials. This will lead onto detail regarding soil resistivity which can be impacted by conditions such as moisture levels and number of layers. The principle of an earth grid will be explained with a review into their performance and what voltages may be present.

Following on will be an outline of ventricular fibrillation and issues the human heart can encounter when electricity is involved. In particular this will look at fibrillation in relation to current and time and the importance these have on the heart.

The applicable national and international standards will be identified and considered regarding their approach and specification criteria for level of safety. The identification and review of these standards will be done to assist in the determination of which standards need to be regarded in terms of safety thresholds when working in cable pits and any additional requirements. In addition, the identification and review will also contain relevant research from applicable codes, guides and industry best practice. These standards and guides will be compared against each other into risk based and deterministic methods of approach.

Finally the knowledge gap will identify the need for this project and its importance for the safety of the worker.

2.2 Cable Construction

Underground HV cables are typically made of multiple layers. These layers, as shown in Figure 2.1, have different purposes and have been listed below with a short description.

- HV Conductor, also commonly known as the core, is the main current carrying component. It is typically made out of strands of copper or aluminium alloy.
- Conductor screen is the layer that protects between the conductor and insulation and also known as the inner semi-conducting layer.
- Inner insulation which is the main insulating material to protect the cable from leakage. Typically this is polyethylene construction however in the past this was of paper construction.

- Insulation screen is the layer to protect the insulation from the metallic sheath is also known as outer semi-conducting layer.
- Metallic sheath which is a conductive layer can be used to protect the core physically. This is also known as a ground shield.
- Amour layer, if required, is used to additionally physically protect the cable from damage however bending radius may increase if present.
- Outside insulation layer which needs to encase the whole cable and help prevent damage.

Cables are also able to be configured to include the three conductors in a single cable such that it is capable of carrying the three phases or as a single conductor. Most of the work in this project will be based around single conductor cables.

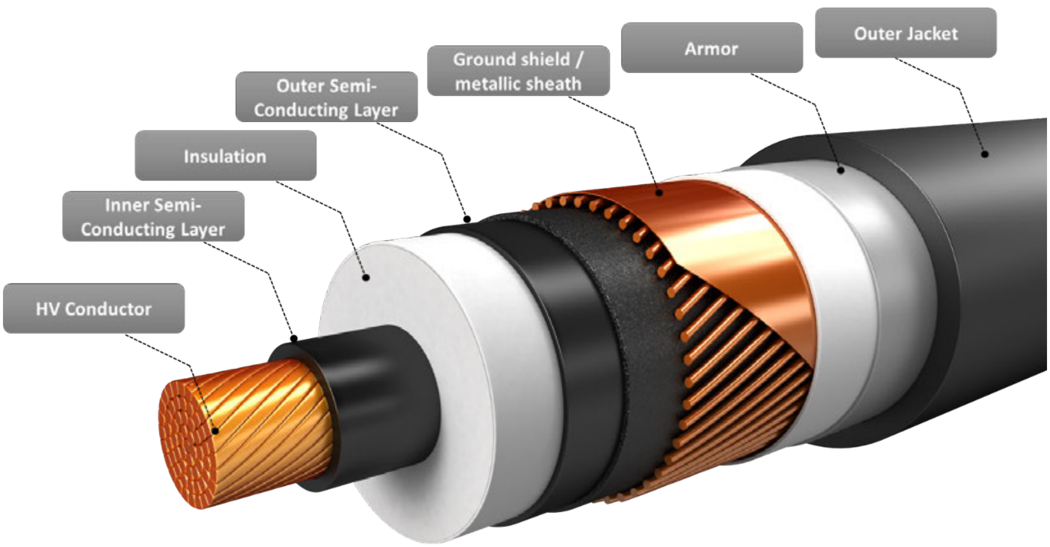

Figure 2.1: Typical construction of cable. (Rugged Monitoring 2020)

2.3 Cable Sheath

The sheath of a cable, along with the jacket and any armouring required, provide a protective outer covering for the cable installation during handling and protection against the ingress of moisture when buried in the ground. This section will go into detail the properties of cable sheaths.

2.3.1 Sheath Earthing

One of the requirements for HV cables connected within and/or between substations, as stated in AS2067, is that all sheaths or screens shall be connected to earth. Typically the connection will be to the substation earth grid. If this connection between the sheath and earth is broken, the cable core and sheath together act as a capacitive divider. As a result a hazardous voltage can be present causing worker safety and/or equipment voltage limits to be exceeded. Single core and triplex cables alike experience this effect. (Standards Australia 2018*b*)

2.3.2 Sheath Voltage

Whenever a current flows in a single core cable and the sheath is not bonded to earth at both ends, a voltage is induced on the sheath. The level of sheath voltage that is induced depends on the amount of flux that is interlinked with the metallic sheath. This sheath voltage increases as the centre line spacing of the cable is increased. Energex restricts the sheath voltage to 1000 V under fault conditions.

Permissible voltages are still limited by upper limits such as:

- Break down voltage of the outer cable layer under fault conditions, and
- Flash-over voltage of the sheath sectionalising joints.

2.3.3 Sheath Current

Sheath currents result in losses that are dependant on the cable's core current. These can be split into two categories according to the type of sheath bonding, which are:

- Sheath eddy current losses
- Sheath circulating current losses

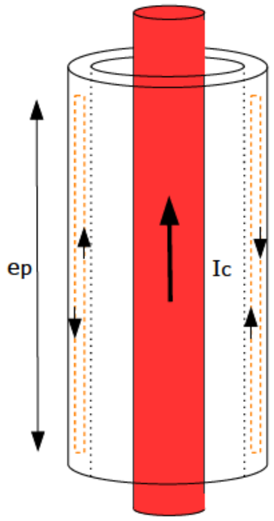

Figure 2.2: Eddy currents form in the cable sheath, depicted by the arrows, as a result of the magnetic field generated by the conductor current I_c. (Gouda & Farag 2015) Adapted.

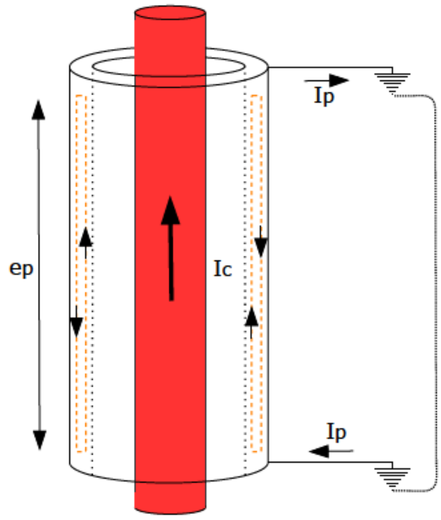

Figure 2.3: Circulating currents I_p form when the cable sheath is earthed. (Gouda & Farag 2015) Adapted.

Sheath Eddy Current Losses

An eddy current is defined as induced current on the surface of a conductor due to the changing magnetic flux. The loops or eddies on a conductor's surface are induced by the magnetic field of the current running through the conductor (I_c).

An induced voltage in the sheath,(e_p), results in current flow through the metallic sheath. The induced voltage is highest on the internal surface of the sheath, while it is lowest on the external surface of the sheath.

Figure 2.2 shows how this situation induces eddy currents circulating in the sheath. Eddy currents and losses are produced in single-core and three-core cable sheaths, irrespective of bonding method. When the cable conductors are in close proximity to one another, the eddy currents and losses are at their maximum.

Sheath Circulating Current Losses

As shown in Figure 2.3, in cases where the single conductor cable sheaths are bonded in more than one place, the current that is caused by the induced voltage flows in the fully completed cable circuit, resulting in I^2R losses. These losses are called circulating currents and may achieve up to the the same value as the core current. Circulating currents cause energy loss and reduce transmission efficiency. Cable temperature rise is one of the effects caused and adds to the heat generated by the losses in the cores and the dielectric. The heat in the cable influences the cable's life and decreases the capacity of transmission. A dry zone can form around the cable leading to a failure in the insulation from overheating. These sheath currents may be mitigated in a cable system, by varying sheath bonding techniques such as single point or cross bonding as described in Section 2.3.4.

2.3.4 Sheath Bonding Arrangements

There are various sheath bonding methods which are introduced as guidelines for connection in (Cigré 2020*a*). Single point bonded, solid bonded and cross bonding are the most common types of earthing of cable systems. These have been detailed below.

Solid bonded

Solid bonded sheath arrangement is where the sheath is earthed at both ends of the cable. This can sometimes incorporate midpoint earth as well. Attributes of this arrangement are as listed below:

- Common and simple system
- No monitoring or maintenance once installed
- Whilst in service there is negligible sheath voltage
- Commonly used for feeders between substations
- Not often used in short runs eg transformer cables
- Circulating currents formed in the sheath which de-rates the cable due to thermal rise. Approx. 10-15% less than special bonded sheaths.
- Induced voltage in sheath is greatest a the middle of the cable run as shown in Figure 2.4.

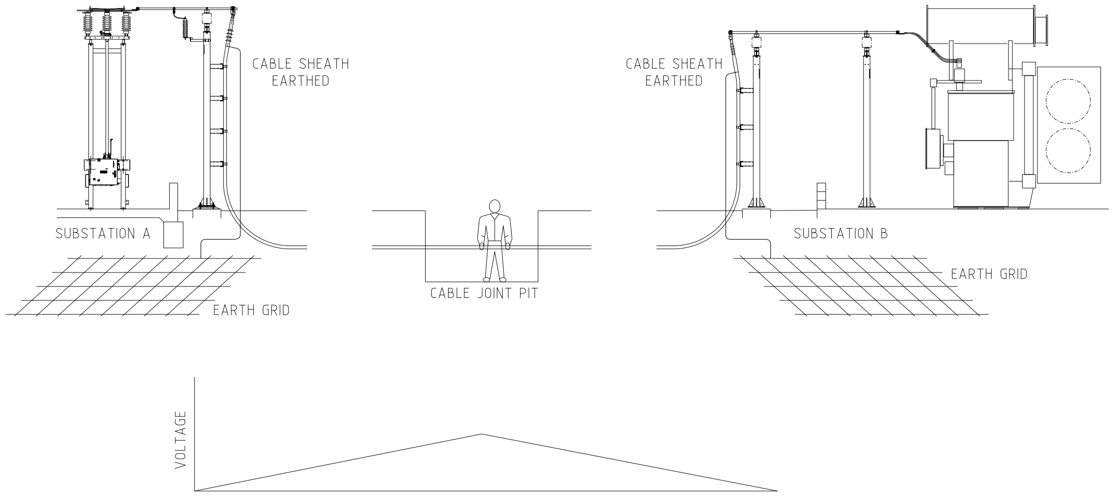

Figure 2.4: Solid bonded cable showing both ends of the cable. The induced voltage increases as the distance from the earthed end increases till the mid point of the cable and then decreases.

Single Point Bonded

Single point bonded is as the name suggests, the cable sheath is bonded to earth at only one end of any isolated section. Single point bonded cable characteristics are noted below:

- Used in short runs and typically within substations, for example transformer cables, circuit breaker interconnecting cables.
- Long runs employ a sheath voltage limiter (SVL) and these are placed at the unearthed end of the cable and these are used in the event of transient conditions.
- Length is limited due to sheath voltage rise at the remote (unearthed) end. It is possible to use a screen break joint to extend the length to double.
- On long runs an earth continuity conductor (ECC) is utilised.
- Circulating currents are not an issue and this means that there is almost negligible sheath loss.

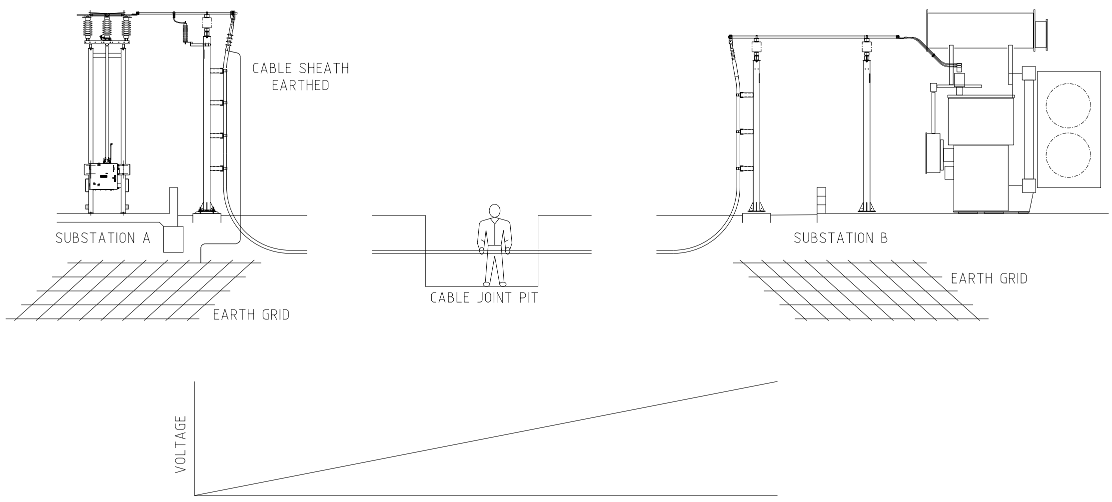

Figure 2.5: Single point bonded cable showing one end of the cable earthed while not earthed at the other. The induced voltage increases as the distance from the earthed end increases.

Cross bonded

Crossing bonded is typically a solid bonded set-up where the sheath is earthed at both end of the cable with the addition of the cable sheaths being transposed. Attributes for this type of bonding are listed below:

- Can give up to 25% more rating
- Applicable for long circuit lengths (typically 110 kV systems in Energex however there are some 33 kV)
- Period maintenance is required, and cost of installation is high
- Induced sheath voltage (circuits designed for theoretical maximum of 150V)
- Transient incidents such as lightning and switch may allow high voltages to appear across sectionalising insulation
- A balanced three phase system will allow the sheath voltage to cancel each other such that voltage is close to zero

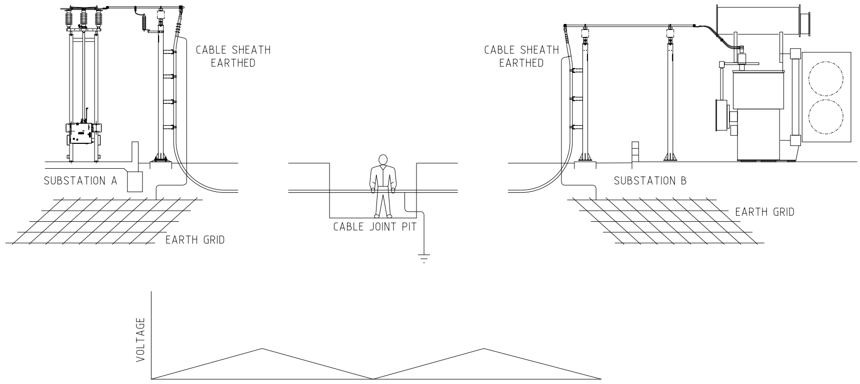

Figure 2.6: Cross bonded cable showing the configuration of the sheaths interchanged between phases. The induced voltage increases as the distance from the earthed end increases.

2.4 Induced Voltage

The potential of a cables core, screen and metal sheath can be influenced by a number of types of induced voltage. The induced voltage category can vary depending on the method of transfer between an electrical source and the inducted object. These categories are:

- inductive coupling
- capacitive coupling
- conductive coupling

When dealing with induced voltages, all three types of coupling need to be considered. Depending on how the metallic cable sheath is bonded to earth and the electrical systems around it, each type of coupling has a different effect on the cable system. Induced voltages need to be limited, to ensure safe working conditions whilst working on cable systems, as these may have an effect on the human body.

2.4.1 Inductive Coupling

A conductor is affected by magnetic coupling if it is even partially in contact with a power line or cable. Magnetic coupling is as a result of time-varying magnetic flux between the electrical source and insulated conductor, in this case. An induced voltage will be induced lengthways on insulated conductors or metal parts in the vicinity of the current (under normal or fault conditions). The insulated conductor for the purposes of this project is the cable that is being repaired or maintained but can also apply to installation. Magnitude of the induced voltage as a result of inductive coupling, is dependant on the current that is in the source of the system, distance in-between and the length that they are together.

Cigré (2020*a*) show, longitudinally induced voltage is calculated by:

$$U_i = Z_{12} \cdot I \tag{2.1}$$

where: Z_{12} is the mutual impedance between the two conductors,
I is the inducing current of the electrical source

Significantly, Equation 2.1 for induced voltage, is a worst case scenario and does not include the screening factor of other metallic components such as the metallic sheath.

2.4.2 Capacitive Coupling

When an energised power system is operating, an electric field is set-up between the source of power and any conductive object that is not earthed. A capacitive voltage divider is formed along the unearthed electrical object. The capacitive voltage divider affects the amount of voltage seen on the unearthed object in relation to the voltage at the source.

Unearthed metal objects or parts of a cable system near high voltage conductors, for example overhead lines and other underground cables, can become capacitively coupled to the high voltage conductor. The whole cable is affected even if only a portion of it is exposed to the electric field. Induced electric charge due to capacitive coupling can remain on the conducting parts of the insulated cable even after removing the source of the capacitive coupling. The induced electric charge if not earthed, can remain for some time and is commonly referred to as 'static electricity'. The occurrence of capacitive coupling in underground cables generally has a lower risk over other conductor systems.

When a cable is left disconnected a standing voltage may be present and it is recommended that the core of the cable and the metal sheath are shunted and locally earthed to prevent this.

2.4.3 Conductive Coupling

Conductors that are connected to a ground system that is in the path of earth return fault currents could transfer potential rise from that earth system to any of the other earth systems that they may be joined to. HV cables can often be the connection between two substations which will have different earthing systems due to a number of reason, such as soil resistivity layers, size of earth grid and so on. This connection and situation will cause a transfer of earth potential rise which is discussed in Section 2.7. The locally earthed and remotely earthed locations will therefore have a voltage difference. This has been shown graphically in Figure 2.7 which depicts the two ends of the cable at different substations with remote location earth pit along the cable.

2.5 Substation and its Earthing System

A substation within Energex is part of the electrical distribution system. Essentially a substation transforms voltage from high to low by way of transformers - though it may perform it in reverse as well as other functions. Typically a mesh grid of interconnected bare copper conductors is placed 500 mm below the surface of the ground and metallic structures within the substation are connected. In the event of a fault, the fault current returns through the earth grid to the source, typically the neutral of the substations transformer. The equivalent circuit for an earth fault can be seen in Figure 2.8.

As a result, for a ground fault current to be sufficiently high, the path from fault back to the transformer neutral should have a resistivity as low as possible. The earth grid for a substation is integral to the performance and safety of its operation by reducing the resistivity of the ground it is situated. Within the Energex network there are many substations that are interconnected using ring networks, providing stability against outages and allowing greater flexibility when performing maintenance. As such, many of

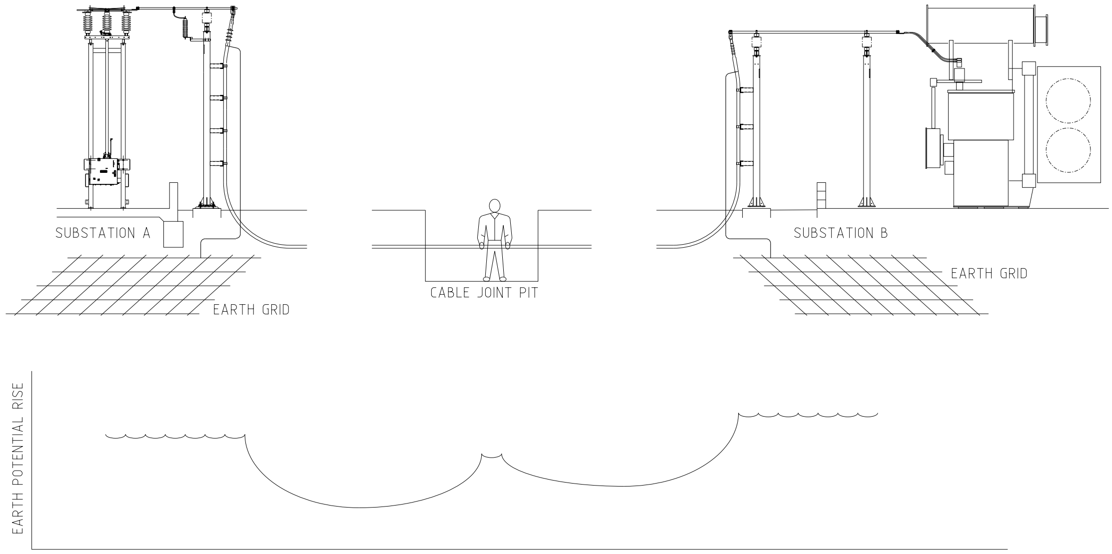

Figure 2.7: Cable route shown which is connected at two different earth grids with a remote cable joint earth pit depicted in the middle. This may cause an earth potential rise or difference in voltage at the other earth grids when a fault occurs.

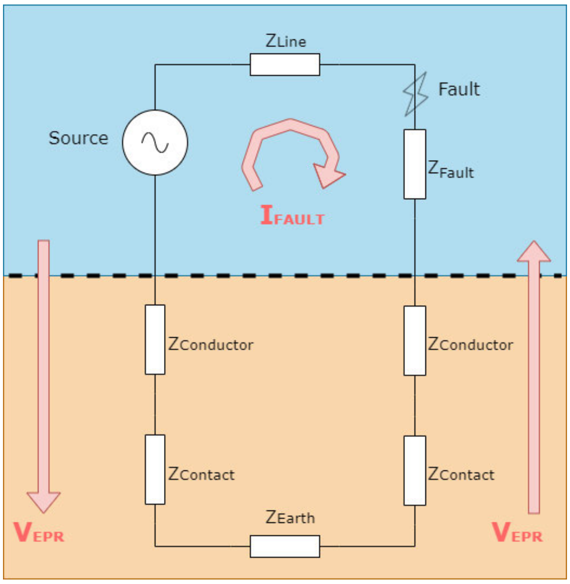

Figure 2.8: Equivalent circuit of Earth fault condition. (SafeEarth 2018) Adapted.

the substations are positioned in urban and high residential areas and feeders are placed underground.

2.6 Earthing and Earthing Conductors

Earthing as per AS3000 is defined as "*connected to general mass of earth in accordance with the appropriate requirements of this Standard*". (Standards Australia 2018*a*)

Earthing conductor is the term used for a protective conductor that connects an earthing termination or terminal to an earthed electrode. The copper conductors are placed beneath the surface of the soil, typically 500 mm below surface level. These conductors are joined with other conductors to form a grid or mesh of earthing conductors. Earth rods are then placed at strategic places within the mesh to help provide additional contact with the ground. The length of the earth rods depend on many site conditions such as soil conditions. In a fault, an earth grid at the location of the source serves as a collector for returning fault currents to return to the source or as a means of dissipating the energy generated by the fault.

Earthing conductors are required to be a minimum conductor size for earthing. The reason for this is to be sufficient in cross-sectional area to be able to carry any fault currents without undergoing damage or degradation that may be reasonably expected (Code of Practice 2020). For the purposes of this project the conductor to be utilised will be a minimum of 16 mm^2. Common practice within Energex involves the use of 16 mm^2, 35 mm^2, 70 mm^2 and 120 mm^2 cable conductor and is dependant on the application and current capacity required.

2.7 Earth Potential Rise (EPR)

Known as Earth potential rise (EPR), ground potential rise is the maximum created voltage that has been raised on the earth when compared with a remote earth. It is measured from the point of injection into the earth grid. EPR occurs when an earth fault condition is present as shown in Figure 2.8. Whilst distribution cables are often three core design, transmission cables due to their size, are often single core only. To maximise the rating of the cable, the sheaths are bonded in one such manner as described in Section 2.3.4. These systems may introduce high voltage earths which are connected to the cable sheaths. The presence of these high voltage earths can extend to earth potential rise at these earths or any other connected earth grid systems under an earth fault. In some cases this can be kilometres away. The potential rise magnitude is dependant on the relative impedances as discussed in Section 2.4, distance from remote ends and earth impedance. It is possible for any faults in the field to produce an EPR at the site of the fault as well as the supplying substation. Metallic pipelines and other lines (such as telecommunications lines) in the vicinity of these earth's may be subjected to short duration high voltages from such events. As such, Standards Australia (2006) stipulate that the maximum allowable earth potential rise is dependant on the fault duration.

Earth potential rise can be calculated as outline in (IEEE 2013) simply by:

$$EPR = I_g \cdot R_g \tag{2.2}$$

where: I_g is the ground current,
R_g earth grid resistance (Ω)

The earth grid resistance R_g computation is shown below:

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} \tag{2.3}$$

where: ρ is the soil resistivity (Ω·m),
A area covered by the earth grid (m^2)

2.8 Step, Touch and Transferred Voltage

The voltage gradients on the earth's surface near the earthing system due to the earth potential rise can create hazards known as step, touch and transferred voltage. The transferred voltage from touch due to earth potential rise is visually demonstrated in Figure 2.9.

As an individual stands near an earthed energised object, a step potential occurs between that person's feet. This is the difference in voltage between two points located at different distances from the electrode, given by the voltage distribution curve shown in Figure 2.9. By simply standing near the earthed point, a person could be injured during a fault.

During earth fault conditions, it is important to keep the step and touch potentials within acceptable limits at a substation in order to ensure people's safety. There are various national and international standards that address these maximum permitted touch and step potentials, which can be found in Section 2.14. Figure 2.9 shows the various contact scenarios, including step and touch which are described below.

Touch potential

An earthed structure's touch potential (V_t) is defined as the potential difference between an outstretched hand touching it and a person's foot. A person is assumed to reach a maximum distance of approximately one metre. When the grounded object is earthed at a distance that is is remote from the place where a person is in contact with it, the magnitude of the touch potential may be nearly equal to the full voltage across the grounded object. As an example, this situation could be where a worker in a remote cable pit is fixing the cable sheath which is connected to the substation earth grid.

Mesh potential

The potential difference between a structure that has been earthed and a point of the earth grid mesh. This is basically a touch potential that is in a worst case setting.Where a grid consists of a mesh size that is equal, the meshes near the corners of the grid will have the greatest potential.

Step potential

Step potential is where a person is positioned such that their feet are outstretched and separated by one metre without touching any earthed structure.

Transferred potential

By means of a metallic conductor that carries an earth referenced potential from or into a substation, a special case of touch potential is produced. The touch potential during fault conditions can be extremely high, since it is possible for the resulting potential to equal the entire earth potential rise.

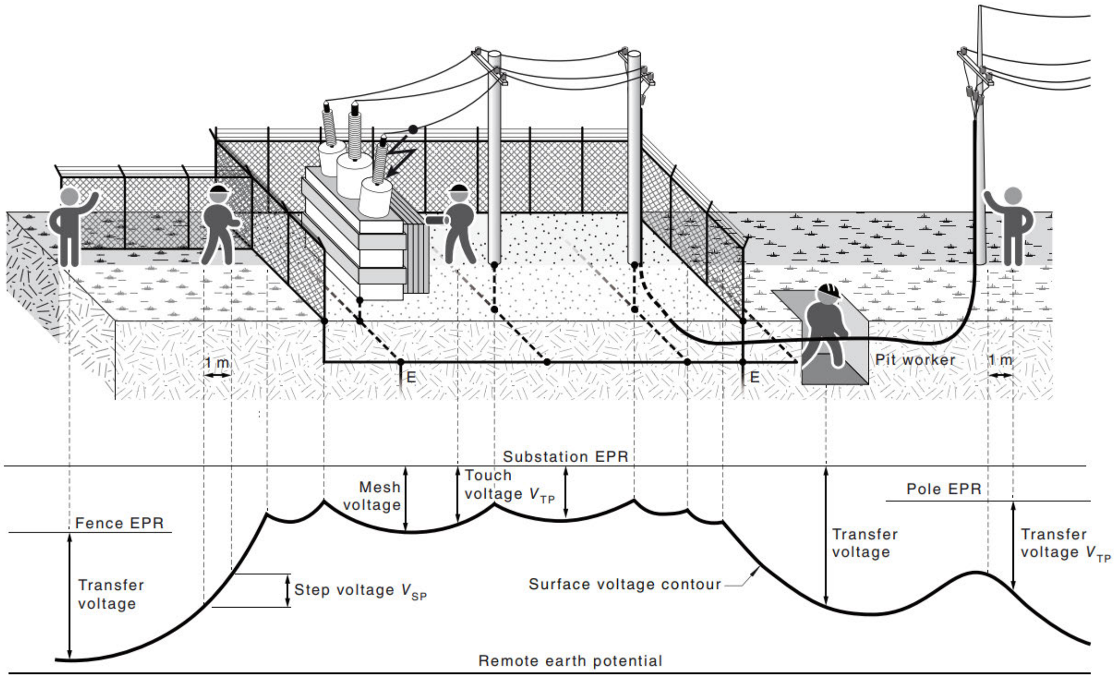

Figure 2.9: Step, touch and transferred voltage hazards from fault or induced voltage. (Standards Australia 2018*b*)

2.9 Transients, Faults and how they interact

Earthing systems provide a reliable and safe method of power system operation. It is also able to provide a true reference for any protection systems in place to operate in an attempt to limit damage to the network.

If a fault or electrical discharge occurs within an earthing system, whether it is at a substation or remote location, a steep front is induced that causes inductive effects in the earthing system. An offset voltage rise occurs in the area of the earthing system near the injection point during events such as these. The distribution is uneven and can be explained by waves of current and voltage travelling along the earth grid conductors. This can be problematic for workers in a remote pit location where the EPR can be significant under such circumstances.

Current work practices within Energex are such that no work is to be conducted when weather conditions are likely in order to prevent this situation from happening.

2.10 Soil Resistivity

In electrical terms, soil resistivity is a quantifiable measure of the soil and its resistance to the flow of electricity. The resistivity of the soil is impacted by varying factors made up of soil composition, temperature and the amount of moisture present. As soils types are rarely homogeneous, their resistivity differs according to their depth and geographical location. Ideal situations for soil resistivity would be to have the lowest possible resistance. This can be debated though and is dependant on the situations where step and touch voltages are concerned, as a high resistivity ground can be safer if the right measures are put in place.

Soil resistivity, as noted above, due to its varying nature is extremely difficult to set at a baseline value. Much effort has been spent in trying to find a method in determining the soil resistivity that will suit all situations. Unfortunately this has been relatively unsuccessful due to the largeness of the topic as outlined by the IEEE (2013), who tasked a commission for simplifying calculations.

There are a number of approaches to take when required to take soil resistivity measurements. The most common approaches to soil resistivity are the Wenner and Schlaumberger methods. While it has been decided for this project to limit this component of research, due to the physical size of the work area and possible variation in soil conditions, for completeness the Wenner method will be described below. For modelling purposes some typical values will be used for the area concerned in the modelling phase and can be found in Section 4.4.

Typical values are shown in Table 2.1.

Table 2.1: Range of earth types and their resistivity. (IEEE 2013)

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

2.10.1 Wenner Method

The Wenner method is most common due to its simplified approach by using four electrodes equally spaced as shown in Figure 2.10. The method used to calculate the soil resistivity (ρ) is shown in Equation 2.4.

$$\rho = 2\pi a R \tag{2.4}$$

where: ρ is the soil resistivity (Ω·m),
R resistance measured, and
a spacing of the probe.

Two electrodes are used as the fixed current injection point I as well as the return point. The remaining two electrodes are measured for the voltage difference that has been generated by the generated electric field. As the spacing of the electrodes is increased, the penetration in both horizontal and vertical directions is increased giving a better understanding of the conditions. The electrodes are stepped out equally in steps of 1 m up to 10 m and then increasing the step size to 5 m. Typically this is taken out to a distance of 25 m or more depending on the cables length. This can pose a serious challenge and hazard in urban environments as the public and or traffic are likely to interfere with measurements, especially if roads require crossing to get the outer results.

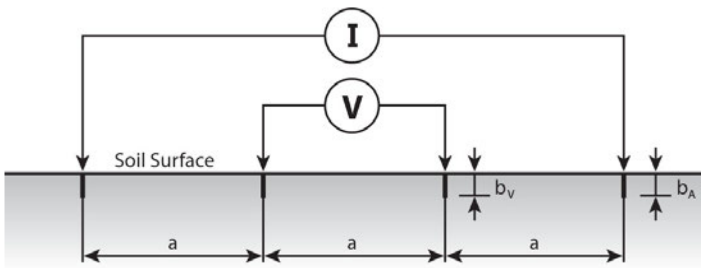

Figure 2.10: Wenner method showing four electrodes spaced equally to measure soil resistivity. (EasyPower n.d.)

2.11 Act, Regulation and Code

Acts of legislation form the pinnacle of the framework of modern society that assists in ensuring the safety and well-being of local and global communities. Acts are a class of documents that establish safety, responsibility, and benefit for the greater community.

- Acts
- Regulation
- Codes of Practice
- Australian Standards
- Industry and company guidelines
- Best practice

The Queensland Workplace Health and Safety Act and Regulation 2011 legislate the overarching action that must be taken for workers. Section 17 of the Act regarding the management of risks states:

> A duty imposed on a person to ensure health and safety requires the person -
> (a) to eliminate risks to health and safety, so far as is reasonably practicable; and
> (b) if it is not reasonably practicable to eliminate risks to health and safety, to minimise those risks so far as is reasonably practicable.

Further in Section 35 of the Regulation it states:

> A duty holder, in managing risks to health and safety, must -
> (a) eliminate risks to health and safety so far as is reasonably practicable; and
> (b) if it is not reasonably practicable to eliminate risks to health and safety - minimise those risks so far as is reasonably practicable.

As such, these sections must be followed to avoid penalty. This validates the reasoning behind providing a safe work area for underground workers placed in this project's particular scenario.

The Electrical Safety Code of Practice, whilst more specific than the Act and Regulation, seems to only provide guidance and often refers to standards and industry best practice. The Code of Practice provides a risk based approach by reducing it as far as reasonably practicable. Particularly for HV distribution centres, the Code of Practice (2020) asks for compliance with ENA (2006) and IEEE (2013). Specifically regarding step and touch voltages, special and frequented locations "shall be assessed and suitably controlled in accordance with safe design principles and best practice standards and guidelines" (Code of Practice 2020). Further, step voltages "should not exceed twice the values of prospective touch voltage" (Code of Practice 2020). However in reviewing a number of standards, both national and international, it was observed that some were deterministic and some probabilistic in approach which made it difficult to understand as to which approach should be used for the later modelling phases.

2.12 Relevant Standards

The standards and guides have been split to assist in distinguishing between the two levels. Below details the differences between national standards. The following national standards that cover the topics regarding HV cables are listed below. As a result most of these were accessed to determine their suitability.

- AS3000:2018 (Electrical installations wiring rules)
- AS2067:2016 (Substations and high voltage installations exceeding 1 kV a.c.)
- AS7000:2016 (Overhead line design)
- AS4853:2012 (Hazards on metallic pipelines)
- AS3835.1:2006 (Earth potential rise - Protection of telecommunications network users, personnel and plant - Code of practice)
- AS60479.1-2010 (Effects of current on human beings and livestock)

AS3000:2018 details the wiring rules that are required to be met when working with low voltage cabling. Interestingly (Standards Australia 2018*a*) defines 'earthed' as "connected to general mass of earth in accordance with the appropriate requirements of this standard". There is a little ambiguity around this statement as to whether this means if there is an intention to bond something to the earth to form an equipotential or just connected to something that is earthed.

AS2067:2016 specifies earthing standards and situations that are to be met in HV situations. Substations fall into this section and is highly detailed is given specifically in the appendices and how to conduct earthing in these environments. This latest version has received an upgrade in its earthing content.

AS7000:2016 details the earthing requirements for overhead wires. It details the when, how and where to connect an earthing system to the overhead wire system including transition points such as underground to overhead pole terminations.

AS4853:2012 looks at ensuring hazards are not created on underground metallic pipelines. Due to the nature and placement in the soil, these pipelines form part of the earth and need to be taken into consideration when earthing systems are being designed.

AS3835.1:2006 provides the framework for the protection of telecommunication users and equipment in relation to earth potential rise. It specifies a 430 V requirement to be met such that earthing systems do not breach this level. It provides a hard limit and has been in effect for many years.

AS60479.1-2010 is not an earthing standard, however it looks at the effect of current flowing through humans and livestock, in particular, it details the effects of ventricular fibrillation of the heart.

There is an important distinction between AS3835 requirements for Australia, which are based on the average expected failure frequency of sub-transmission and transmission circuits, rather than the limits referring to body current as described in AS60479.

2.13 Relevant Earthing Guides

The relevant industry earthing guides are listed below:

- ENA EG1 (Substation Earthing Guide)
- ENA EG0 (Power supply systems)
- IEEE 80 (Guide for Safety in AC Substation Grounding)
- IEEE 81 (IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System)

ENA EG1 - This is an Australian earthing guide that looks at substation design.

ENA EG0 - This Australian earthing guide looks at quantifiable assessment of risk instead of specifying a safe voltage. principles of this are evident in a number of Australian standards such as AS7000, AS2067 and AS4853. It defines an earthing design process and risk management is explicitly considered as part of the process. It also provides a method for quantifying hazards through the calculation of ventricular fibrillation. Additionally it provides a method quantifying the 'likelihood' through a coincidence of probability.

IEEE 80 - This is an American earthing guide for substations and is widely utilised.

IEEE 81 - This is another American earthing guide specifically for use in measuring and testing.

2.14 Comparison of Earthing Standards and Guides

These approaches are the traditional or prescriptive method against the seemingly newer risk based method as outlined in (ENA 2010). The prescriptive response to earthing safety, relies heavily on set values for calculations and results measured against hard limits. This has been traditionally the way that many utilities have taken according to and arguably the simpler approach when formulating policy and working procedures. Newer approaches to calculation have emerged however, with guides such as EG-0. These involve using risk based methods for calculating allowable body currents along with probability curves, comparing against risk profiles and weightings that are driven to reduce the level of risk to as low as reasonable. Their application to the project will be considered and compared in preparation for the modelling in later stages of this project. Comparison of prescriptive and risk based methods of standards and industry guidelines as shown in Table 2.2

Table 2.2: Comparison of prescriptive and risk based methods of standards and industry guidelines

Prescriptive	**Risk Based**
AS3000	AS2067
AS3835	AS4853
EG1	EG0
IEEE 80	AS7000
	Cigre B1.44

Standards Australia (2006) give static voltage limits for EPR with no risk to be taken into consideration as shown in Table 2.3. Standards Australia (2018*b*) by comparison of amendments has changed from IEEE source of safety criteria (1984), to a European one, then to a ENA (2010) for the latest revision of 2018. Touch voltage criteria as set out in ENA (2010) is based on what is the actual risk and its formula based probability of a fatality is set out below in Equation 2.5.

$$P_{fatality} = P_{coinc} \times P_{fib} \tag{2.5}$$

where: $P_{fatality}$ probability of fatality,
P_{coinc} probability of coincidence, &
P_{fib} probability of fibrillation.

ENA (2010) the quantified risk analysis methodology utilises as its basis the fact that a fatality due to an earth fault can only occur if both of the following situations exist:

- a person is present when a fault occurs, and the
- touch (or step) voltage generated is sufficient to allow a large enough current to pass through the body for sufficient time to cause fibrillation of the heart muscle.

Therefore, the evolution of earthing and obtaining a safe voltage, has become a risk based approach that aims to reduce the hazard to a level that is as low as practicable, away from a deterministic one. This allows utilities to mitigate risks without over capitalising on expenditure if the risks can be assessed low enough.

Table 2.3: Australian EPR hazard voltage limits. (Standards Australia 2006)

	Limit Category		
	Category A	**Category B**	**Category C**
Reliability	High	High	Not high
Fault duration	≤0.35 s	≤0.5 s	Any
EPR hazard voltage limits (V)	1500 or 1000	10000	430

2.15 The Human Body and Ventricular Fibrillation

By definition, ventricular fibrillation is a malfunction of the heart's rhythm. It is characterised by extremely rapid and chaotic electrical impulses. These impulses, as can be seen on the right in Figure 2.12, cause the ventricles, depicted in Figure 2.11, to quiver uselessly, instead of pumping blood. When the blood pressure plummets as a result of ventricular fibrillation, vital organs are cut off from receiving blood. (LeMone 2011)

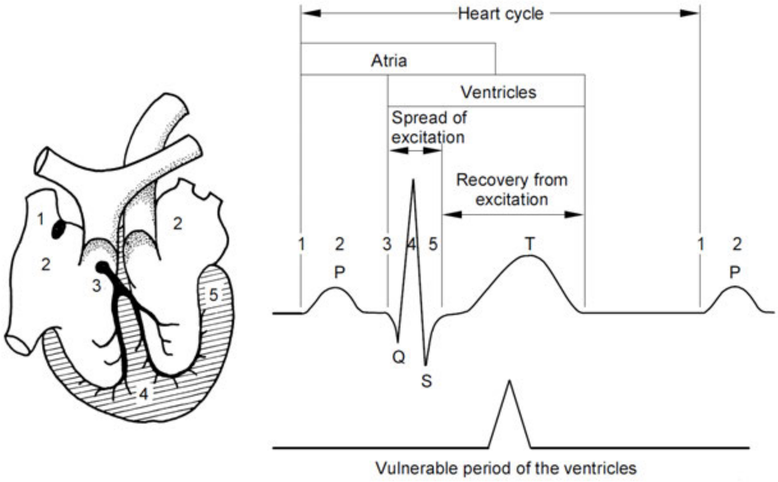

Figure 2.11: Occurrence of the vulnerable period of ventricles during the cardiac cycle. (Standards Australia 2010)

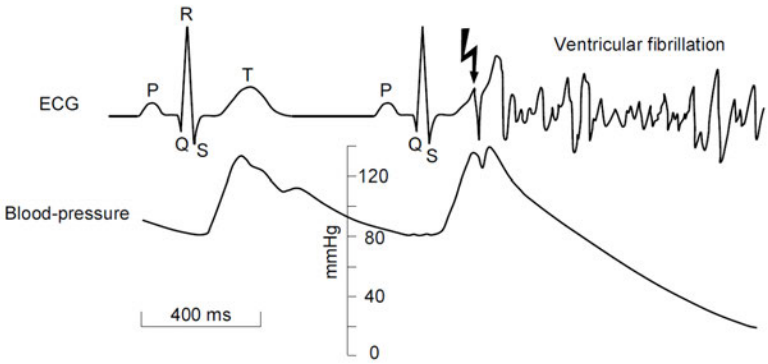

Figure 2.12: Triggering of ventricular fibrillation in the vulnerable period - Effects on electrocardiogram (ECG) and blood pressure. (Standards Australia 2010)

Dalziel discussed that when electricity makes contact with the outside parts of the body, which are positioned such that the current path is through the chest, muscular contraction of the chest muscles may take place when above the threshold. This may produce ventricular fibrillation which is nearly always fatal, among other effects. Dalziel states regarding the extreme importance of the fibrillating threshold that "No man should knowingly be subjected to shocks of this magnitude" (Dalziel 1956). With human experimentation impossible at normal voltages, Dalziel's experiments were scaled down from actual voltages but in doing so has allowed insight into what the human body thresholds are, as shown in Table 2.4.

Table 2.4: Notable average level currents for effects in men developed by Dalziel's self experiment research. (Dalziel 1956)

Effect	
Perception Level (the least amount of current detectable by the ungloved hand)	1.1 mA
Painful Shock, painful but muscle control not lost	9 mA
Painful Shock (Let Go Threshold)	16 mA
Possible Ventricular Fibrillation:	
With a duration of 0.030 s	1000 mA
With a duration of 3.000 s	100 mA

Dalziel (1956) assumed 99.5% of all individuals could safely handle the path of current with magnitude and duration without entering ventricular fibrillation by establishing Equations 2.6 and 2.7 below:

$$i_b(t) = \frac{k}{\sqrt{t}} \qquad 0.03 < t < 3 \text{ only} \tag{2.6}$$

where: t is the current duration in seconds,
k 0.116 for 50 kg body weight
k 0.157 for 70 kg body weight

$$v(t) = \frac{k \cdot Z_b}{\sqrt{t}} \qquad 0.03 < t < 3 \text{ only} \tag{2.7}$$

where: t is the current duration in seconds,
k 0.116 for 50 kg body weight
k 0.157 for 70 kg body weight
Z_b 1000 Ω body impedance

Equations 2.6 and 2.7 were developed further by the IEEE as the prospective step and touch voltage equations shown in Table 2.5. These are recommended and used by ENA

(2010) and IEEE (2013).

Table 2.5: Step and Touch equations for different scenarios. (IEEE 2013)

	Prospective Touch Voltages	**Prospective Step Voltages**
50 kg body weight (To be used in areas with with public access)	$\frac{116-0.174C_s\rho_s}{\sqrt{t}}$	$\frac{116-0.696C_s\rho_s}{\sqrt{t}}$
70 kg body weight (May be used in/restricted area within a substation)	$\frac{157-0.1236C_s\rho_s}{\sqrt{t}}$	$\frac{157-0.942C_s\rho_s}{\sqrt{t}}$

Where:

C_s De-rating factor relating to surface layer thickness and resistivity.

ρ_s Resistivity of surface material (Ω·m).

t Duration of shock current (seconds).

The human body is made up of different tissue densities. Electric current flowing through these different parts (such as skin, muscles, tissue, blood) exhibit an impedance which is made up of both resistive and capacitive components which has been covered in greater detail in Standards Australia (2010). This impedance can be reduced with the application of personal protective equipment (PPE) such as electrically rated safety footwear which are rated for particular voltage. Therefore, when modelling is conducted it can be expected/assumed that a worker will be following procedures and will be using the appropriate footwear as they are not a member of the public but an employed worker.

2.16 Current Work Practices and Industry Best Practice

A search for current work practices in use around Australia was conducted regarding the earthing practices whilst working in a joint bay. This is detailed below along with industry best practice which has been reviewed and detailed.

2.16.1 Energex - Current Work Practice

Current work practice procedures for Energex was found in their internal work practices document management system. Energex (2011) detail in their work practice the method of working with induced voltages and transferred earth potential rise on cables of 33 kV and above. Specifically this is for installing and working on the metallic parts of an insulated cable of 33 kV and higher. This work practice briefly details safety procedures and practices that must be followed as part of their safety policy. Before work can begin a work-site hazard management form must be completed to identify hazards that may exist at each particular work-site, if multiple. The procedure provides background on transferred earth potential rise to help the workers understand the dangers and how it may apply to their particular work site.

At the work site, local working earths must be established to limit the rise in potential difference. A local earth is to be connected/bonded to both sides of the metal components (that have been cut). If a local earth is not available then a temporary local earth must be established. Whilst the work of connecting local earths is carried out, the worker is to wear the appropriate class insulating gloves.

The work practice does not clearly define how much direct earthing is to be applied, nor does it refer to earth matting or mesh to be placed in the work area.

2.16.2 Transgrid - Current Work Practice

Transgrid (2020) state in their work practice, that where the work has the possibility of hazardous voltage rise occurring, the preferential use of bonded earth mat working condition must be considered. In the case when this method is not able to be utilised then the direction is to work with the approach of insulated working conditions. In addition the local work site earth mats should not have remote earth's connected. Where work is to be conducted and the management of induced currents and voltages is needed then the cable is to be isolated.

For a bonded earth working condition, as defined in Transgrid's work practice, the earth mat is to comprise of a material that is conductive for example galvanised mesh with an aperture of 25 mm. From the working position, the mesh must continuously cover and be bonded on the floor, wall, and ceiling as necessary. At each end of the pit, an earth rod must be driven a minimum of 600 mm into the ground and bonded. This system may require additional consideration as the tested overall resistance between the equipotential conductors and the surrounding earth must be less than 10 Ω. All conductors are to be a minimum size of 16 mm^2. A barrier is to be placed around the work area in order to prevent public which is to be at a minimum of one metre. If a tent has been erected and the frame is connected to the local earth then the barrier is to be extended beyond this.

It is important that all equipment used in the work area be properly insulated and that all insulated parts be kept as clean and dry as possible. Any metallic objects that are exposed are to be covered in an insulating material that can withstand 17 kV AC. Strict handling of equipment is to occur so that objects should not be passed to each other if in contact with any area other than the insulated work area. This includes objects that are earthed that may come in contact with the unearthed metallic components of the cable. These directions are in addition to the bonded earth condition requirements as outlined above.

Additionally, a barrier shall be erected at least one metre from the edges of the working area or associated tent frame to prevent persons from coming into contact with the bonded earth mat. A non-conductive ladder or staircase shall be used to access the bonded earth mat, as well as an insulated platform or mat to prevent step potential effects. This arrangement can be seen in Figure 2.13.

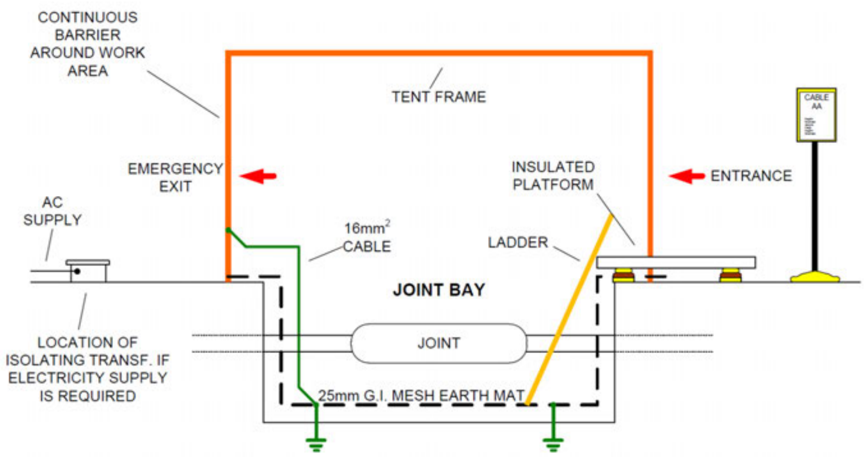

Figure 2.13: Transgrid's arrangement for a bonded earth mat condition in a joint bay. (Transgrid 2020)

2.16.3 Recommended Industry Best Practice

In any situation when working with de-energised cables, Cigré (2020*a*) appropriately caution of the dangers and risks that might be present. The timing of these can be unpredictable because external system faults may be outside of the electrical system. Switching errors may also present risks to the system along with transients. Due to this, Cigré (2020*a*) recommend an approach that implements the most suitable safe working conditions. Implementation needs to consider three fundamental safe working elements:

- performing work with currents while earthed
- performing work without currents while earthed (may still be small currents due capacitive coupling)
- working insulated (with induced or standing voltage)

(Cigré 2020*a*) recognises that for earthed working, firstly equipotentiality is the most important aspect of ensuring safe work. Establishing a connection to earth is then required and this must be applicable to the estimated induced current, including redundancy connections for each step.

Earthed working with currents allows greater control of potential differences however, large currents may still be present and still able to flow. All metal objects must be equipotentially connected to avoid hazards due to potential differences. This method also allows EPR from remote ends of the cable to be transferred in the working area, and as a consequence earthing mat needs to utilised for the soil to be equipotential otherwise isolated working needs to be adhered. This method of working needs coordination and management of earthing connections, correct tools and ensuring that all conductors are earthed.

Earthed working without currents involves isolating the cable and sheaths at each end as well as any earth continuity cables and earth wires that may be part of the system. This is to prevent any dangerous voltage at the working site between the soil and the interconnected conductive elements. There may still be small currents due to capacitive induction.

Working insulated is the method where the worker is insulated from contacting objects in the work area at different potentials. While PPE is typically utilised as a final preventative measure, this method would be conducted as a result of not being able to perform the work in without other controls. Utilisation of insulating tools, insulating mats/blankets and additional equipment is needed, for example those shown in Figure 2.14. Insulating equipment requires undergoing "test and inspection" to ensure that it meets the requirements for the working area. Correctly rated insulating gloves and boots are also required. While this is not the preferred method, it may be necessary if an earth potential is not available. Situations like this exist in tunnels and while this is not covered in the project it is becoming more frequent in urban settings.

Figure 2.14: Examples of insulating working tools. (Cigré 2020*a*)

2.16.4 Work Practices with other Australian Utilities

Apart from Transgrid's work practice which has been detailed above in this section, no other utilities in Australia had documentation that was available at the time of investigation. This may be due to many reasons, including size of underground network or lack of formal procedure into this topic.

2.17 Knowledge Gap

Conducting a thorough review of the literature by way of research, study and comparison, a knowledge gap has been identified in relation to the project title. While Energex has outlined through its works practices a method to provide safe workplace, the specificity regarding the requirement for earth mats in joint bays has not been found. Transgrid's work practice set out more clearly its expectations when working on cables in remote locations. Research into the standards and industry guides did not show a clear direction into how to explicitly deal with EPR at the remote site when working on cables. This has identified a gap, as first mention in Section 1.1, through which there is an unknown into the effectiveness of placing earth mat for the safety of the worker in the situation of repairing a 33 kV cable in an earth pit. The research and knowledge will enable the development and modelling for this project to be conducted.

2.18 Chapter Summary

This chapter has provided the background and introduction to this project. Additionally it has presented the information obtained from diverse sources, which are relevant to this project in a single location which can be easily referred to at any time. HV cables were discussed to provide a necessary overview and lead into induction of voltage and current. EPR and the associated step, touch and transferred voltages were presented along with an overview of earthing. The documentation of current work practices and procedures has been provided along with the completion of the identification and review of the relevant standards and industry guides. Ventricular fibrillation caused by current in the human body along with the associated calculations were shown. Finally the knowledge gap within the industry standards have been discussed in preparation for the remainder of the project.

Chapter 3

Methodology

3.1 Chapter Overview

The methodology which was adopted in order to successfully fulfil the objectives in Section 1 are outlined in this section. The purpose of this chapter is to provide sufficient detail and context for the remaining chapters and the objectives that that they will provide. The tasks required to complete this project work successfully were:

1. Research and review of standards and practices;
2. Types of cable configurations and earthing;
3. Induced currents and voltages as well as transient voltages;
4. Model earth grids within substations and cable joint area using simulation software;
5. Review and compare results with actual models from injection testing to validate modelling data, and
6. Closure through the output of formal documentation.

3.2 Research

This stage in the project was simply research driven and the examination completed characterised the overall state of the task also giving information to the recreation and demonstrating areas. Critical data was accumulated during this stage and a careful hunt assisted with widening understanding and diminish mistake in the strategies utilised for this venture. The initial three tasks as outlined in Section 3.1 was a mix of creating a progress report, further investigation into explicit themes related and formalisation of the task degree and results. This section's outcome was dependent on:

- collation of materials including technical brochures, standards, guides, papers and texts;
- thorough understanding of cables, cable jointing and work practices associated;
- thorough understanding of earthing and earth grid modelling;
- comparison and review of standards, guides and best practices to understand legal obligation and minimum requirements specific to this work, and
- the need to identify the topics researched early in order to direct the research and modelling work for the project.

Due to the relatively unknown and subjective nature of earthing in relation to the requirements when jointing underground HV cables, this body of work listed above, was the most challenging. This was due to the knowledge required of each topic, arranging the material into relevant components and then understanding their interaction with each other. It was important to go through these steps as the remainder of the project was dependant on this knowledge and understanding of the interaction. The research phase components of the project were presented in Chapter 2.

3.3 Modelling

The modelling component of the project was initiated in the early stage of the project. This was to determine which software would be suitable to produce the results required for the project. Initially, Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) was suggested when forming the ideation of the project due to it being readily accessible and use in the industry. However, it was also necessary to ensure its suitability by way of ensuring other software was not more suitable. MATLAB was investigated however due to the time constraints of having to program systems and models along with the inability to find material utilising this language in this field, it was decided to not follow that direction. Investigation into other software, for example ETAP and XSGLAB was undertaken. This software may have been suitable , however the cost of the programs before trying was not able to be justified for this project. As such the choice in modelling software became clear, since CDEGS was available for minimal cost.

3.3.1 CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis)

Acquisition and installation of CDEGS modelling software was through the IT department. This process, being a long lead time item, was performed very early in the project to ensure that it was operational prior to this phase of modelling. Further details and clarification can be found in Section 4.2. Once the decision was made regarding its suitability and functionality, training material was sought and studied. This required a great amount of effort in understanding how the software and its packages interacted with each other. It comprises of a soil resistivity analysis module (RESAP), frequency domain earthing analysis (MALZ) and cad module (SESCAD) for the inputting of the model. Each of these modules required further assistance through the use of additional online training material and some subject matter experts.

3.4 Analysis and Results

The initial models were run which allowed insights into what the modelling was doing. During the phase collation of field test results was undertaken and were analysed with the modelling outputs. This allowed comparison of the accuracy of the modelling software.

The modelling undertook rework during the project such that, three scenarios were formed and this has been explained in further detail in Section 4.9. Further fine tuning was applied to the scenarios as well as 'what if' situations to gain understanding in the response of the systems.

Validation was sought to ensure the integrity of the data acquired in the modelling phase was accurate. This was completed through the application of modelling a substation with minimal return earth paths against results that had been sought through remote injection test methods. This helped with providing a confidence in the results of CDEGS against the modelled data for the projects specific requirements.

3.5 Delivery and Closure

The delivery phase intends to finalise the project as well as all the remaining aspects ready for academic submission. This section of closure will include leaving notes associated with the modelling to allow users in the future to take on further work, writing up the results, and finally presenting these results with appropriate teams within Energex. Should the material and results of the project provide material of a suitable nature, a publishable paper could be further developed in order for the engineering community. The project delivery and closure phase outputs are:

- An academic level thesis for submission to University of Southern Queensland for ENG4112;
- Modelling commenting and labelling before storing, and
- Presentation to share with teams within Energex for awareness and implementation.

3.6 Chapter Summary

This chapter has provided the background and introduction to this work that will be conducted for the project. It has demonstrated that much of the background information, documentation of work practices, and comparative review of standards has already been covered in Chapter 2. Supporting this, are the remaining tasks of development, modelling results and analysis that have been depicted to complete the project and produce the formal documentation by way of this thesis.

Chapter 4

Modelling Development and their Application

4.1 Chapter Overview

This chapter will consider the development of the modelling to be conducted in the project. Modelling software choices available will be briefly discussed and as well as the choice made for this project. Validation modelling will then be shown by way of comparing a software model of a substation against actual injection tests at the same site. This will assist in the acceptance of using the chosen software as an acceptable finite modelling tool for this project. The chapter will continue and detail the various specifications required, gathered and used in building the model for the project. A limited number of scenarios will be considered in order to best capture the typical working methods that would be considered in the field. Certain aspects of the modelling and scenarios will be adjusted to help understand some of the 'what if' situations.

4.2 Modelling Software

When looking at software for the modelling component of the project, there were a number of software choices that could have been made possible. The use of MATLAB was considered for a mathematical approach and while a model may have been possible as shown by Kapijan et al. (2017) and Wu et al. (2016), time constraints on the project made an attempt to modify not feasible. As such MATLAB was used lightly for calculating as required. SafeGrid Earthing software was considered as it promoted distribution network earthing analysis, however upon further investigation, significant financial investment which was not possible. Additionally, time investment would have been required to produce modelling suitable to this software. Ground Grid Systems software, a module with ETAP, was also investigated and looked promising, even for the use of validation, however it also required significant financial investment. A student version was available but was not possible due to not meeting all of the companies student requirements. Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) was finally chosen as the modelling software and further details are provided below.

4.2.1 Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS)

Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) software package is a set of engineering tools that can be used to analyse situations that involve earthing and electromagnetic fields (EMF). The complete CDEGS package contains eight engineering modules. The license that was available through Energex had access to three of these modules which were used. These were:

- SESCAD - graphical CAD input,
- RESAP – Soil Resistivity Analysis, &
- MALZ – Low Frequency Grounding / Earthing Analysis.

SESCAD module takes input CAD files and creates a .m file to represent the earthing conductors including fault node and a ground plane over which the gradients of EPR can be realised.

Soil resistivity results from the field, can be input into the RESAP module. RESAP analyses the data and models the soil layers appropriate to the actual results giving a percentage error in the output report for confidence.

MALZ takes the CAD file from the SESCAD module as well as the RESAP model, if available, and models various plots that show step potentials, touch potentials. Fault current, protection timing and personal protective equipment are all used to generate safety thresholds and is also part of generating the various plots. Some of these inputs have been detailed in the sections below.

Upon reviewing literature were the use of CDEGS modules were involved, and while not much was found specifically comparing CDEGS MALZ module, it could be seen that many had utilised the software to model specific conditions appropriate to their works. Szczepański (2015) utilised the MALT component within CDEGS to find good conformity of the resistance for the electrode system they were comparing.

The HIFREQ module was used by Ztoupis et al. (2014) to compare the measurement and calculation of power frequency electric fields generated by high voltage overhead power lines. A number of case studies were created and compared to measurements taken which showed an appropriate level of agreement according to Ztoupis et al. (2014).

Various inputs are required for the use of CDEGS to compute through MALZ the step and touch potentials required to analyse and compare the scenarios detailed in Section 4.9 which have setout below.

4.3 Protection Timing and Fault Level

Protection timing also know as the fault clearing time, was an input for the modelling process and was discussed with the Protection department at Energex. Through further clarification and much discussion, for the purposes of this project work it was decided to utilise a timing of 200 ms. This timing was derived from the protection pick-up and initiate trip of the circuit breaker, giving a typical primary protection timing in the network. Backup protection was also discussed as to its timing and use. A worst case backup fault clearing time of three seconds.

The fault level details were also sought and discussed with the department. The phase to ground fault level for 33 kV was currently at 1950 A for the site. Further an average of 33 kV faults in the network was taken resulting in an average fault level of 1920 A, as shown in Table E.1, which confirmed the use of 1950 A as the fault level to be used. The fault level was applied at the output stage in CDEGS MALZ due to the model using a scalable 1 A fault to assist in the speed of the computations as shown in Figure 4.1. It is important to note that if a study was being conducted on a specific feeder between substations then the specific protection scheme timing and fault level should be utilised in the modelling and calculation.

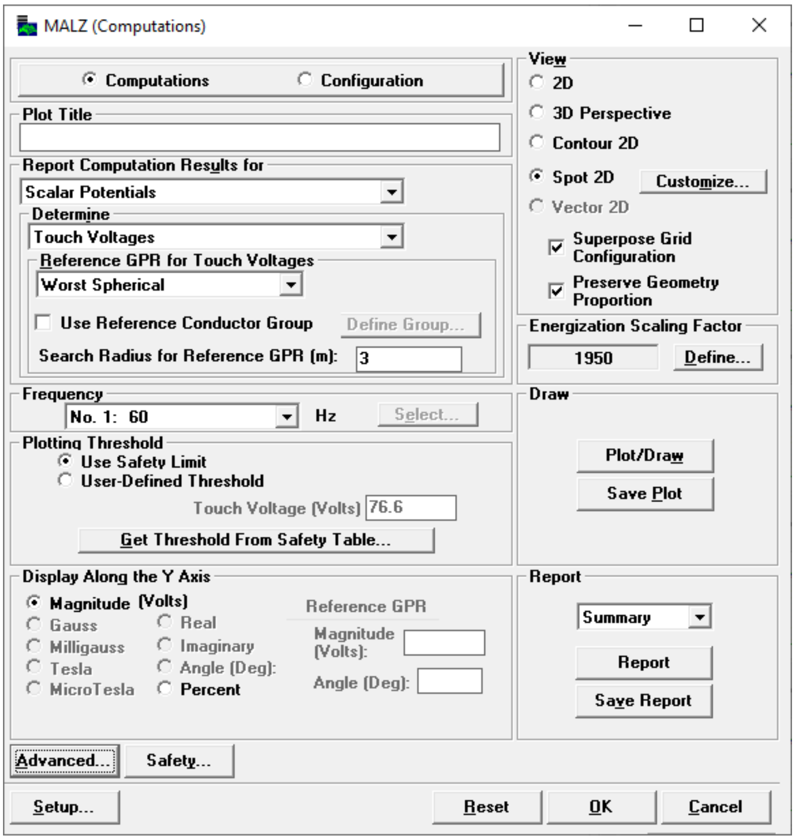

Figure 4.1: Input screen for MALZ showing fault current input of 1950 A.

4.4 Specifications for Soil Resistivity

Soil resistivity can be measured using the Wenner Method as described in Section 2.10.1 and can be broken down into different layers due to soil being non-homogeneous. Using a single layer soil model can be slightly misleading when looking at the results as the soil conditions may in fact consist of high on low resistivity, which can in turn increase the allowable working voltage for the worker. Two layer soil model conditions were considered initially, for their increased accuracy in modelling results. However as the project developed through the development phase and how this was to be applied to the modelling, it was decided to opt for the simpler single layer soil resistance and use a range of values as required. Initial modelling in CDEGS using a range of values between 1 Ω·m and 500 Ω·m was conducted through the input screen as shown in Figure 4.2. From the initial modelling results, it was evident that there was a change to both the step and touch potentials, as the soil resistivity changed.

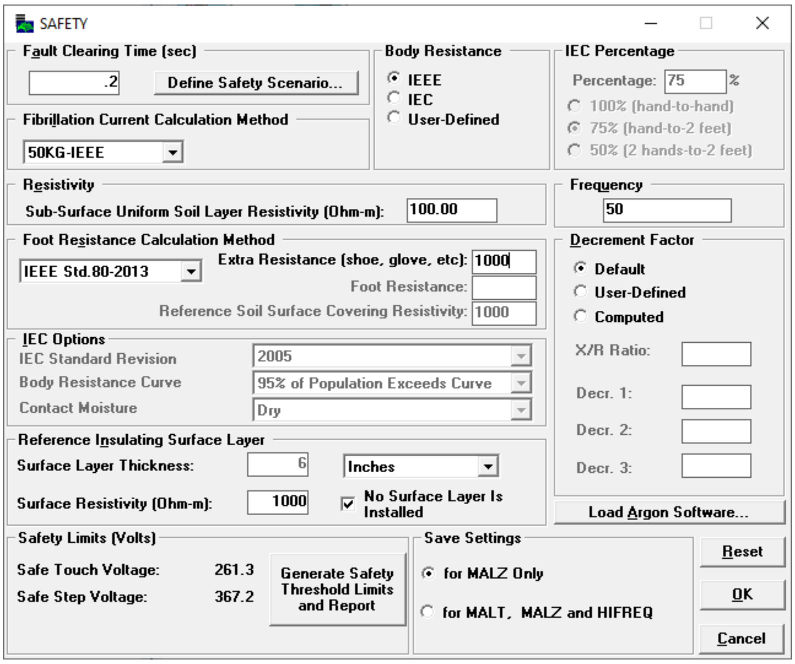

Figure 4.2: MALZ Safety threshold inputs for modelling.

The physical size and location of the Energex network means that it covers a various range of soil types and conditions. As such it was difficult to determine a suitable value as each location could affect the modelling differently. It was felt that considering all of the different criteria of soil conditions would be too time consuming and a deviation from the scope of the project.

The default setting in CDEGS was already set at 100 Ω·m and as this was the typical value for dry soil, as per Table 2.1 it was decided that the scenarios would be modelled with this value. Additional tests would be conducted with a high resistivity value of 300 Ω·m with a value of 10 Ω·m determined for the low resistance representing wet organic soil type conditions. These modelling specifications have been collated in Table 4.1.

Table 4.1: Soil resistivity values used for modelling.

Level	**Soil resistivity(Ω·m)**
Default	100
High	300
Low	10

4.5 Specifications for Substation Earth Grid

The earth grid to be modelled in CDEGS for substation A, was constructed using the existing earth grid layout drawings available in the Energex drawing management system - Refer Appendix B.1. The bare copper earth grid conductor size was noted as 70 mm^2 at a buried depth of 500 mm. Copper earth rod locations were noted and place which were 13 mm in diameter and 1.8 m long, buried to the same depth as the earth grid conductor. As set out in Section 4.4 the soil resistivity also applied for the substation modelling. Dimensions specified on the layout drawing were applied to the SESCAD substation model.

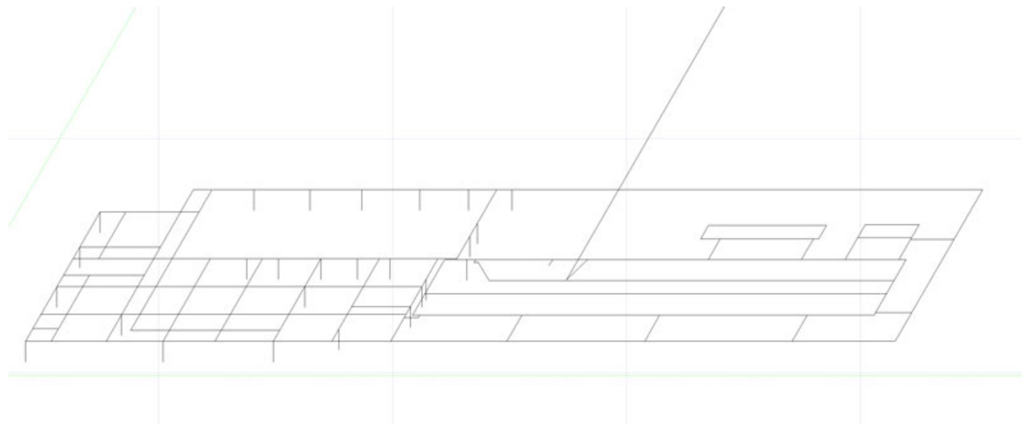

Figure 4.3: SESCAD drawing of the earth grid at substation A with simulated 33 kV cable shown leaving the substation.

4.6 Cable Specification - 33 kV

The 33 kV cable specifications for the purposes of modelling were not required. However it is important to note that all cables in this voltage are constructed with a metallic sheath. The metallic sheath will be required in the modelling and has been represented as an insulated conductor leaving the substation as shown in Figure 4.3. The cable sheath bonding method for modelling, will be treated as a single point bonded arrangement as described in Section 2.3.4. The sheath will be connected to the substation earth grid as it would be for a single point bonded arrangement. At the joint bay, the cable sheath will be connected in a number of scenarios as set-out in Section 4.9. These cables are installed to a minimum depth of 600 mm below the surface.

4.7 Overall Model

In considering all of the information gathered, the system data for a model of the system was created using CDEGS CAD package SESCAD. This consisted of obtaining the earth grid drawing for the substation A and importing this as a .dxf (Drawing Exchange Format) file. The conductors and earth rods checked for correctness of size, position and depth according to the original approved design. The remote joint bay as discussed in Section 4.9, was modelled. An insulated conductor was placed connecting the substation earth grid and the remote joint bay. The distance of separation was set at 3 km, to resemble working between two substations. Substation B was not required to be modelled. Since the cable was single point bonded at substation A, the assumption was made that there would be no sheath connection at substation B. If the cable was configured and connected to the earth grid at each end as a solid bond arrangement, a repair would require the sheath to be cut thereby losing the earth connection to substation B.

4.8 Substation Earth Grid Model - CDEGS

The substation earth grid model that was used as part of the joint bay was obtained and entered in SESCAD. The conductor, as per the design drawing, was 70 mm^2 bare copper conductor and was placed at a depth of 500 mm below the ground level. The conductor grid connections were crimped connections were joins occurred. Earth rods were 13 mm diameter copper rods, 1.8m in length and driven to a depth of 500 mm below ground level to match the bare copper conductor. A source fault current of 1 A was applied to the earth grid at a location were a circuit breaker was located that may fail within the substation. The source fault current was then able to be scaled quickly in the MALZ module to see the effects easily without running the computations repetitively.

4.9 Joint Bay Scenario Models

The joint bay area is an area that is excavated to reveal the cable for a typical sheath repair or cable joint. The dimensions of the joint bays for modelling purposes, were taken as an average size. Some joint bays can be much longer depending on the number of joints and cable configuration, for instance a trefoil arrangement may require each joint to be staggered, however these scenarios can be scalable. Specifically, the pit was modelled as an 8 m x 4 m flattened area as this included the side and end walls of the pit. In consultation with designers and field crews, it was determined to form three separate models in CDEGS showing a typical work area set-up, a perimeter earth grid set-up and the earth mat or mesh arrangement that initiated the project. The three scenarios are listed below and a CDEGS SESCAD representation of each is shown in Figures 4.4, 4.5 and 4.6.

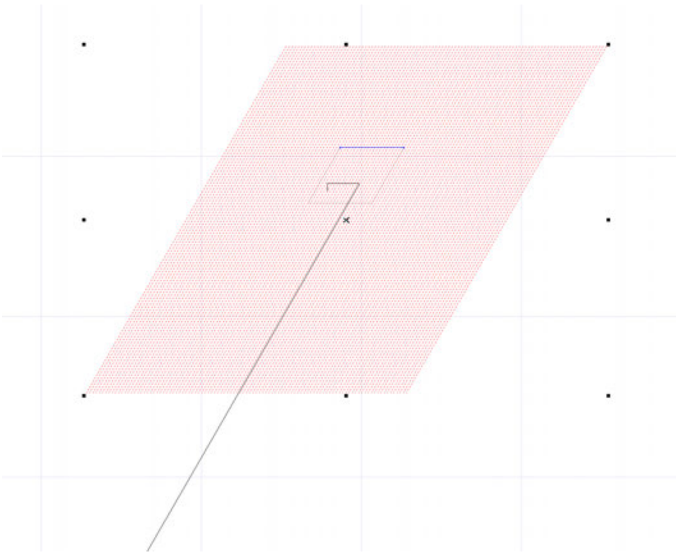

Figure 4.4: Simulation for CDEGS of joint bay with cable sheath connected to earth rod - Scenario 1. Modelled ground plane area shown in red.

The first was a joint bay was the simplest scenario were the sheath of the cable is connected by a suitable conductor to an 500 mm earth rod in the ground. The second scenario expanded on this and was to see what effect conductor size and amount had on the area. In this case 70 mm^2 was placed around the perimeter of the area with a central piece that connected to the mains cable sheath. Finally the third scenario was set-up with a mini mesh earth grid for the whole area with a 1 mm diameter and a spacing of 50 mm to replicate the instances that it had been used within the network. In summary these are listed below:

- Scenario 1 - earth pit with a single earth rod connection to the cable sheath (Figure 4.4),
- Scenario 2 - earth conductor around the perimeter of the pit and connected in the middle to the cable sheath (Figure 4.5),
- Scenario 3 - mini mesh earth grid in and around the pit (Figure 4.6).

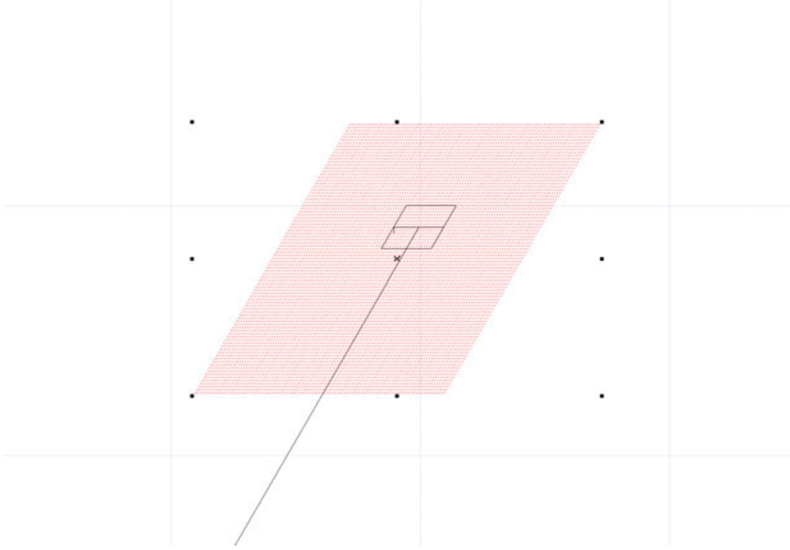

Figure 4.5: Simulation for CDEGS of joint bay with cable sheath connected to earthing conductor around and through the middle of the joint bay - Scenario 2.

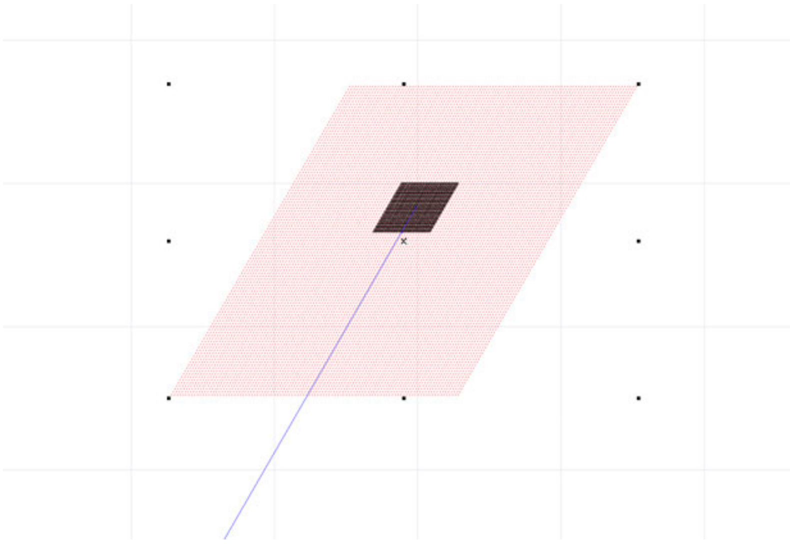

Figure 4.6: Simulation for CDEGS of joint bay with cable sheath connected to mini mesh grid - Scenario 3.

Further a ground plane covering the greater area was placed in the model above and around the joint bay area which determines the area to focus the output showing the different lines of potential.

4.10 Principle of Earth Injection Test

Here, it is helpful to explain the concept of earth injection and the testing involved. Essentially, this set-up involves injecting an off-mains frequency, in other words non-

50 Hz AC, into a remote earth. Typically a generator is used as the injection source and feed into a remote earth such as the end of an out of service feeder at another substation. When the current is injected into the earth grid under test, it will return either through the earth's mass or via alternate paths, such as these:

- overhead earth wires,
- cable sheaths,
- buried metallic pipes.

A voltage rise is caused by the return current, in combination with the earth system impedance. Measured step, touch, and reach voltages can be scaled to be relevant to actual fault levels for compliance with relevant standards.

4.11 Earth Injection Test

An earth injection test is conducted between two substations. Typically a 33 kV feeder is utilised for the test and is disconnected at air break switch. A generator is set up at the substation were it is connected to feeder side of the air break switch as shown in Figure 4.7. The generator is then switched on and set to inject a scalable current such as 20 A at a frequency that is not 50 Hz. Typically a frequency such as, 56 Hz, is used and this differentiates between the rest of the network which is operating at 50 Hz when measuring the return current. The generated current flows through the feeder cable to substation two and returns via ground or alternate paths as listed in Section 4.10.

The substation under test is then measured in a number of places such as each underground feeder cable and towers supporting outgoing feeders using a Rogowski coil. The results of the measurements are totalled and subtracted against the injected current from the generator source. The resultant is the amount of current that returns directly through the earth grid and it is this remaining current that the EPR for the substation is calculated from. For reference, it is helpful to note that substation remote injection testing is conducted a number of times throughout a substations life. As upgrades occur, fault levels may increase and protection timing may decrease and as a result it is important to understand how this may affect workers inside as well as the public outside of substation.

Figure 4.7: Generator connected to sealing end and set up for injection as part of remote earth testing.

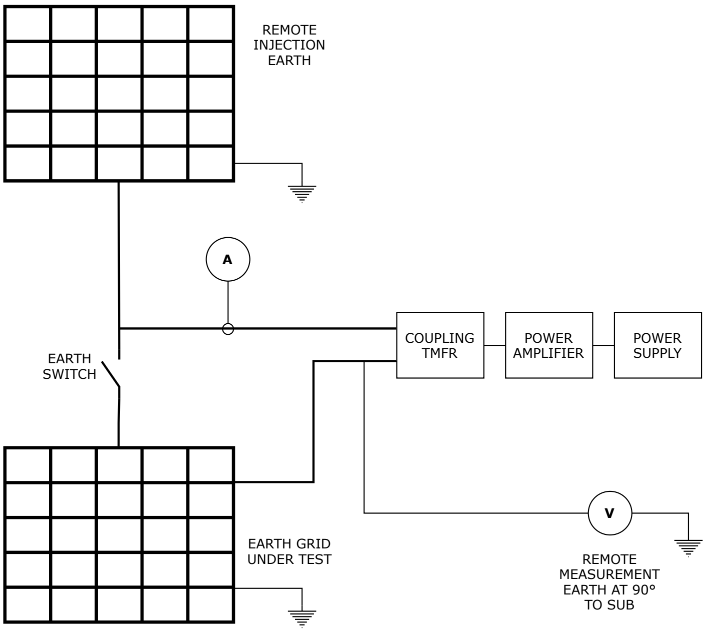

Figure 4.8: Remote earth injection testing configuration schematic.

4.12 Validation of CDEGS against Substation Remote Earth Injection Test

In an attempt to verify the results from modelling in CDEGS it was proposed to compare these against the results from a recent remote earth injection test within the network.

Figure 4.9: Probes and frequency selective multimeter which are used for remote earth injection testing.

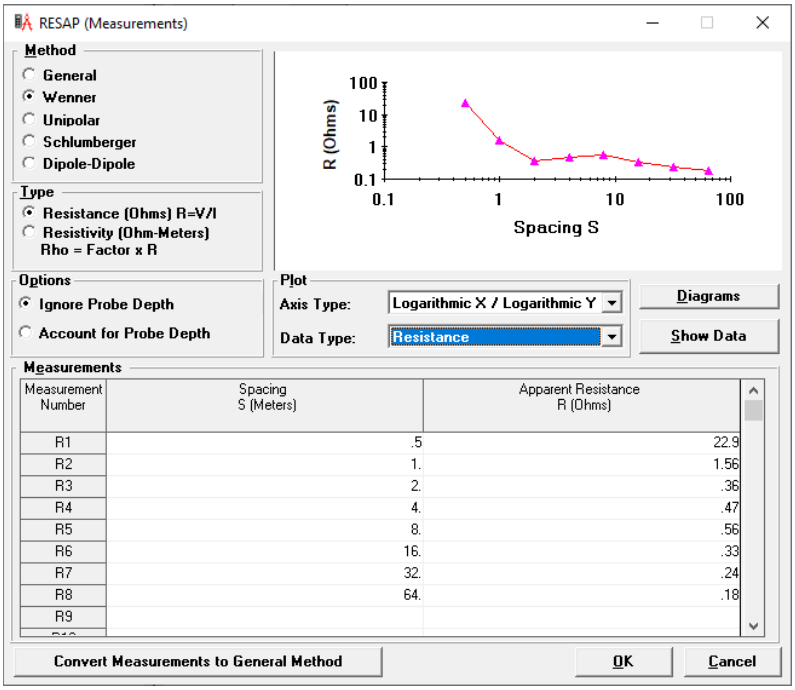

Figure 4.10: Wenner method soil results at validation substation.

The substation results that were selected were as a result of identifying that its feeders had no underground cables or overhead earth wires attached. The reason for selecting this sites results were in order to try and eliminate the amount of returned current through any connected sheaths, which would ensure that the return of all remote current would travel back via the earth grid in the substation to the source.

For cables with cross bonded sheaths, typically only 5 to 15% of the current will return through earth as stated by Cigré (2020*a*). Further for cables that are single point bonded or carry an ECC only 30 to 60% will return whereas the largest component will return through any metallic parallel path. As such modelling a substation that contained underground feeders or overhead wires was

The soil test conducted at the validation substation site was completed using the Wenner method and data collected as shown in Appendix C. The soil resistivity measurements taken on site for both traverses, were input into the RESAP module within CDEGS as shown in Figure 4.10. The computation model generated the soil profile as shown in Figure 4.11 with an RMS error 14.9%.

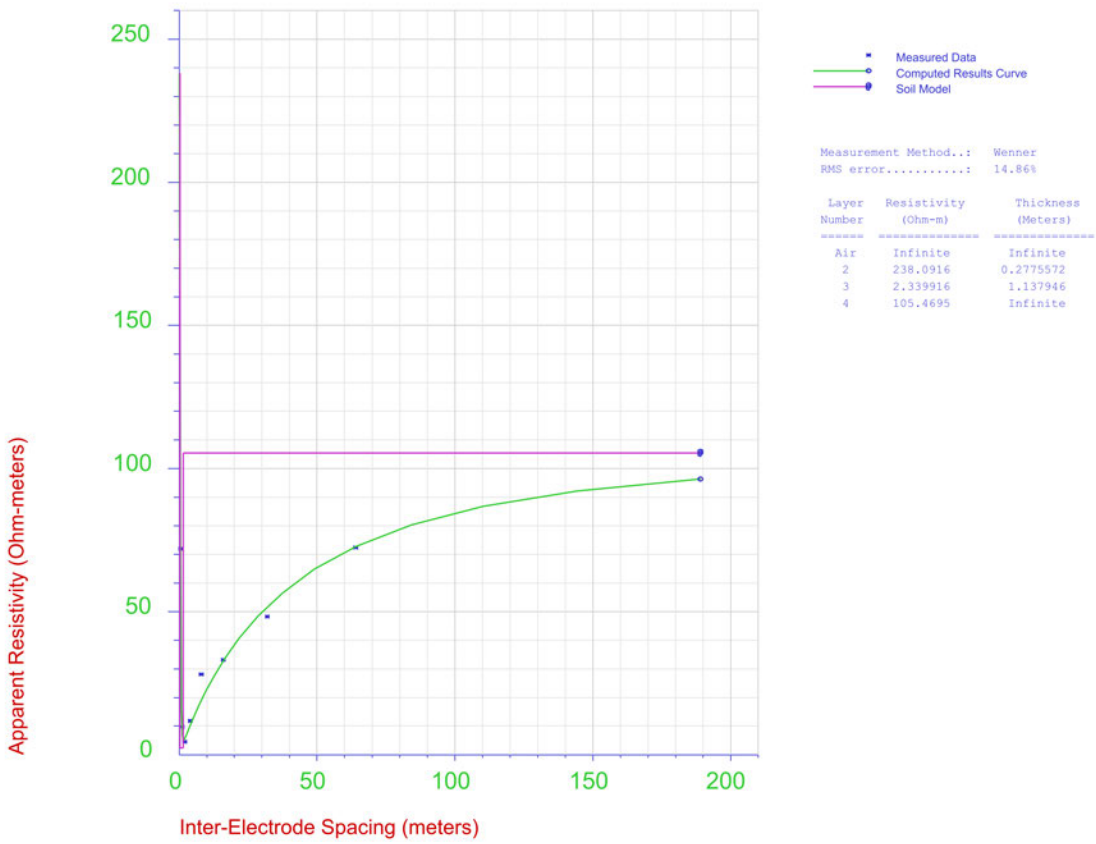

Figure 4.11: CDEGS RESAP module output showing the soil resistivity at the validation substation.

The substation earth grid was entering into SESCAD and together with the soil resistivity data from RESAP, a MALZ computation was able to be calculated. The fault current was replicated to the substations settings of 727 A and a primary clearing time of 700 ms. The results for step and touch potentials were then given and can be seen in Figures 4.13 and 4.14 respectively. The measured results shown in Appendix C, for both step and touch potentials were scaled to site settings as described above. All resultant measurements passed the criteria as set out by the IEEE80.

Firstly comparing the step potentials from the CDEGS model plot against the scaled measurements taken on site, shows that the site does not have any issues. As the plot from CDEGS only has a minimum threshold and any voltages present under this are shown as not hazardous, its is difficult to determine exactly what voltage would be at the same position and voltage measured on site. Secondly the touch potentials from the measured results were compared with the modelled plot. Again it was difficult to see a direct comparison between the two however, looking through the scaled site measurements revealed that the highest values were still below the minimum threshold for touch potential. It could be derived from these comparisons that the modelled data and plots reflect the measured site data and conditions, albeit slightly conservative.

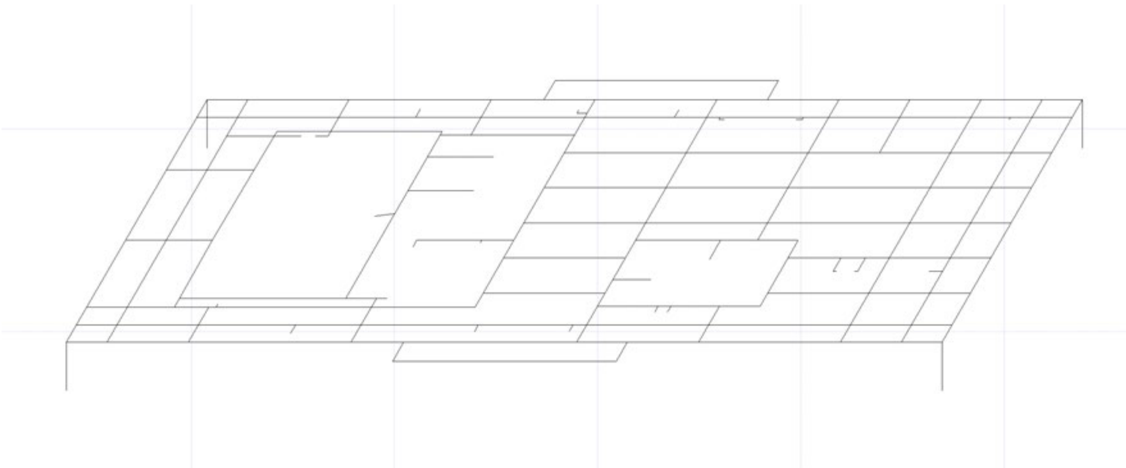

Figure 4.12: SESCAD model of validation substation earth grid.

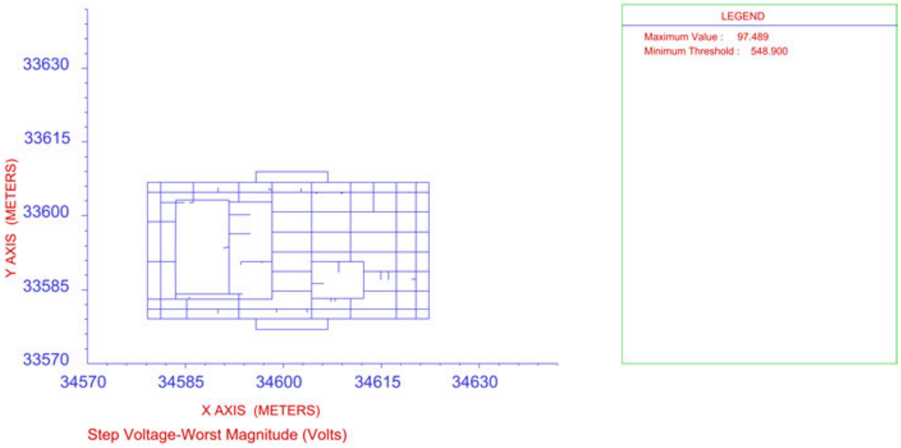

Figure 4.13: Step potential model of the validation substation.

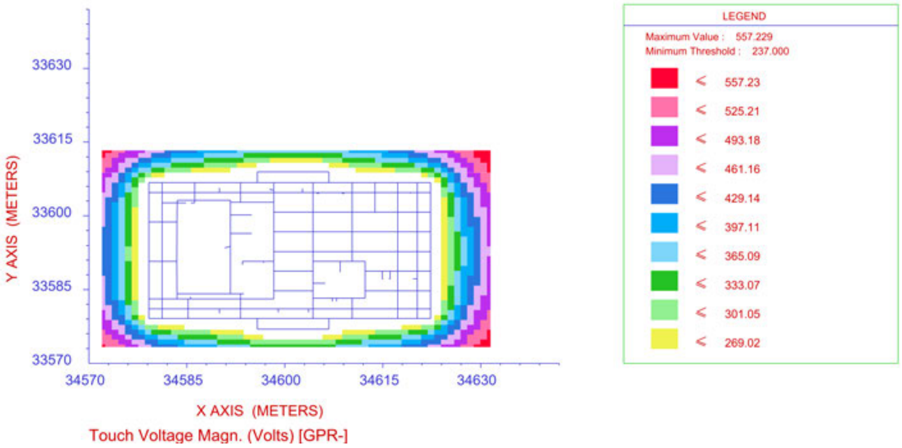

Figure 4.14: Touch potential model of the validation substation.

4.13 Chapter Summary

In conclusion of the modelling development phase for the project, the specific details required to set-up an appropriate CDEGS model were established. The choice of CDEGS as the software to be utilised for the project has been explained along with looking at research that has been conducted using this particular software. The models and various parameters have been shown and detailed. Validation process has been attempted by comparison of field remote injection tests results with CDEGS modelling at another substation. Whilst these validation plots generated were not able to replicate the field results in the same manner, they do verify each other in that they reflect the same result at the substation. As such continuation continued by setting up the scenarios and models previously discussed in preparation for the results and analysis phase which will be seen in Chapter 5.

Chapter 5

Results and Analysis

5.1 Chapter Overview

In this chapter, the results of the modelling that were undertaken using CDEGS will be presented. Prominent voltage profile plots will be shown, with any additional plots made available in Appendix D. The source substation step and touch voltage profile will be given and discussed for completeness of the situation. Further, these results will involve the three main scenarios which were discussed in Section 4.9. To recap these were:

- earth pit with a single earth rod connection to the cable sheath,
- earth conductor around the perimeter of the pit and connected in the middle to the cable sheath,
- mini mesh earth grid in and around the pit.

Analysis of these results will be carried out in preparation for the the concluding chapter.

5.2 Substation Earth Grid Model - CDEGS

The substation earth grid model and settings for modelling were previously discussed in Section 4.8. The model was run as part of each joint bay scenario and the following plots were produced. Figure 5.1 displays the results for a worst case step voltage. It can be seen that the there is little issue for step potential within the substation with the results and minimum voltage threshold improving when lowering the protection timing, weight of person and adding appropriate boots.

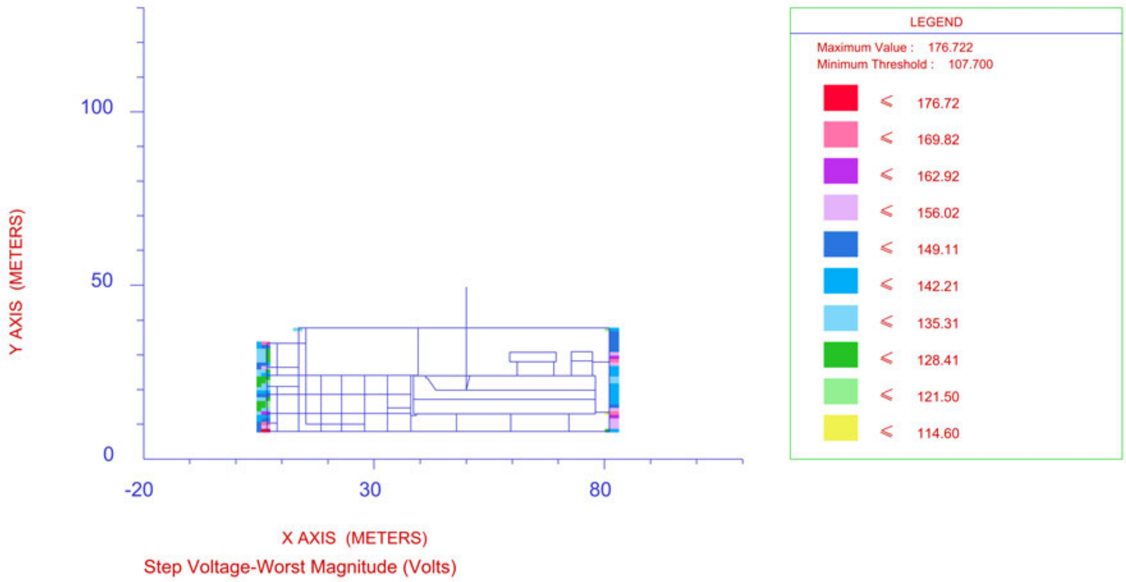

Figure 5.1: Source substation A - Step potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

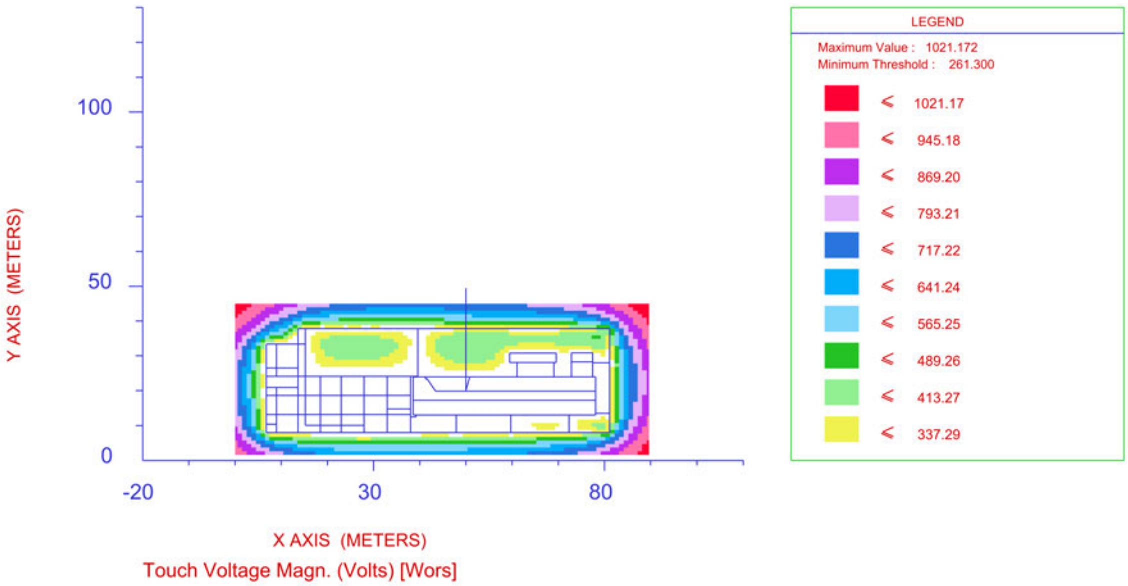

Figure 5.2: Source substation A - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

Touch potentials at the substation for a 200 ms protection timing show that within the substation the area is acceptable as shown in Figure 5.2. While there are voltages present in the modelled plot due to the lack of earth grid in the ground, as there is no metallic structures in the area to touch this would be considered a safe area. Figure 5.3 shows an increase to the touch voltage levels that would not be considered safe however, this improves significantly with the addition of appropriate boots.

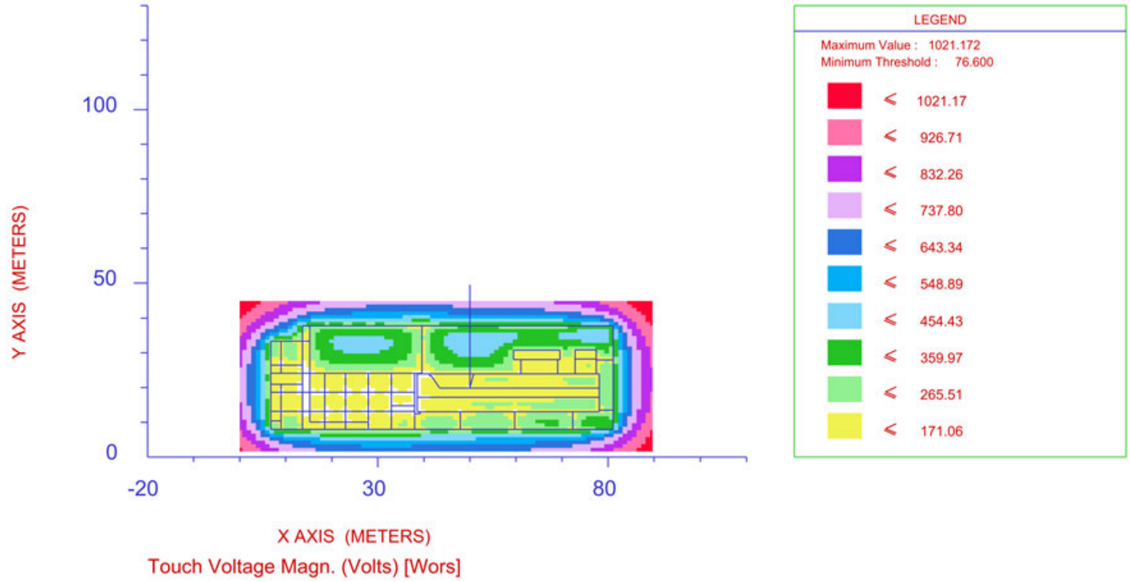

Figure 5.3: Source substation A - Touch potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

5.3 Joint Pit Earth Grid Model - CDEGS

The modelling results from this section have been broken down into subsections to assist the reader in understanding and seeing the comparisons for each set-up. Both step potentials and touch potentials have been modelled and shown, with discussion as to how they performed and what was further looked at. Each scenario firstly looks at the step potential with a default setting of 200 ms protection timing, fault current of 1950 A, a 50 kg person with no boots and a soil resistivity of 100 Ω·m. It is assumed that a typical sunny day within South East Queensland is in effect.

5.3.1 Scenario 1

The worst case step potential CDEGS output for this first scenario is shown in Figure 5.4. The resultant plot shows no ground voltage present within the joint bay area for a single earth rod connection to the cable sheath. Initially it could be thought that it should be higher however as discussed earlier in Chapter 2, there is less chance for current to flow through the heart as it is only step voltages that are being looked at in this case.

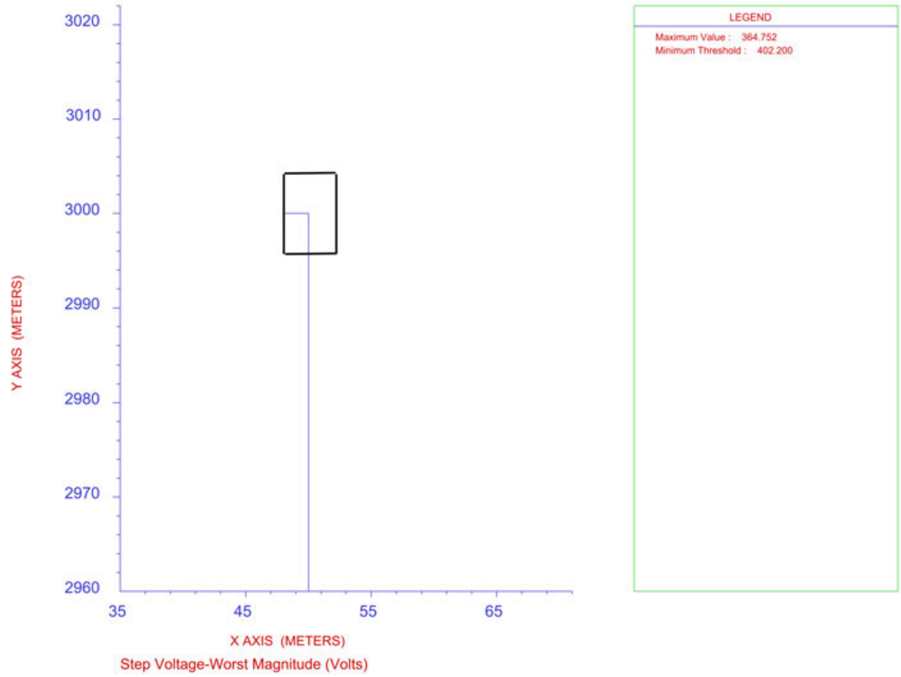

Figure 5.4: Scenario 1 - Step potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

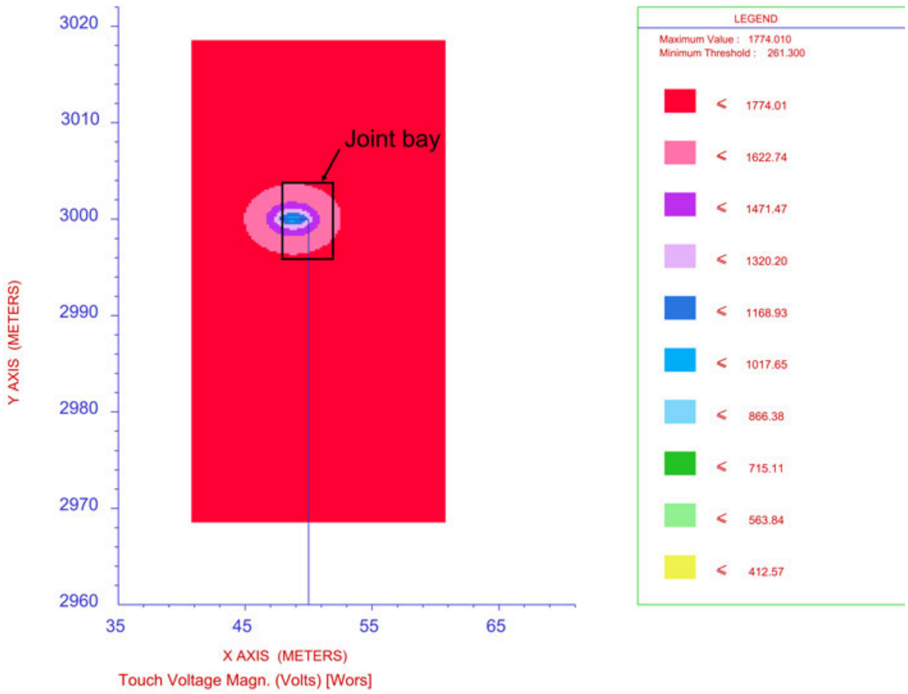

Figure 5.5: Scenario 1 - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

On the other hand, Figure 5.5 shows a situation that, under worst case fault at the substation, would result in a transferred voltage out to the joint bay. This could be fatal if the worker was contacting the sheath and or any of the connecting earth connection. The voltage gradients show that it decreases the closer to the conductor the worker is however it step to the next voltage gradient quickly. The results for a 3 s clearing time can be seen in Figure 5.6 and as such the protection timing compared to Figure 5.5, shows no change to the transferred voltage with only the minimum threshold voltage becoming lower.

As such, since the step potential plot for a worst case scenario was already acceptable and the touch potential plots showed no decrease in transferred voltage at the joint bay, it was decided to not model further iterations with different inputs for this scenario.

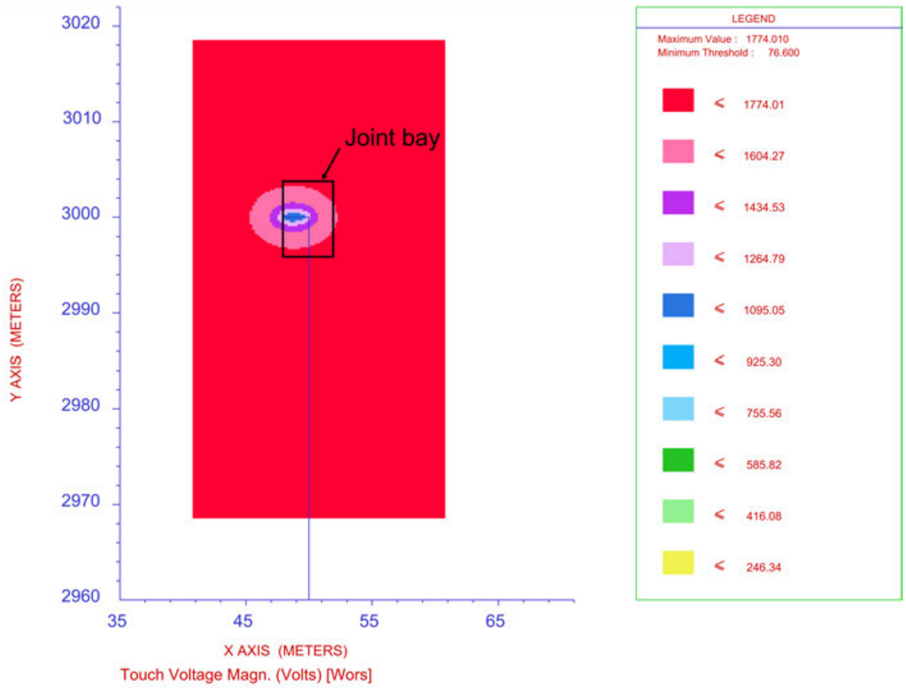

Figure 5.6: Scenario 1 - Touch potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

5.3.2 Scenario 2

For the second scenario the perimeter of the joint bay had the addition of copper earthing conductor running as an additional connected loop. Step potential results with a protection timing of 200 ms indicates that there will be an increase in voltage as shown by the gradients around the earthing conductor in the joint bay as shown in Figure 5.7. In comparison to the first scenario it will be noticed that this has increased to a situation that would be unsafe when crossing the grid. This may be due to the transferred voltage from the substation now raising the EPR as opposed to the first scenario which had minimal impact to the area. No further modelling was conducted on this scenario for step voltages as the results present enough detail for comparison of the three scenarios. While the step potential plot showed unsafe voltages around the earthed conductor in

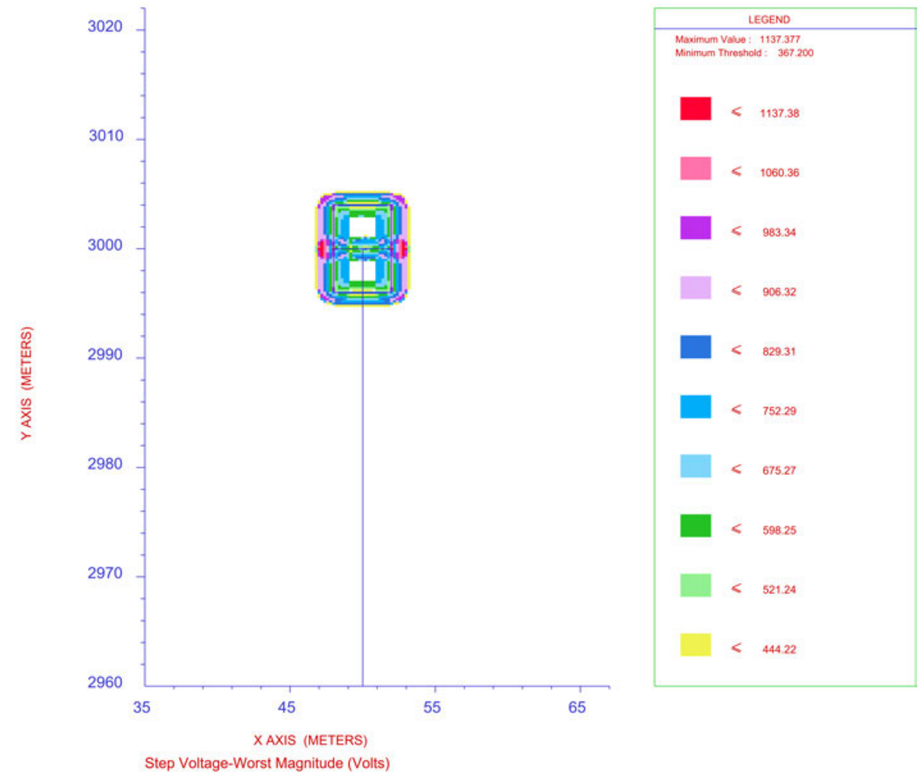

Figure 5.7: Scenario 2 - Step potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

the pit, the touch potentials remained well above the acceptable minimum threshold for the whole area, as seen in Figure 5.8. In comparison directly with the first scenario for the same settings it can be seen that it had improved and the voltage gradients were lower in the joint bay. The previous scenario showed that there was little change when comparing the protection timing, however as Figure 5.9 shows the colours representing the gradients, shows an increase in voltage. For the person in the joint bay wearing appropriate boots, the situation improves as did increasing the soil resistivity to 300 Ω·m, seen in Figures 5.10 and 5.11 respectively. Decreasing the soil resistivity to 10 Ω·m, seen in Figure 5.12 increased the touch potential slightly however it was not as high as the situation where the 3 s protection timing was in effect.

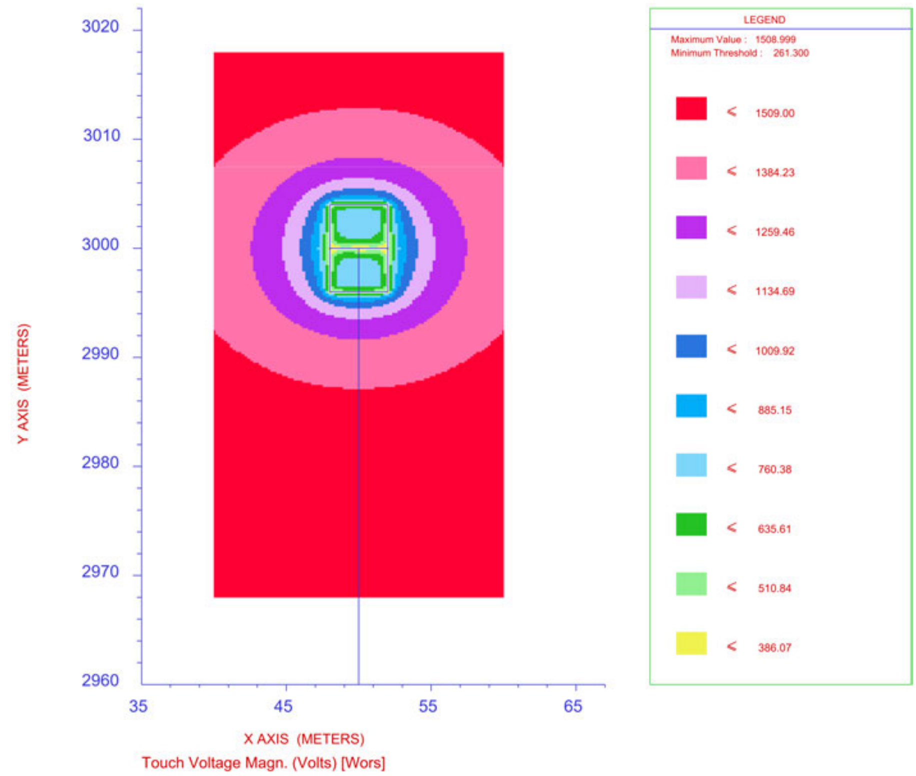

Figure 5.8: Scenario 2 - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

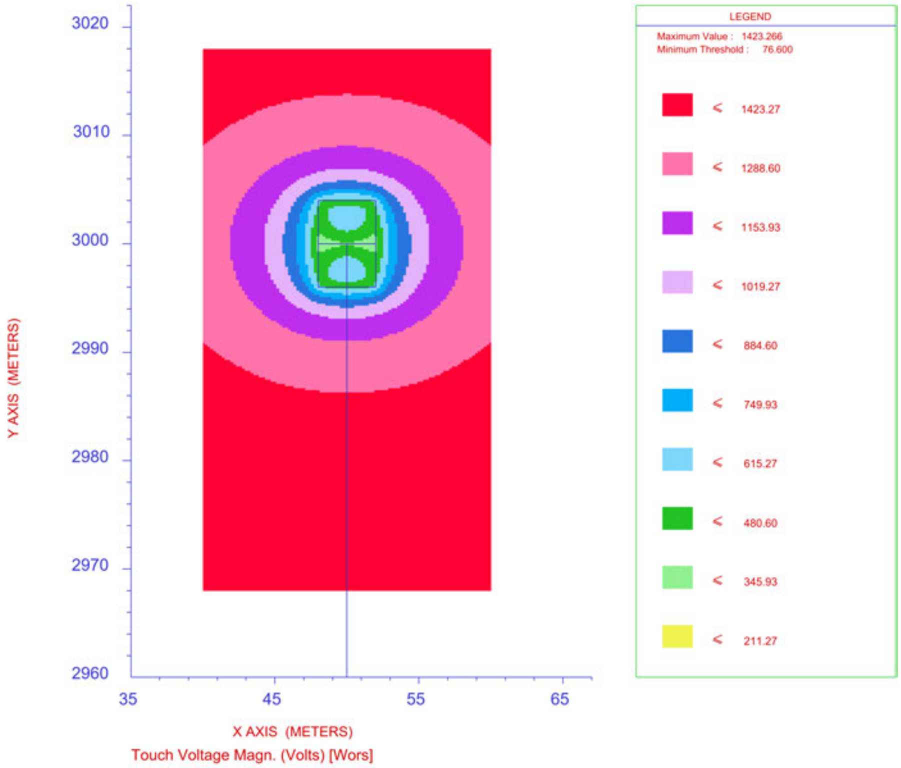

Figure 5.9: Scenario 2 - Touch potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

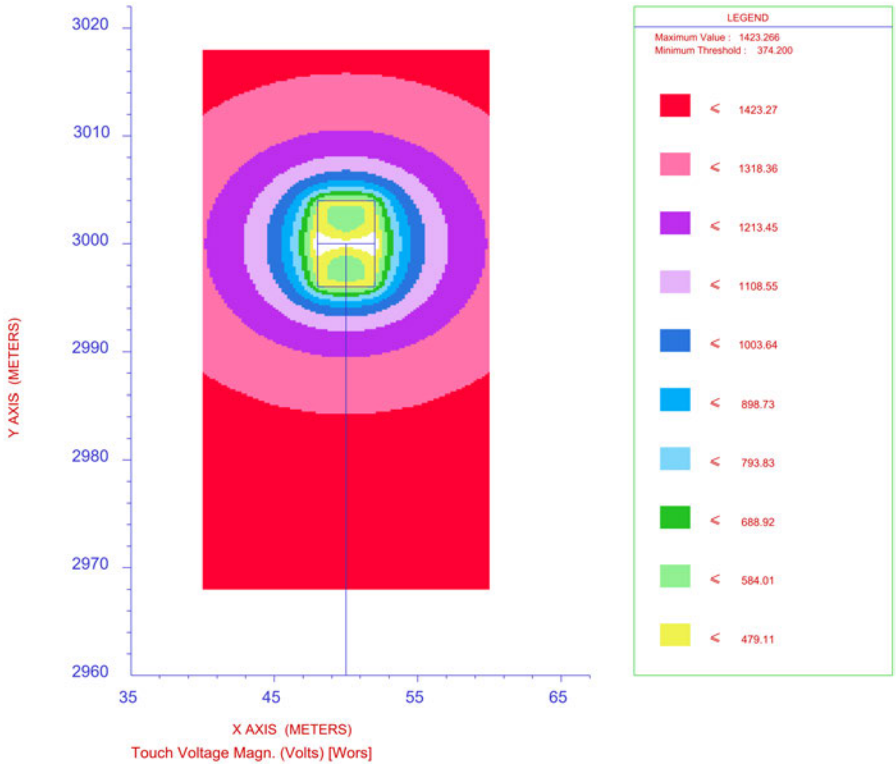

Figure 5.10: Scenario 2 - Touch potential model with 200 ms protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m.

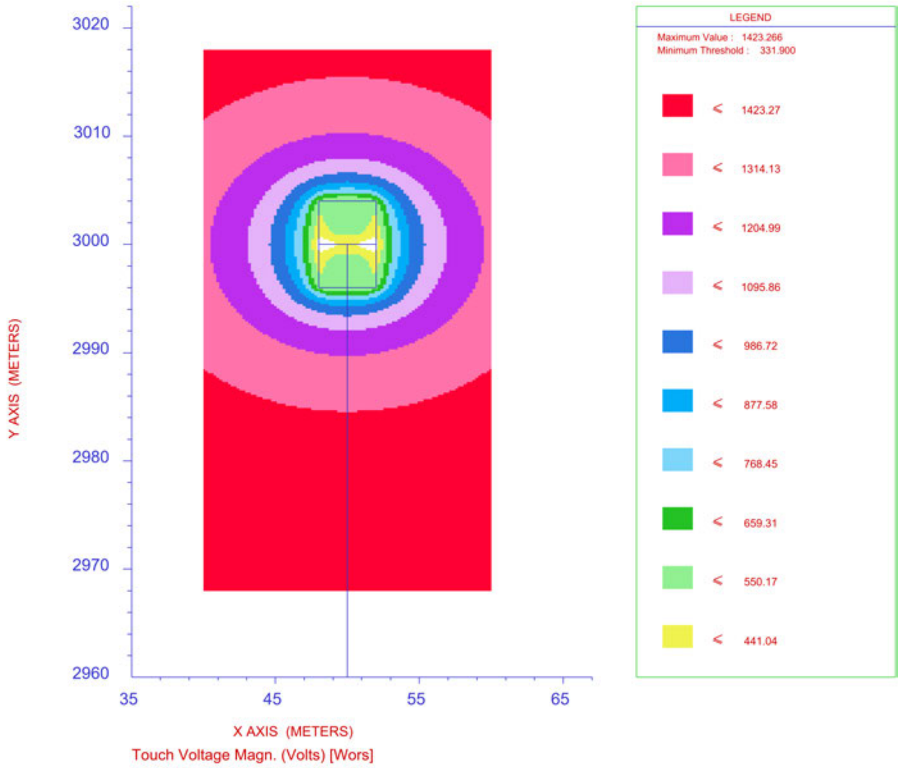

Figure 5.11: Scenario 2 - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 300 Ω·m.

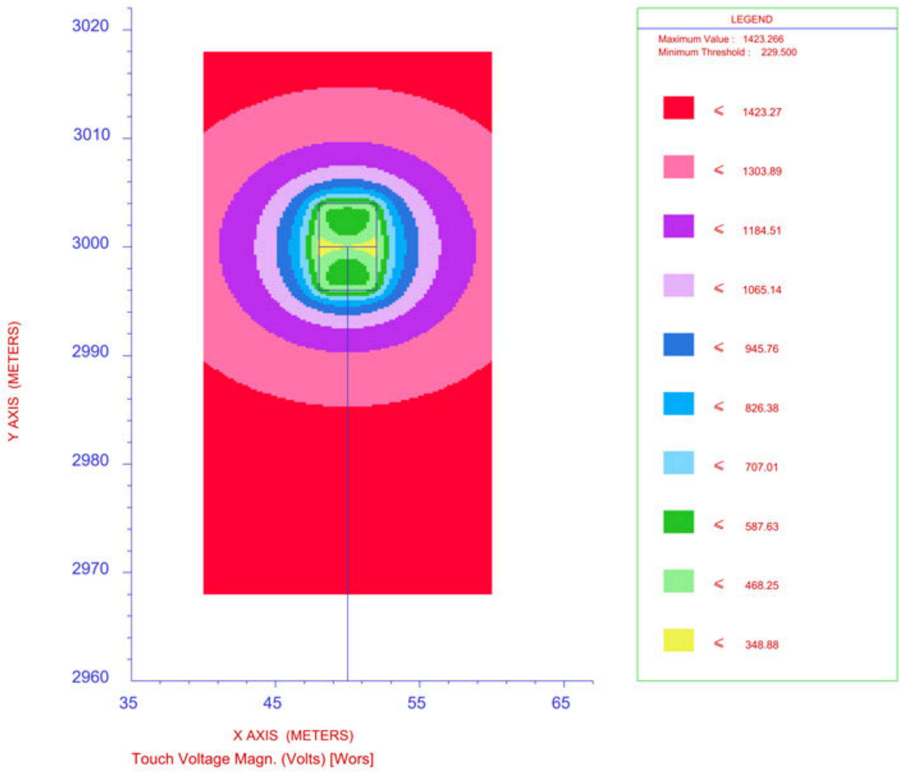

Figure 5.12: Scenario 2 - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 10 Ω·m.

5.3.3 Scenario 3

For the third and final scenario the joint bay was covered in mesh and connected to the HV cable sheath. Step potentials within the joint bay in scenario two demonstrated unsafe voltages appearing with the introduction of additional grid to the area. For this third scenario, the result reduced this step potential as shown in Figure 5.13 to a safe situation once again. This is as a result of the area now becoming similar to that experienced within the substation because the worker is unable to step between two areas that have different potentials. Modifying the situation setting with a 70 kg person shows in Figure 5.14 that the voltage is under the threshold. If this were increased to a 3 s protection as pictured in Figure 5.15 and 5.16 unsafe voltages begin to appear towards the edges of the pit. In looking at these results it prompted discussion around the safety of the worker transitioning between the joint bay and area beyond. It was identified that other working practices, in particular cable pulling for overhead transmission lines, employ transition areas to prevent unsafe step and touch situations occurring. A simple solution to decreasing the step potential might be to extend the mesh to spill over the edge of the joint bay area and extend across the surface till the voltage gradient has decreased enough to become safe.

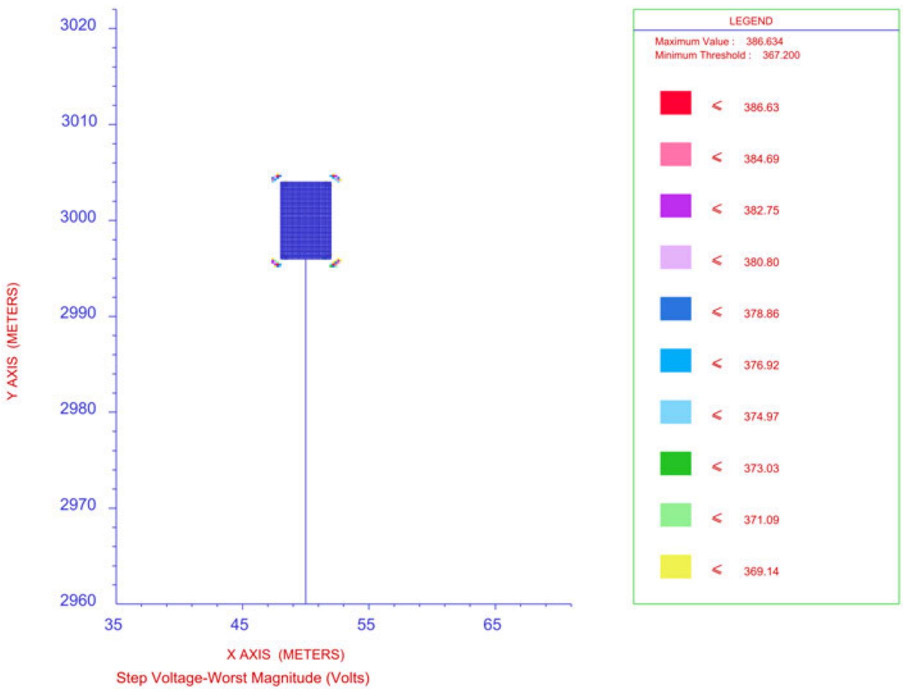

Figure 5.13: Scenario 3 - Step potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

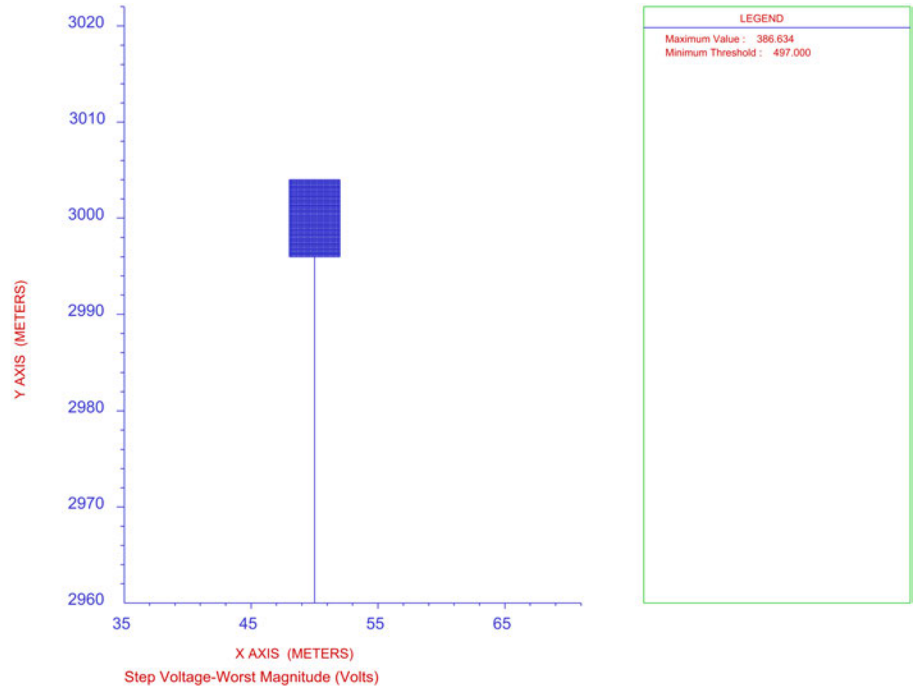

Figure 5.14: Scenario 3 - Step potential model with 200 ms protection timing for a 70 kg person without boots on a soil profile of 100 Ω·m.

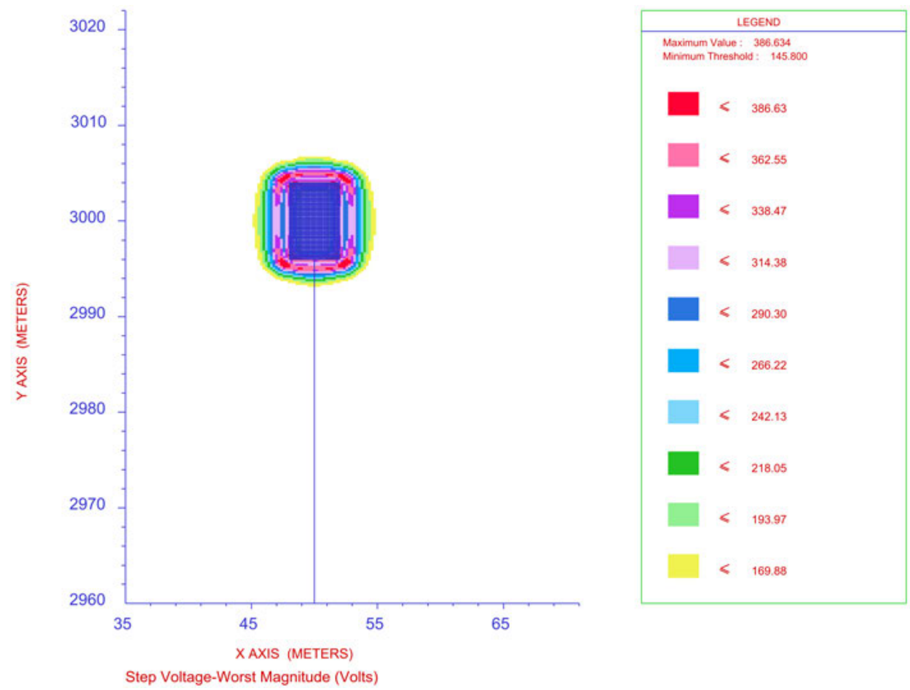

Figure 5.15: Scenario 3 - Step potential model with 3 s protection timing for a 70 kg person without boots on a soil profile of 100 Ω·m.

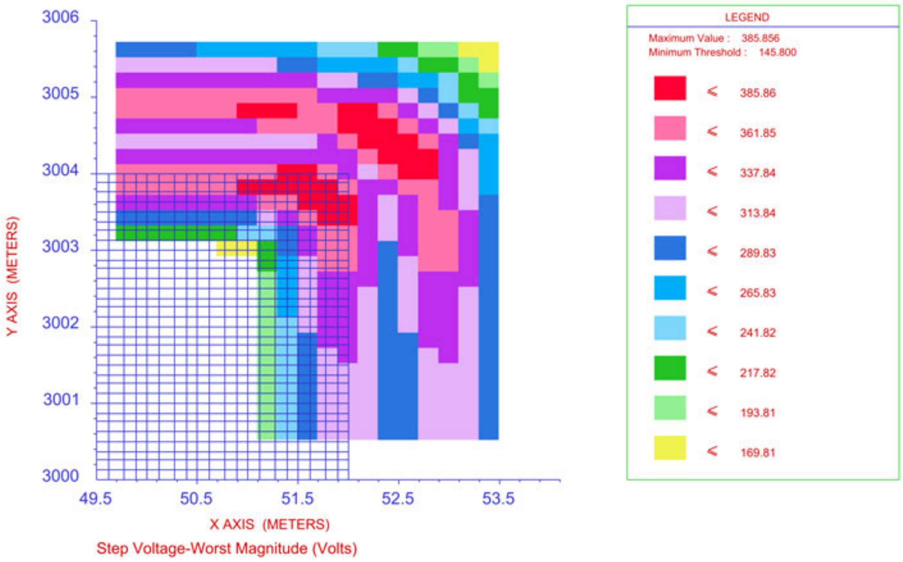

Figure 5.16: Scenario 3 - Step potential model with 3 s protection timing for a 70 kg person without boots on a soil profile of 100 Ω·m - zoomed in on the corner.

Touch potentials on the other hand for Scenario 3, clearly indicate a safe environment on the earth mat for both 200 ms and 3 s, which can be seen clearly in Figures 5.17, 5.18 and 5.19. As discussed earlier extending the mat over the edge of the pit would allow transitioning to be conducted in a safe manner.

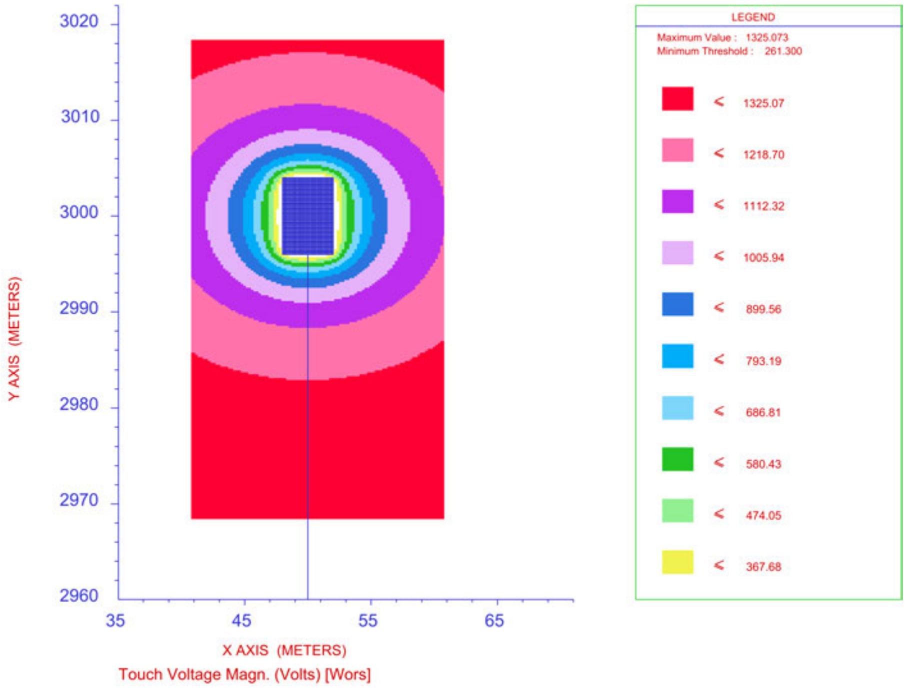

Figure 5.17: Scenario 3 - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

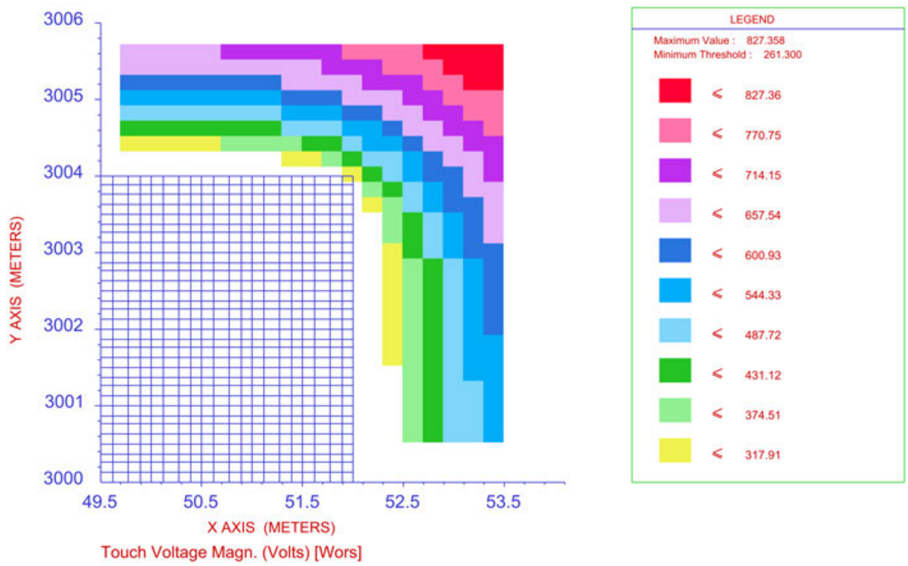

Figure 5.18: Scenario 3 - Touch potential model zoomed in on the corner with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

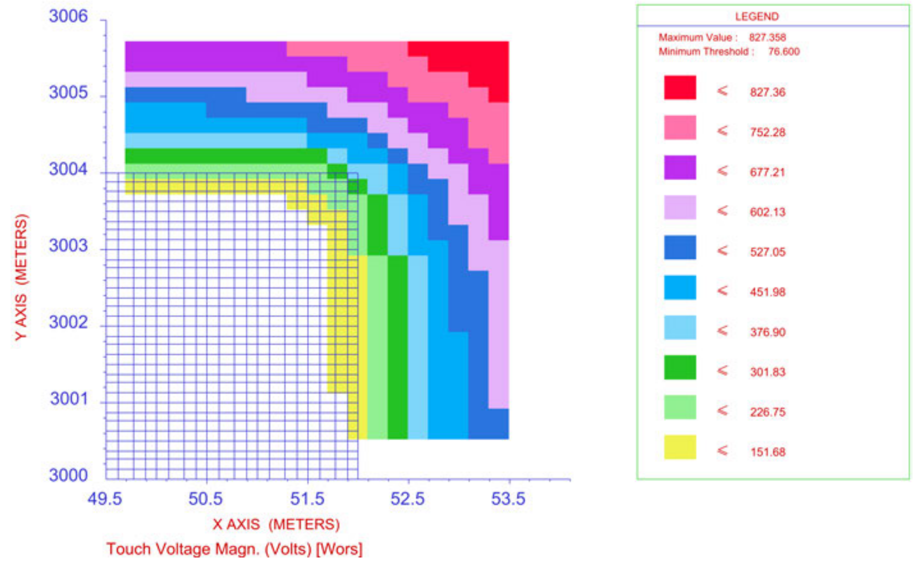

Figure 5.19: Scenario 3 - Touch potential model zoomed in on the corner with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m.

5.4 Analysis

While the step potential modelling in Scenarios 1 and 3 within the joint bay show that there is little issue, the introduction of additional earthing conductor in between these measures pose a different situation by creating a step potential hazard. In this case adding more earthing conductor does not improve the situation unless the whole area has a grid size that prevents step potentials occurring.

Touch potentials within the joint bay in the first scenario present a dangerous situation for workers while a transferred voltage generated by the fault current at the substation exists. The second scenario presents an improvement over the first scenario in the joint bay with the area becoming safe and below the threshold. The third scenario and main object to the research conducted in this project for touch potentials demonstrates through the modelling software that the mesh provides a safe working environment for the workers in the joint bay. Combined, the step and touch potentials with a mesh grid are mitigated and present a situation that is safe from a transferred voltage perspective under a worst case fault at the substation where the cable sheath is connected. Modelling these situations and scenarios has shown that by placing a mesh in the joint bay is effective and raises the EPR to a similar situation as experienced in the substation where the fault occurs.

It should be pointed out here that while the modelling indicates the mesh provides a safe environment, it is strongly recommended to perform injection testing to a similar situation in the field to prove the modelling. Further, as this modelling could not take into account all situations across the Energex network, it would be prudent before taking this work and applying it directly to work practices without further testing and modelling of other feeders at different fault levels. Considering the safety aspects of the situation, from a voltage perspective as already stated it would be worth further pursuing and testing. However from a working environment perspective a further detailed look should be undertaken into implementing the mesh in a joint bay as this may cause additional hazards. Trip hazards on the mesh may be one hazard that could present itself when working in the area with the requirement to ensure that every part of the bay is covered in mesh to create the safe working zone. Hence trials would be recommended to be performed before implementation into work practices.

5.5 Further Analysis - Reduction of fault current

While a substation fault will always return to its source, not all of the current will uniformly return through the ground. As the Energex network has such a large interconnected network the fault returning back on other cable sheaths and overhead earth wires is possible, and not just through the ground itself. This could be demonstrated through the results from remote earth injecting testing at different substations. A search for these results was made and the data found. Due to the number of remote earth inject tests that have been conducted within the Energex network, it was considered to conduct a survey of those results to identify an average figure that could be used to model a scenario that reflected the return current.

Analysis of the results also raises the question as to the probability of this occurring and if low enough would it be possible to not install a mesh system over the first or second scenario. Worst case scenarios also may not be a true indication of the actual transferred voltage. Due to this it was thought to look briefly at the probability of a worst case scenario occurring in addition to what the percentage of fault current would be present. A sample of over 50 substation remote earth injection tests were gathered to provide a sample of the network. The average of these results, which can be seen in Table F.1, was found to be 27.9% of the injected current. As such this translated to a fault current of 543.7 A at the substation.

5.5.1 Step Potentials

Step potential plots for Scenario 1 and 2 which can be seen in Figures 5.20 and 5.21 respectively, indicate the reduction in fault current also improves the situation at the joint bay with both scenarios becoming safe. The unsafe situation return however for Scenario 2 when the protection timing is increase out to 3 s shown in Figure 5.22

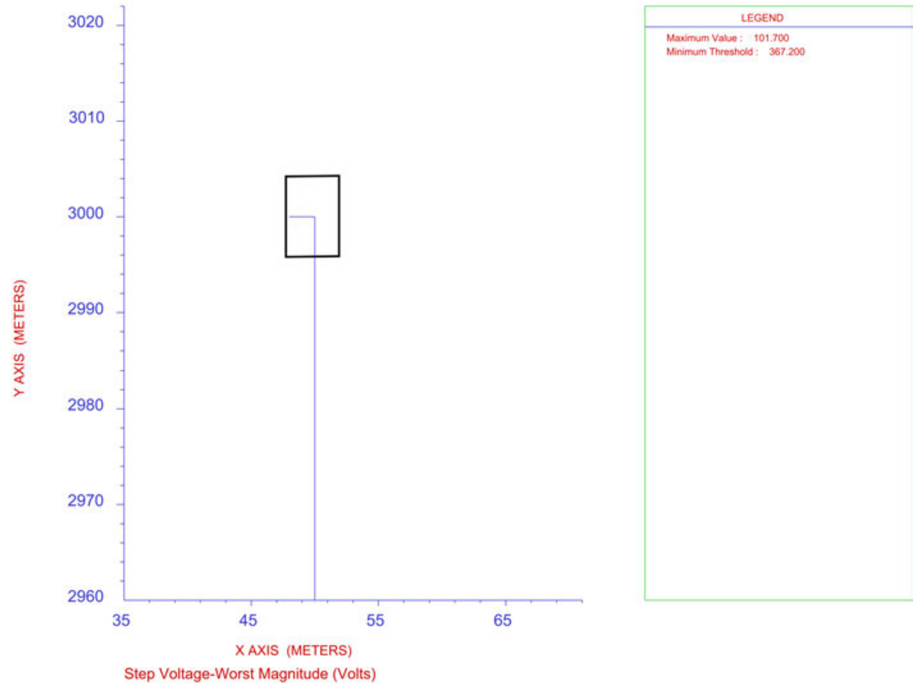

Figure 5.20: Scenario 1 - Step potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

5.5.2 Touch Potentials

Output plots for the touch potentials were gathered and are shown below. Scenario 1, as shown in Figure 5.23, compared with the previous hazardous situation in Figure 5.8 improved so that the joint bay area had an allowable touch voltage situation. The downgrade in fault current changes the situation to a more positive one, however as seen in Figure 5.24 the potential gradients return with a 3 s clearing time. Figures 5.25 and 5.26 are included in an attempt to show the effects of increasing body weight, boots to a safer level while at a 3 s protection time.

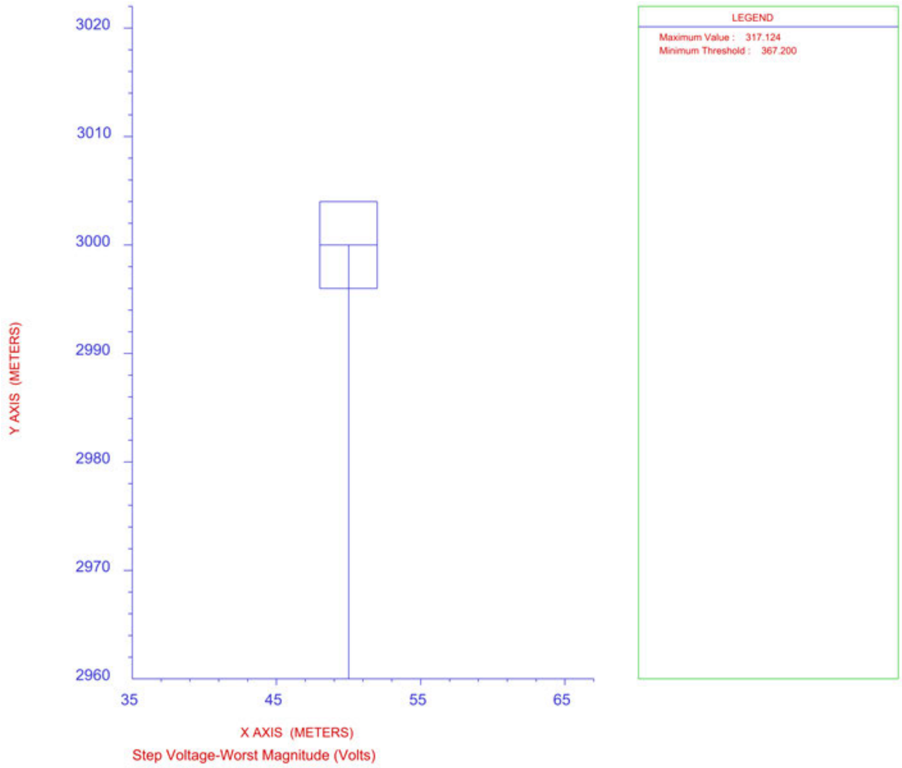

Figure 5.21: Scenario 2 - Step potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

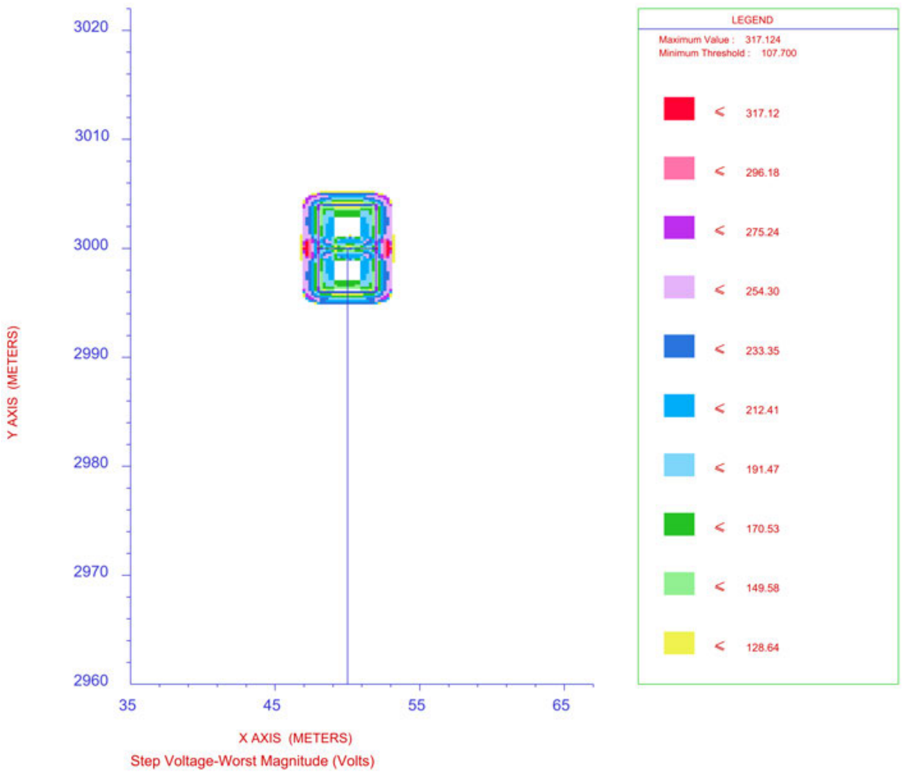

Figure 5.22: Scenario 2 - Step potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

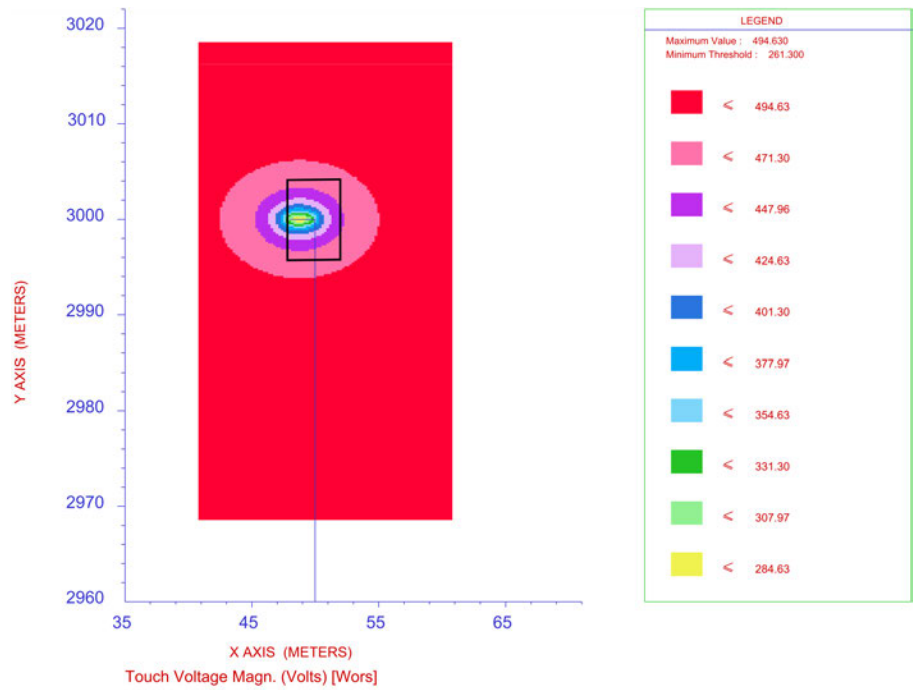

Figure 5.23: Scenario 1 - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

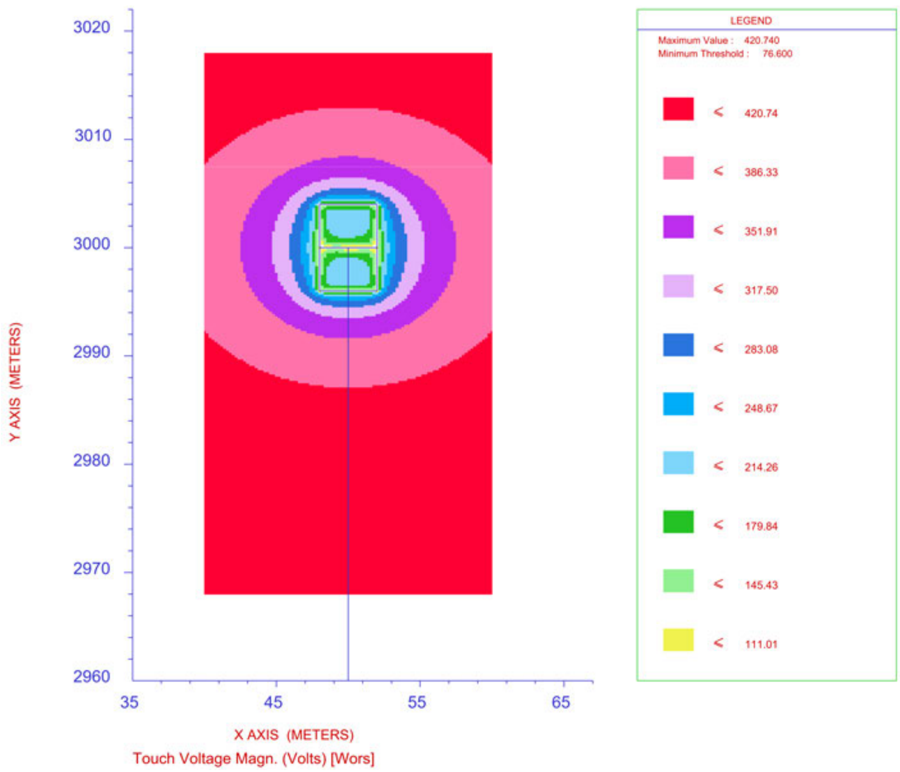

Figure 5.24: Scenario 2 - Touch potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

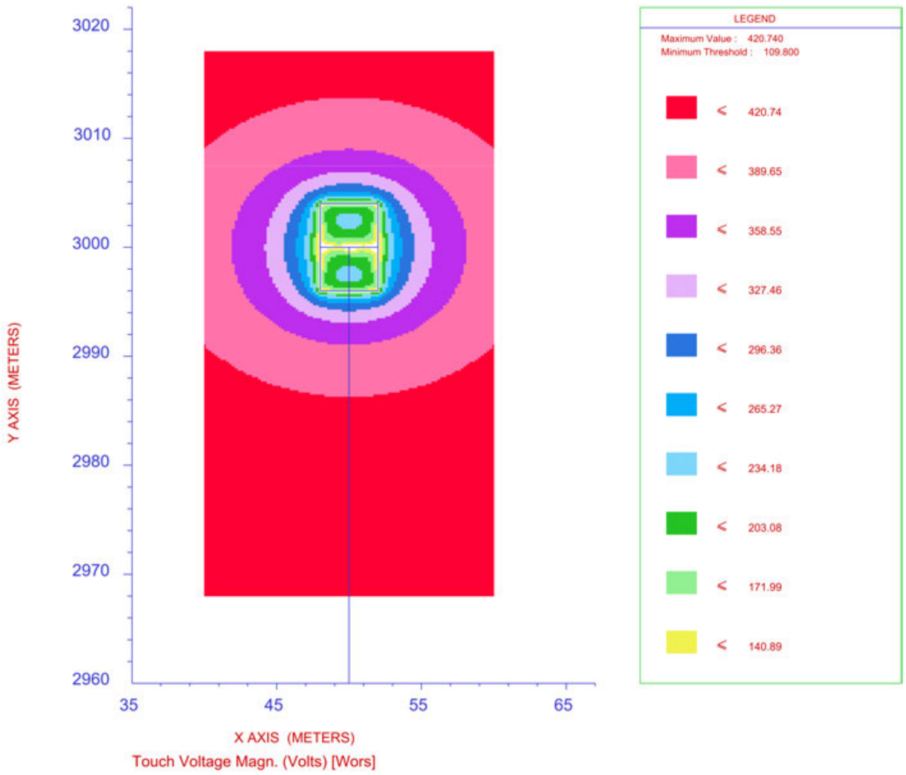

Figure 5.25: Scenario 2 - Touch potential model with 3 s protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

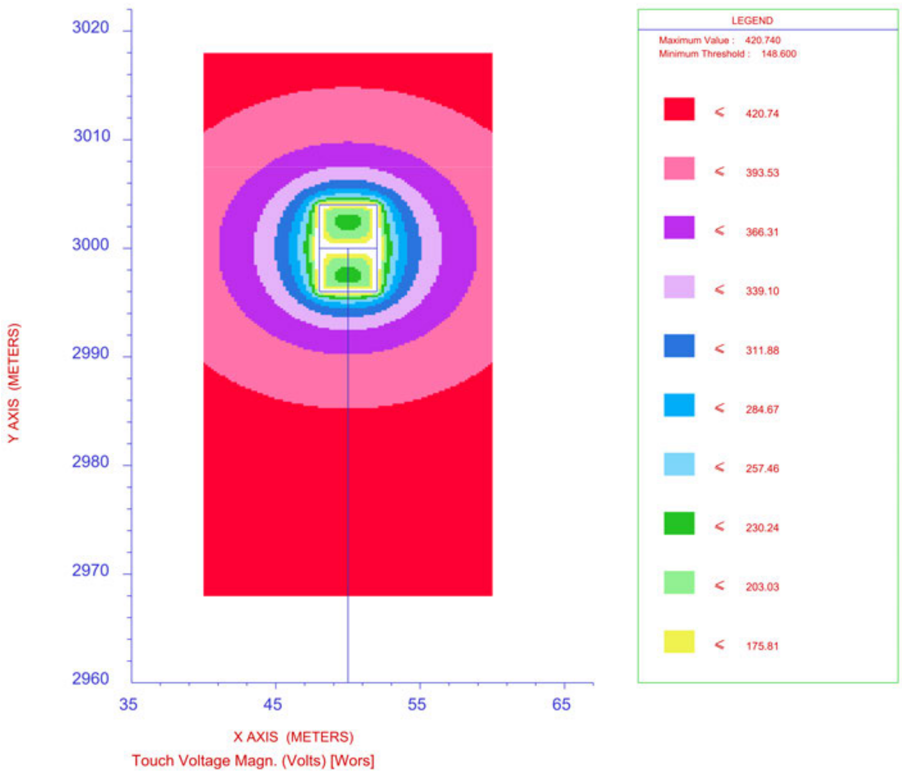

Figure 5.26: Scenario 2 - Touch potential model with 3 s protection timing for a 70 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

Additionally six 1.8 m earth rods were placed around the joint bay in Scenario 2, in order to see if this reduced the voltage gradients in the area for touch potentials. As shown in Figure 5.27, there was improvement to the gradients being further away from the outside of the joint bay. This however returned with a 3 s protection timing in place, shown in Figure 5.29 and as such may not be worth the effort, considering the additional risks associated with driving objects into the ground near cables. Further results showing differing inputs can be seen in Appendix D.

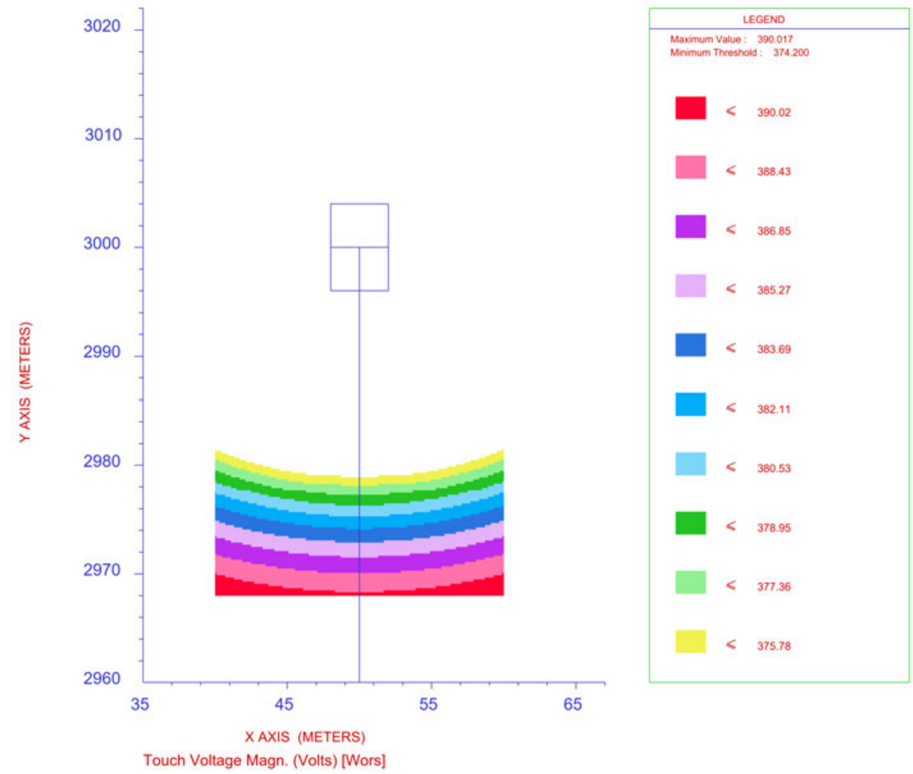

Figure 5.27: Scenario 2 - Touch potential model with 200 ms protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

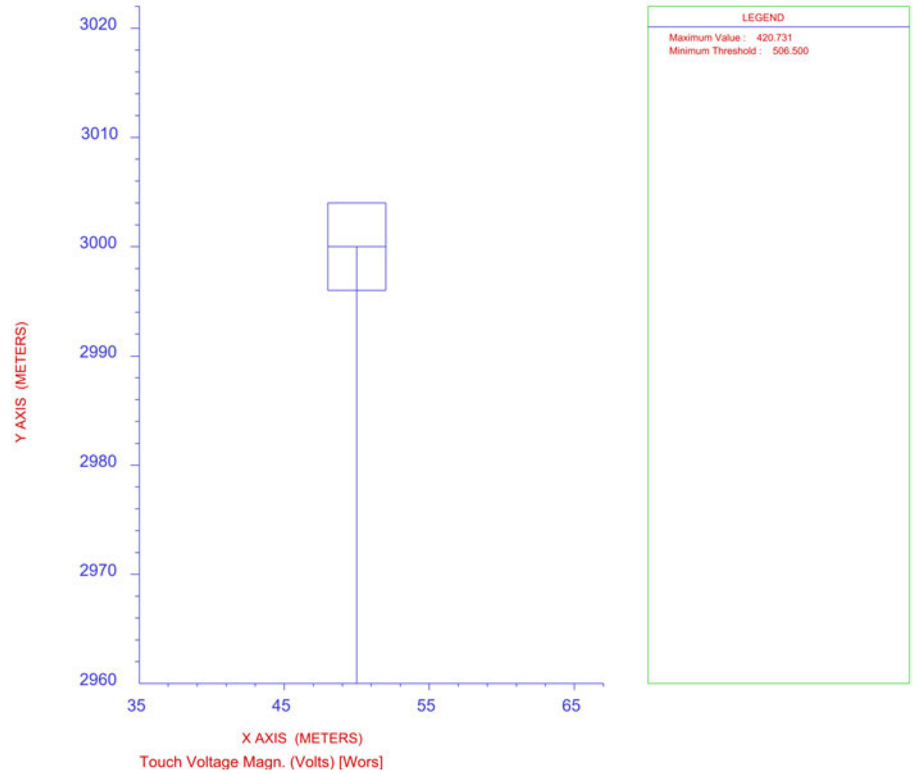

Figure 5.28: Scenario 2 - Touch potential model with 200 ms protection timing for a 70 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

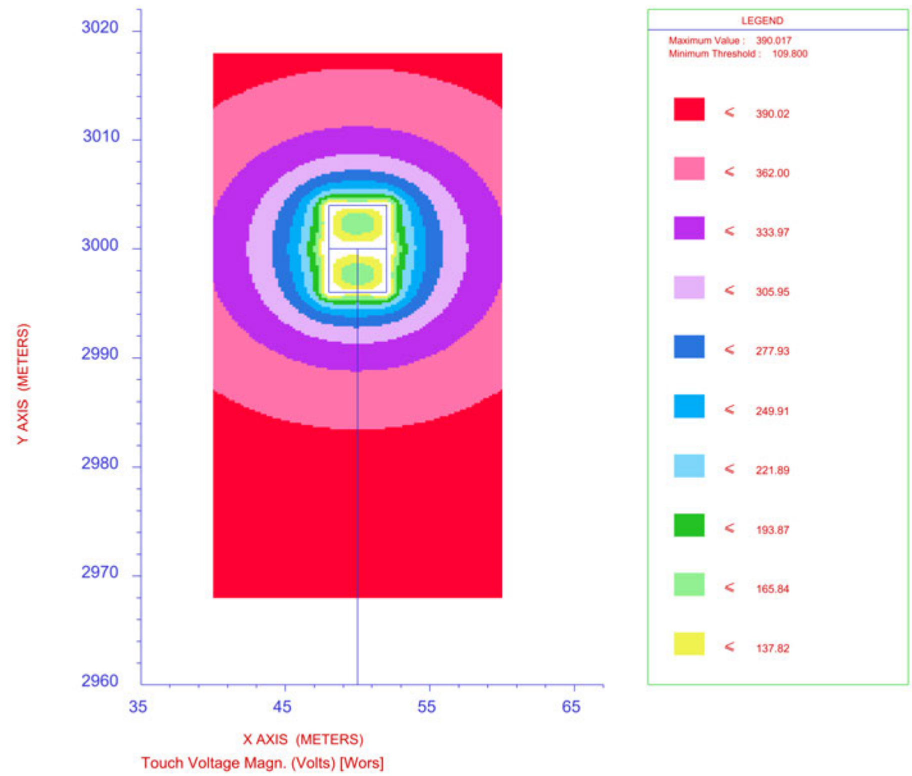

Figure 5.29: Scenario 2 - Touch potential model with 3 s protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

5.6 Chapter Summary

In conclusion of this chapter the results from the source substation have been given. It can be seen that while the source substation can have a safe working environment from a step and touch potential perspective, the joint bay may not exhibit the same situation. The three joint bay scenarios showing both the step and touch potentials that were modelled have also been presented. It can be seen clearly that as more conductor is placed within the joint bay the safer it becomes from both step and touch perspectives. The earth mat or mesh grid modelling in Scenario 3 shows that it is effective when placed in the joint bay under all presented situations and thereby achieving the objectives set-out by the project. Analysis of the results as shown prompted further work and modelling. This was conducted by taking a sample of remote earth injection tests that had been conducted and finding the mean of the results and then remodelling some of the scenarios to gain insights into a more realistic situation.

Chapter 6

Conclusions and Further Work

6.1 Conclusions

While it can be seen that an earth mat in a cable pit as modelled can be effective, this project work is not definitive in answering all aspects of its use. It has however addressed the aim and objectives as set out in Section 1.2. Documentation of the current practices and work procedures was conducted. Further, the identification and review of the relevant national and international standards was completed and all of this was included in Chapter 2. The selection of a suitable modelling software was discussed and an attempt to validate against a substation where a remote earth injection test had been performed was attempted and discussed. The modelling stages of the project were set-up in Chapter 4 with the results given and analysed in Chapter 5. Finally further work will be discussed below.

It can be seen that while the source substation can have a safe working environment from a step and touch potential perspective, the joint bay may not exhibit the same situation. The three joint bay scenarios that were modelled show clearly that the more conductor that is placed the safer it becomes from both step and touch perspectives.

Particularly the touch potential results in scenario one and two, show that care is needed when working in situations such as these. Ensuring effective local earth connection would be a minimum requirement. If this is unachievable then a revised method of approaching the work should be found. The earth mat or mesh grid modelling in scenario three shows that it is effective when placed in the joint bay under worst case situations such as a phase to ground fault of 1950 A.

It is suggested that preceding work at a joint bay, a detailed look at the conditions should be conducted for the situation. Fault level and current return percentage should be looked at along with the soil resistivity at the site. Pending the outcomes of looking at these criteria, modelling may be required and should the modelling be close to the safety thresholds, then a site test would be recommended to be performed to verify the situation before proceeding.

Where faults may be higher, soil conditions different, protection clearing times longer, care needs to be taken through the use of remodelling these situations that would be reflective of their unique situation. The project was successful in delivering results regarding the modelling of three typical cable pit scenarios. Additionally through this modelling it was shown that an earth mat can be effective in protecting workers in the cable pit from transferred voltages that occur from worst case conditions. This work however, has also made way to a plethora of additional questions. In particular regarding EPR, is the earth mat required for all situations where the fault level is reduced? Questions such as these would require further analysis, calculation and modelling. Some of these question have been documented in the following section.

6.2 Further Work

Many questions have been raised through discussions, whilst working through this project,that have not been able to be answered due to the scope of works set out in the project specification as well as time constraints. Some of the questions have been placed in this section as suggestions for further work that could proceed upon this projects completion.

Regarding probability, further work could be conducted by way of risk analysis as to whether the mesh grid or even an improvement in earthing to the joint bays is required. While the earth mat is effective as shown in the results from Chapter 5, it may not be necessary at all sites and applications relating to 33 kV joint bays. As mentioned previously in Section 5.5, with the reduction of fault current due to the return paths, works practices may not require updating to include installing a temporary mesh grid for every joint bay situation.

Regarding the aforementioned, it would be recommended to perform analysis on substations within the network and determine the fault level returning through the ground. For those substations that have a higher percentage return than modelled in Section 5.5, further modelling would need to be conducted to determine if underground feeders from these would require improved joint bay working conditions. Additionally analysis of fault currents would also apply as there may be some that are greater than the fault current modelled in this project. It is possible that there will be scenarios that will not require additional earthing within the joint bay.

Further investigation could be also be undertaken by increasing the mesh size. By increasing the mesh size it may be possible that the improvement over scenario two as shown in Section 5.3.2 along with the reduction in fault current as already discussed.

While working isolated by the method of insulated equipment is not preferred, it could be further looked at whether isolation could occur through the disconnecting of both the the core and sheath of the cable at both ends. This could reduce the magnitude of the transferred voltage down to the potential levels experienced that may occur under induced voltages and currents. Although this method currently contravenes the practices that are to be adhered in Queensland however the future may give way to looking at this in further detail.

Finally the timing of the fault clearing impacting the situation at the joint bay could be looking at. Both step and touch potentials benefit from lower protection timing and therefore implementing backup protection that operates with faster timing would provide a safer situation for the worker. Cost may inhibit the implementation of this method.

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Appendix A

Project Specification

ENG4111/4112 Research Project

Project Specification

For: Mr Ryan Siddans

Title: Effectiveness of earth mat when jointing high voltage underground cables (33kV and above) in work area from induced voltages and currents.

Major: Electrical and Electronic

Supervisors: Assoc Prof Tony Ahfock (USQ)
Mr Conlan Mallet (Energex/EQL)

Enrollment: ENG4111 – EXT S1, 2021
ENG4112 – EXT S2, 2021

Project Aim: The objective of this project is to find out and fill the gaps in work practices and knowledge associated with what the requirements are for the safety of workers when jointing underground high voltage cables (33kV and above) that is necessary due to induced voltages and currents that are formed as part of the properties of long lengths of conductive material such as copper. Current technical guidelines and company work practices recommend the use of wire mesh and an earth stake however the attributes of mesh and earth stake have not been specified therefore creating uncertainty of safety provided during a number of fault scenarios.

It is planned that a range of scenarios (solid bond, single point bonded inc earth continuity cable, cross bonded) are modelled and calculated with different types of temporary earth mats and number of earth stakes in conjunction with earth fault.

Programme: Version 1, 17th March 2021

1. Identify, analyse and compare the standard methods of earthing protection utilised with working areas associated with jointing underground HV cables.
2. Research approaches recommended by industry best practice (eg CIGRE) as well as current work practices within DNSP (Energex/EQL) in Queensland and construct a simplified analytical model.
3. Review applicable standards (eg AS2067, AS7000, EG0 etc)
4. Build theoretical models using simulation software for scenarios and perform calculations to determine recommended conductor sizes/position of earthing.
5. Investigate the various sizes of earthing mesh mats available including ones from readily available parts, the placement and the impact they have on the safety of the workers in the work area. Included – safety of public and exclusion zone requirement if required.
6. Prepare an academic dissertation communicating the activities, approaches, methodologies and results of the project.

If time and resource permit:

7. Validate the findings from (4.) using data from field injection test through Energex/EQL. Subject to financial requirements at EQL and timing.
8. Document and present recommendations demonstrate various scenarios and situations compliant with work practices for the safe working when jointing HV cables. Possibly use fault level reports and standard clearing timings.
9. Lightning/ transient scenarios and calculation of boundary of range of safe working limit to ensure safe working conditions eg 50km

Appendix B

Modelled Substation Drawings

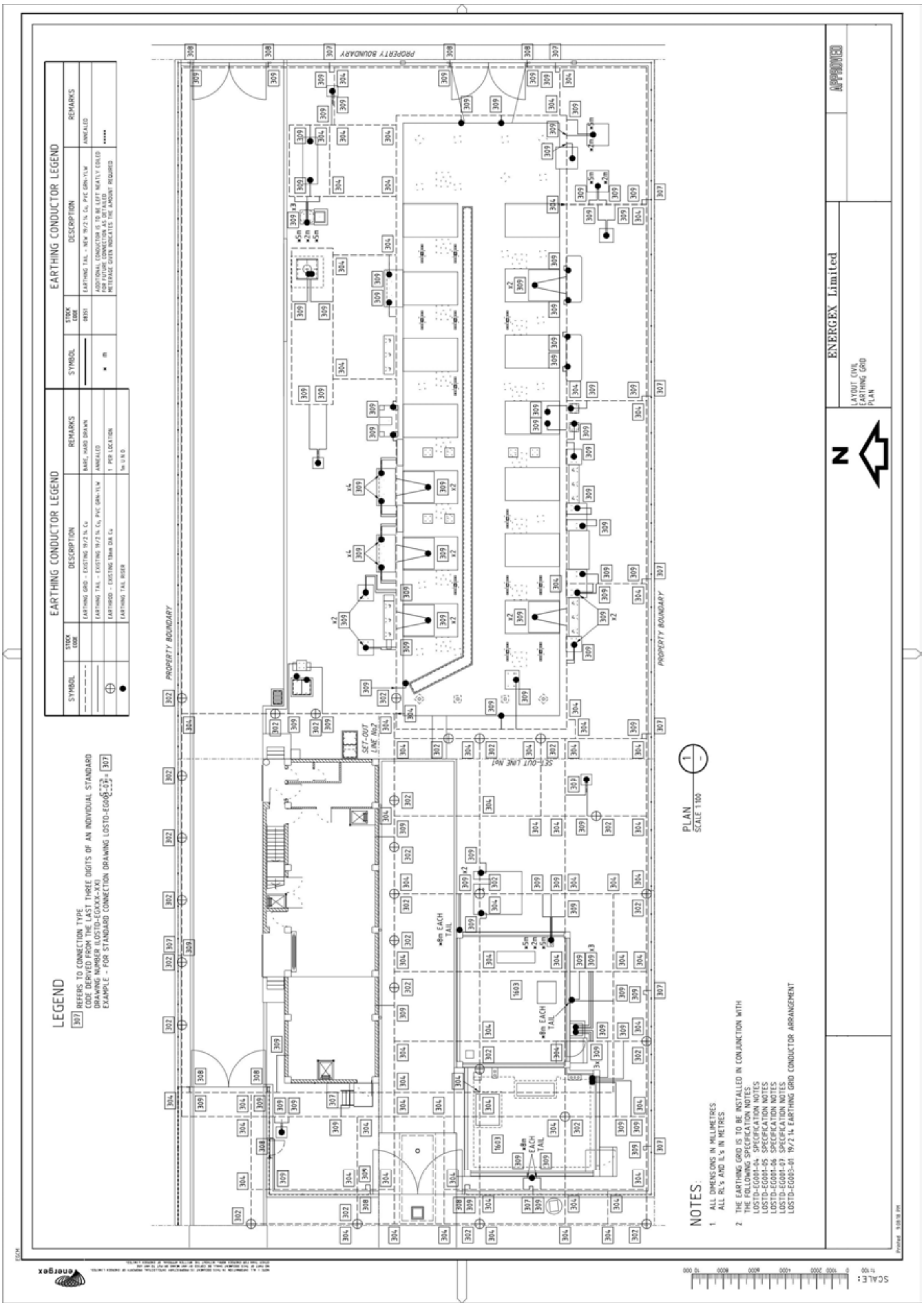


Figure B.1: Substation A earth grid plan used for modelling (Source: Energy QLD).

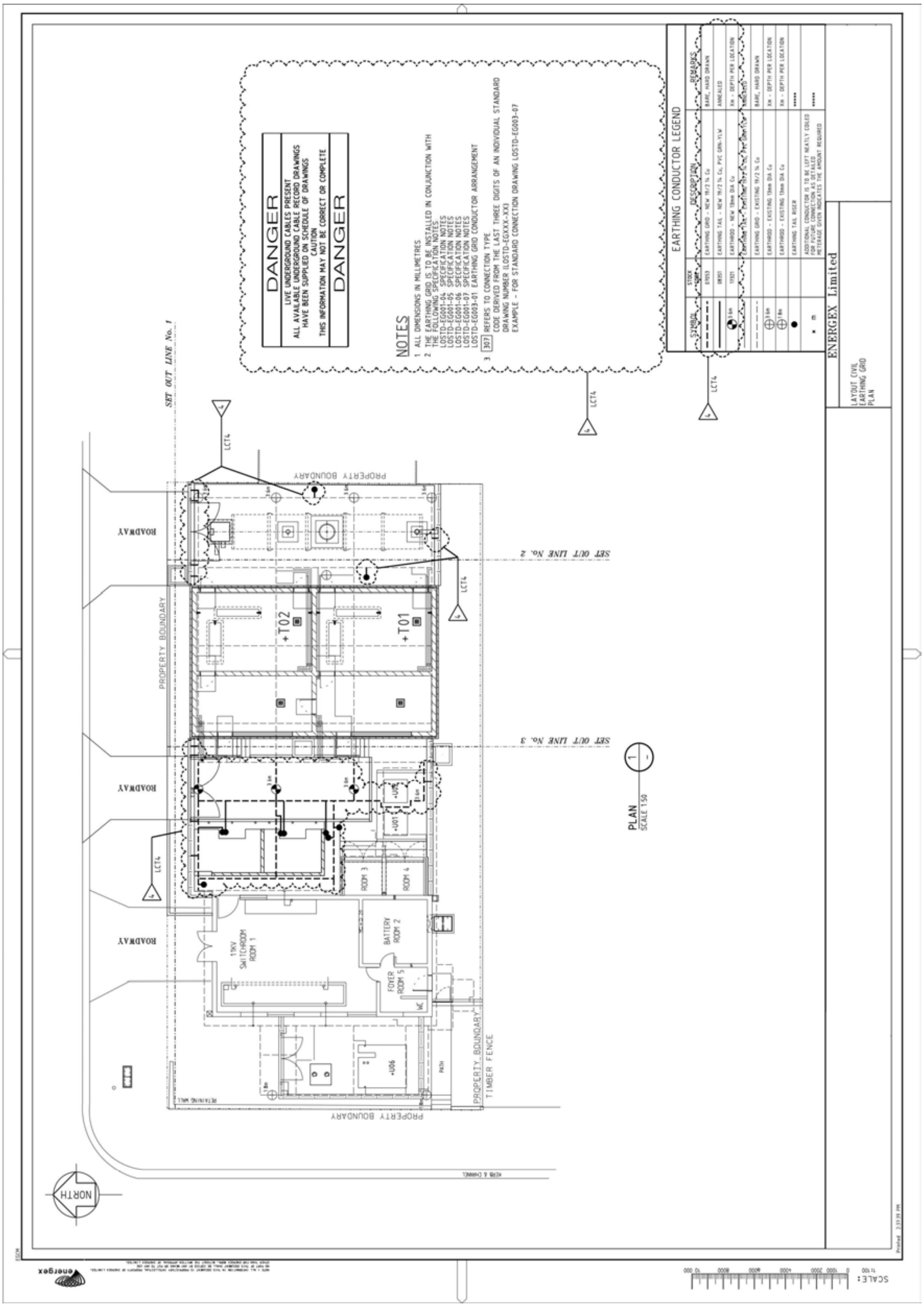


Figure B.2: Substation B earth grid plan used for modelling (Source: Energy QLD).

Appendix C

Substation Validation Data

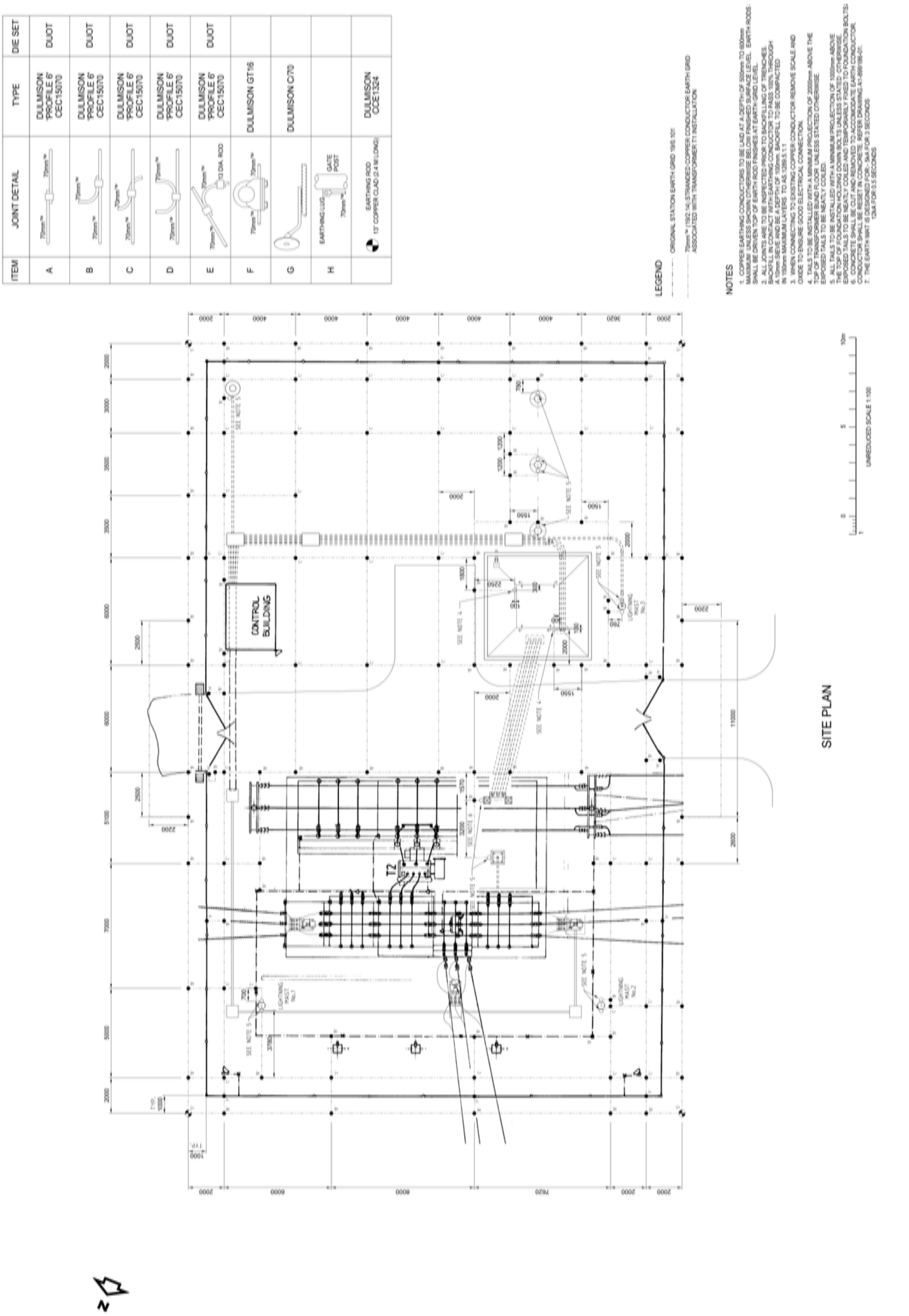


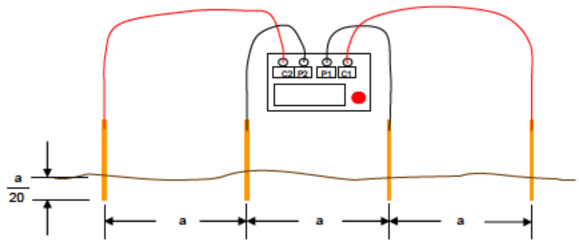
Figure C.1: Substation earth grid drawing used for validation (Source: Energy QLD).

Test Result (Soil)

SUBSTATION **DATE** 8/05/2021

Test Equipment Used		
Instrument	**Model/Asset number**	**Serial Number**
Earth Resistivity Meter		

Weather Conditions	Soil Conditions	Soil Type
Sunny	Wet	Loam
Partly Overcast	Moist	Clay
Overcast	Dry	Sand
Raining	Very Dry/Arid	Stone/Granite
Temperature:		Other:



Wenner's Method: Resistivity (ρ) = 2πaR — Soil Testing

a (m)	2πa (m)	Position 1 R (Ω) C2-P2-P1-C1	Position 1 R (Ω) P2-C2-C1-P1	Position 1 ρ (Ωm)	Position 2 R (Ω) C2-P2-P1-C1	Position 2 R (Ω) P2-C2-C1-P1	Position 2 ρ (Ωm)	ρ Average (Ωm)
0.5	3.14	22.900	22.900	71.942	27.500	27.500	86.394	79.168
1	6.28	1.560	1.540	9.802	1.690	1.820	10.619	10.210
2	12.57	0.360	0.460	4.524	0.610	0.790	7.665	6.095
4	25.13	0.470	0.510	11.812	0.390	0.560	9.802	10.807
8	50.27	0.560	0.450	28.149	0.250	0.300	12.566	20.358
16	100.53	0.330	0.360	33.175	0.250	0.770	25.133	29.154
32	201.06	0.240	0.860	48.255	0.170	0.520	34.181	41.218
64	402.12	0.180	1.270	72.382	0.190	0.080	76.404	74.393
128	804.25							
256	1608.50							

a (m)	2πa (m)	Position 3 R (Ω) C2-P2-P1-C1	Position 3 R (Ω) P2-C2-C1-P1	Position 3 R (Ω)	Position 4 R (Ω) C2-P2-P1-C1	Position 4 R (Ω) P2-C2-C1-P1	Position 4 R (Ω)	ρ Average (Ωm)
0.5	3.14							
1	6.28							
2	12.57							
4	25.13							
8	50.27							
16	100.53							
32	201.06							
64	402.12							
128	804.25							
256	1608.50							

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Figure C.2: Soil test results for the substation used for validation (Source: Energy QLD).

Substation Earth System Injection Analysis Tool

STEP, TOUCH and REACH MEASUREMENTS (INSIDE SUBSTATION)

Test Equipment Used		
Instrument	**MAKE/MODEL**	**SERIAL No**
Tunable Voltmeter		
Spectrum Analyser		
Multimeter (RMS voltmeter)		

Surface type	Natural
Analysis Criteria	IEEE

	HV FAULT	LV FAULT
Fault current (amps)	727	3997
Primary *clearing* time (msecs)	700	420

GLOVE SELECTION: NAR ANALYSIS ONLY!!!	
Glove Type	Nil

NON-CONFORMANCES	HV FAULT	LV FAULT
Number of non-conformances STEP	0	0
Number of non-conformances TOUCH	0	0
Number of non-conformances REACH	0	0

ALLOWABLE VOLTS	HV FAULT			LV FAULT		
	STEP	TOUCH	REACH	STEP	TOUCH	REACH
EG0 Prospective						
IEEE Prospective	243.95	201.72	187.65	314.93	260.43	242.26
IEEE Loaded	187.65	187.65	187.65	242.26	242.26	242.26

STEP

Grid ref	Description	Msd Volts	Pros/ Loaded	HV FAULT Scaled Volts HV Fault	HV FAULT IEEE PASS/FAIL	LV FAULT Scaled Volts LV Fault	LV FAULT IEEE PASS/FAIL
S1	Substation Area, Gravel Area	0.035	P	1.34	PASS	7.36	PASS
		0.001	L	0.04	PASS	0.21	PASS
MAXIMUM STEP VOLTAGE		0.04		1.339		7.363	
For IEEE analysis, do you want to look at prospective (P) or loaded (L) voltages?			P				

TOUCH

Grid ref	Description	Msd Volts	Pros/ Loaded	HV FAULT Scaled Volts HV Fault	HV FAULT IEEE PASS/FAIL with Nil gloves	LV FAULT Scaled Volts LV Fault	LV FAULT IEEE PASS/FAIL with Nil gloves
1	Main Gate, N Arm, Opened Fully Inwards	0.311	P	11.90	*PASS*	65.42	*PASS*
		0.000	L	0.00	*PASS*	0.00	*PASS*
2	Main Gate, S Arm, Opened Fully Inwards	0.067	P	2.56	*PASS*	14.09	*PASS*
		0.000	L	0.00	*PASS*	0.00	*PASS*
3	Substation Fence, W Side	0.399	P	15.27	*PASS*	83.94	*PASS*
		0.015	L	0.57	*PASS*	3.16	*PASS*
4	Substation Fence, SW Corner	0.442	P	16.91	*PASS*	92.98	*PASS*
		0.045	L	1.72	*PASS*	9.47	*PASS*
5	Substation Fence, S Side	0.443	P	16.95	*PASS*	93.19	*PASS*
		0.075	L	2.87	*PASS*	15.78	*PASS*
6	Substation Fence S Side	0.475	P	18.18	*PASS*	99.93	*PASS*
		0.089	L	3.41	*PASS*	18.72	*PASS*
7	Substation Fence, S Side	0.429	P	16.41	*PASS*	90.25	*PASS*
		0.045	L	1.72	*PASS*	9.47	*PASS*
8	Substation Fence SE Corner	0.431	P	16.49	*PASS*	90.67	*PASS*
		0.034	L	1.30	*PASS*	7.15	*PASS*
9	Substation Fence, E Side	0.339	P	12.97	*PASS*	71.31	*PASS*
		0.007	L	0.27	*PASS*	1.47	*PASS*
10	Personnel Gate Opened Fully Inwards	0.375	P	14.35	*PASS*	78.89	*PASS*
		0.057	L	2.18	*PASS*	11.99	*PASS*
11	Rear Gate, S Arm, Opened Fully Inwards	0.426	P	16.30	*PASS*	89.62	*PASS*
		0.065	L	2.49	*PASS*	13.67	*PASS*
12	Rear Gate, N Arm, Opened Fully Inwards	0.362	P	13.85	*PASS*	76.15	*PASS*
		0.064	L	2.45	*PASS*	13.46	*PASS*
13	Substation Fence, E Side	0.331	P	12.67	*PASS*	69.63	*PASS*
		0.033	L	1.26	*PASS*	6.94	*PASS*
14	Substation Fence, NE Corner	0.325	P	12.44	*PASS*	68.37	*PASS*
		0.093	L	3.56	*PASS*	19.56	*PASS*
15	Substation Fence, N Side	0.381	P	14.58	*PASS*	80.15	*PASS*
		0.030	L	1.15	*PASS*	6.31	*PASS*
16	Substation Fence, N Side	0.308	P	11.79	*PASS*	64.79	*PASS*

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Figure C.3: Substation step and touch potential measurements (Source: Energy QLD).

STEP, TOUCH and REACH MEASUREMENTS (INSIDE SUBSTATION)

		0.045	L	1.72	PASS	9.47	PASS
17	Substation Fence, N Side	0.264	P	10.10	PASS	55.54	PASS
		0.035	L	1.34	PASS	7.36	PASS
18	Substation Fence, NW Corner	0.224	P	8.57	PASS	47.12	PASS
		0.012	L	0.46	PASS	2.52	PASS
19	Substation Fence, W Side	0.214	P	8.19	PASS	45.02	PASS
		0.016	L	0.61	PASS	3.37	PASS
20	Pole 6049849, Earth (If Accessible)	0.161	P	6.16	PASS	33.87	PASS
		0.152	L	5.82	PASS	31.98	PASS
26	CB4014 Control Box	0.008	P	0.29	PASS	1.60	PASS
		0.000	L	0.00	PASS	0.00	PASS
28	Lightning Mast	0.238	P	9.10	PASS	50.00	PASS
		0.001	L	0.03	PASS	0.15	PASS
29	Lighting Post	0.020	P	0.75	PASS	4.10	PASS
		0.003	L	0.10	PASS	0.57	PASS
30	CB4015, Control Box	0.644	P	24.64	PASS	135.48	PASS
		0.441	L	16.87	PASS	92.77	PASS
42	Pole 2033667 Earth (If Accessible)	0.255	P	9.76	PASS	53.64	PASS
		0.130	L	4.97	PASS	27.35	PASS
48	Lightning Mast	0.214	P	8.19	PASS	45.02	PASS
		0.000	L	0.01	PASS	0.06	PASS
49	Lighting Post	0.415	P	15.88	PASS	87.30	PASS
		0.067	L	2.56	PASS	14.05	PASS
50	Tap	0.098	P	3.73	PASS	20.51	PASS
		0.018	L	0.68	PASS	3.74	PASS
51	Duct Cover	0.008	P	0.31	PASS	1.68	PASS
		0.000	L	0.00	PASS	0.00	PASS
52	Duct Cover	0.025	P	0.96	PASS	5.26	PASS
		0.002	L	0.08	PASS	0.42	PASS
53	Control Building, Door	0.001	P	0.04	PASS	0.21	PASS
		0.000	L	0.01	PASS	0.04	PASS
54	Control Building AC	0.373	P	14.27	PASS	78.47	PASS
		0.130	L	4.97	PASS	27.35	PASS
55	Control Building, Panel	0.409	P	15.65	PASS	86.04	PASS
		0.005	L	0.19	PASS	1.05	PASS
56	Duct Cover	0.016	P	0.61	PASS	3.37	PASS
		0.000	L	0.00	PASS	0.00	PASS
57	Communications Pole	0.326	P	12.47	PASS	68.58	PASS
		0.001	L	0.03	PASS	0.19	PASS
58	Duct Cover	0.003	P	0.11	PASS	0.63	PASS
		0.000	L	0.00	PASS	0.00	PASS
59	Duct Cover	0.015	P	0.57	PASS	3.16	PASS
		0.000	L	0.01	PASS	0.04	PASS
60	Pole, Earth (If Accessible)	0.267	P	10.22	PASS	56.17	PASS
		0.000	L	0.02	PASS	0.08	PASS
61	CB17292, Control Box	0.317	P	12.13	PASS	66.69	PASS
		0.068	L	2.60	PASS	14.31	PASS
62	CB17293, Control Box	0.453	P	17.33	PASS	95.30	PASS
		0.150	L	5.74	PASS	31.56	PASS
65	Lightning Mast	0.256	P	9.80	PASS	53.85	PASS
		0.000	L	0.01	PASS	0.06	PASS
MAXIMUM TOUCH VOLTAGE		0.64		24.641		135.477	
For IEEE analysis, do you want to look at prospective (P) or loaded (L) voltages?			P				

REACH							
				HV FAULT		LV FAULT	
Grid ref	Description	Msd Volts	Pros/ Loaded	Scaled Volts HV Fault	IEEE PASS/FAIL with Nil gloves	Scaled Volts LV Fault	IEEE PASS/FAIL with Nil gloves
R1	Between 1 and 2	0.014	P	0.54	PASS	2.95	PASS
		0.000	L	0.00	PASS	0.00	PASS
R2	Between 11 and 12	0.001	P	0.04	PASS	0.21	PASS
		0.000	L	0.00	PASS	0.00	PASS
R3	Between 49 and Fence	0.088	P	3.37	PASS	18.51	PASS
		0.088	L	3.37	PASS	18.51	PASS
R4	Between 29 and Fence	0.374	P	14.31	PASS	78.68	PASS
		0.355	L	13.58	PASS	74.68	PASS
MAXIMUM REACH VOLTAGE		0.37		14.310		78.678	
For IEEE analysis, do you want to look at prospective (P) or loaded (L) voltages?			P				

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Substation step and touch potential measurements. (cont.)

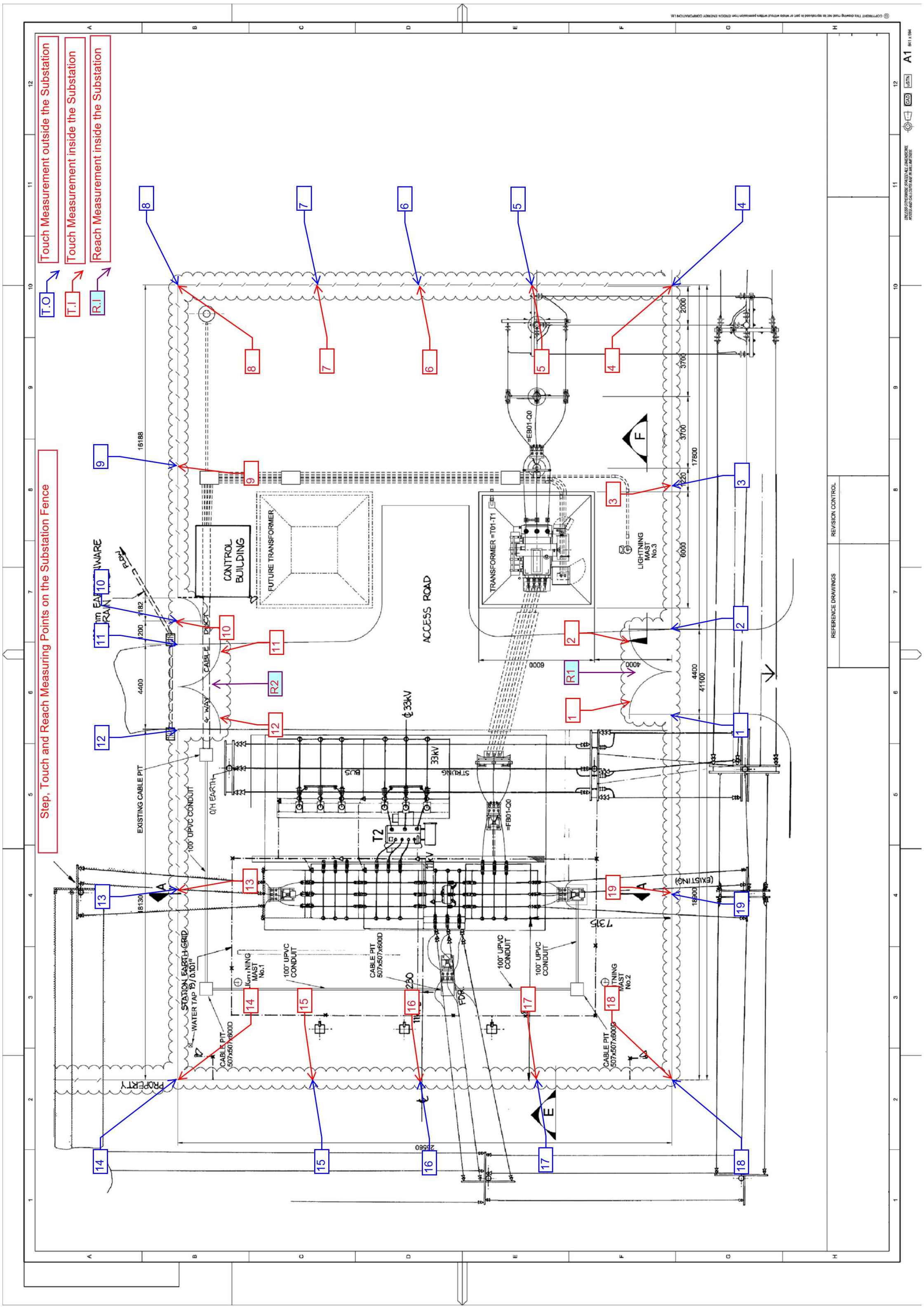

Figure C.4: Substation plan showing locations where measurements were taken (Source: Energy QLD).

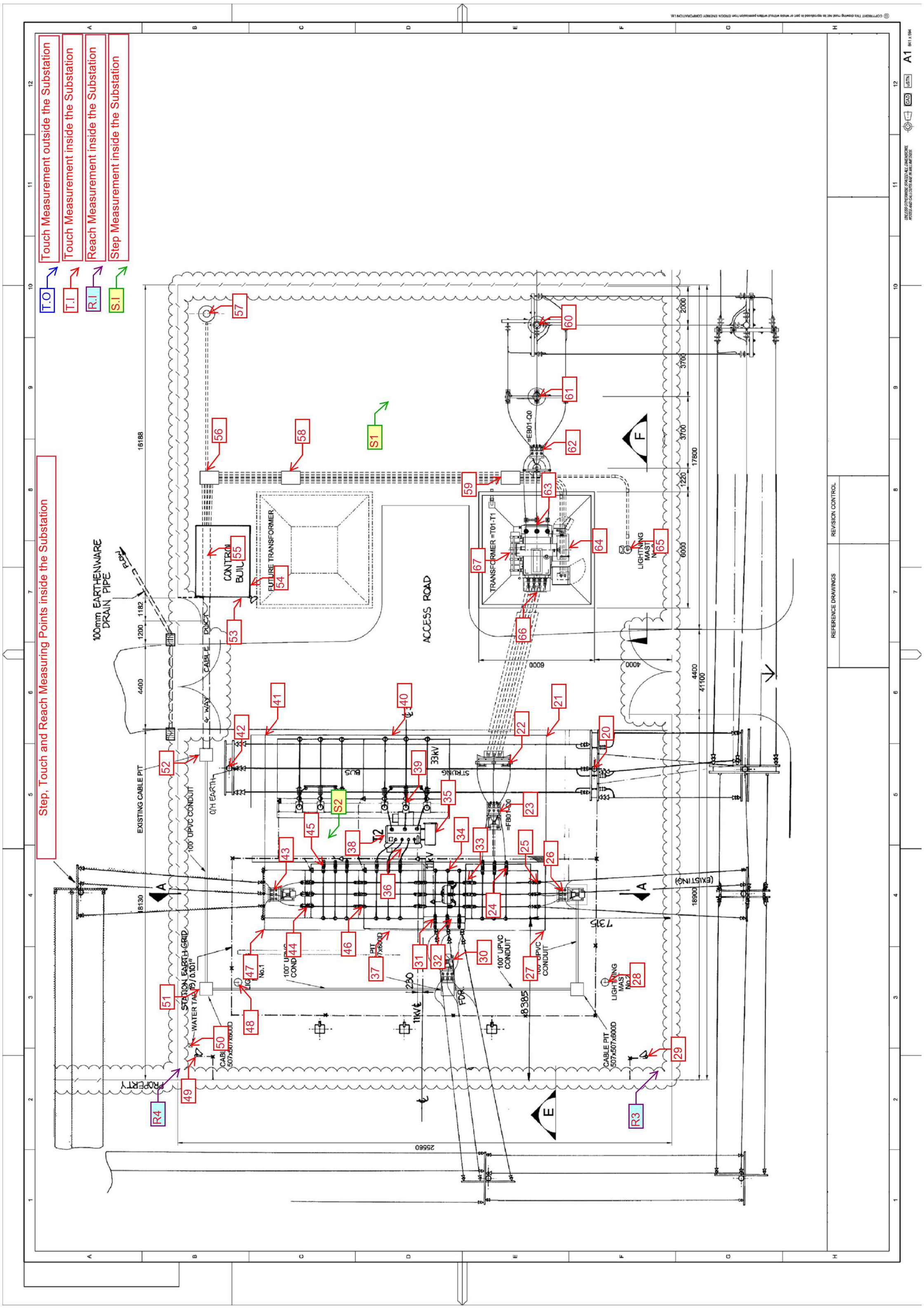

Figure C.5: Substation plan showing locations where measurements were taken (Source: Energy QLD).

Appendix D

Additional Modelled Results

The data presented over the following pages of Appendix D are results that were conducted to see what effect changing parameters would take.

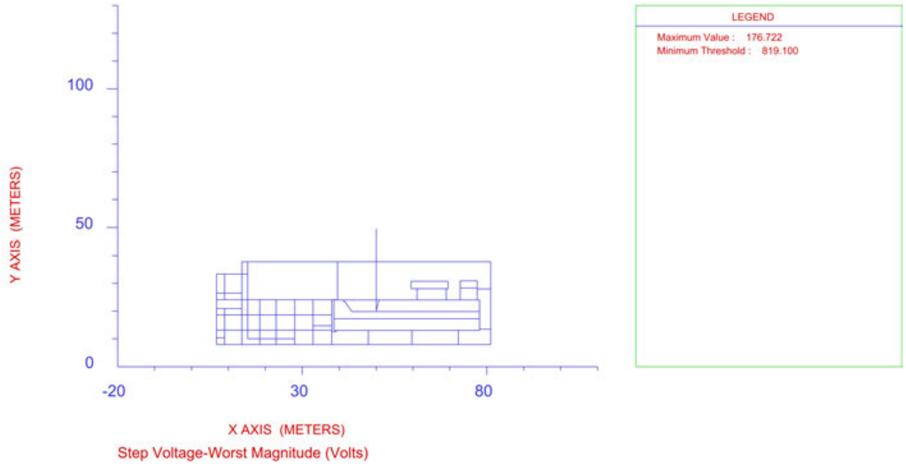

Figure D.1: Source substation A - Step potential model with 200 ms protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m.

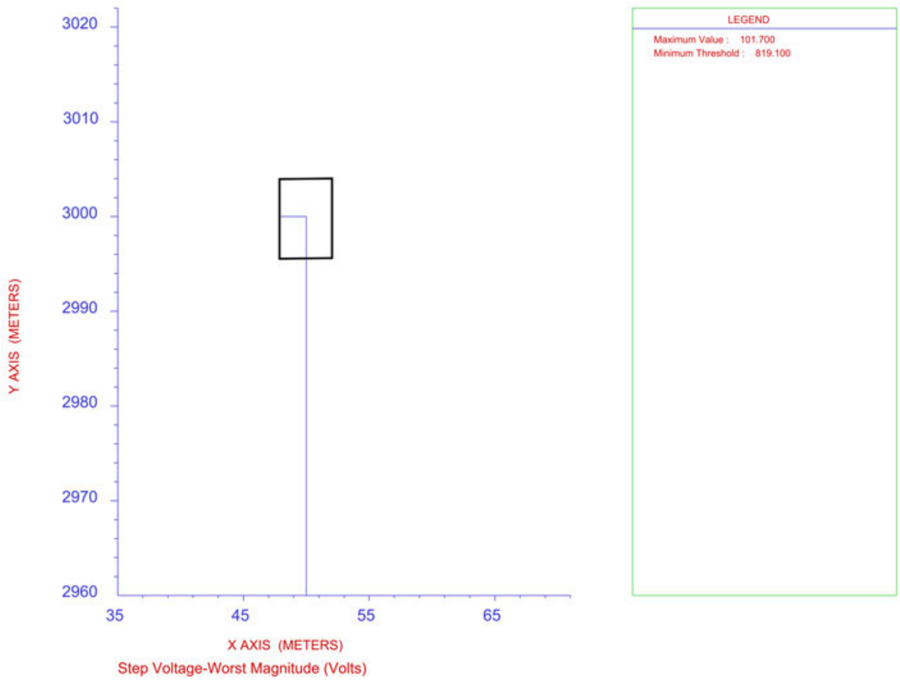

Figure D.2: Scenario 1 - Step potential model with 200 ms protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

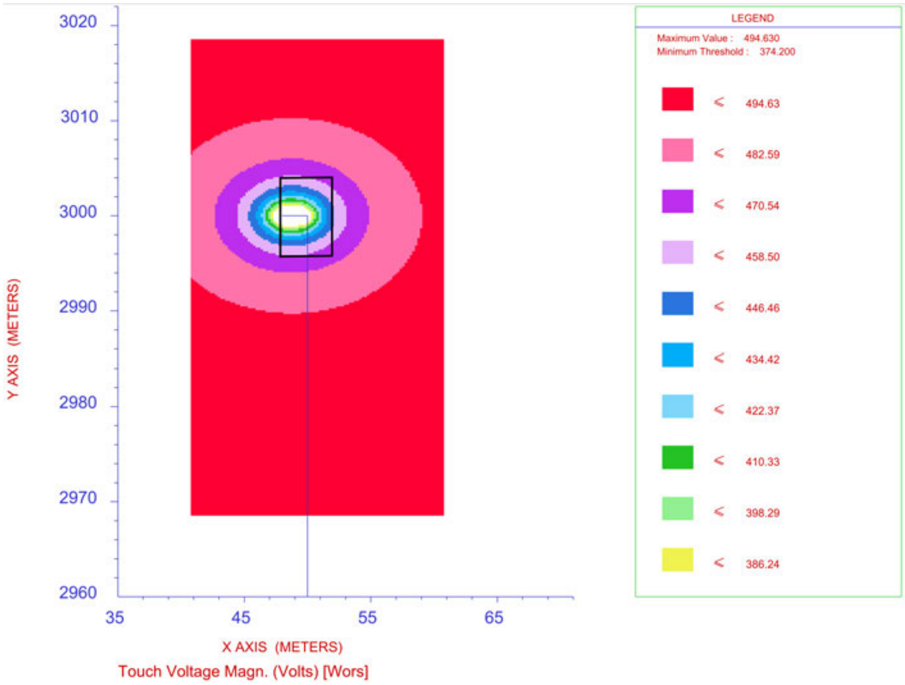

Figure D.3: Scenario 1 - Touch potential model with 200 ms protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

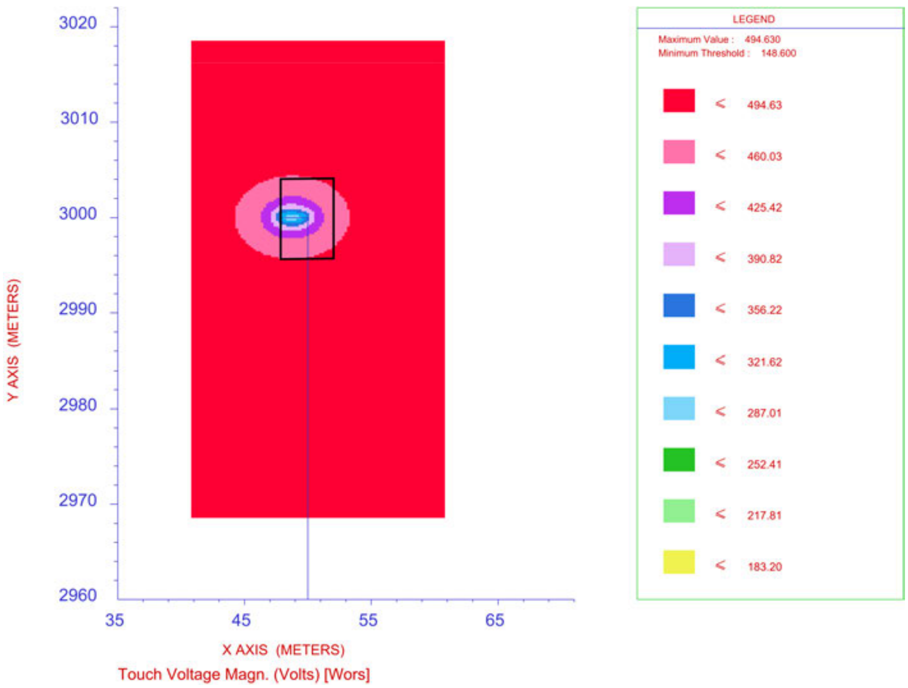

Figure D.4: Scenario 1 - Touch potential model with 3 s protection timing for a 70 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

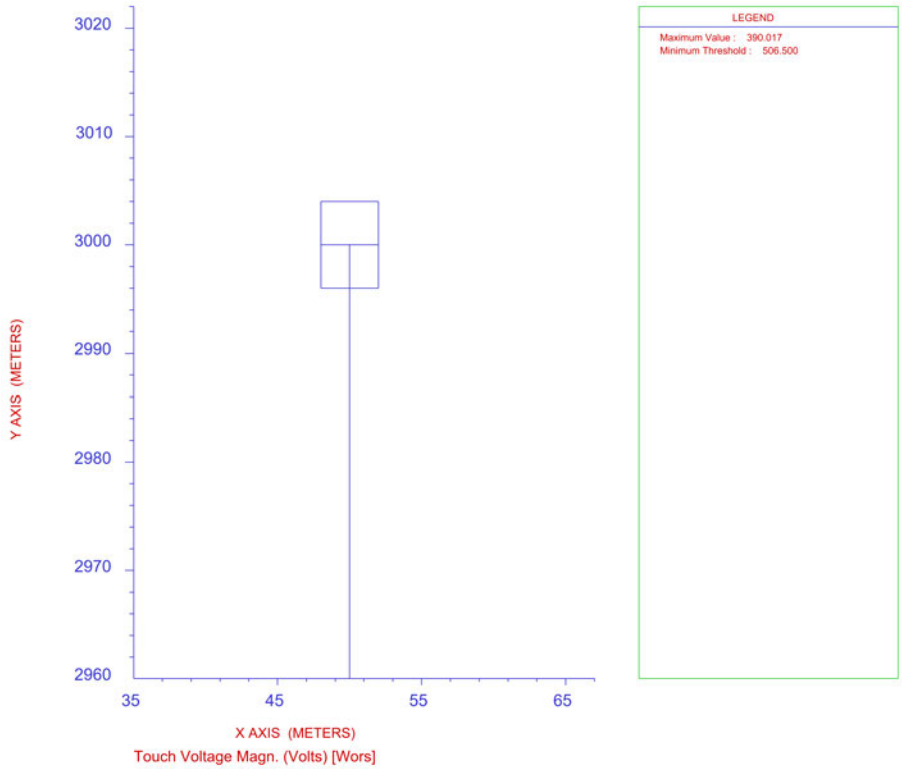

Figure D.5: Scenario 2 - Touch potential model with 200 ms protection timing for a 70 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

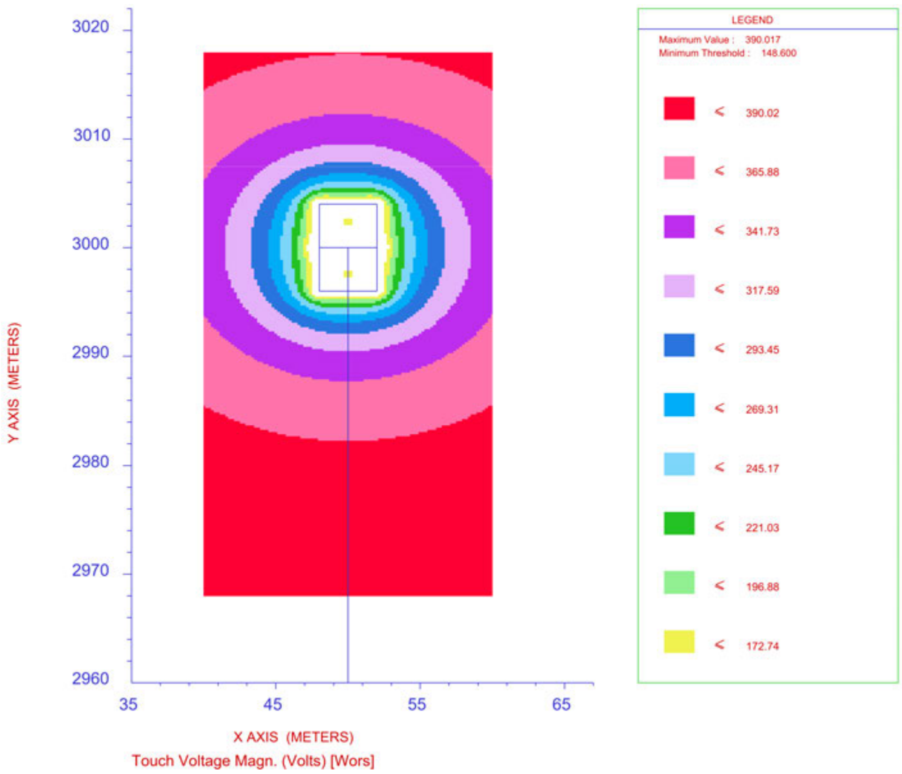

Figure D.6: Scenario 2 - Touch potential model with 3 s protection timing for a 70 kg person with boots on a soil profile of 100 Ω·m. Fault current reduced to 543.7 A.

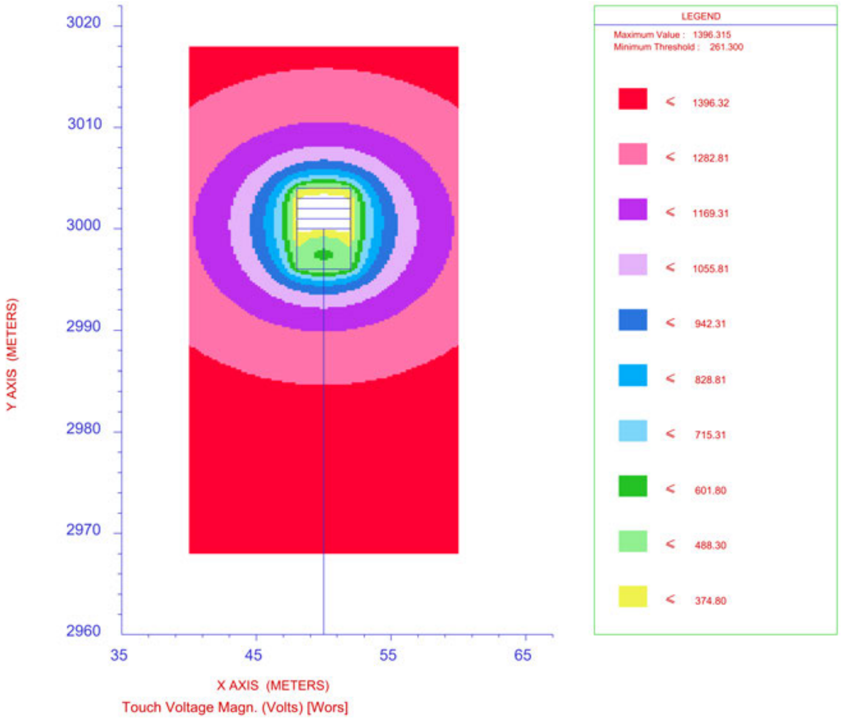

Figure D.7: Scenario 2 - Touch potential model with 200 ms protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m. Additional grid has been added to the top section and shows a decrease in voltage as a result.

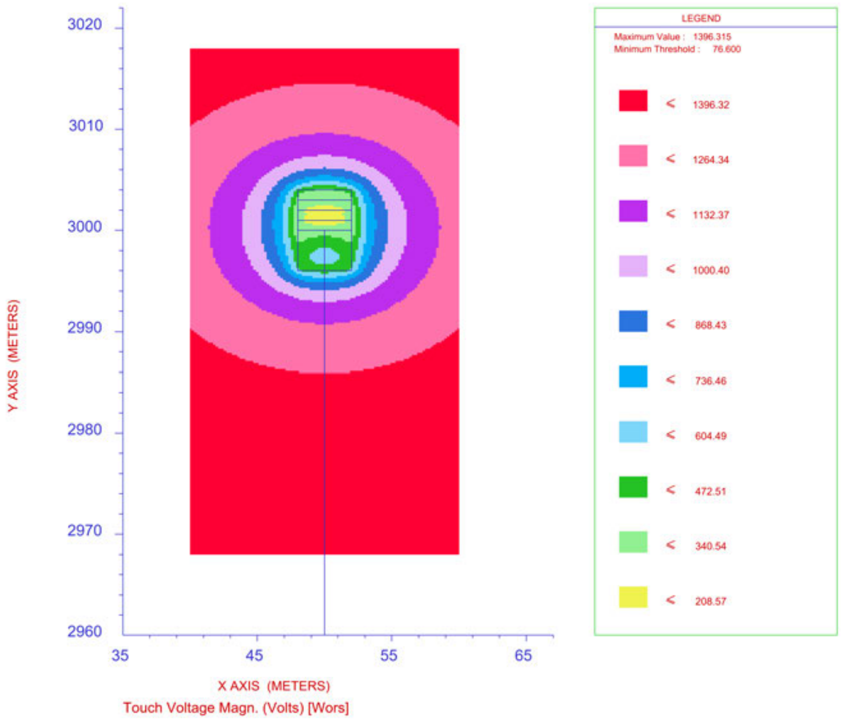

Figure D.8: Scenario 2 - Touch potential model with 3 s protection timing for a 50 kg person without boots on a soil profile of 100 Ω·m. Additional grid has been added to the top section and shows a decrease in voltage as a result in comparison to the lower section.

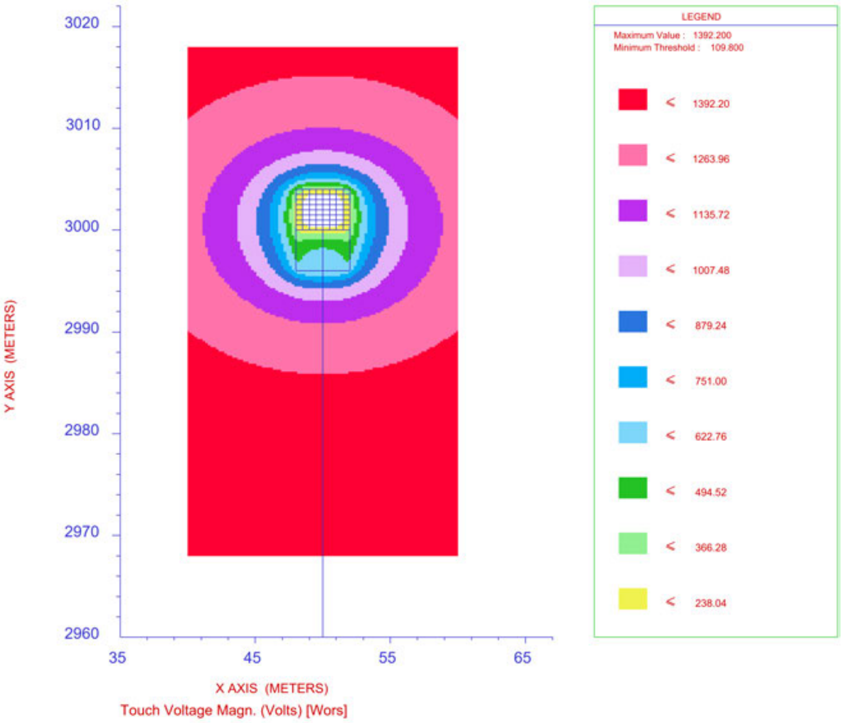

Figure D.9: Scenario 2 - Touch potential model with 3 s protection timing for a 50 kg person with boots on a soil profile of 100 Ω·m. Additional grid has been added to the top section and shows a decrease in voltage in comparison to the lower section.

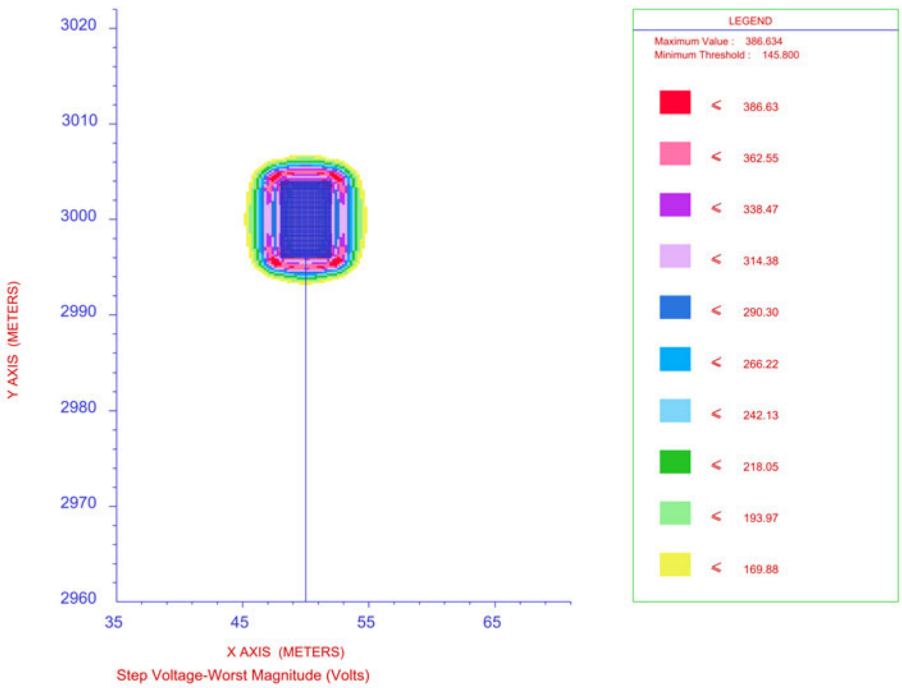

Figure D.10: Scenario 3? - Touch potential model with 3 s protection timing for a 70 kg person without boots on a soil profile of 100 Ω·m.

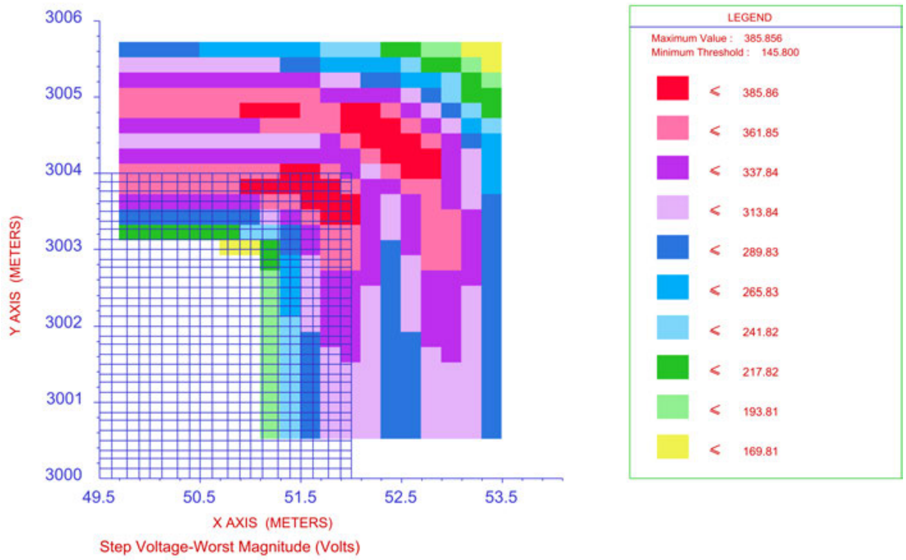

Figure D.11: Scenario 3? - Touch potential model with 3 s protection timing for a 70 kg person without boots on a soil profile of 100 Ω·m. Area has been zoomed to the corner to see the results within the mesh for clarity.

Appendix E

Fault Level Average Calculation for 33 kV

Table E.1: Average fault level within the network used to verify fault current setting of 1950 A for modelling.

Voltage (kV)	1-Ph Fault Level (kA) (Power Factory)	2-PhG Fault Level (kA) (Power Factory)
33	1.11	0.57
33	0.87	0.49
33	1.02	0.54
33	0.89	0.50
33	1.16	0.58
33	1.09	0.56
33	1.12	0.57
33	1.05	0.55
33	1.12	0.57
33	1.12	0.57
33	2.31	1.23
33	2.26	1.21
33	2.25	1.21
33	1.67	0.94
33	2.26	1.21
33	2.22	1.19
33	2.13	1.15
33	2.14	1.14
33	2.11	1.13
33	2.18	1.16
33	2.03	1.11
33	0.66	0.45
33	2.91	1.69
33	2.48	1.49
33	2.47	1.46
33	0.71	0.46
33	2.23	1.29
33	1.08	0.60
33	1.00	0.54
33	1.12	0.58
33	0.88	0.57
33	1.96	1.15
33	0.62	0.40
33	2.41	1.38
33	2.42	1.39
33	3.32	1.80
33	3.32	1.80
33	2.62	1.48
33	1.96	1.15
33	2.17	1.25
33	2.23	1.28
33	0.69	0.43
33	0.78	0.49
33	2.19	1.20
33	0.40	0.27
33	1.33	0.79
33	1.12	0.57
33	1.15	0.58
33	1.17	0.59
33	1.16	0.58
33	1.16	0.58
33	1.02	0.54
33	2.18	1.26
33	3.35	1.81
33	1.79	1.06
33	3.03	1.66
33	2.12	1.23
33	2.56	1.44
33	1.70	1.00
33	3.13	1.73
33	3.13	1.73
33	2.20	1.27
33	2.22	1.19
33	2.13	1.16
33	1.48	0.84
33	1.48	0.84
33	1.01	0.53
33	1.08	0.56
33	1.17	0.58
33	1.13	0.57

Voltage (kV)	1-Ph Fault Level (kA) (Power Factory)	2-PhG Fault Level (kA) (Power Factory)
33	1.13	0.57
33	1.08	0.55
33	1.08	0.55
33	1.55	0.96
33	1.37	0.84
33	3.16	1.76
33	1.99	1.18
33	2.98	1.68
33	1.58	0.98
33	2.71	1.55
33	1.66	1.00
33	1.79	0.99
33	1.55	0.88
33	2.18	1.17
33	2.14	1.15
33	1.96	1.07
33	1.69	0.94
33	1.77	0.98
33	1.68	0.94
33	1.96	1.07
33	2.11	1.13
33	2.11	1.13
33	1.86	1.03
33	1.61	0.90
33	2.19	1.18
33	2.29	1.23
33	2.05	1.12
33	2.04	1.11
33	2.31	1.16
33	2.54	1.43
33	2.54	1.43
33	3.22	1.75
33	2.66	1.49
33	2.86	1.59
33	3.35	1.80
33	3.29	1.78
33	3.26	1.77
33	3.26	1.77
33	3.25	1.76
33	0.68	0.44
33	0.94	0.59
33	2.14	1.18
33	1.57	0.90
33	1.39	0.79
33	1.89	1.02
33	2.01	1.08
33	1.64	0.91
33	2.12	1.12
33	1.79	0.97
33	2.01	1.08
33	1.83	1.00
33	1.50	0.83
33	1.98	1.08
33	2.19	1.18
33	1.87	1.04
33	1.76	0.97
33	0.68	0.44
33	0.79	0.50
33	0.79	0.50
33	1.15	0.68
33	0.53	0.34
33	0.54	0.32
33	0.54	0.32
33	1.85	1.03
33	0.99	0.60
33	2.09	1.14
33	1.94	1.07
33	1.59	0.82
33	1.41	0.75
33	1.36	0.73

Voltage (kV)	1-Ph Fault Level (kA) (Power Factory)	2-PhG Fault Level (kA) (Power Factory)
33	1.29	0.70
33	1.29	0.70
33	1.48	0.78
33	1.44	0.76
33	1.38	0.74
33	1.56	0.81
33	1.13	0.61
33	0.78	0.44
33	1.13	0.61
33	0.87	0.50
33	1.29	0.81
33	1.19	0.74
33	2.09	1.25
33	1.30	0.81
33	1.78	1.31
33	0.70	0.41
33	0.53	0.31
33	0.52	0.32
33	1.83	1.66
33	2.89	1.65
33	1.19	0.74
33	0.63	0.38
33	1.11	0.69
33	0.77	0.44
33	2.94	1.62
33	2.29	1.32
33	3.42	1.84
33	2.63	1.47
33	1.88	1.06
33	2.19	1.18
33	2.19	1.18
33	1.07	0.57
33	1.91	1.07
33	2.24	1.20
33	1.08	0.57
33	0.95	0.51
33	1.05	0.56
33	1.05	0.56
33	2.21	1.20
33	2.16	1.18
33	2.08	1.14
33	2.15	1.17
33	2.15	1.17
33	2.61	1.43
33	2.86	1.59
33	3.16	1.72
33	1.30	0.77
33	2.07	1.19
33	2.57	1.44
33	3.35	1.80
33	2.91	1.60
33	0.88	0.49
33	1.08	0.58
33	1.18	0.63
33	2.29	1.23
33	2.21	1.19
33	2.21	1.19
33	0.72	0.45
33	0.75	0.48
33	1.48	0.85
33	1.00	0.61
33	0.89	0.54
33	2.20	1.19
33	1.56	0.90
33	3.05	1.68
33	2.87	1.58
33	2.95	1.63
33	2.99	1.65
33	3.10	1.69
33	2.96	1.65

Voltage (kV)	1-Ph Fault Level (kA) (Power Factory)	2-PhG Fault Level (kA) (Power Factory)
33	2.64	1.48
33	2.64	1.48
33	2.74	1.54
33	2.74	1.54
33	3.04	1.67
33	1.18	0.70
33	1.05	0.64
33	1.38	0.82
33	2.22	1.20
33	2.02	1.09
33	0.75	0.46
33	0.90	0.54
33	2.12	1.13
33	1.35	0.77
33	2.08	1.12
33	0.90	0.54
33	1.85	1.01
33	1.87	1.02
33	3.35	1.81
33	2.84	1.57
33	3.37	1.81
33	3.35	1.81
33	3.23	1.77
33	3.23	1.77
33	2.39	1.32
33	2.67	1.50
33	2.67	1.50
33	2.82	1.56
33	2.81	1.55
33	3.07	1.69
33	2.12	1.16
33	2.18	1.19
33	2.32	1.24
33	1.48	0.92
33	2.24	1.22
33	1.91	1.05
33	2.20	1.19
33	1.95	1.07
33	1.70	0.95
33	1.61	0.92
33	2.97	1.64
33	3.04	1.67
33	2.99	1.65
33	3.12	1.70
33	2.96	1.65
33	2.50	1.41
33	2.50	1.41
33	0.78	0.49
33	0.80	0.49
33	1.32	0.77
33	2.20	1.20
33	1.05	0.64
33	1.97	1.10
33	2.98	1.62
33	2.38	1.34
33	3.02	1.63
33	3.15	1.69
33	3.02	1.64
33	2.92	1.60
33	3.01	1.63
33	2.60	1.44
33	2.60	1.44
33	2.64	1.46
33	2.28	1.16
33	2.28	1.16
33	2.28	1.16
33	2.28	1.16
33	2.27	1.15
Average	1.92	

Appendix F

Remote Injection Return Current Results

Table F.1: Remote injection test results at approximately 50 substation sites and average percentage current return (Source: Energy QLD).

SITE	INJECTION (A)	FREQ	No OF RETURNS	CURRENT IN SOIL (A)	PERCENTAGE RETURN	EPR(v)	EARTH MAT (Ohms)	DATE
1	25	56	7	10.6	42.40	0.94	0.09	Dec-13
2	25	56	8	1.1	4.40	0.45	0.41	Feb-14
3	20	56	7	14.8	74.00	1.51	0.1	Apr-13
4	20	56	16	2.1	10.50	0.24	0.12	Dec-17
5	30	56	3	2.2	7.33	1.07	0.48	Sep-12
6	20	56	12	2.1	10.50	0.371	0.18	Jun-18
7	20	56	22	5.9	29.50	0.36	0.06	Jul-17
8	20	56	10	0.6	3.00	0.47	0.78	Jan-19
9	26	56	9	0.3	1.15	0.065	0.22	Jan-14
10	30	56	12	0.6	2.00	0.29	0.48	Dec-18
11	15	56	NO RETURN CURRENT FOUND		0.00	12.8	0.85	Jan-14
12	25	56	12	4.4	17.60	0.125	0.03	Jan-17
13	5	56	3	0.2	4.00	0.02	0.1	Sep-18
14	30	56	23	12.8	42.67	0.09	0.01	Mar-21
15	20	56	10	1.3	6.50	0.1	0.08	Jan-16
16	25	56	16	3	12.00	0.34	0.11	Mar-19
17	20	56	10	1.5	7.50	1.32	0.88	Aug-13
18	25	56	9	11.9	47.60	1.04	0.09	Aug-16
19	25	56	6	9.9	39.60	0.5	0.05	Jan-14
20	25	56	8	2.1	8.40	0.8	0.38	Jun-19
21	20	56	12	1.7	8.50	0.587	0.34	Sep-17
22	20	56	1	18.3	91.50	39.03	2.13	
23	15	56	4	3.6	24.00	1.11	0.31	Jan-11
24	20	56	19	0.8	4.00	0.46	0.56	Jun-19
25	25		6	9.04	36.16	2.34	0.26	Apr-19
26	20	56	4	19.3	96.50	1.08	0.06	Nov-16
27	20		3	6.6	33.00	1.12	0.17	Apr-15
28	25	56	6	12.54	50.16	1.34	0.11	Feb-14
29	20	56	14	2.9	14.50	1.71	0.59	Dec-18
30	20	56	7	3.49	17.45	0.44	0.13	Oct-20
31	30	56	13	4.1	13.67	0.09	0.03	Nov-17
32	20	56	10	1.4	7.00	0.26	0.18	Aug-16
33	20	56	19	1.7	8.50	0.31	0.18	May-18
34	18	56	2	5.9	32.78	1.987	0.164	Jul-12
35	20	56	15	8	40.00	0.7	0.09	May-20
36	25	56	9	1.7	6.80	0.78	0.46	Sep-18
37	20	56	14	2.4	12.00	1.047	0.44	Aug-19
38	20	56	6	18	90.00	0.97	0.05	Nov-12
39	20	56	11	3.3	16.50	0.7	0.21	Oct-16
40	20	56	10	2	10.00	0.32	0.16	Jul-21
41	20	56	9	7.4	37.00	4.2	0.57	Mar-15
42	20	56	8	0.7	3.50	0.56	0.93	Jul-14
43	25	56	7	3	12.00	0.507	0.169	Jun-21
44	25	56	14	2.4	9.60	0.66	0.28	Dec-18
45	20	56	10	1.9	9.50	0.66	0.34	Feb-18
46	30	56	13	5.4	18.00	0.82	0.15	Sep-15
47	25	56	14	0.55	2.20	0.09	0.16	Dec-12

SITE	INJECTION (A)	FREQ	No OF RETURNS	CURRENT IN SOIL (A)	PERCENTAGE RETURN	EPR(v)	EARTH MAT (Ohms)	DATE
48	20	56	10	1.2	6.00	0.85	0.7	Jul-19
49	20	56	7	1.9	9.50	0.71	0.37	Jan-21
50	20	56	1	19.65	98.25	6.07	0.3	Aug-12
51	20	56	10	6.6	33.00	1.27	0.19	Mar-16
52	20	56	1	19.6	98.00	0.91	0.05	Jul-15
53	30	56	8	5.3	17.67	0.515	0.097	May-15
54	30	56	12	15	50.00	0.155	0.01	Feb-14
55	20	56	5	15.4	77.00	2.51	0.16	Mar-20
56	20	56	2	19.3	96.50	2.1	0.11	Nov-17
Average percentage return:					27.88			
Modelled Current:					1950 A			
Percentage Return Current:					543.7 A			