University of Southern Queensland

Faculty of Health, Engineering and Sciences

Earthing Systems and Earth Fault Protection in Power System Distribution Network.

A dissertation submitted by

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Abstract

Ergon Energy and Energex Limited are both subsidiary companies of Energy Queensland and have the responsibility to provide safe and affordable electricity to customers in Queensland. In maintaining a safe distribution power network, earthing and power system protection plays a vital role. This research project performs analysis on different earthing systems and various forms of earth fault protection utilised in distribution power network to improve the detection of high impedance earth faults.

Earth faults are not only by far the most frequent of all faults, but the fault currents may be limited in magnitude by the neutral earthing impedance, or by the earth contact resistance which makes detection challenging for conventional protection schemes. Currently, normal earth fault protection together with sensitive earth fault protection has been employed in both distribution networks to detect and clear earth faults. There have been incidences where earth fault detection has been extremely challenging as fault values drop significantly and the protective device does not have sensitivity to detect and isolate the faulty equipment.

In Energy Queensland’s distribution power network, the neutral of supply transformers at zone substations are either solidly or impedance earth in order to provide a path for earth fault current to flow and allow subsequent operation of protective device. As part of this research project, analysis was carried out on the different forms of earthing systems currently utilised and its implications on earth fault protection. Earth faults were simulated on 11kV feeder model in DigSilent Power Factory Software package. Test cases were developed for earth fault scenarios and the results for each of the different simulated scenarios were recorded and have been discussed in results discussion.

This research project led to the identification of alternate earthing systems and improved earth fault detection capabilities in protective devices. Rapid Earth Fault Current Limiters as an alternate form of earthing / earth fault protection has been identified as part of this research study which may be utilised in Energy Queensland’s distribution power network to enhance earth fault detection capabilities. Rapid Earth Fault Current Limiters performance in-terms of detection of current and speed of operation in comparison to existing traditional earth fault protection schemes and protection relay. Further work is required however in carrying out a detail feasibility study in the application of Rapid Earth Fault Current Limiters in energy Queensland’s network.

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Sanjay Narayan

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Abbreviations

HIF	High Impedance Fault
SEF	Sensitive Earth Fault
VS-SEF	Voltage Supervised Sensitive Earth Fault
OC	Overcurrent
EF	Earth Fault
CT	Current Transformer
VT	Voltage Transformer
NEF	Neutral Earth Fault
NSEF	Neutral Sensitive Earth Fault
NER	National Earthing Resistor
NEX	Neutral Earthing Reactor
EPR	Earth Potential Rise
LFI	Low Frequency Indication
DFM	Digital Feeder Monitor
HIFAS	High Impedance Fault Analysis System
IDMT	Inverse Definite Minimum Time
DT	Definite Time
CB	Circuit Breaker
ACR	Automatic Circuit Breaker
GFN	Ground Fault Neutralizer
REFCL	Rapid Earth Fault Current Limiter
ASC	Arc Suppression Coil
RCC	Residual Current Compensator
FPI	Fault Passage Compensator
PBST	Powerline Bushfire Safety Taskforce
EMTP	Electromagnetic Transient Program
WOSO	Woodstock South
PMR	Pole Mounted Recloser
EQL	Energy Queensland Limited

Chapter 1 Introduction

1.1 Chapter Overview

This chapter outlines the motivation to undertake the research project, project initiation, project aims and the structure of the dissertation.

1.2 Introduction

Energy Queensland is the largest electricity distributor in Australia and has the responsibility to provide safe and affordable electricity to customers in Queensland. Its two subsidiary companies, Ergon Energy and Energex Limited have the responsibility of maintaining and building a safe and reliable power network so that communities can enjoy the benefits of having electricity to their premises. There are many challenges faced by these two subsidiary companies and one of the issues that are common to both is to be able to have a safe distribution power network. In maintaining a safe network, power system protection plays a very vital role in being able to meet the stipulated standards.

Ergon Energy and Energex Limited operate power system distribution networks which are built on different topographic layout and as such have their own challenges in providing adequate protection for the network. As topology differs, the behaviour of the network to different soil and environmental conditions during a system fault scenario differs. Earth faults are the most frequent type of all faults. The fault current for earth fault may be limited in magnitude by the neutral earthing impedance, as well as the fault resistance which makes detection challenging for conventional protection schemes. Traditionally, IDMT earth fault protection together with Sensitive Earth Fault protection has been employed in both distribution networks to detect and clear earth faults. Sensitive Earth Fault Protection was introduced primarily to clear high impedance earth faults with typical setting in the range 3amps, 3second to 8amps, 8second. Even with low pickup values there have been cases where the earth fault current was not able to be detected or the fault did not stay long enough to initiate a trip to the protective device.

A common fault scenario that occurs in both networks is a phase to ground fault. The fault current varies significantly depending on the impedance of the fault path and if the fault is not detected and cleared than it can pose a safety risk to the public. Electrical faults occur within the distribution network due to deterioration of assets, wild life, severe weather events and traffic accidents.

In Energy Queensland's distribution networks, the system neutral is earthed in order to provide a path for earth fault currents, this enables the detection of the fault and the subsequent operation of protective device. The neutral point of transformers at the zone substations are earthed by direct connection to the earth grid or connected through a current-limiting device such as a neutral earthing resistor or neutral earthing reactor. When a star-connected winding is not available (as with a delta-connected transformer winding), the neutral point is obtained by connecting an earthing transformer. In all substations there is an earth grid, consisting of a number of earth electrodes connected together by a copper earth bus, to which all transformer neutrals are connected.

1.3 Motivation

1.3.1 Project Initiation

Earth faults are the most frequent occurring faults in a distribution network and in some cases are not able to be detected with traditional protection types. This may occur in instances where the earth fault current is not high enough to operate the Sensitive Earth Fault Protection. It has always been a focus area to ensure that the network is adequately protected against all types of faults with earth faults seen as the most critical. There have been incidences where earth fault detection has not been possible and this poses safety risks to workers, the general public, plant and property. This research study focuses on reviewing the availability of technologies which can be utilised in the distribution power network to improve the detection of earth faults and exploring opportunities to improve safety in the distribution network.

With safety being key focus of Energy Queensland, continuing to investigate the feasibility of new technologies that support improvements in safety aligns to the organisations values. In addition to a corporate safety focus, Energy Queensland has legal obligations in designing, building, maintaining and operating the power system – this project supports these obligations. The project will provide an opportunity to explore other techniques that are effective and potentially used by other utilities. This research study will provide further insights into the improvements that can be made in the network in order to have a safe and reliable power system.

1.3.2 Project Aims

Presently, there are four main types of neutral earth connection of zone substation transformer star-point or delta connected winding being utilised in the Energex and Ergon distribution networks. These are:

- Solidly grounded system
- Resistance grounding (Neutral Earthing Resistor)
- Reactive grounding (Neutral Earthing Reactors)
- Earthing transformers

The aim of this project is to investigate the effects of different earthing systems on the operation and effectiveness of earth fault protection schemes, with a focus on the Energy Queensland's distribution network.

The primary objectives of this research project were to:

- Investigate the different earthing system's used in Energy Queensland's distribution network.
- Investigate the benefits and challenges of existing and alternate earthing systems.
- Investigate the various forms of earth fault protection currently used by distribution network service providers within Australia.
- Develop suitable distribution network models for the analysis of different earthing systems.
- Research and investigate alternate protection functions currently available in protective devices from suppliers / manufactures which can be utilised for detecting earth faults.
- Research and investigate the availability of new technologies that may provide better earth fault detection capabilities.

During the execution of this research project, analysis was carried out on the different forms of earthing systems currently being utilised and its implications on earth fault protection. This study will form a vital part of research in an area which has its own challenges in meeting the various standards and industry practices to be able to provide a reliable and safe power network. It will provide an ideal opportunity to explore alternate forms of earthing systems and also other forms of protection which can assist in earth fault detection.

The successful completion of this research was important as it will result in:

- Exploring opportunities to improve safety in the network during an event of earth fault situation arising from broken conductor coming into contact with plant or property, human error leading into contact with power lines or other related causes.
- Possible solutions in detection of low values of earth fault current.
- Identification of alternate earthing systems and improved earth fault detection capabilities in protective devices.

It is important for any organisation to have safety as the number one priority as it helps to reduce hazards and accidents. If someone does get hurt, an employee, contractor or member of the public, there is human, reputational, legal and financial impact on those close to the incident and the organisation.

If time and resources permit, further research detailed in the Project Specification in Appendix A will be undertaken.

Chapter 2 Background

2.1 Chapter Overview

This chapter highlights the functions of protection and earthing. It provides an overview of Energy Queensland’s distribution network, distribution feeder protection and earthing system currently utilised in the distribution network.

2.2 Functions of Protection

Protection relays form an integral component of the power system network as they perform functions critical to the safe and reliable operation of the network. Some of these functions are:

- Detect faults and hazardous abnormalities in order to isolate the faulty section of the network within an acceptable time.
- Minimise danger to life and property.
- Reduce the extent of damage to network assets.
- Minimise the effect that a fault or abnormality has on the remainder of the network.
- Minimise the extent and duration of plant, equipment and circuit outages.
- Be reliable and secure to avoid mal-operation.

The protection systems installed are also required to comply with and perform to the requirements of:

- National Electricity Rules
- Electrical Safety Regulations
- Good engineering practice and industry guidelines
- Connection contract obligations
- Codes of practice for Earth Potential Rise (EPR) and Low Frequency Induction (LFI)

During a system fault, there can be thousands of amps of fault current generated causing significant risk to the power system network. There are also instances where fault currents are very low and thus it is difficult for protective devices to detect and clear these faults. Regardless of how well the network is designed, faults will always occur on a power system and these faults may pose a risk to life and/or property. The provision of adequate protection to detect and disconnect elements of the power system in the event of fault is therefore an integral part of power system design.

Faults on the distribution network are typically considered as symmetrical and unsymmetrical faults. Symmetrical faults are severe balanced faults and occur less frequently in the power network. The two main types of symmetrical faults are, line to line to line to ground (L-L-L-G) and line to line to line (L-L-L). Unsymmetrical faults are very common and occur more frequently in the distribution power network. The three main types of unsymmetrical faults are, line to ground (L-G), line to line (L-L) and double line to ground (LL-G) faults. Line to ground fault is the most common fault and causes unbalance in the power system. Hence protection must be designed as such that it is able to protect the power system in all different fault conditions.

2.3 Functions of Earthing

The electrical earthing system is designed to provide safe and correct operation of the network under normal, earth fault and transient conditions. It is fundamentally required to provide safety to people, protect plant and equipment and support operational security. During earth fault conditions, large earth fault currents may flow via the general mass of earth en-route to the neutral point of the source transformer. The earthing system, its components and earthing conductors shall be capable of conducting the expected fault current or portion of the fault current which may be applicable and without exceeding material or equipment limitations for thermal and mechanical stresses.

Earthing systems are required to manage the transfer of fault energy in such a manner as to limit the risk to people, equipment and system operation to acceptable levels. An earthing system is required to perform this function for the life of the electrical network for which it is installed, for the range of configurations of the network and nearby infrastructure that are foreseeable. The earthing system is required to manage any hazardous potential differences to which personnel or members of the public may be exposed. It is required to ensure proper operation of protective devices such as protection relays and surge arresters to maintain system reliability. Elimination of all hazards associated with earthing systems is rarely possible.

During a fault involving earth, Earth Potential Rise (EPR) may exist on earthed assets, in these cases voltages in the form of touch, step and transfer potentials may be present on and around the installation. These voltages are defined as follows:

- **Touch potential**: the difference between EPR of an earthing system and the ground surface potential at a distance of 1.0m. This is the difference between a person's hand touching an energised object and their feet which is typically assumed to be 1.0m out from the energised object.
- **Step potential**: the difference in ground surface potential between a person's feet spaced 1m apart.
- **Transfer potential**: the potential difference that may exist between the local earthing system and a metallic object (e.g. fences, pipes) bonded to a distant location that may be at a different potential.

The level of hazard present at a site during a fault or transient condition is site specific and determined by factors including but not limited to soil conditions, protection clearing times, fault current and current path. Under fault condition, the flow of current to earth will result in gradients within the path of fault current.

2.4 Energy Queensland's Energex distribution network overview

Energex provides power to homes and businesses in South East Queensland (SEQ) region. Its distribution network contains a mixture of short and long radial distribution feeders that are susceptible to network faults due to adverse weather conditions as well as due to normal failure of equipment or human intervention. The network also consists of parallel and ring connected feeders Energex's distribution network operates at a nominal phase to phase voltage of 11kV AC, and phase to neutral voltage of 6.35kV AC.

The 11kV network is supplied by:

- 33/11kV Dyn11 zone substation transformers, with a secondary neutral connected to ground either directly, via a 3ohm Neutral Earthing Resistor (NER), or via 3ohm/6ohm Neutral Earthing Reactor (NEX).
- 110kV/11kV YNd11 distribution supply transformers, with a secondary connection to earth via a 9ohm earthing transformer.
- 132kV/11kV YNd11 distribution supply transformers, with a secondary connection to earth via a 9ohm earthing transformer.

2.5 Energy Queensland's Ergon Energy distribution network overview

Ergon Energy has the responsibility of providing electricity to homes and businesses in the North Queensland (NQ) and Western region. Its distribution network consists of long radial distribution feeders which are built through dense bushland, farming properties or dry and sandy soil conditions. Around 70% of the electricity network exists in rural Queensland, a vast service area with long distances between communities. This part of the network have a proportionately high investment in sub-transmission assets, compared to the Energex's network and also one of the largest Single Wire Earth Return (SWER) networks in the world. In this research project, earth faults in SWER network are not considered. In comparison to Energex's meshed or interconnected network, the radial design of the rural network and the limited capacity of the SWER lines limit options when responding to peak demands and outages.

Ergon Energy's distribution network operates with a nominal phase to phase voltage in the range 3.3kV and 22kV AC, predominately the distribution voltage are 11 and 22kV. Ergon Energy also has around 64,000 kilometres of SWER distribution network which operates at 11kV, 12.7kV and 19.1kV voltage levels.

The 11kV and 22kV network is supplied by:

- 33/11kV Dyn11 zone substation transformers, with a secondary neutral solidly connected to ground.
- 110kV/11kV and 132kV/22kV Dyn11 distribution supply transformers, with a solidly neutral connection to earth on the secondary side.
- 66/11kV and 66/22kV Dyn11 zone substation transformers, with a secondary neutral solidly connected to ground.

2.6 Distribution feeder protection overview

In both the Energex and Ergon distribution network, identical feeder protection schemes have been utilised. Distribution feeders are typically protected using non-unit protection schemes based on a combination of two or three phase Overcurrent (2OC/3OC), Earth fault (EF) and Sensitive Earth Fault (SEF) protection. Inverse Definite Minimum Time (IDMT) and Definite Time (DT) elements are typically employed to obtain speed and ensure discrimination is achieved, thus limiting the thermal damage sustained by the network apparatus and reducing conductor clashing during the fault. The interruption of fault current is typically achieved by a Circuit Breaker (CB) or Automatic Circuit Recloser (ACR) located within the source substation, or a pole mounted ACR located along the feeder or fuses.

Primary and back-up protection schemes are installed to ensure that if primary protection fails to isolate a fault, it will be isolated by the back-up protection. Co-ordination is achieved between protective devices either by current or time or a combination of both. This is done to ensure that relay nearest to fault operates first to minimise system disruption due to the fault. In-order to prevent incorrect protection operation, a grading margin of 300msec to 400msec is maintained between protective devices on that feeder. The protective device closest to the fault provides primary protection and operates first for that fault and the device further upstream to his device provides back up protection in situations should the primary protective device fails whilst in service.

SEF protection is designed to provide detection of high impedance earth faults on distribution overhead feeders. These high impedance earth faults which cannot be detected by normal earth fault protection, typically involve, but are not limited to, wire/s down load side with a high contact resistance to earth. In the distribution network, SEF is typically set to a minimum of 3 amps for 3 seconds to a maximum of 8 amps for 8 seconds. Neutral Sensitive Earth Fault (NSEF) protection is also implemented in substations which provides back up protection for SEF.

Figure 1 depicts a traditional network setup with the implementation of earth fault and SEF protection currently being utilised in distribution network.

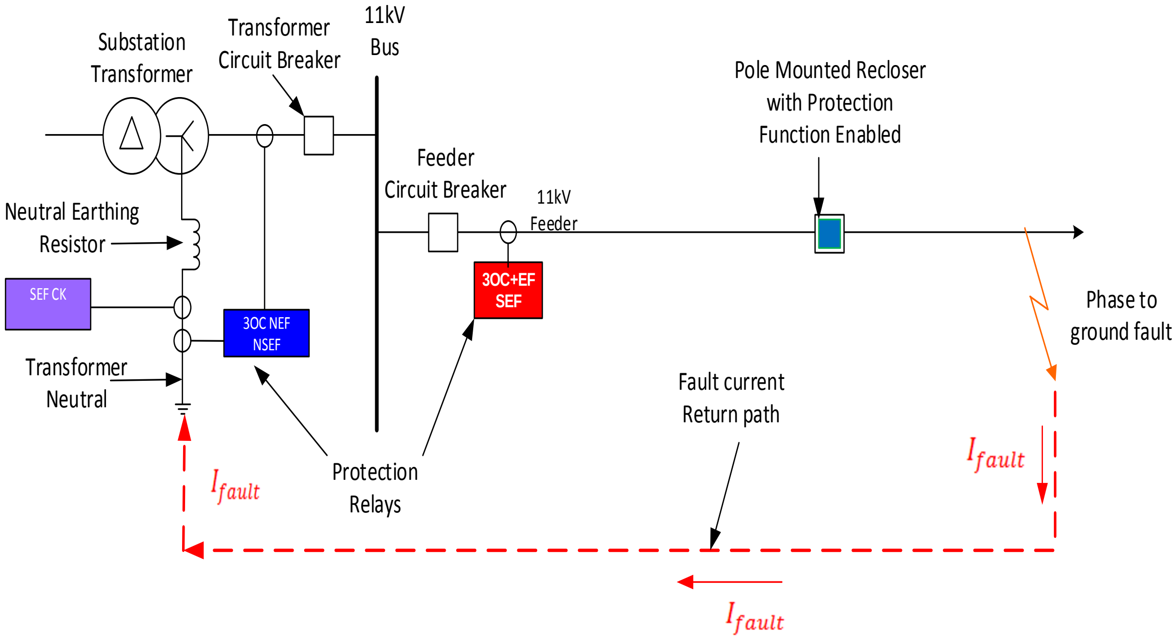


Figure 1: Typical Earth Fault protection implementation

2.7 Earthing System employed in Energy Queensland's distribution networks

There are a number of different methods of earthing that have been utilised in Energy Queensland's power system network. The substation earth grid is constructed as a mesh of copper conductors buried under ground the substation. Power transformers at the substation have the neutral point connected to the substation earth grid via various methods, as discussed further below in this section. Having an earth connection of the power transformers allows the fault current to return to these power transformers. Traditionally, and as the distribution network of Energy Queensland has evolved over the years, the following earthing systems have been installed:

- **Solidly grounded system -** Only a limited number of zone substations in the Energex region have the neutral point of the star connected winding on 11kV side of the power transformer that are solidly grounded as shown in figure 2 below. As the distribution network as developed over the years in Energex region it has adopted a resistance/reactance grounding method. It is mainly due to step and touch potential issues created by large earth fault currents therefore, earth fault currents has always been limited in Energex distribution power networks. This is not the case in the North Queensland distribution region where majority network utilises a solidly grounded system. Earth fault currents are not limited in these distribution networks largely due to very long distribution feeders and network topology that earth fault currents drop quite significantly towards the remote portions of the feeders and it becomes difficult for protective devices to detect these faults. Earth fault current at the zone substation is normally in excess of 2000A – 5000A.

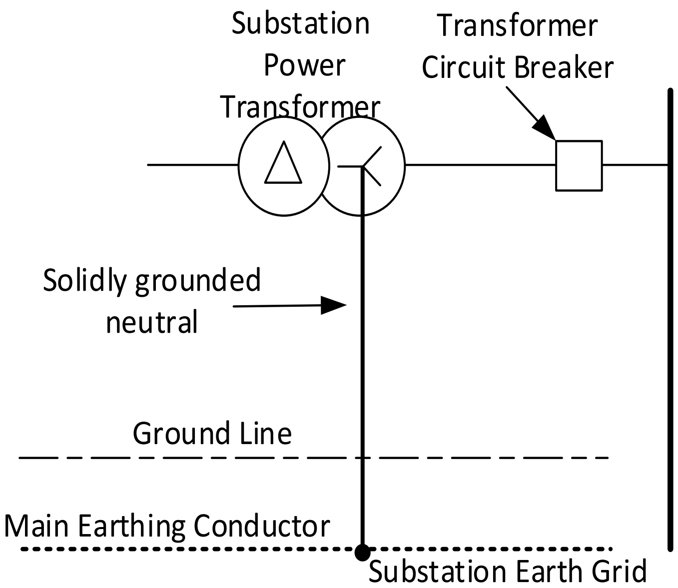


Figure 2: Solidly grounded earth system

- **Neutral earthing resistor (NER)** – a number of zone substations in Energex's network have NER installed in the neutral point of the supply transformer. NERs limit fault currents to a value that does not cause major damage to switchgear or transformers beyond what has already been caused by the fault itself. It also provides safety to general public and personnel working in substations and other electrical infrastructure as there is control of the minimum and maximum magnitudes of phase to earth fault currents. If there are multiple transformers operating in parallel at a particular substation, all will share the same NER. All the neutral points of the transformers will be running to the NER cubicle and then a common grounding point via the NER as shown in figure 3 below. The size of this resistor is 3ohms and limits the fault current to around 2000Amps that would flow through the neutral of a transformer in the event of a close in earth fault. However the earth fault current value will decrease as the fault moves away from the source as the impedance of the conductors and ground return path comes into effect.

Using V = IR with a phase to ground voltage of 6350V (11000V/1.732)

$$I = \frac{6350V}{3\Omega}$$

$$I = 2117A$$

The fault value of 2117A is for a fault with an infinite 11kV bus.

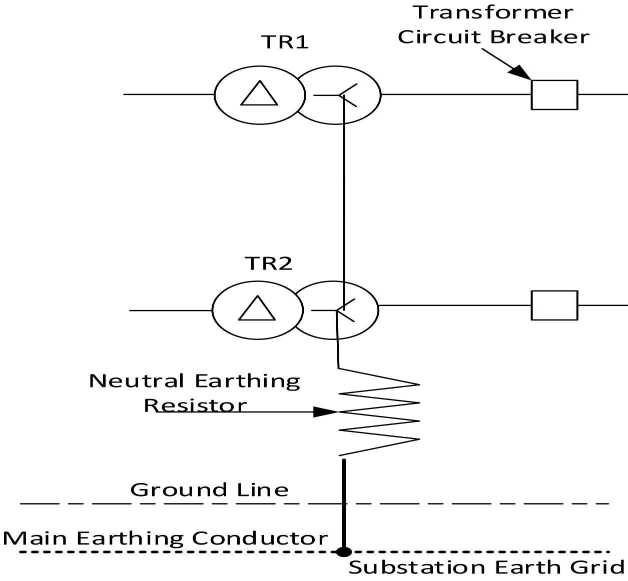


Figure 3: Neutral earthing resistor in two transformer application

Figure 4: Neutral earthing resistor in field

- **Neutral earthing reactors (NEX's) –** these have been installed only in Energex's network and more as a replacement for NER's. When new distribution substations are built or when NER's reach end of life, NEX's have been installed mainly due to ongoing maintenance cost associated with NER's. NER's are larger in size and involves larger installation area as compared to NEX's. The principle of operation is quite similar to NER's except NEX's are basically a large wound coil as shown in figure 5 below and set to 6 ohms and each transformer will have its own NEX as shown in figure 6.

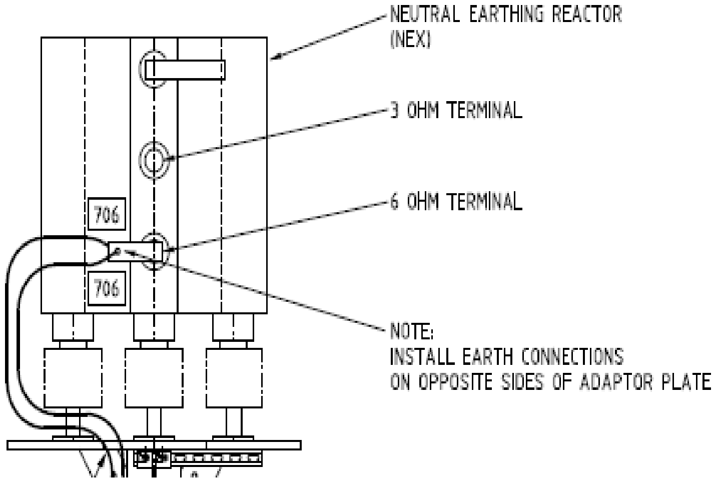


Figure 5: Neutral earthing reactor connection

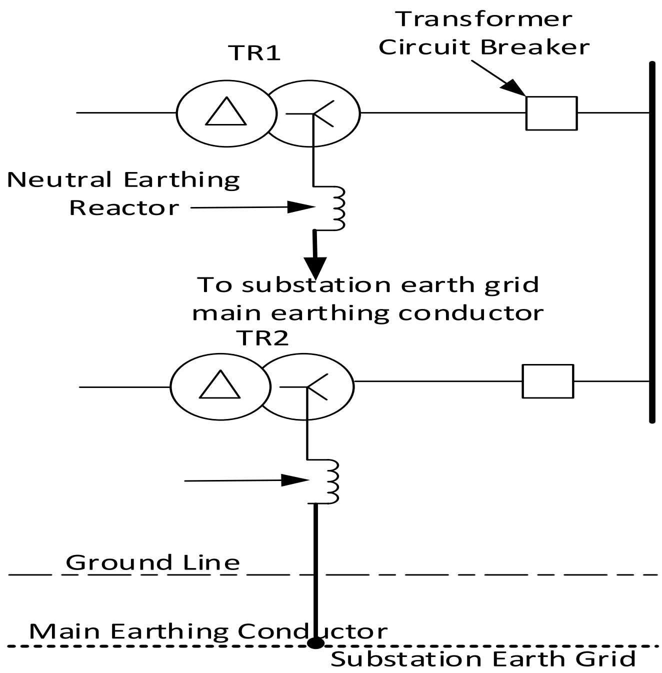


Figure 6: Neutral earthing reactors in two transformer application

Figure 7: NEX in field

- **Earthing transformers –** are only used in bulk substations where the secondary winding is delta connected as shown in figure 8. An earthing transformer is a three phase transformer connected to the power system to provide a neutral connection for earthing via impedance. They are intended to be inoperative during balanced voltage conditions, carrying significant current only during earth faults as it provides a low impedance path for zero sequence current whilst remains high impedance for positive and negative sequence currents. The main purpose of earthing transformer is to provide an earth reference for an otherwise unearthed part of a power system (i.e. a part supplied from a delta winding of a power transformer), and so restricts the voltage rise on the un-faulted, phase or phases during a fault involving earth.

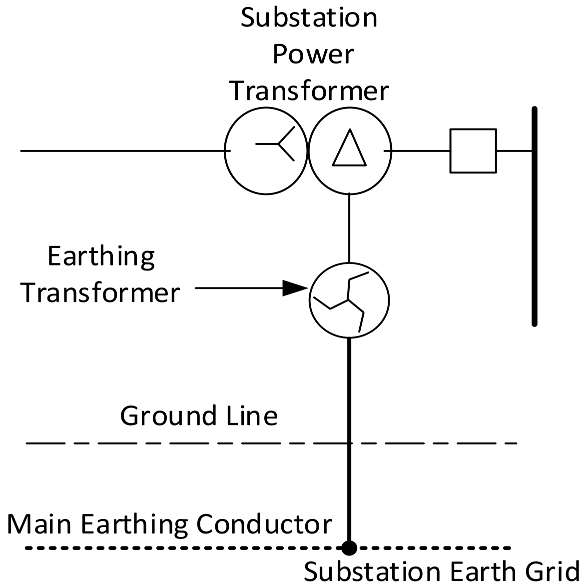


Figure 8: Earthing transformer application

Earthing transformers are constructed with "zig-zag" connected windings, as shown in figure 9. Under normal, balanced system conditions, an earthing transformer draws only a small magnetising current, much the same as an unloaded power transformer. When a phase to earth fault occurs, however, the residual voltage produced by the fault causes significant current to flow into the fault and back through the earthing transformer windings as shown in figure 9.

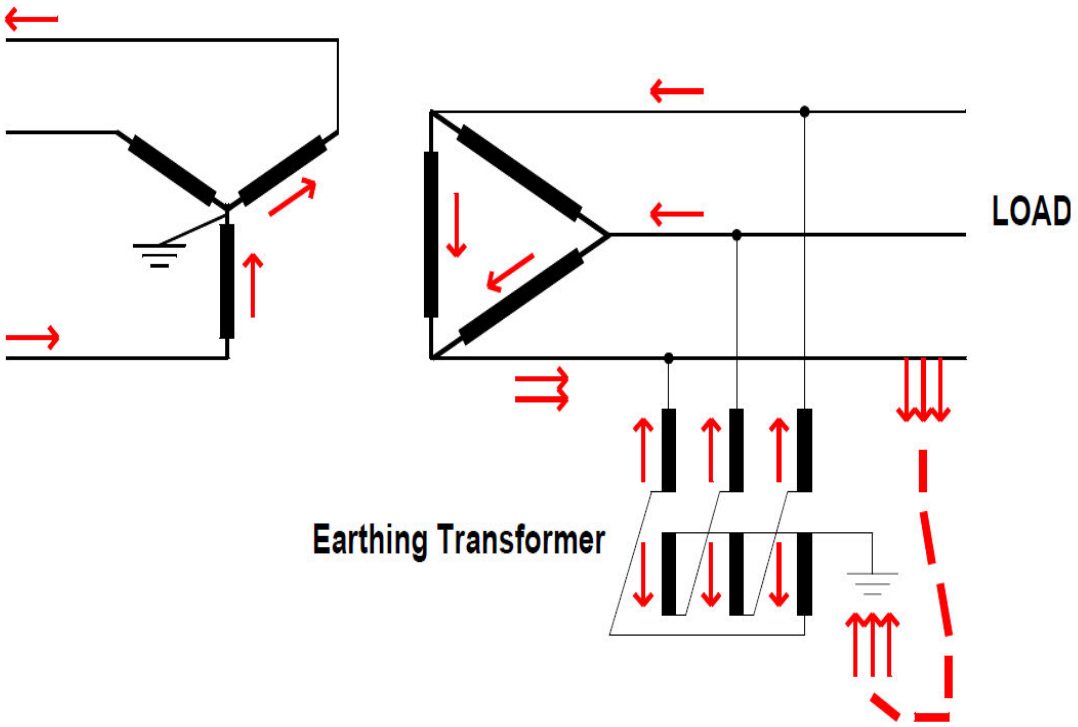


Figure 9: Current flow during a single phase fault on a system with an earthing transformer

During a single phase earth fault at the earthing transformer terminals, the maximum fault current is calculated by:

$$I_{fault} = 3 \times I_{\emptyset\_et} = \frac{3 \times V_{\emptyset}}{Z_{\emptyset\_et}}$$

$$I_{fault} = 3 \times \frac{11000}{\sqrt{3}} \times \frac{1}{9\Omega} = 2117 Amps$$

The fault value of 2117A is for an earth fault at the earthing transformer terminals.

Chapter 3 Literature Review

3.1 Chapter Overview

An extensive literature review was undertaken in this chapter to confirm that the research project would fulfil a genuine capability gap, to assist in identifying alternate forms of earthing and improved earth fault detection capabilities for low values of earth fault current.

3.2 Different earthing systems

Shipp & Angelini (1988) highlight the characteristics of different power system grounding techniques being applied and misapplied within the electrical industry. During the early days of electrical industry only two methods of earthing systems were considered: solidly grounded systems and ungrounded systems. One of the real hazards with an ungrounded system is the occurrence of a second ground fault. Although nothing happens after a single ground fault, the second ground fault acts like a phase to phase fault. Therefore it is important to remove ground faults from ungrounded systems as soon as possible. A comparison of all voltages and currents of solidly grounded versus ungrounded systems supports that in a solidly grounded system, a very high ground fault current is available, but with low or suppressed system voltages. In an ungrounded system, the available ground fault current is very low but the voltage on the normal line to ground insulation is increased from a line to ground value to a full line to line magnitude.

Ungrounded systems are not a preferred method as line to ground faults are not cleared from the system and multiple ground faults can and do occur on ungrounded systems. The occurrence of a second ground fault on another phase will lead to line to line voltage impressed on their line to ground voltage. The phase to ground insulation is overstressed by 73% and this leads to an accelerated degradation of the insulation system, due to the collective over-voltages impinged upon it, through successive ground faults over a period of several years. Industry practices have mainly utilised solidly, resistance and impedance grounding methods over the years.

Many people are of the opinion that an ungrounded system is safer. This opinion says that since contact with a single phase does not complete a circuit, you will not get shocked. This is not the case in the real world where there is always capacitive coupling to ground. Personnel safety and the possibility of fire are not significantly different between an ungrounded system and a high resistance grounded system under solid ground fault conditions. Another area of consideration is continuity of service. A high resistance grounded system limits the ground fault current to a value only slightly higher than an ungrounded system. These values are small enough that it is acceptable to not trip safety devices and let faults remain on the system. The advantages of high resistance grounded systems are the easier location of the fault and the elimination of transient over-voltages which can lead to premature insulation failure.

Levine(2010) discusses in great detail the advantages and disadvantages of different types of neutral grounding systems. It does a comparison on ungrounded, solidly, reactive, low resistance and high resistance grounded system's as highlighted in tables 1 to 3.

Ungrounded Earthing System	
Advantages	***Disadvantages***
• Low value of current flow for phase to ground fault • No flash hazard to personnel for accidental line to ground fault • Continued supply on the occurrence of first line to ground fault • Probability of line to ground arcing fault escalating to phase – phase or three phase fault is very small	• Difficult to locate phase to ground fault • Does not control transient over-voltages • Cost of system maintenance is higher due to labour of locating ground faults • A second ground fault on another phase will result in a phase – phase short circuit

Table 1: Advantages and Disadvantages of Ungrounded Earthing System

Solidly Grounded Earthing System	
Advantages	***Disadvantages***
• Controls transient over voltage between the neutral and ground • Not difficult to locate the fault • Can be used to supply line-neutral loads	• Severe flash hazard • High values of fault current • Single-phase fault escalation into 3-phase fault is likely • Main breaker may be required • Loss of supply • Equipment damage

Table 2: Advantages and Disadvantages of Solidly Grounded Earthing System

Resistance and Reactive Grounded Earthing System	
Advantages	***Disadvantages***
• Low values of fault current • No flash hazard • Controls transient over voltage • Less likelihood of equipment damage • Safer for personnel	• (Levine, 2010) does not highlight any known disadvantages so this can be evaluated further as part of this research project.

Table 3: Advantages and Disadvantages of Resistance and Reactive Grounded Earthing System

Shipp & Angelini (1988) and Levine (2010) both highlight that solidly, resistance or reactive grounding techniques are a more preferred method than an ungrounded system. This research project can further critically evaluate the various earthing systems in power system distribution network.

The risk of serious and fatal arc blast injuries is potentially reduced by the use of high resistance grounding Nelson (2015). Nelson (2015) suggests that an arcing ground fault on a solidly grounded system will typically propagate into a three-phase fault in the sub-cycle range, whereas a ground fault on a high resistance grounding system will not. During a series of test conducted as part of this study, it was noted that a phase to phase fault quickly propagated into a three-phase fault within ¼ of a cycle and that the speed of propagation was so fast that there was no significant decrease with the incident energy. A similar characteristic was noted for a phase to ground fault during the testing however a single phase to ground fault will not propagate into an arcing multiphase fault and that the incident energy at the point of the fault is zero. From the study it can be seen that high resistance grounding technique plays a vital role in reducing arc blast incidences. However it does not totally improve electrical safety for contact or touch dangers, which are still the predominant cause of serious injuries and death.

Burgess & Ahfock (2011) proposed a new method of minimising the transient over-voltages in the power system network by using arc suppression coils. It suggests that arc suppression coil systems are able to improve the high voltage system reliability and safety. It is based on the Petersen coil principle whereby the coil performs the arc suppression by compensating the post-fault steady state current. The high voltage system supply point neutrals are earthed through inductors which are tuned to the total line to earth capacitance of the system. When an earth fault occurs there is very little voltage on the faulted phase and the voltages on the other phases and the neutral are displaced accordingly. This results in the normal line to line voltage being applied between the two healthy phase lines and earth for the duration of the fault. If the inductor is properly tuned, the capacitive current resulting from the voltage displacement is equal and opposite to the current in the earthing inductor. The residual current fault current will be very small and will not be sufficient to maintain the arc. Therefore there is no arc damage at the point of the fault and many faults self-extinguish.

One of the authors had personal experience of an arc suppression coil system, hence the increased risk of simultaneous faults when arc suppression coil system is being used in the system was highlighted. It was reported that due to the incident of cross-country faults, arc suppression coil was taken out of service from a transmission network. Due to these known incidences, electricity supply authorities have been reluctant to install arc suppression coil systems in Australia.

Dahal, et al.(2017) presents the impact of frequency of lightning strikes on ground potential gradients across substations. The substation earth grid and the lightning strike were modelled in CDEGS tool. The various frequencies of strikes were applied from various locations within the substations. The voltage gradients resulting from the strikes at various frequencies were observed. The results showed that when the insulator flashover occurs near a substation earthing system due to lightning strikes, a high amount of fault current is dispersed to the ground through the substation earth electrodes. Such influx of high impulse current generates significant gradients of voltage across the substation grounding system. Such voltage gradients could be dangerous to personnel and equipment within the substation. This analysis shows that the distribution of voltage gradients under impulse current is dependent on the frequency of impulse voltage. The lower the frequency of strike voltage, the lower number of voltage gradients are present across the substation. The higher the frequency of impulse voltage, a higher number of voltage gradients are present in the substation.

3.3 Ground fault neutralizer (GFN)

A GFN is a type of Rapid Earth Fault Current Limiter (REFCL) and is an adaptation to traditional Petersen Coil / Arc Suppression Coil (ASC) systems where a tuned reactance is placed in the zone substation neutral. A REFCL is a network protection device, normally installed in a zone substation that significantly reduces the arc fault energy generated during a phase to ground fault. The reduction in an arc fault energy can be so effective that earth fault fire ignition on 22kV three phase networks is almost eliminated.

The use of this technology is on the increase as it has been used by a number of countries globally. It is being rolled out in Victoria, Australia, after the February 2009 bushfires whereby it was found by the bushfire taskforce that many of the fires were actually started by power lines with existing protection far too insensitive to detect line to ground faults. The task force identified Rapid Earth Fault Current Limiters (REFCLs) as a new technology used primarily for supply reliability outside of Australia. They are being installed in Victoria as a world-first use of this technology to lower the risk of powerline faults starting bushfires. Testing of REFCLs at two zone substations, demonstrated REFCLs potential to prevent the most common kinds of faults on 22kV powerlines from starting bushfires. The test results assisted the Victorian Government and electrical distribution business to develop a sequence introduction of REFCLs onto the Victorian network through amendments to the Electrical Safety (Bushfire Mitigation) Regulations 2013.

3.3.1 Operation of REFCLs

A REFCL operates on polyphase (3-wire) high voltage powerlines. REFCLs can detect single phase to earth faults and once the fault is detected it reduces the voltage on the faulted phase to a very low level within 2 seconds or less. REFCLs allow the electricity distribution system to continue operating for a short time rather than switching power off altogether when a fault is detected. If the fault persists, the REFCL then shuts down the power to the affected lines. But this aspect of a REFCL's operation also means that the two, non-faulted wires receive significantly more voltage than normal during these brief over-voltage conditions. Such over-voltages can have a negative effect on a high voltage customer's electrical equipment and installations if not properly assessed and modified where necessary.

Winter (Dec 2006) highlights that the GFN was initially developed for safe post-fault protection in resonance grounded overhead networks, but now also have the option of pre-fault detection. GFN has been developed by a company called Swedish Neutral, which has capabilities to detect earth faults with response times of less than 60ms. Instead of tripping the faulty feeder, the GFN cancels out the fault current by injection of an anti-phase current into the neutral and brings the fault current down to practically zero making it possible to maintain safe operation without disturbing power supply to customers. It is connected to the neutral of the supplying power transformer (Y – winding) as shown in figure 12 or a separate grounding transformer (Z-winding). A complete GFN system is composed of a modern solid core arc suppression coil (ASC), a cabinet with power electronics for voltage/current injection (RCC – Residual Current Compensator) and the GFN control cabinet as shown in figures 10 and 11 below.

Winter & Winter (2019) mentions that beside the controls for the RCC voltage / current injection, the GFN also provides automatic returning for the arc suppression coil and a new twin-scheme fault locator with superior detection capabilities. The arc suppression coil forms a parallel resonant circuit with the phase to ground capacitive leakage of the network. By this resonant circuit the source impedance for single phase to ground faults increases in the order of ten to twenty times, sufficient to quench single phase flashover faults on overhead lines.

Figure 10: Control Cubicles and Transformer

Figure 11: Arc Suppression Coils

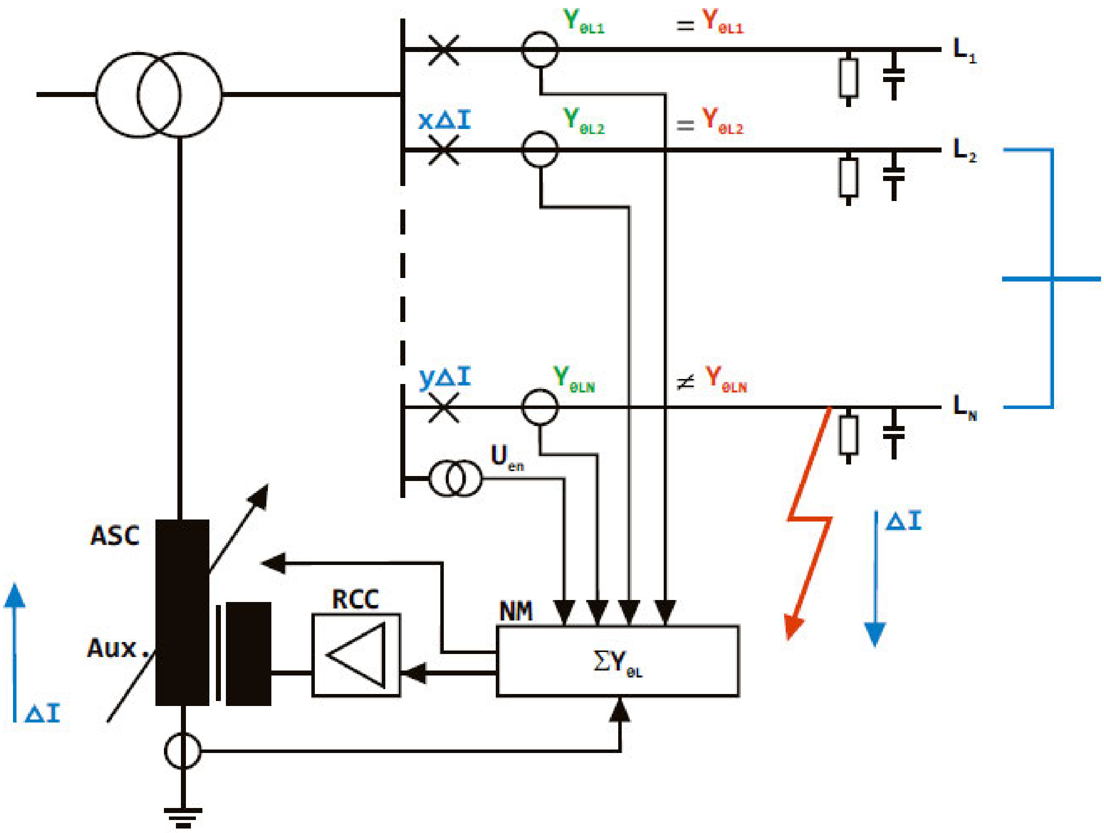


Figure 12: Typical Ground Fault Neutraliser setup

This technology does possess features which have been further investigated as part of this research project. It does have capabilities which can be utilised in resolving the issue of earth fault detecting to both Energex and Ergon Energy's distribution network. Whilst the use of REFCL's has being rolled out and also currently being installed in Victorian distribution power networks, the suitability of the device in EQ's distribution network has been investigated as part of this research project. Analysis on existing HV components of the network to see if it can withstand full system voltage displacement will need to be carried out.

3.3.2 Victorian Government Legislation

Marxsen(2014) highlights that after the 2009 bushfires in Victoria, the Victorian Bushfire Royal Commission initiated the Powerline Bushfire Safety Taskforce (PBST) in 2011. The PBST's primary purpose was to investigate different options to reduce the harm to people and property from bushfires started by electrical assets. The PBST identified REFCLs installed in zone substations as an efficient and effective technology.

The Electricity Safety (Bushfire Mitigation) Amendment Regulations 2016 which came into operation on 1 May 2016 set out new requirements for major electricity companies including the requirements for major electricity companies including the requirement for Polyphase Electric Lines (defined as multiphase distribution between 1kV and 22kV at selected zone substations to have the following abilities:

- To reduce the voltage on the faulted conductor for high impedance faults to 250 volts within 2 seconds.
- To reduce the voltage on the faulted conductor for low impedance faults to;
  - 1900 volts within 85 milliseconds ; and
  - 750 volts within 500 milliseconds; and
  - 250 volts within 2 seconds; and
- Demonstrate during diagnostic tests for high impedance faults to limit;
  - Fault current to 0.5 amps or less; and
  - The thermal energy on the electric line to maximum I^2t value of 0.1

The Amended Bushfire Mitigation Regulations define the low and high impedance faults as follows:

- High impedance = a resistance value in Ohms that is twice the nominal phase to ground voltage. This is equal to 25.4kΩ or a fault current of 0.5 amps on a 22kV network.
- Low impedance = resistance value in Ohms that is the nominal phase to ground network voltage divided by 31.75. This is equal to 400 Ohms or a fault current of 31.75 Amps on a 22kV network.

3.3.3 Findings of REFCL Trials in Victoria

Marxsen(2014) highlights rigorous tests on a real electricity distribution network carried out in Victoria, have confirmed that Rapid Earth Fault Current Limiter (REFCL) technology can reduce the fire risk associated with bare-wire overhead powerlines. Tests confirmed that when a live high voltage conductor falls to the ground under worst case fire weather conditions such as those experienced on Black Saturday 2009, a REFCL can reduce the conductor-soil arcing in many circumstances to levels below that required to start a fire. The test program confirmed that under worst case fire conditions, ‘wire on ground’ powerline earth faults on Victorian rural power distribution networks with traditional network protection systems create an inherent risk of fires and that this risk is markedly reduced in a network protected by a REFCL.

The specific findings of the research program are:

- In worst case fire conditions, ‘wire on ground’ powerline faults on networks with traditional non-REFCL protection create an inherent risk of fire. There is a very low threshold level of current into soil above which ignition is close to 100 per cent probable in today’s non-REFCL networks.
- Existing non-REFCL Sensitive Earth Fault (SEF) protection schemes have the potential to prevent some fires. However, they cannot eliminate the majority of fire risk from ‘wire on ground’ powerline faults. Other over-current earth fault protection schemes have limited if any, potential to cut fire risk.
- REFCLs dramatically reduce energy release into the environment from ‘wire on ground’ powerline faults. They collapse the voltage on the fallen conductor to reduce fault current, reduce arc power and bring about faster arc self-extinction. Tests with and without a REFCL vividly demonstrate this dramatic reduction of arc energy.
- REFCLs can detect and respond to ‘wire on ground’ powerline faults that traditional non-REFCL network protection cannot ‘see’. For supply reliability and security purposes,

traditional SEF protection is usually set to detect nine amps of fault current in rural networks. REFCLs detect two amps and tests demonstrated detection of less than one amp.

- REFCLs can significantly reduce fire risk for a wide range of 'wire on ground' powerline faults. By detecting earth faults that traditional protection systems cannot 'see' and by dramatically reducing energy released into the local environment when earth faults occur, REFCLs reduce the chance of ignition across a wide range of earth faults.
- There are some 'wire on ground' powerline earth faults where today's REFCL products may not prevent ignition. High current faults may result in bounce ignition before a REFCL has time to reduce the fault current. The reduction in residual fault current may not be sufficient to completely remove the risk of slower ground ignition.
- REFCLs offer benefits to public safety. REFCLs quickly reduce the voltage on a fallen conductor and can potentially transform high voltage electrocution risk of irreversible serious internal and external burns, to low voltage electrocution risk of reversible injury that is responsive to immediate first aid, especially CPR. A GFN has the potential to reduce voltage on a fallen conductor to levels where even low voltage electrocution risk is low.
- REFCLs offer benefits to supply reliability. Improved supply reliability is a major motivator of utilities' adoption of REFCLs around the world.

Successful management of an earth fault incident on a GFN-protected network in high fire risk conditions requires the GFN to perform the following section of actions:

a) Detect the fault.
b) Ascertain which phase of the faulted network is carrying the fault current to earth.
c) Compensate residual current by injecting a voltage into the network neutral connection to move the voltage of the faulted phase close to zero.
d) After a few seconds, test to see if the fault is still present.
e) If the fault is still present, identify the feeder on which it is located.
f) Trip the faulted feeder to remove the fault from the network.
g) Switch off the residual current compensation so network voltages return to normal levels.

The test program confirmed the first three of these actions:

- Fault current of just one amp was detected by the GFN, albeit with sensitivity heightened above normal levels by reducing the neutral voltage detection threshold from 30 per cent to 20 per cent. With normal sensitivity settings, the GFN detects earth faults of two amps magnitude.
- Residual current compensation reduced the soil current to zero (the voltage on the conductor dropped to 200-400 volts - insufficient to drive any current across the conductor/soil interface).

The next two tasks in the sequence (to confirm whether the fault is still present and if so, reliably identify the feeder on which it is located) pose fire risk challenges as they require some soil current to flow for the GFN to make the required measurements. The final two tasks (trip the faulted feeder, switch off the residual compensation to return the network to normal operating condition ready to deal with another fault) are relatively straightforward.

In summary, the GFN offers virtual elimination of residual fault current into the soil but then faces a challenge during confirmation of the continued presence of the fault and identification of the faulted feeder, both of which require some current to flow. The challenge is to perform these functions at a level of current flow too low to produce a ground ignition event or to do it faster than ‘time to ignite’ at the particular current level used.

3.3.4 REFCL Implications

Based on the test results of the trails performed in Victoria Marxsen(2014), the following implications were highlighted:

- Fully exploit modern technology in non-REFCL protection systems - The test program demonstrated that sensitive earth fault (SEF) protection systems may have the capability to prevent some ‘wire on ground’ fire starts. This capability depends on SEF fault detection sensitivity and speed of action. Over the last few decades, SEF relays have changed from analogue devices with internal moving parts to digital devices offering very high precision and reliability in both current measurement and timing of response. Many of these new devices offer improved measurement technology such as 50Hz filters to reduce their sensitivity to network transients.
- Monitor transient faults in REFCL networks to assess relevance to fire risk - REFCL protected networks deal with transient faults by temporarily displacing network voltages to reduce the fault current to such a low level that most faults simply go away (arcs self-extinguish), whereupon the network can return to normal voltage levels. It is not clear what sort of event could start a fire while presenting to a REFCL-protected network as a transient fault. In traditional non-REFCL network protection, there are many examples of transient faults that can start fires, including conductor clashes (that emit molten metal particles) and bird/animal contacts (that result in a burning carcass falling into the dry vegetation under a pole).
- For sustained faults in REFCL networks trip the faulted feeder and do not reclose - The test program has shown that REFCLs can greatly reduce fire risk from sustained earth faults such as fallen conductors. On a Code Red day, once a REFCL fault-confirmation test has demonstrated that an earth fault is permanent, there is little option available to a network owner but to trip the faulted feeder - provided of course that it can be confidently identified. Unlike traditional non-REFCL network protection, reclosing onto a known permanent earth fault serves little purpose in a REFCL-protected network – the REFCL reduces the fault current to such an extent that downstream devices will not operate to isolate the section of the network containing the fault. Hence the rule on high fire risk days should be to ‘trip and do not reclose’ which immediately highlights the challenge of fault location. Some feeders are very long (50-100 kilometres) and physical patrol is a task not undertaken lightly.
- Temporarily increase REFCL fault detection sensitivity on high fire risk days - Every REFCL system faces the same hierarchy of decisions when a fault occurs: Is there a fault on the network? What phase is it on? Is it permanent? What feeder is it on? The challenge of answering these questions increases as the hierarchy is traversed. As a first step, it is relatively easy to detect faults with very high sensitivity. Today’s REFCL products operate to reliably detect faults that draw two amps of current from the network. This level of sensitivity is a marked improvement on traditional non-REFCL systems, but could be even further improved. The limits to fault detection sensitivity are determined by a number of factors.
- Promote continued development of the GFN fault confirmation test - Whilst it is relatively easy to detect faults with very high sensitivity, it is much harder to identify the feeder on which the fault has occurred. To do that, some accurately measurable 50Hz fault current is essential. Unambiguous identification of the faulted feeder without allowing enough current flow to start a fire is perhaps the toughest challenge facing REFCL developers. There is little

point in knowing there is a fault on the network if there is no information to identify the feeder that has to be tripped to prevent a fire.

3.3.5 REFCL Implementation Challenges

From Marxsen(2014), trials performed in Victoria, power system distribution network owners must address a number of implementation challenges as highlighted below:

- Learn by doing - culture change for network owners and suppliers - The change from non-REFCL to REFCL-based network design and operation is profound. Fire risk priority is a new challenge for REFCL developers. Intuition and integrated expert thinking about REFCL operation takes years to develop. Overseas utilities that have made the change to REFCL network protection report the most difficult challenge is the culture change required to get full value from the new technology. They comment that it takes four to five years for network operations staff, protection and control engineers and network planners to learn the new technology and how to apply it to the point they have successfully integrated this knowledge into their work.
- Harden networks to reduce risk of cross-country faults - When an earth fault occurs, the REFCL response creates voltage stress on network equipment connected to un-faulted phases, which can lead to a second fault. Outcomes can be worse than if a REFCL were not installed. Victoria's existing networks have many old items of network equipment that are not rated for continuous operation at 22kV; when an earth fault occurs on a REFCL-protected network, over-voltage on un-faulted phases can lead to failure of some of these items. Such equipment failure constitutes a second earth fault on the network, termed a 'cross-country fault' because it is usually remote from the initial fault and is always on one of the un-faulted phases subject to over-voltage stress caused by REFCL response. REFCLs can only deal with multiple earth faults if they are all on a single phase. With a cross-country fault, the network has a two-phase-to-earth fault and high currents will flow in both fault locations; two fire starts are possible, i.e. a worse result than if a REFCL had not been installed.
- Upgrade networks to REFCL compatible equipment - Some network equipment currently used in power system distribution network is not compatible with REFCL operation and must be upgraded or replaced with equipment that is compatible. These include open-delta voltage regulators, three-phase equipment in earthed star configuration, non-directional earth fault protection, etc. Incompatible equipment can prevent correct REFCL operation and may produce dangerous network conditions with a REFCL in service.
- Minimise network imbalance - The three phases of the network have different capacitances to ground. The REFCL will tune to the total network capacitance. Residual earth fault current will differ by faulted phase and be larger than if network capacitance was balanced. Fault detection sensitivity is also constrained. When an earth fault occurs on a resonant earthed network, the fault current falls to a low level made up of three components:
    - Resistive leakage current from the network to earth – the sum of all the tiny currents across the surfaces of tens or hundreds of thousands of insulators, plus current due to energy lost in cable insulation and in the iron core of the REFCL coil itself. A GFN uses its RCC to cancel this current, but an ASC cannot do the same.
    - Current due to mismatch in the tuning of the REFCL coil to the network. REFCL designers take pains to ensure tuning is accurate to within an amp or two.
    - Current due to imbalance in the capacitance to ground in each of the three phases of the network. This is under the control of the network owner.

Capacitive imbalance has some potential negative effects on REFCL performance:

- It increases residual current, i.e. ground fire risk.
- It increases the standing level of neutral voltage, i.e. it constrains fault detection sensitivity.

Long single phase (two-wire) spurs teed off three-phase lines can create significant capacitive imbalance. As fire risk reduction relies on low residual fault current, capacitive imbalance can pose a risk to fire safety and so must be managed.

- Fault location - REFCLs reduce fault current to such low levels a fault may not generate enough visible evidence to reveal its location. Permanent faults may not be located for long periods. When a permanent fault occurs in power system distribution networks, protection systems isolate the section of the network that contains the fault and with some exceptions in remoter areas, a line crew then patrols the isolated section of network to find and repair the fault so power can be restored. Often the evidence of the fault is obvious – a car into a pole, a tree fallen across the line, etc. The fault current itself is often sufficient to do enough damage to make the fault location plain. With a REFCL, the fault current can be as low as a few amps and many faults leave no evidence at all. This is not a problem for momentary faults, but it is a challenge in the ten to 15 per cent of faults that are permanent. In this small but very important category of faults, the network operator can face some potentially unpalatable options, such as:
  - Allow the network to remain in a condition of full neutral voltage displacement while searching for the fault using sophisticated remote sensing devices.
  - Revert to non-REFCL network protection and allow high earth fault currents to flow to expose the fault location in the usual way. The fire risk inherent in this option means it is only acceptable at times of low fire risk. This approach can lead to further challenges if the fault is not detected by traditional protection systems but only by the REFCL – a not uncommon outcome, given the REFCL's superior fault detection sensitivity.
  - Trip the whole feeder to remove power supply to the fault. If a patrol finds no obvious cause, open all switches along the length of the feeder and restore power from the substation end section-by-section until the fault appears again. This can result in lengthy customer supply outages and the whole feeder may sometimes be restored to supply without the fault re-appearing.

Most stakeholders facing this challenge look to a future where smart grid schemes gather and analyse information from devices spread across the network, identify the most likely fault location and initiate appropriate switching to isolate the relevant section of network. Such devices can be built into pre-existing equipment, such as ACRs, or they may be new FPI (Fault Passage Indicator) products with sensitive current detection and remote communication facilities.

From all the literature and test results available it can be seen that GFN does offer the most effective and latest technology that is available in the market that can address the issue of low level fault current detection. The suitability and viability of this device in Energy Queensland's distribution network will be discussed further as part of this research project.

3.4 Earth Fault Detection

Wang, et al.(2017) paper presents a protection scheme for faulty feeder detection based on the grey relation degree that can characterize the similarity among curves. Slope relation degree, is chosen to characterize the similarity of transient zero-sequence current waveforms between one feeder and other feeders, and the slope relation matrix that represents the relationship among all feeders can be established. When single phase-earth fault occurs in resonant grounding system, the similarity of transient zero-sequence current waveforms between faulty feeder and sound feeder is lower than that between any two sound feeders. Therefore a variety of grey relation degree, such as absolute degree and relative relation degree can be used to characterize the relationship among transient zero-sequence waveforms. This paper designs a multi-agent protection system for faulty feeder detection, including protection starting agent, current data extraction agent, calculation agent and fault analysis agent. As the detection is based on numerous equations and step by step process, this could lead to errors and probably won't work as intended during a fault scenario. The protection method proposed in this paper is applied to detect the faulty feeder for distribution networks. Besides, it is applicable to the system where at least 3 or more feeders are present, so the protection method has certain limitations. The process and method of extracting fault data and exactly how to improve the margin to detect the faulty feeder is not discussed in this paper which will require further research.

Abdel-Fattah & Lehtonen(2010) paper presents a transient probabilistic-based technique for earth fault detection in isolated and compensated neutral medium voltage networks. It utilises Bayesian theorem as a probabilistic-based selectivity function to indicate the probability of the feeder to be faulted and is given as*:*

$$\Pr(feeder\ i\ is\ the\ faulty) = \frac{f_1(I_{ni})/f_o(I_{ni})}{\sum_{i=1}^{n} f_1(I_{ni})/\,f_o(I_{ni})}$$

A 21kV, 251km medium voltage distribution network was simulated by ATP/EMTP program. Extensive simulations were performed to validate and trial the technique, for different fault conditions. The analyses were calculated in a sliding window of 2.5ms. Based on the results from the simulations, it is found that the performance of the probabilistic-based selectivity function is superior; it is not affected completely by different fault conditions and can cover the problem of low fault currents such as in isolated and compensated neutral networks and high resistance conditions. Although the theory and analysis does make logical sense, there is still lot of work required in terms of manufacturers developing algorithms to incorporate this logic. This will allow relays to analyse the waveforms itself rather than deploying other devices in the network. It would be a very costly exercise without having protection relay manufacturers involved.

Gomes, et al.(June 2018) has identified the presence of high frequency content during a high impedance earth fault involving vegetation. The testing process involved using a real dataset comprising a large number of experiments, sampled in a functioning 22kV network in the presence of noise. There were three main types of test conducted using a built in test rig. The first fault type simulates a tree branch laid across two conductors, one earthed and one with the nominal phase voltage (12.7kV). The second type followed the same geometry, but with both conductors energized (22kV). The third test was conducted by dropping the high voltage conductor into vegetation, either grass or bush. The current and voltage waveforms were sampled simultaneously in two channels to ensure wideband, and low sampling noise. The study however could not conclude that this method could be used to detect a high impedance earth fault scenario. It highlighted that further work needs to be undertaken as voltage signals and their respective high frequency content can be hard and expensive to obtain considering network topologies and existing hardware.

Theron, et al.(January 2018) emphasises how important it is to detect and isolate high impedance earth faults. The study looks into the effectiveness of existing techniques that are currently being utilised and also highlights some of the newer developments that are available. One such technique is using negative sequence current for detecting of broken conductors. The down side of using this is the risk of unnecessary tripping due to load. In a three phase system, if one phase is lost (open bridges), it will be seen as a phase-phase fault which will generate negative sequence current and depending on the load, the feeder can trip on negative sequence protection which some of the power utilities do not want to trip for that scenario. Another technique the study looks into is the use of watt metric protection which is used in Peterson coil grounded systems. It seems to be a well established form developed over the years which can be further investigated as part of my study to see if it can be used in the distribution network. It also looks into ground wire grid form of protection which is a mechanical solution. It includes laying of guard wire under the power conductor. Since it requires wire mesh along the entire length of the distribution feeder, it will be a very costly exercise considering the geographical area of the Energex and Ergon networks. The newer technique this paper highlights is fundamental analysis and harmonic analysis which are yet to be introduced and trialled by relay manufactures as it will require algorithms developed and features introduced as part of the relay software.

Ravlic, et al.(2017) specifically highlights the method of using Fourier transform and design of intelligent system to detect earth faults. The different simulation condition takes into consideration, three phase load switching, three phase line without load switching and also three phase capacitor bank switching as these events generate similar transients to a high impedance earth fault which can lead to mal-operation of protective devices. Various phase to ground faults were simulated and the amplitude plus phase of the first, third, fifth and seventh harmonics of the zero sequence line currents were extracted using Fourier transform. Whilst from the results obtained from this study suggest that this method can be utilised, it will require further research from relay manufacturers to develop relay algorithms which incorporates this logic. The other down side is it will require voltage transformers at sites where this feature will be utilised and this is not entirely possible due to cost and other hard ware installation constraints.

Wester (1998) reviews several mechanical and electrical methods of detecting high impedance faults. One type of mechanical HIF detection method consists of a device(s) mounted to a cross arm or pole. A unit is mounted under each phase wire and it provides a low impedance ground fault by catching the falling conductor. The force of the falling conductor releases an internal spring that ejects a bus bar to make contact with the fallen wire and create a ground fault. Sagging condutors that do not come in contact with earth or a grounded object could be detected by this mechanical method. Another type of mechanical HIF detection method uses a pendulum mounted aluminum rod with hooked ends. It is suspended from an under-built neutral conductor. The falling conductor is caught and produces a low impedance ground fault, which operates conventional overcurrent protection.

The electrical methods reviewed by Wester (1998) includes:

- High Impedance Fault Analysis System – this method measures the third harmonic current phase angle with respect to the fundamental voltage. The device calculates and stores the average ambient third harmonic current phasor. When a fault occurs, the new third harmonic current phasor is vectorially subtracted from the stored value. A high impedance fault is issued if the magnitude is above setting and angle matches a predetermined value for a down conductor.

- Open Conductor Detection – this method detects loss of voltage to determine a broken conductor. The system measures the voltage at each end of a single phase lateral. When the voltage of any phase drops below the specified threshold, a transmitter sends a signal on the neutral conductor to a receiver at the upstream device which opens if voltage is present.
- Digital Feeder Monitor – is based on the high impedance fault detection technology which uses a high waveform sampling rate (32 samples/cycle) for the AC current inputs in conjunction with a high-performance microprocessor to obtain the frequency response required for arcing fault detction.

The mechanical methods suggested in Wester (1998) will be a very costly exercise to the distribution power utilities, considering each unit will have to be mounted to a pole and will only cover one span of overhead conductor. The mechanical methods are not economically viable but could potentially be installed around schools or identified problem portion of the network. The electrical units can also be utilised but have to install one unit per distribution feeder which again will lead to significant cost considering insatllation and maintenace cost's to these devices.

Zamanan, et al.(2007) presents a new method of detecting HIF's in distribution systems using real coded genetic algorithm (RCGA) to analyse the harmonics and phase angles of the fault current signals. The method is used to discriminate HIF's by identifying specific events that happen when a HIF occurs. It looks at the the arcing nature of high impedance fault current, HIF model, harmonic model, genetic algorithm and fitness function. A practical power system is simulated in Simulink to demonstrate the ability of the RCGA to track harmonics during normal and abnormal conditions in a power system. A decision whether there is a HIF is based on the existence of the 3rd and 5th harmonics and the angle shift of the 3rd harmonic with respect to the fundamental current. After many simulations, a threshold was specified for the harmonics and the angle shift to determine a HIF. For the 3rd and 5th harmonics a 1% and a 0.5% of the fundamental current were set as threshold values respectively.

From Zamanan, et al.(2007) test results it can be seen that before the HIF occurs, the load current is normal with no change in the phase angle and no harmonic currents. After the HIF has been applied there is an increase of 13.7 amps in the load current, which can be interpreted by the protection relay as a load increase instead of a fault, simple because the HIF does not draw sufficient current for the relay to act. In a normal fault, the current in the fault will be much greater than the relay setting, therefore the relay will react to the fault. In the HIF case this will not happen because the setting in the realy is much less than the HIF current. During the existence of the HIF there is a noticeable change in the circuit harmonics. The existence of the 3rd and 5th harmonics, plus the slight increase of load current and the angle shift of the third harmonics with respect to fundamental current, together confirm the existence of the HIF, since these are the peculiar characteristics of a HIF.

The identified method involves equations and algorithms that will need to be incorporated in protective devices to achieve it's intended purpose. Relay manufactures will have to develop their own alogorithm which can work in conjuntion with the proposed RCGA hence it will require resources and adequate funding towards it.

Wang, et al.(2018) proposes a new faulty phase selection method for single-phase grounding faults in distribution networks with full compensation arc suppression technology. The full compensation arc supression technology in distribution networks could be divided into current arc-extinguishing methods and voltage arc-extinguishing methods. The current arc-extinguishing methods use the neutral point grounding reactance to compensate the ground fault residual current. The voltage arc-extinguishing method involves adjusting the voltage of the faulty phase whereby the arc-suppression technology is designed to guarantee the faulty phase voltage equals zero by injecting current through the neutral point.

A resonant grounded distribution network with full compensation arc suppression technology is as shown in figure 13 below.

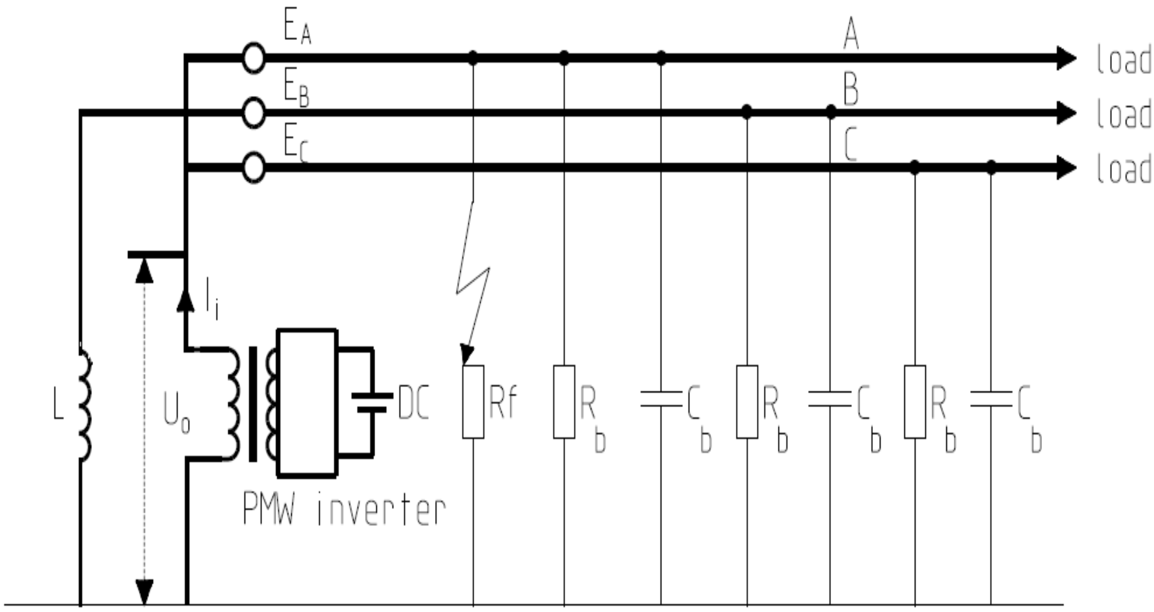


Figure 13: Resonant grounded network with full compensation arc suppression technology

E_A, E_B, E_C, are respectively the three-phase power supply voltage in the distribution network. U_o, represents the neutral point displacement voltage after the ground fault occurs while L is the inductance of the arc-suppression coil. Compensated current I_i, is injected by the PWM active inverter. By setting a reasonable value, letting $U_o = -E_A$, and thus the fault phase voltage $U_A = E_A + U_o$ = 0, that is the fault phase recovery voltage is always 0 and hence the arc can be suppressed effectively. In Wang, et al.(2018), the electromagnetic transient simulation software PSCAD is used to establiah a 10kV asymmetric neutral point arc suppression coil grounding system. From the waveforms and test results obtained by the simualtions in can be concluded that if the phase selection is correct, the selected phase voltage will be close to 0 when the theoretical current value determined by the zero residual current arc suppression is injected. If the phase selection is wrong, the wrongly selected non-fault phase will approach to a non-zero certain value with the increase of grounding resistance when the current is injected. The simulation analysis shows that the proposed method can correctly perform faulty phase selection which can be used to improve the full compensation arc suppression methods in distribution networks.

3.4.1 Voltage Supervised SEF Protection

Anegondy, et al. (2019) highlights a new approach to detecting vegetation faults by developing algorithm to improve sensitivity detecting high impedance faults using zero sequence or residual current based on high-accuracy phase current measurements supervised by zero and negative sequence voltages. Extensive system simulation studies have been performed using an Electromagnetic Transient Program (EMTP) model for a feeder in a proposed pilot project in Evoenergy distribution power network. Evoenergy operates power network in Australian Capital Territory (ACT) and faces similar issues of detecting low values of fault current. The vegetation or downed conductor fault detection algorithm has been aimed at detecting a broken or downed conductor utilising Voltage-Supervised Sensitive Earth Fault (VS-SEF) settings incorporated in pulse closing device. It has been developed to identify a broken or downed conductor situation, trip or alarm and prohibit reclosing on the circuit, thus isolating the fault and avoiding any potential ignition of a bushfire.

The algorithm was developed considering the following scenarios:

- Tree branch touching the conductor, and downed conductor on the ground, a scenario wherein a conductor snaps and lands on dry ground or grassland.
- Downed conductor, but not touching the ground, a scenario wherein a conductor snaps and hangs above the ground.

3.4.1.1 Point on wave closing

Pulse-closing is a new technology and an alternative to conventional reclosing for overhead distribution system protection as highlighted in Anegondy, et al., (2019). It uses a new method to test for the continued presence of faults that reduces the energy (I^2t) to less than 5% as compared to conventional reclosing. While the consequences of initial fault clearing cannot be avoided, subsequent fault testing using pulse-closing causes almost no decrease in the bus voltage and significantly reduces power system equipment stress, including the substation transformer through which the fault is supplied. In fact, this revolutionary fault-testing method is so un-intrusive, its operation is virtually imperceptible to all upstream loads. The reason pulse-closing is essentially transparent to upstream loads is because the very slight voltage dip caused by a fault-testing pulse lasts for a maximum of 0.5 cycles. As a result, once the initial fault is cleared, upstream loads and those on adjacent feeders are no longer affected by repeated testing for fault presence.

Pulse-closing generates a 0.25- to 0.5-cycle minor loop, or pulse, of current by rapidly closing and opening single-phase fault-interrupting contacts at specific voltage point-on-wave angles as shown in figure 14 below. A pulse is immediately analysed to determine whether it reflects fault or load current. If the predicted symmetrical current is less than the specified fault current threshold, the pulse current algorithm concludes that there is no fault and closes the per-phase contacts. Conversely, if the predicted fault current is greater than the fault current threshold, the process concludes that a fault still exists on the line and the device mechanism inhibits closure. This approach ensures that there is no heavy current closing that may result in sparks causing bushfire ignition dangers.

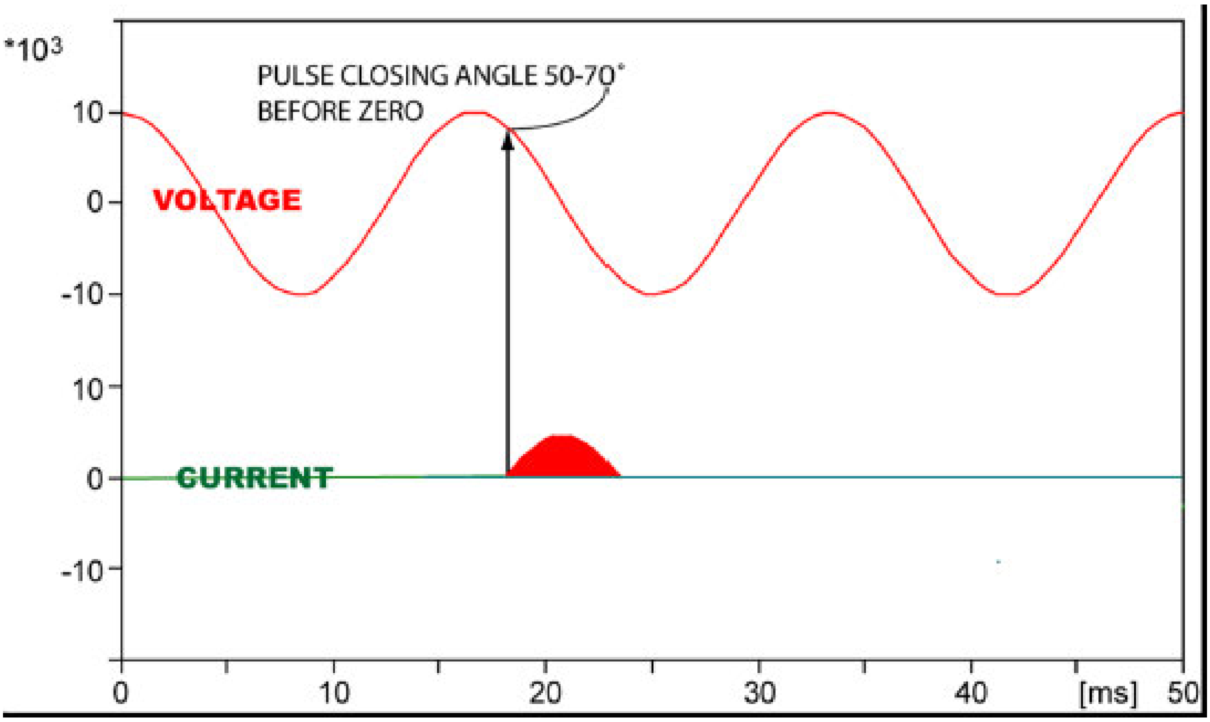


Figure 14: Pulse-closing concept waveform

Due to its low energy closing, transformer terminated lines are not subjected to high intensity fault closures nor overvoltage. This would benefit the transformer by extending its design life. Should the pulse-closing device trip or open three-phase (for whatever reason), and a pulse-closing operation precedes its reclosing, protection-level transformer magnetizing inrush current never occurs because pulse-closing occurs near peak voltage on each phase whereas maximum inrush current occurs when closing at a voltage zero when the voltage is increasing in the same direction as the polarity of the remnant flux trapped in the transformer core during opening. This will obviate any protection-related mal-operations due to transformers being energised under no-load conditions.

3.4.1.2 Voltage-Supervised Sensitive Earth Fault (VS-SEF) logic

As per Anegondy, et al., (2019), this protection scheme detects high-impedance faults by using a combination of under-voltage, neutral voltage displacement, SEF pickup, and non-operation of the normal overcurrent and earth fault protection. High-impedance faults caused by fallen conductors on ground or vegetation results in loss of voltage on one or more phases that could produce either a partial or a complete loss of voltage depending on the arc resistance. The under-voltage protection could be set to as low as 50% of nominal voltage. This unbalance results in neutral voltage displacement in the form of zero sequence voltage. Sensitivity studies have demonstrated an increase in the neutral displacement voltage and the negative sequence voltage.

In case of high resistive vegetation faults, an operation of VS-SEF at or above one ampere is used in conjunction with under-voltage, neutral voltage displacement, negative sequence and the non-operation of the normal overcurrent earth fault and SEF protection to confirm a possible vegetation fault that may result in bushfire consequences. In case of high impedance vegetation fault, the neutral current could be as low as a few amperes or less. To distinguish between a normal scenario and a faulted scenario, the system unbalance is monitored through the sequence components and the decision to trip is made when there is voltage unbalance in the network, a single phase high voltage, and a residual zero sequence current is detected. The system unbalance setting monitors both negative and zero sequence components present in the network. Either of the components present above the threshold setting signifies an unbalance in the network, which may be because of an actual fault. Restrain values can be set for both negative and zero sequence components to allow phase overcurrent or other elements to operate instead of SEF.

The developed logic for VS-SEF is as shown in figure 15 below.

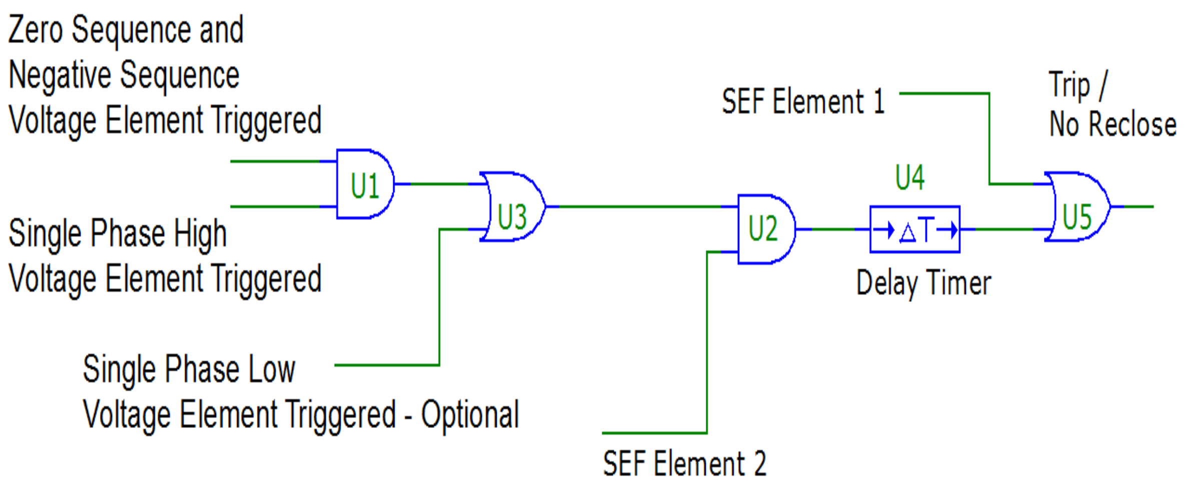


Figure 15: VS-SEF logic block diagram

Secondary injection testing has been conducted using test plans developed on an Omicron test kit. The aim of the Omicron injection testing was to prove the VS-SEF algorithm and the secondary level sensitivities of the zero sequence current and the sequence components of voltages under downed conductor or vegetation faults scenarios. The following VS-SEF tests have been conducted:

- As per the logic, the SEF combined with a single phase low voltage will initiate the trip after the delay timers – definite time delay timer for VS-SEF and single phase low voltage time to active timer.
- Tests were also performed to prove that the unbalance voltage components do not affect the low- voltage scenario.
- As per the logic, the single phase high voltage must be active with unbalance voltage components, such as zero sequence and negative sequence and then combined with SEF for an effective trip.
- Apart from the timers for high voltage and definite time for VS-SEF, the trip time also depends on the unbalance time to active timer.

Evoenergy's Mackenzie feeder network data was represented in an EMTP simulation model. A simplified model was developed for the purpose of analysing the sensitivity of sequence components during downed conductor and vegetation faults while taking into account the worst-case tolerances in current and voltage measurements. The results indicate that the sensitivity of the zero sequence component of the voltage increases marginally with load. The faults at the lateral end towards the load indicate minimum change in the sequence components. However, these factors have been considered with an onerous tolerance factor of the instrument transformers. With improved sensitivity and tolerance of instrument transformers, the practical results would indicate a much better fault detection performance. This factor has been taken into account while designing the algorithm and its performance during the final high-power laboratory tests.

3.4.1.3 Sensitivity observations of VS-SEF operation

Anegondy, et al., (2019) highlights the following VS-SEF sensitivities from comprehensive laboratory tests:

- The averaged RMS values of the false residual current 3I0 due to measurement tolerances in phase currents varied from 0.14 amperes to 0.32 amperes.
- The non-trip values for heavy inductive loading ranged from 0.81A to 1.11 amperes.
- The trip value of SEF ranged from 1 ampere to 2 amperes.
- The total time to trip varied from 0.164 seconds to 0.405 seconds; the SEF element of the VS-SEF logic is additionally time delayed due to the inverse time logic provided to avoid spurious pick-up.
- The voltage-supervised SEF has three components, a single-phase positive sequence under-voltage unit that will assert only for a fault and would restrain the SEF for normal conditions where the ambient zero sequence conditions would cause a false trip.
- The overvoltage element is conditioned utilising a change in zero sequence voltage or a negative sequence voltage. For ground currents of the order of 1 ampere under balanced conditions, both zero sequence and negative sequence voltage will de-assert and block the logic. For genuine high impedance fault conditions, both these parameters will assert to activate the VS-SEF logic.

Based on the extensive secondary injection testing, EMTP simulation, and primary high power laboratory tests, the pulse-closing voltage-supervised sensitive earth fault detection algorithm appears to have demonstrated an average sensitivity of 1.25 amperes with a clearing time of less than two seconds for either vegetation or downed conductor faults.

Although SEF protection is currently employed in Energy Queensland's distribution network, the new VS-SEF detection method developed by Evoenergy, can be explored and tested further to find its actual effect in Energy Queensland's network..

3.5 Fault Resistance

Abdel-Fattah & Lehtonen (2012) investigates the effect of fault resistance during an earth fault scenario. The investigations include the effect of the fault resistance on the fault current, fault voltage, the transient recovery voltage and the rate of rise of the transient recovery voltage using a realsitic 20kV medium voltage network model. It does highlight that in medium voltage overhead networks of utilities across the world, approximately 80% of faults are transient and 80% of faults involve one phase to earth only. The fault current magnitude, fault resistance and the rate of rise of the transient recovery volatge can affect the earth fault characteristics. In unearthed MV network the maximum earth fault current, at zero fault resistance, is limited by the total earth capacitance of the network but for compensated newtork the maximum earth fault current is limited by the total leakage conductance of the network and compensation branch. The actual earth fault currently mainly depends on the maximum value and the fault resistance. For the same network, the maximum value is constant, however the fault resistance on the network earthing conditions and the fault characteristics. The effect of the fault resistance on the fault currents in unearthed and compensated neutral networks is presented in Figure 16 below.

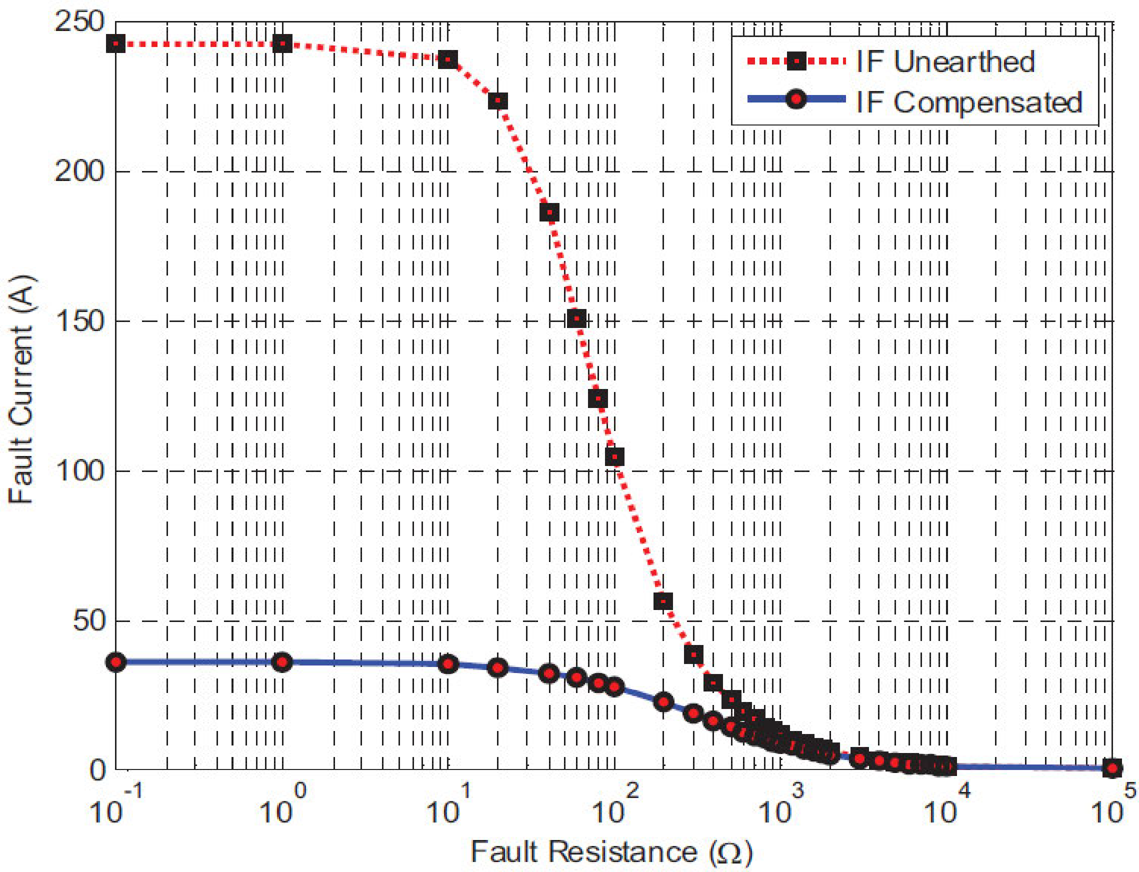


Figure 16: The effect of the fault resistance on the fault currents

It can be seen from Fig.16, that the fault resistance can affect the fault current in both networks. The significant change can be seen in the range of 10-1000 Ω of the fault resistance. From the simulation results it was seen that the higher values of the fault resistance, starting from 10Ω, sharply decreases the transient recovery voltage in unearthed neutral networks, up to 10kΩ. However, the higher values of the fault resistance, starting from 10Ω, sharply increases the transient recovery voltage and rate of rise of the transient recovery voltage in compensated neutral networks, up to 10kΩ.

Pawlik, et al.(2017) presents a derivation of the closed-form solution to both the earth return self and mutual impedance expressions developed by Carson. During an earth fault on a power system the fault current returns to the source and in a three phase a.c. power system, if the fault is supplied by an overhead line, the current that enters the ground appears to be coupled to the power line by the time varying magnetic field. From an earthing perspective, understanding and definining the behaviour of the earth return current is more significant. The nett magnetic field of the earth return current defines the coupling into auxiliary paths and metallic third party assets, is highly dependent on expressions representing the earth return phenomenon. From the a.c source, the longitudinal electromagnetic field is defined by the current in the wire and the current returning through the earth and must satisfy radial conditions as well as boundary conditions at the both surface of the wire and the earth-air interface. The boundary conditions ensure the longitudinal current in the ground is redistributed into the path of least energy as it propagates through the earth, but result in an additional impedance in the earth return circuit as the time varying magnetic fields inductively energise the half spaces. The increase in impedance will be a function of the frequency, the soil conductivity, and the height above ground of the conductor.

From Abdel-Fattah & Lehtonen (2012) and Pawlik, et al.(2017) it can be seen that fault resistance plays a major part in determining the value of fault current present. The value of fault current decreases with a higher value of fault resistance and as such also has an effect on voltages on healthy phases. As part of the fault analysis in this research project, various values of fault resistance will be utilised in simulation to analyse it's effects on fault current and also monitor phase voltages during a system fault.

3.6 Effect on Voltages during earth faults

Topolanek, et al., (2014) focuses on the operational experience with an automatic system for additional earthing of the faulty or healthy phase during an earth fault. The paper presents the simulation and experimental verification of additional overvoltage on healthy phase during an earth fault in the system. The overvoltage caused by healthy phase earthing in supply substation during an earth fault can lead to insulation breakdown of equipment in affected distribution network. The principle of the method of short-time earthing of the healthy phase is shown in figure 17 below in simplified diagram of the MV supply substation.

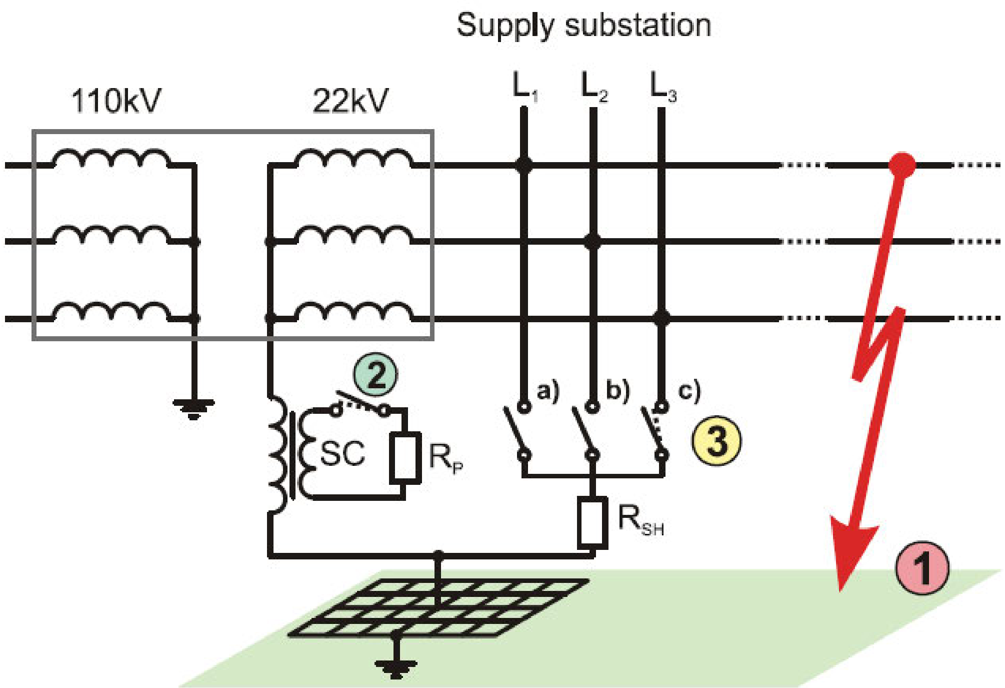


Figure 17: Simplified scheme of MV supply substation with automatic systems for additional earthing

The supply transformer station is equipped with three single-pole switches (No.3 in figure 17). Each of these switches can be used to connect any phase to ground thorough a shunt resistor R_{SH}. This resistor limits the current through the substation earthing systems and its value is 10Ω. When earth fault occurred in the A-phase, the healthy B-phase which lags the faulty phase is always earthed by automatics for healthy phase earthing for fault localization.

Complete RMS values of phase to neutral voltages recorded during the experimental measurements for the moment when fault location occurred are shown in table 4 below. The percentage values of the voltages, which are related to nominal phase voltage of the network (22kV/√3), are shown in the table below. The results shown below were recorded during experimental measurement, where earth fault was ignited in A-phase and the healthy B-phase was earthed for earth fault location. From the results of this experimental measurement it is apparent that overvoltage in C-phase reached the highest value during localization of low-impedance earth faults. The maximal value of recorded overvoltage in healthy C-phase is 25.65kV. This value reaches to the double value of operation phase voltage on the secondary side of supply transformer. Such high overvoltage could damage insulation strength of C-phase.

Configuration of the network			***Type of EF***	*Phase voltage in the supply substation*					
Ex. No.	***Capacitive current***	***Compensation state***		***U_a***		***U_b***		***U_c***	
				[kV]	[%]	[kV]	[%]	[kV]	[%]
0.1	202 A	compensated	solid EF	x	x	x	x	x	x
1.1	38 A			13,82	109	10,02	79	25,64	202
2.1		overcomp.		13,70	108	10,13	80	25,62	202
3.1			300Ω/arcing	13,70	108	9,89	78	25,27	199
4.1			arcing EF	13,74	108	10,12	80	25,61	202
5.1		compensated		13,80	109	10,06	79	25,65	202
6.1			3 kΩ	22,84	180	0,14	1	22,97	181
7.1			1,5kΩ/arcing	x	x	x	x	x	x
8.1			1,5kΩ/arcing	13,92	110	9,86	78	25,57	201

Table 4: Effective values of phase voltages recorded at supply substation during experiment

Chapter 4 Methodology

4.1 Chapter Overview

This chapter outlines the methodology that was utilised to model the earth fault current characteristic of various earthing systems and variance in earth fault values on 11kV feeder model with the incorporation of fault resistance. The background study and literature review has identified a number of key areas to consider when doing this research project which has been incorporated in various phases of this methodology.

4.2 Task Outline

The research project mainly consisted of six distinct phases as follows:

1. Literature review
2. Existing and alternate earthing details phase
3. Development and fault modelling phase
4. Investigation into alternate protection phase
5. Investigation into new earth fault detection technology phase
6. Analyse actual phase to ground fault data from field

Major details and contents of each project phase are outlined in Tables 5 to 8. The different phases of the research project were completed simultaneously at times in-order to complete the entire task successfully and be able to meet all required submission deadlines.

4.2.1 Phase 1 – Literature review

This phase mainly involved performing extensive literature research to identify what has been done in this area so far and the remaining area of knowledge gap. There have been a vast number of researches done around this area but it has not been adequately established regarding the detection of low values of earth fault current.

4.2.2 Phase 2 – Existing and alternate earthing

Phase 2 of the research project as shown in Table 5 involved carrying out study and analysis of existing earthing systems. Earth fault values differ depending on which type of earthing system is being utilised at a particular distribution substation therefore the benefits and challenges of existing earthing system was looked at in this phase. It also involved doing analysis and detail study of alternate earthing system as highlighted in literature review. Energy Queensland's network has a vast number of legacy networks with different designs and equipment so investigating into alternate earthing systems to be integrated into these networks was looked at as part of this study. Limitations in existing earth fault design currently implemented in Energy Queensland's distribution network such as detection of high impedance earth faults and also seeking information regarding different forms of earth fault protection utilised by other power utilities in Australia was also carried out in this phase.

Task Designation	*Task Descriptions*
Phase 2	Existing and Alternate Earthing details Phase
2A	Existing Earthing Details • Study the existing earthing models of Energy Queensland's distribution network • Note the challenges, advantages and disadvantages of existing earthing systems
2B	Earth Fault Protection Design • Understanding the limitations and challenges of existing earth fault protection utilised in Energy Queensland's distribution network • Investigate the various forms of earth fault protection currently used by distribution network service providers within Australia to see if it would be beneficial and suitable to Energy Queensland's distribution network
2C	Alternate Earthing Systems • Investigate the availability of alternate earthing systems being utilised by other power utilities • Perform analysis of the alternate earthing systems to see it's viability and suitability to Energy Queensland's distribution network

Table 5: Methodology – Phase 2

4.2.3 Phase 3 – Earth fault modelling

Phase 3 of the research project mainly involved earth fault modelling on 11kV feeders at Ergon Energy's Woodstock South (WOSO) substation. The substation as shown in figure 18 consisted of a 66/11kV 6.3MVA power transformer which was feeding into three 11kV feeders. The neutral or star connection on 11kV side of the power transformer was solidly earth.

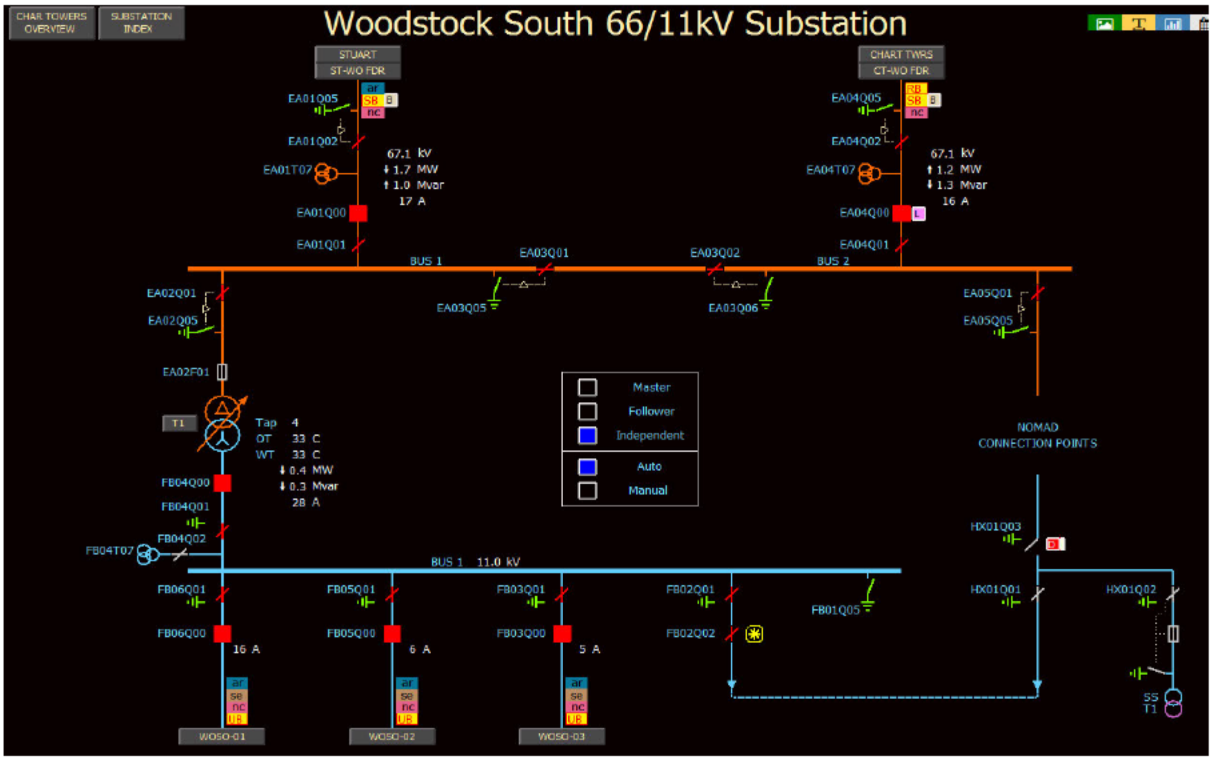


Figure 18: Woodstock South 66/11kV Substation

Woodstock South substation model was obtained from the master database and validated with the current network configuration. Table 6 below outlines the detailed earth fault analysis as performed in phase 3 of the research project. Dig-Silent Power-factory software package was utilised to carry out the analysis. Results of the study for various simulated scenarios highlighted in table 6 below were extracted from the software package and copied onto Microsoft excel to validate and analyse the results.

Task Designation	***Task Descriptions***
Phase 3	Fault Modelling Phase
3A	Network Models • Woodstock South network model was obtained from the master database model. • The network model as shown in figures 19 and 20 was verified with the operating schematic diagram as per Appendix C to ensure that the model was correctly configured with correct normally open points and accurate protective device.
3B	Data Validation • The maximum and minimum source impedance for WOSO was obtained and entered into the external grid in Power factory model for earth fault simulations • There were a number of errors as Appendix D flagging up in WOSO power factory model, hence all needed to be corrected before the analysis could be executed. Some of these included wrong transformer types, and incorrect overhead line data.
3C	Fault Simulations • Earth faults were simulated on all three 11kV feeders at WOSO substation. • Performed system normal analysis with maximum and minimum source impedance analysis with zero ohms fault impedance • Performed system normal analysis with maximum and minimum source impedance analysis with varying fault impedance. Introduced fault impedance in the network of 10 to 50ohms. • Measured fault current and phase voltages in all scenarios to see the behaviour of fault current and effect on voltages on faulted and un-faulted phases. • Simulated a 6ohm NEX at source on 11kV neutral to introduce impedance grounding. • Performed system normal analysis with maximum and minimum source impedance analysis with zero ohms fault impedance • Performed system normal analysis with maximum and minimum source impedance analysis with varying fault impedance. Introduced fault impedance in the network of 10 to 50ohms. • Measured fault current and phase voltages in all scenarios to see the behaviour of fault current and effect on voltages on faulted and un-faulted phases. • Checked clearing times achieved by existing protection devices for minimum earth faults on each feeders.

Table 6: Methodology – Phase 3

Figure 19 below represents the geographical layout of the three 11kV distribution feeders utilised in earth fault analysis emanating from Woodstock South substation.

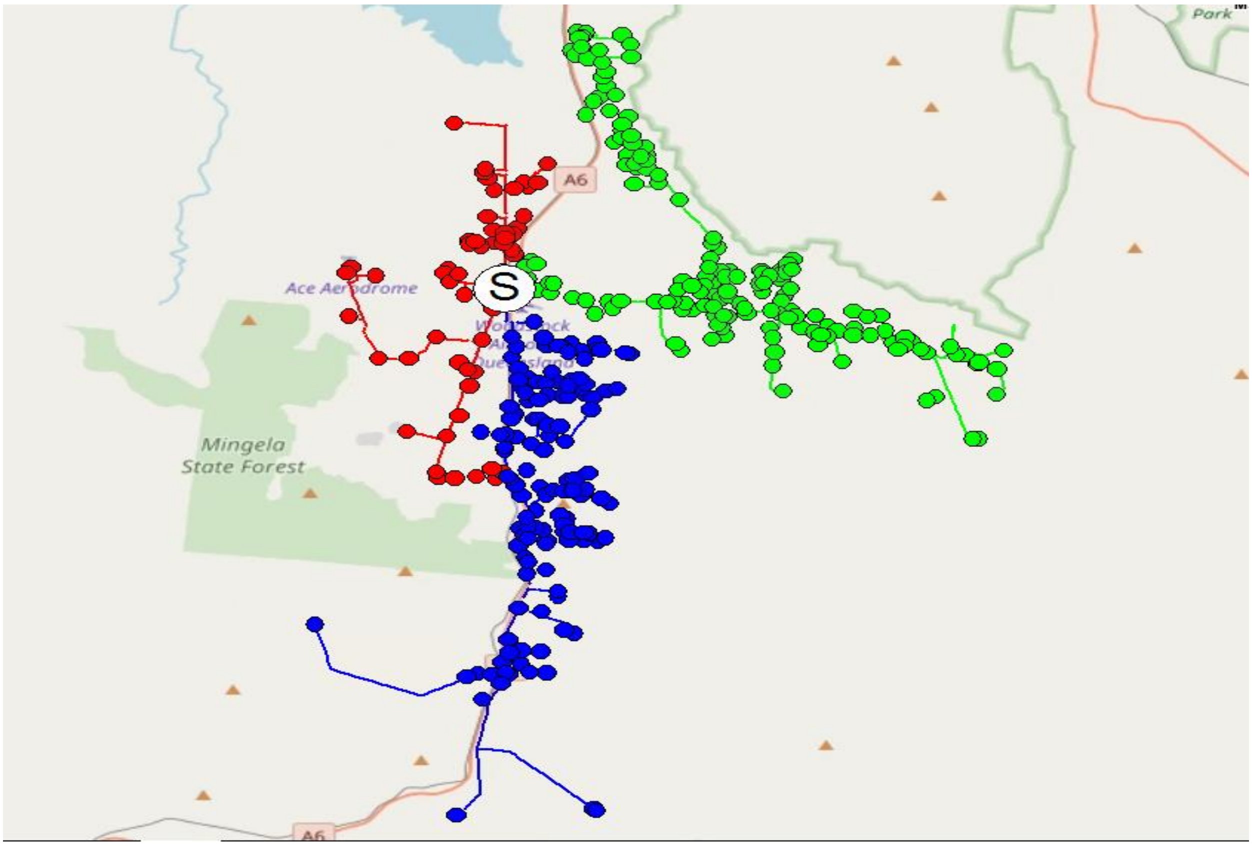


Figure 19: Geographical layout of 11kV feeders at WOSO

Figure 20 below represents the Woodstock South substation model in DigSilent Power Factory. The maximum and minimum values of source impedance and fault resistance were varied in external grid during the earth fault analysis. There was no other earth fault contribution from other sources such as embedded generation in this model. Analysis was performed on each feeder separately so that results could be sorted out easily.

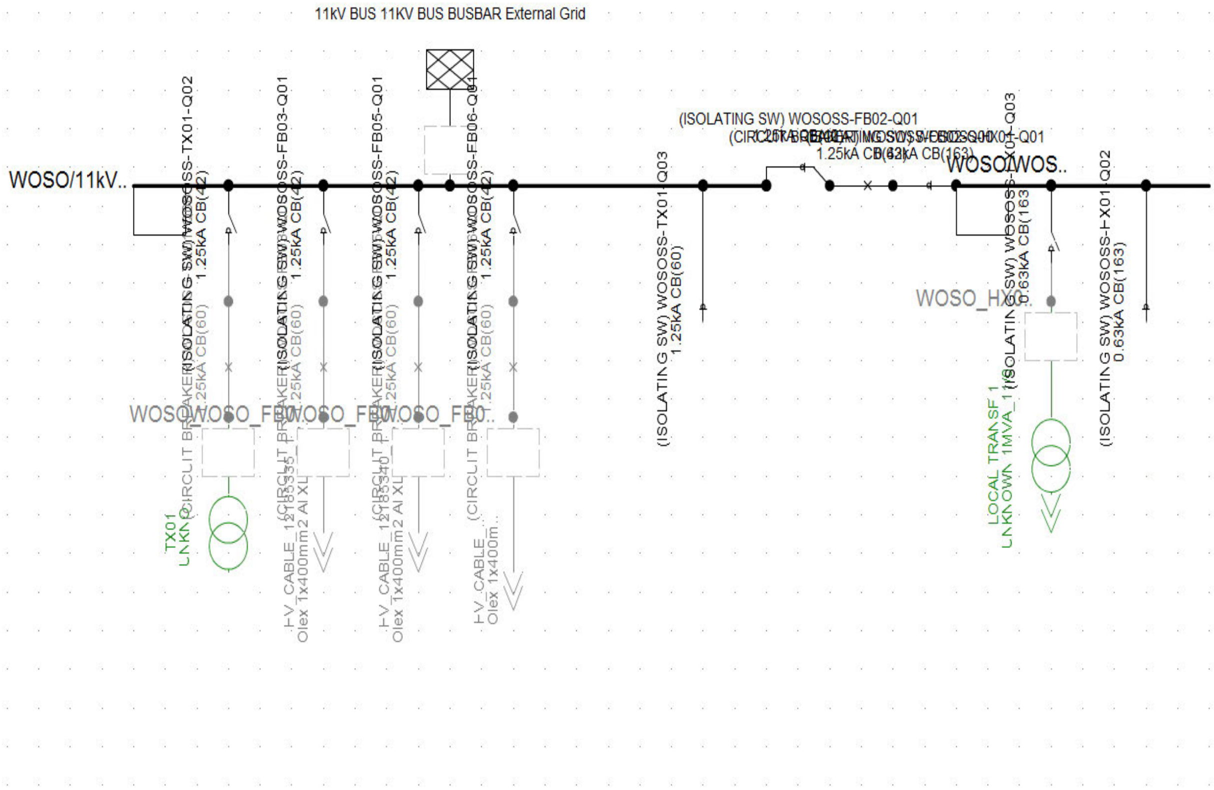


Figure 20: WOSO model in Dig-Silent Power Factory

4.2.4 Phase 4 – Alternate protection

Phase 4 as highlighted in Table 7 below involved liaising with suppliers and manufactures to see if there were alternate forms of protection available in their protective devices that could assist in earth fault detection.

Task Designation	***Task Descriptions***
Phase 4	Investigation into Alternate Protection Phase
4A	Alternate Protection • Research and investigate alternate protection functions currently available in protective devices from suppliers / manufacturers which can be utilised for detecting earth faults.
4B	Suitability of Alternate Protection • Determine the advantages and disadvantages of the alternate protection function to Energy Queensland's distribution network. Need to ensure that alternate protection does not introduce new issues in the network.

Table 7: Methodology – Phase 4

4.2.5 Phase 5 – New detection technology

Phase 5 as highlighted in Table 8 below involved liaising with suppliers and manufactures to see if there were new technologies available in the today's world that could assist in earth fault detection.

Task Designation	***Task Descriptions***
Phase 5	Investigation into new Technologies Phase
5A	New Detection Technologies • Research and investigate the availability of new technologies that may provide better earth fault detection capabilities
5B	Viability of New Technology • Determine the advantages and disadvantages of the new detection technology to Energy Queensland's distribution network. Need to ensure that new detection technology does not introduce new issues in the network.

Table 8: Methodology – Phase 5

4.2.6 Phase 6 – Analysis of actual fault data from field

An actual phase to ground fault data was obtained from protective device's in the field after a high impedance phase to ground fault occurred on a 11kV feeder overhead feeder. The fault had very low values of fault current and the duration of fault current was not long enough for immediate SEF protection to isolate this fault. Waveforms and event records were retrieved from the field devices by field staff. Relevant protection relay applications were utilised to analyse the waveforms and records retrieved from protective devices as more than one protective device was in the protection scheme and had detected the fault for this particular event.

4.3 Interpretation and Analysis of Results

Interpreting and analysing results was a major aspect of this research project. Therefore, it was extremely important that the data was precisely and accurately recorded. The network modelling process in Power-Factory fault modelling software involved simulating a number of fault scenarios and permutations and therefore lot of results needed to be accurately recorded. Microsoft excel was used as a tool to record the results in tabulated form and then represent those data in graphical format. Part of the research also involved correspondence with power utilities and various protection relay manufacturers. It was ensured that if any data was received, it was correctly interpreted and also verified with the sender so that there was no ambiguity.

4.4 Resource Requirements

The majority of the project resources utilised during the research project were software resources, and were either privately owned, or were obtained from Energy Queensland.

The following table 9 outlines the list of software and equipment which was used during the duration of the research project:

Item	*Quantity*	*Source*	*Cost*	*Comment*
PC with Microsoft Windows	2	Energex & Student	Nil	Required work PC to access systems and personal laptop for project write up and research.
Microsoft Word	1	Student	Nil	Report Writing
Microsoft Excel	1	Student	Nil	Data Entry
IPS database	1	Energex & Ergon	Nil	Obtain protection settings
Power On Web view	1	Energex	Nil	Network Overview
POWERFACTORY	1	Ergon	Nil	Network Modelling / Fault Analysis

Table 9: List of Software and Equipment required

4.5 Quality Assurance

The following procedure was utilised to ensure that all simulation and analysis was performed and results recorded to the highest possible accuracy:

1. Fault analysis results obtained from existing earthing systems. This was validated between different substations to ensure that there were not inconsistencies in results.
2. Data (conductor, cable and earthing details) used in modelling of alternate earthing systems was confirmed and validated using other data storage systems used in Energy Queensland.
3. Any equipment details or data obtained from suppliers / manufactures was validated to ensure that it did not consist of errors which would affect the simulation and analysis process.
4. Continuous feedback was obtained from USQ project supervisor to ensure that the research study meets the set criteria.

5. Project supervisor from Energy Queensland was informed so that there was no oversight in any simulations and analysis.

The methodology utilised in this research project resulted in successful completion of this study which will also be beneficial to Energy Queensland.

4.6 Consequences and Ethics

As per competency standard set by Engineers Australia, Professional Engineers are required to take responsibility for engineering projects and programs in the most far-reaching sense. Professional Engineers are responsible for interpreting technological possibilities to society, business and government; and for ensuring as far as possible that policy decisions are properly informed by such possibilities and consequences, and that costs, risks and limitations are properly understood as the desirable outcomes. There are severe penalties issued to professionals if breach is found in engineering practices.

In accordance with the Engineers Australia document *Our Code of Ethics (Engineers Australia n.d.),* it is expected that engineering professionals will act in an ethical manner, addressing safety and sustainability considerations. To ensure that the research project was conducted in a safe, sustainable and ethical manner, continuous analysis of the consequential effects of the research project was undertaken. Additionally, the possible effects that the research project could have after the project has been concluded were examined to ensure that any foreseeable consequences are acceptable.

4.6.1 Risk Assessment

A risk assessment was performed to address safety concerns and mitigate any risk to personnel involved in this research project. The risks were categorised, with appropriate control measures developed as per Appendix B. By thoroughly assessing, controlling and reviewing risks at all times, project safety was maintained at high standards during the duration of the research study. This ensured that due diligence in meeting safety requirements to me and others involved in this project was always at the highest level. Majority of research work and study was required to be carried out within an office environment, therefore there was minimal risk to personnel. Also in doing this research study which had an aim of improving the safety in distribution power network which the society and communities will benefit from.

4.6.2 Peer Review

During the process of completing this research project there were occasions whereby numerous feedback was obtained from peers. This also included engineering personnel from Energy Queensland and also fellow colleagues from Engineering Discipline at USQ. The peer review process provided mutual benefits to the researcher and the peer group. The peer group will gain knowledge from the research to initiate or support further studies, and the researcher benefits by improving in areas of research identified by other professionals. By having the dissertation peer reviewed also meets the guidelines of Engineers Australia *Our Code of Ethics (Engineers Australia n.d.).* The guideline states "*2. Practice Competently – 2.1 Maintain and develop knowledge and skills – seek peer review – support the ongoing development of others.*"

4.6.3 Sustainability

The proposed alternate earthing systems and new earth fault detection techniques was made in view of the economic and viability to Energy Queensland's distribution network. With electricity prices being continuously a talking point for society and political parties, the cost of implementing new technology was carefully thought off. The benefits needed to outweigh the costs involved. In doing a detail sustainable study will meet the guidelines of Engineers Australia *Our Code of Ethics (Engineers Australia n.d.).* The guideline states "*4. Promote Sustainability – 4.2 Practice engineering to foster the health, safety and wellbeing of the community and the environment – incorporate social, cultural, health, safety, environmental and economic considerations into the engineering task.*"

Chapter 5 Findings of Earthing Systems and EF Protection

5.1 Chapter Overview

This chapter highlights the findings of benefits and challenges of existing earthing systems utilised in Energy Queensland's distribution power network and also the earth fault protection employed by some of the distribution power utilities in Australia.

5.2 Benefits and challenges of existing earthing systems

5.2.1 Solidly Earth

The main benefits include:

- Highest magnitude of phase to earth fault currents and simple earth fault protection can be utilised in most places.
- Over-voltages during earth faults are the lowest (around 0.8 time's phase to phase voltage).
- Arcing ground faults cannot occur as the short circuit current is much larger than the capacitive charging and eliminates its influence.
- Lowest capital and maintenance cost as there is no need for extra equipment to be installed between the transformer neutral terminal and substation earth grid.
- Simple to understand by operational personnel.

The main challenges include:

- Presence of high fault currents can cause severe damage to system plant.
- High fault currents present severe flash and shock hazards.
- High fault currents can lead to interference in communication circuits in around the vicinity of power cables and overhead power lines.

5.2.2 Resistance / Reactance Earthing – NER's & NEX's

The main benefits include:

- Low magnitude of phase to earth fault currents hence reducing the risk of severe flash hazards.
- Less likelihood of equipment damage as earth fault current is greatly reduced.
- Safer for work personnel and general public in-terms of reduction in step and touch potential.

The main challenges include:

- High values of transient over-voltages during faults. This needs to be considered carefully in design stages, the rating of surge arrestors and short-time thermal current ratings of underground cable screens and earthing conductors.
- High capital and maintenance cost as equipment needs to be installed between the transformer neutral and substation earth which also needs to be maintained for the life of the equipment. Also high cost of retrofitting on the networks that are not designed to handle the overvoltages.

5.3 Results of Analysis

The following table 10 shows earth fault current and phase voltage values for a simulation of A-phase to ground fault at WOSO 11kV bus with different earthing systems.

Earthing Type	*Fault Current (A)*			*Phase Voltages (kV)*		
	A-Phase	*B-Phase*	*C-Phase*	*A-Phase*	*B-Phase*	*C-Phase*
Solidly	3212	0.000	0.000	0.000	7.0315	6.3933
6ohm NEX	857	0.000	0.000	0.000	10.631	10.2431
3ohm NER	1752	0.000	0.000	0.000	8.2352	11.7171

Table 10: Earth Fault Analysis at WOSO 11kV Bus

Figure 21 below shows the difference in fault current values for A-phase to ground fault simulation on WOSO-01 11kV feeder with different earthing system. This was simulated to look at the difference in fault current values with different earthing systems.

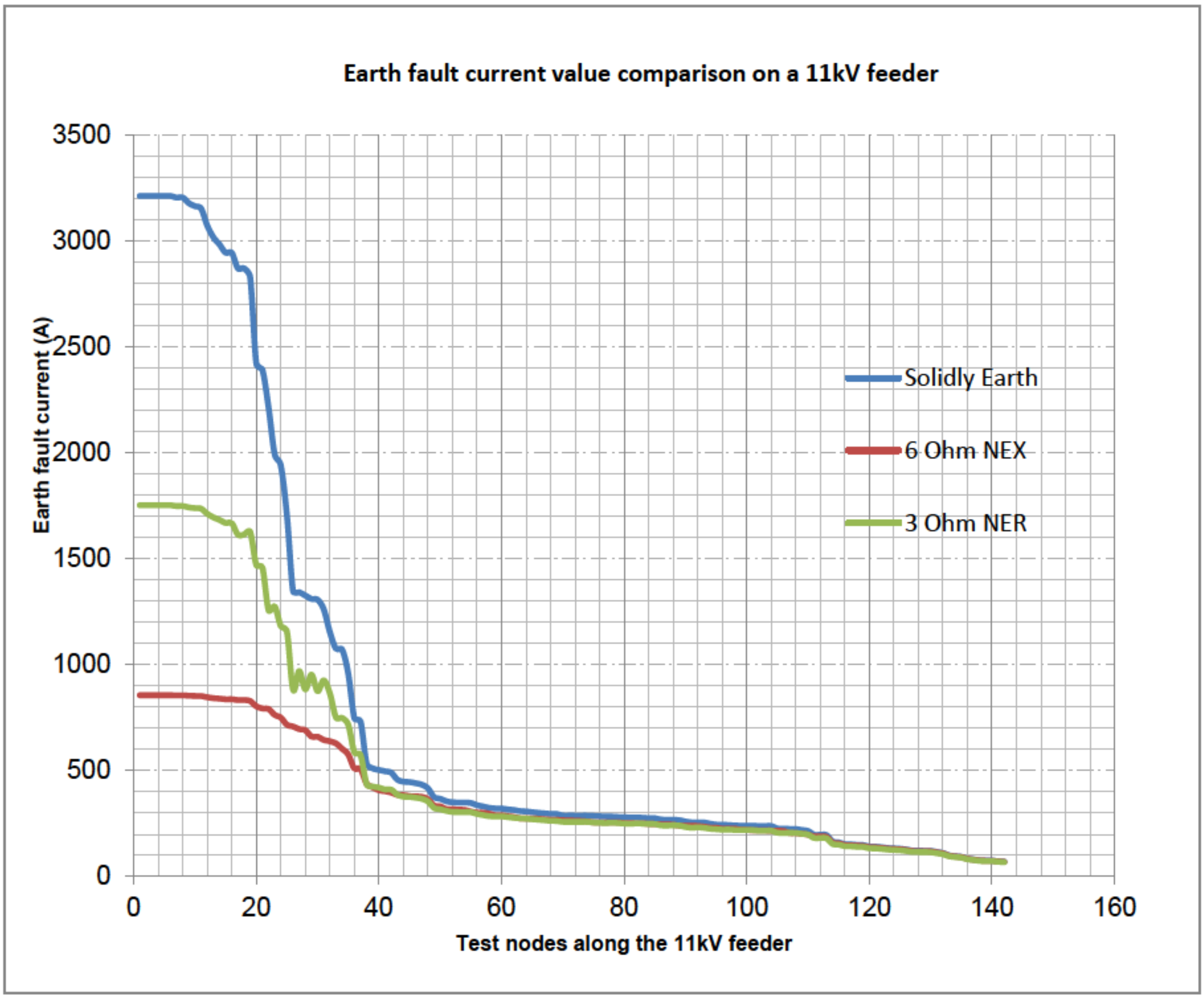


Figure 21: Current Values for Earthing System Analysis on WOSO-01

Figure 22 below shows the difference in voltage values for A-phase to ground fault simulation on WOSO-01 11kV feeder with different earthing system. The voltages on faulted and unfaulted phase were looked at to understand the effects of earth fault currents on system voltages.

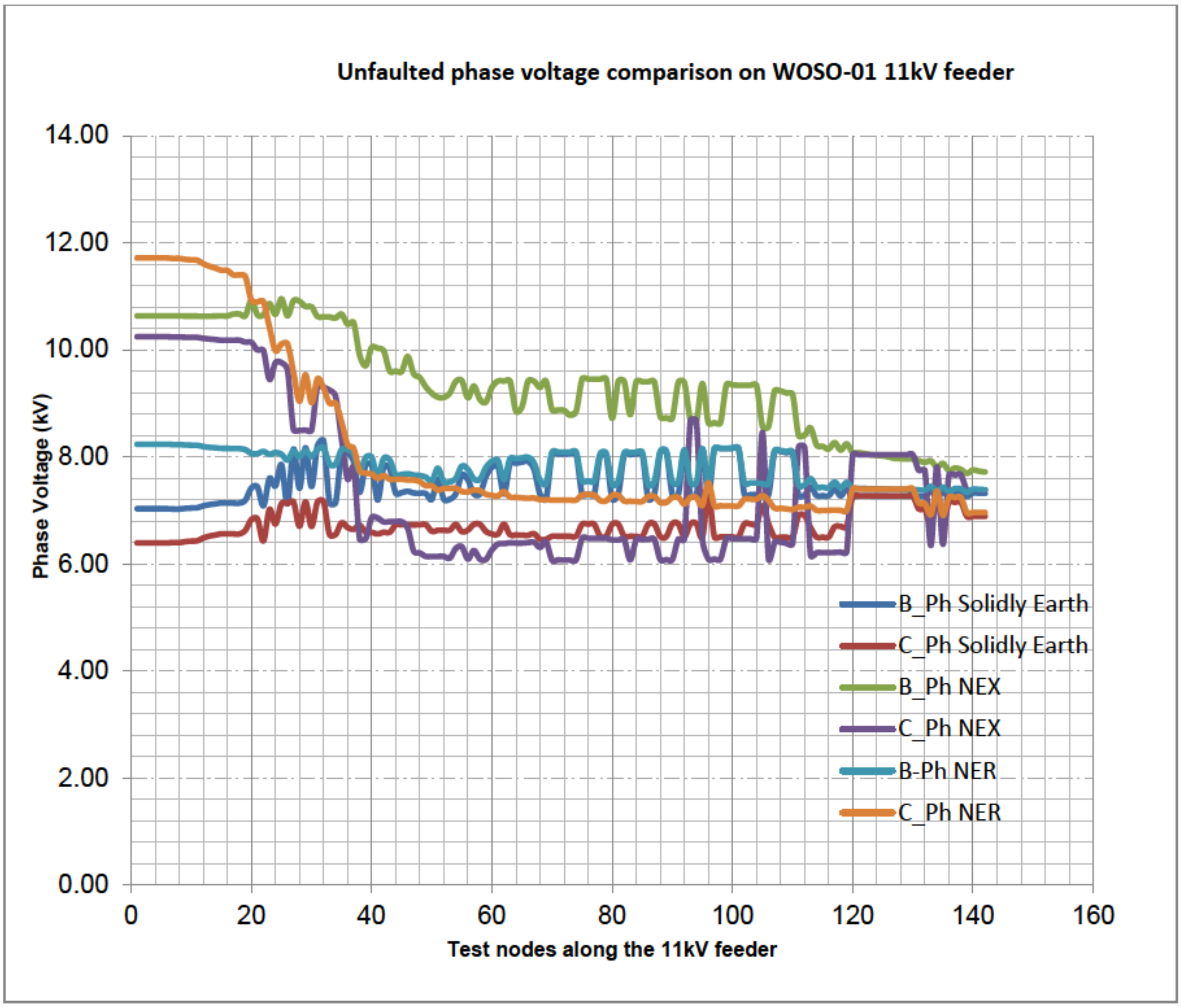


Figure 22: Voltage Values for Earthing System Analysis on WOSO-01

From the above results and analysis it can be seen that highest value of fault current (3212A) is obtained from a solidly earth system. The fault current drops accordingly to the value of resistance or reactance earth system. Phase to phase voltage is high on a resistance or reactance earth system as seen from the results / analysis above as compared to a solidly earth system. The increase in steady state and transient overvoltage caused by impedance earth during an earth fault on the sound phase can result in the fault spreading to other phases. The components and hardware used in the system has to be adequately rated to withstand these transient over-voltages to prevent continuous equipment damages during a fault scenario in other parts of the network. The full extract of results is as tabulated in Appendix E.

5.4 Earth fault protection used by other Australian utilities

As part of the research, few distribution power utilities were contacted to find out about their approach to earth fault protection and if they are introducing new techniques, technologies or schemes that can be beneficial to Energy Queensland's distribution power network.

5.4.1 SA Power Networks

SA Power Networks is the sole electricity distributor in South Australia, delivering electricity from high voltage transmission network connection points, through a network of powerlines to residential and business customers. The distribution power network is very similar to Energy Queensland's network with very long radial feeders. SA Power Networks faces similar issue in detecting low values of earth fault. Currently they have been employing the following around earthing systems and earth fault detection:

- Apart from CBD, all other distribution power system is solidly earth.
- Installed few fault current limiters but due to excessive maintenance issues had to stop installing them.
- Issues of increasing fault levels in the CBD due to embedded generation and hence have started to install NER's in zone substations to restrict earth fault levels.
- Encounter issues in detecting low values of earth fault on long distribution feeders and hence only utilising SEF protection. SEF is generally set to 5A, 5sec and was introduced in 1980's to improve safety. Longest SEF time that is acceptable is under 5sec. Protection grading margin for SEF protection will be allowed but the aim is always to stay under 5sec.
- Have also started introducing SEL751 protection relays as new form of digital protection relays. Challenging part is obtaining low SEF pick up settings due to minimum setting of relay with respect to CT ratio chosen.

SA Power Networks are further interested in exploring high speed clearing device times so that faults can be cleared more quickly to avoid bush fires and catastrophic network damages. Suggestions to manufacturers to develop technology in reclosers so that main trip can be bypassed during bush fire season to a much high speed tripping device.

5.4.2 Western Power

Western Power is a Western Australian State Government owned corporation with the purpose of connecting people with electricity in a way that is safe, reliable and affordable. Their network covers a very large area of 255,064 square kilometres from Kalbarri in the north, to Kalgoorlie in the east and Albany in the south, including the Perth metropolitan area. Unlike all other major urban areas of Australia which are covered by a series of interconnected networks, Western Power's network is isolated and self-contained. With very long radial distribution feeders in the country side, they face similar issue of detecting low values of earth fault. Currently they have been employing the following around earthing systems and earth fault detection:

- Impedance earth in the metro region whilst solidly earth system utilised in country side substations.
- SEF and normal IDMT earth fault protection are utilised to protect feeders against earth faults occurring in the network.

- Earth fault compensation is also used widely in Western Powers network. The idea of earth fault compensation is to cancel earth capacitance by equal inductance, a so called Petersen coil connected to the neutral, which results in a corresponding decrease in earth fault currents as shown in figure 23. Instead of one large controlled coil at the HV/MV substation, in rural networks it is possible to place inexpensive small compensation equipment, each comprising a star-point transformer and arc-suppression coil.

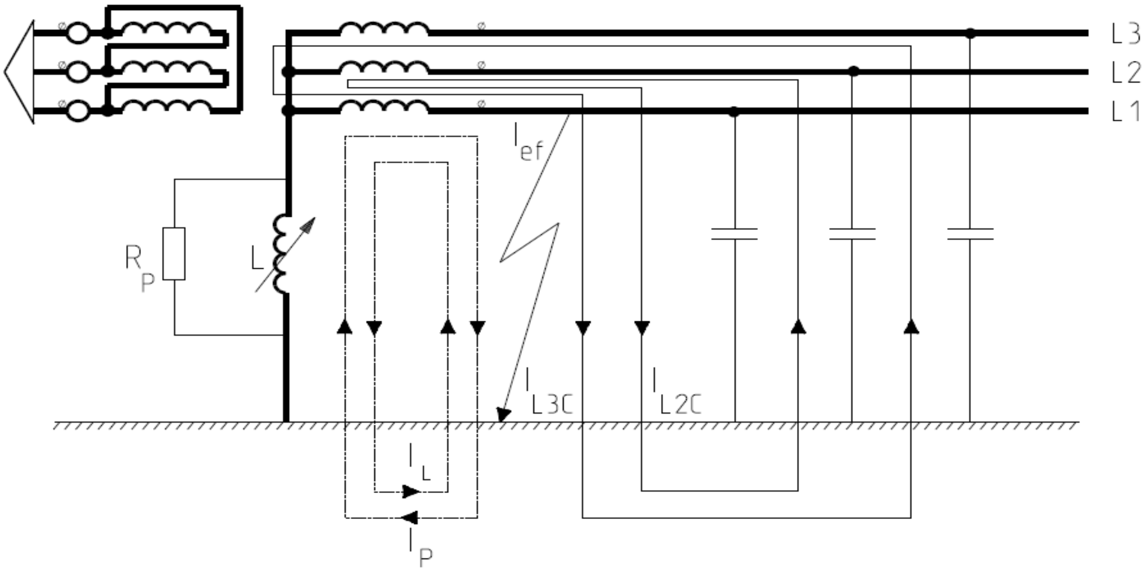


Figure 23: Earth fault in a network with a compensated neutral

In figure 23, the circuit is a parallel resonance circuit and if exactly tuned, the fault current has only a resistive component. This is due to the resistances of the coil and distribution lines together with the system leakage resistances (R_{LE}). Often the earthing equipment is complemented with a parallel resistor R_p, the task of which is to increase the ground fault current in order to make selective relay protection possible. $I_t = I_L - I_P$ is the current of the suppression coil and a parallel resistor, I_{L2c} and I_{L3c} are the capacitive currents of the sound phases, and $I_{ef} = I_{L2c} + I_{L3c} - I_t$ is the earth fault current at the fault point.

Figure 24 below represents the equivalent circuit for earth fault compensated network.

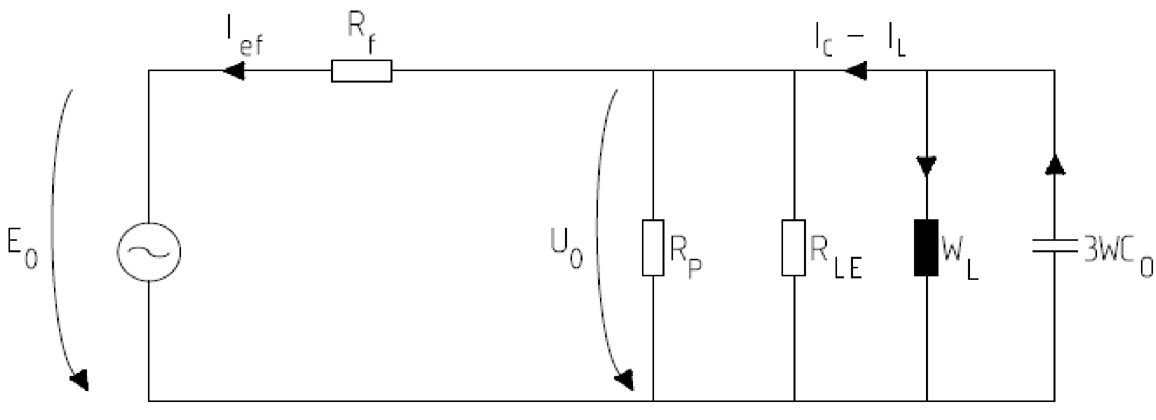


Figure 24: Equivalent circuits for the earth fault compensated network

5.4.3 Endeavour Energy

Endeavour Energy is responsible for the safe and reliable supply of electricity to 2.4 million people in households and businesses across Sydney's Greater West, the Blue Mountains, Southern Highlands, the Illawarra and the South Coast. It is 50.4 percent owned by an Australian-led consortium of long-term investors in the private sector and the remaining 49.6 percent is held by the State of NSW. The network topology consists of a mixture of overhead lines and underground cables with radial and interconnected network. They face similar issue of detecting low values of earth fault. Currently they have been employing the following around earthing systems and earth fault detection:

- All 11kV networks are solidly earth.
- 22kV network utilise NER to restrict earth fault current to around 1000A.
- Normal earth fault IDMT protection is mostly utilised together with SEF protection. SEF is set to a minimum of 4A, 5sec and if protection grading is required for discrimination purposes with upstream protective device, then 1sec grading is only allowed between devices while current is always maintained to a value of 4A.
- Core-balance CT's are utilised in high risk bush fire areas. It is a single CT of ring type, through the centre of which is passed cable that forms the primary winding. An earth fault relay, connected to the secondary winding, is energised only when there is residual current in the primary system. The advantage in using this method of earth fault protection lies in the fact that only one CT core is used in place of three phase CTs whose secondary windings are residually connected. In this way the CT magnetising current at relay operation is reduced by approximately three-to-one, an important consideration in SEF relays where a low effective setting is required. The CT's utilised are very accurate at low levels of fault current which can see down to 0.1Amps of primary current and it is only enabled on total bush fire days and only set to 1Amp pickup.

The correspondence and details obtained from distribution power utilities similar to Energy Queensland, it can be seen that similar issues in the area of earth fault detection is faced by other power utilities as well. Commonly SEF protection has been utilised with varying detection and time delays depending with their practices and philosophies. The utilities are keen in the development of algorithms and devices by manufacturers that can play a vital role in earth fault detection. Some of the utilities are coming up with their own invention and techniques which can assist in achieving better detection capabilities.

Chapter 6 Earth Fault Analysis Results

6.1 Chapter Overview

This chapter focuses on discussing the results of earth fault analysis which was carried out on 11kV feeders out of WOSO substation, looking into fault clearing times of protective devices and also analysis of an actual phase to ground fault with low values of fault current.

6.2 Earth fault analysis discussion

A – Phase to ground fault was simulated on all three 11kV feeders out of WOSO substation. There were two scenarios of source impedance considered:

- Maximum source impedance with system normal
- Minimum source impedance with 66kV Stuart feeder out of service

The following simulations were performed on the feeders:

- Solidly earth system with maximum and minimum source impedance
- Solidly earth system with maximum and minimum source impedance plus fault resistance
- NEX earth system with maximum and minimum source impedance
- NEX earth system with maximum and minimum source impedance plus fault resistance

From the results of earth fault analysis, it can be seen that the highest value of current is obtained from a solidly earth system and is highest at the source substation. Due to the comparatively high reactance of overhead lines, the attenuation of fault power along the line is high and the current values resulting from faults at points remote from the substation are considerably reduced as seen in figure 25 below.

In table 11 below, a comparison of earth fault values for WOSO-01 11kV feeder at the same nodes for the various earthing type simulations are represented. The maximum value of fault current recorded was at the substation busbar so a comparison between the different scenarios was done at that node. The minimum value was recorded at the remote end of the feeder. The same node was considered for comparison of results to accurately see the differences in fault current values for each of the fault scenarios.

Earthing Type	***Fault Current (A)***	
	Maximum	***Minimum***
Solidly + Max Source Impedance	3212	70
Solidly + Min Source Impedance	2014	27
Solidly + Max Source Impedance + 50ohm Rf	139	47
Solidly + Min Source Impedance + 50ohm Rf	124	23
6ohm NEX + Max Source Impedance	856	70
6ohm NEX + Min Source Impedance	704	27
6ohm NEX + Max Source Impedance + 50ohm Rf	137	47
6ohm NEX + Min Source Impedance + 50ohm Rf	122	23

Table 11: Earth Fault Analysis of WOSO-01 11kV Feeder

From the fault current values in table 11, it can be seen that for a solidly earth system and a system with 6ohm NEX, the fault values are significantly high at source while the values are significantly small at the remote end or as the fault moves away from the source along the feeder. Since the driving voltage is high and negligible impedance at the source, it contributes to high values of earth fault current at the source. As the fault moves away from the source the voltage drops and impedance increases along the line hence the fault current drops. Also it can be seen from figure 23 below that regardless of the earthing system and fault impedance, the fault values at the very remote end of the feeder are very much similar. This is due to the fact that since the fault has moved so far away from the source and adding impedance no longer has effect in the fault current. The concerning part however is the small values of fault current at remote ends or along the feeder, if more fault resistance is added which effectively refers to high impedance faults, these values will drop more and will become challenging for protective devices to detect.

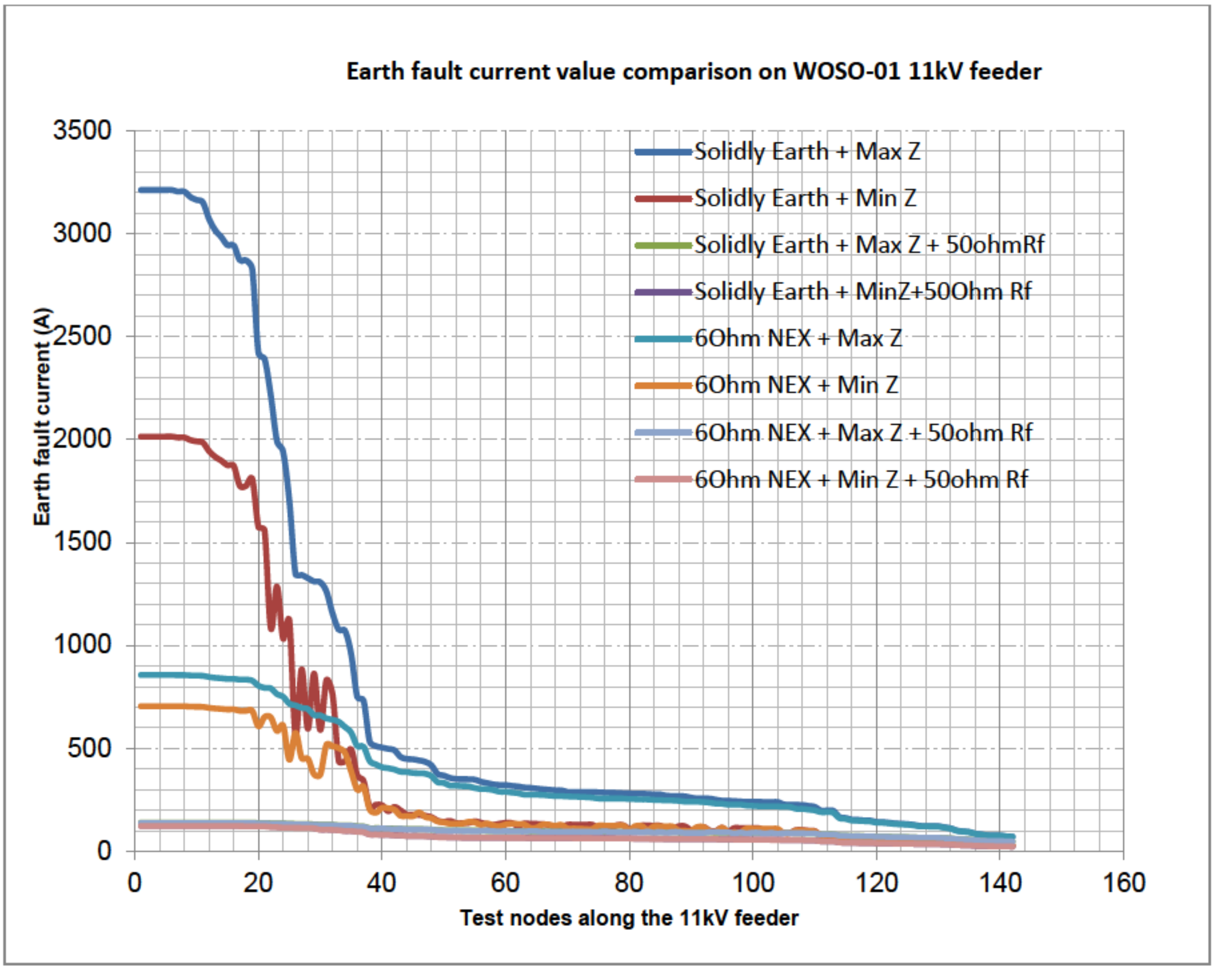


Figure 25: Earth fault current value comparison on WOSO-01 11kV feeder

The results of the analysis of various scenarios are represented in graphical format as shown in figures 26 to figures 33.

Figure 26 below represents the result of analysis for a solidly earth system with maximum source impedance and no fault resistance in the network. Maximum source impedance is obtained whereby the system is operating in a system normal status with both 66kV Stuart feeder out of service. The results are for all the three feeders out of Woodstock substation. From the results it can be seen that maximum value of earth fault current (3212A) for each of the three feeders is at the substation. The minimum value of fault current differs in each of the feeders due to the length and construction of the feeder. The minimum value of fault current recorded for WOSO-01 11kV feeder was 70A in comparison to WOSO-02 feeder which was 131A and WOSO-03 feeder was 55A.

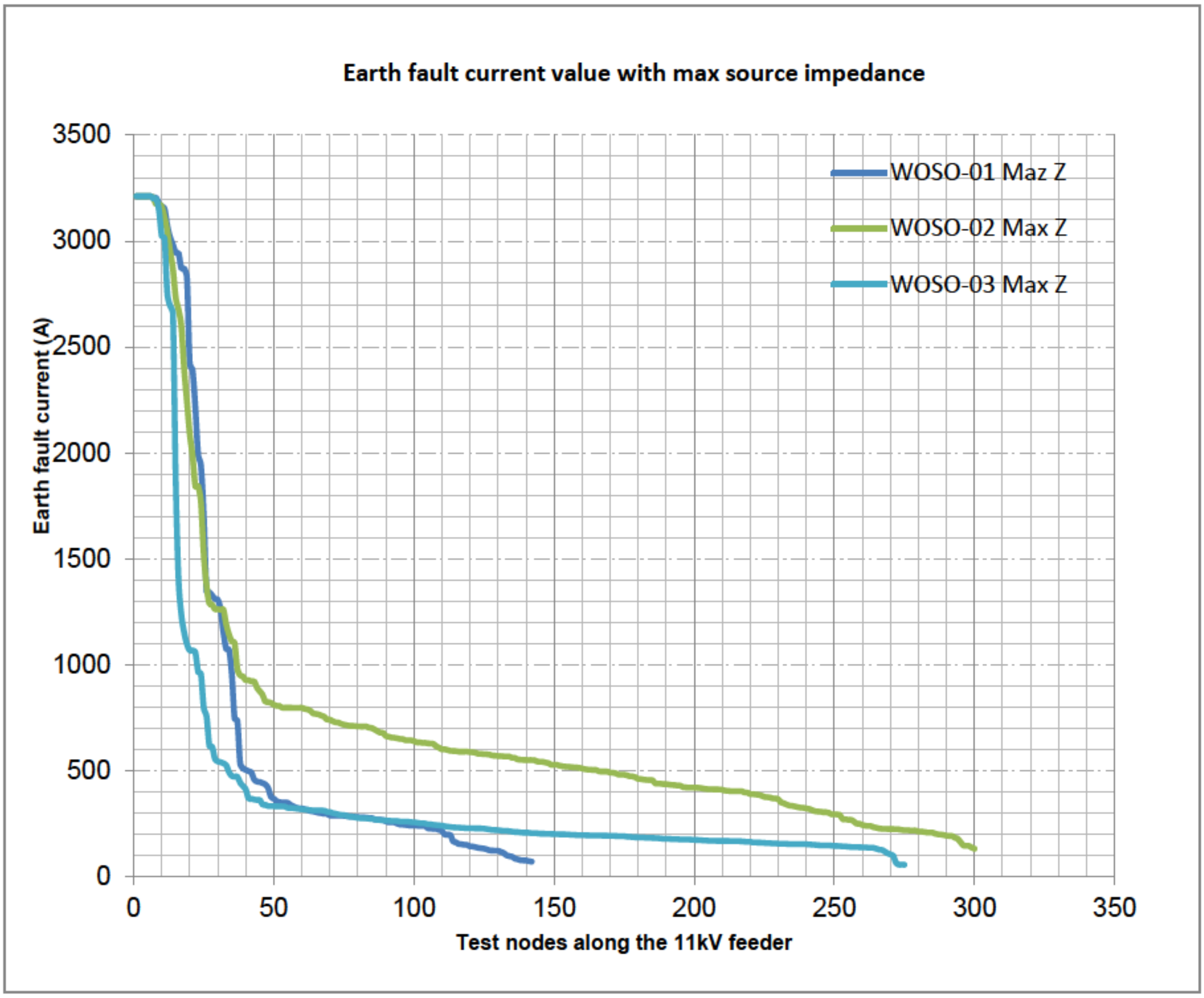


Figure 26: Solidly earth with max source impedance and no fault resistance

Figure 27 below represents the result of analysis for a solidly earth system with minimum source impedance and no fault resistance in the network. Minimum source impedance is obtained whereby the system is operating in an abnormal status with 66kV Stuart feeder out of service. From the results it can be seen that maximum value of earth fault current was 2014A for each of the three feeders at the substation in comparison to the previous scenario which had fault current of 3212A at the same node. The minimum value of fault current recorded for WOSO-01 11kV feeder in this case was 27A in comparison to WOSO-02 feeder which was 56A and WOSO-03 feeder was 23A. It was also noted that WOSO-02 feeder had quite a bit of variation in magnitude of earth fault current.

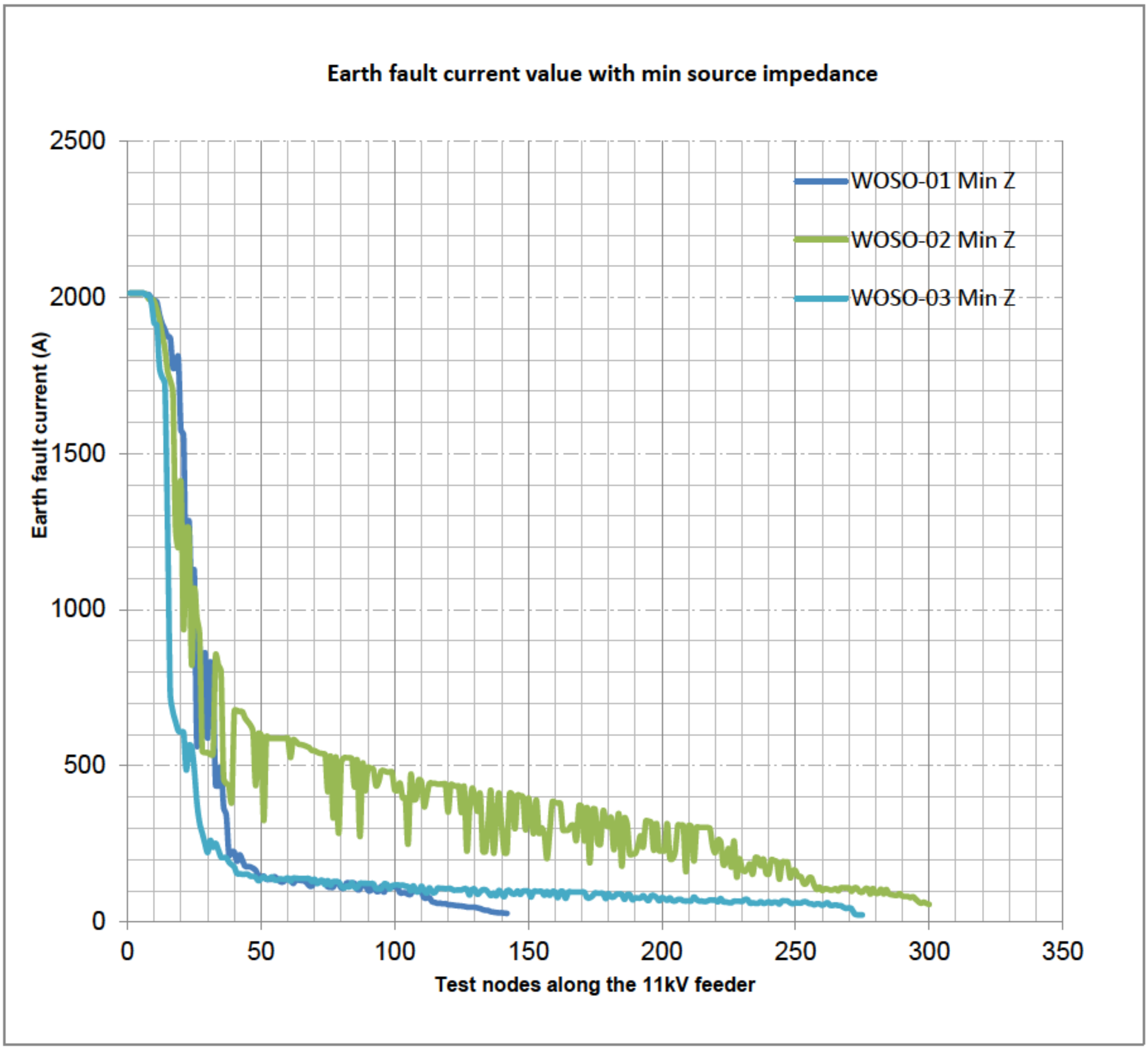


Figure 27: Solidly earth with min source impedance and no fault resistance

Figure 28 below represents the result of analysis for a solidly earth system with maximum source impedance and 50Ω fault resistance in the network. A value of 50Ω fault resistance was introduced in the circuit to see how the earth fault current value varied. From the results it can be seen that maximum value of earth fault current drops quite significantly to only 139A for each of the three feeders at the substation in comparison to figure 26 where the fault current at the same node was 3212A. The minimum value of fault current recorded for WOSO-01 11kV feeder was 47A in comparison to WOSO-02 feeder which was 69A and WOSO-03 feeder was 40A. When comparing these minimum values of earth fault current to figure 26, it can be noted that there was a reduction of around 30% in earth fault current when fault resistance was introduced in the analysis.

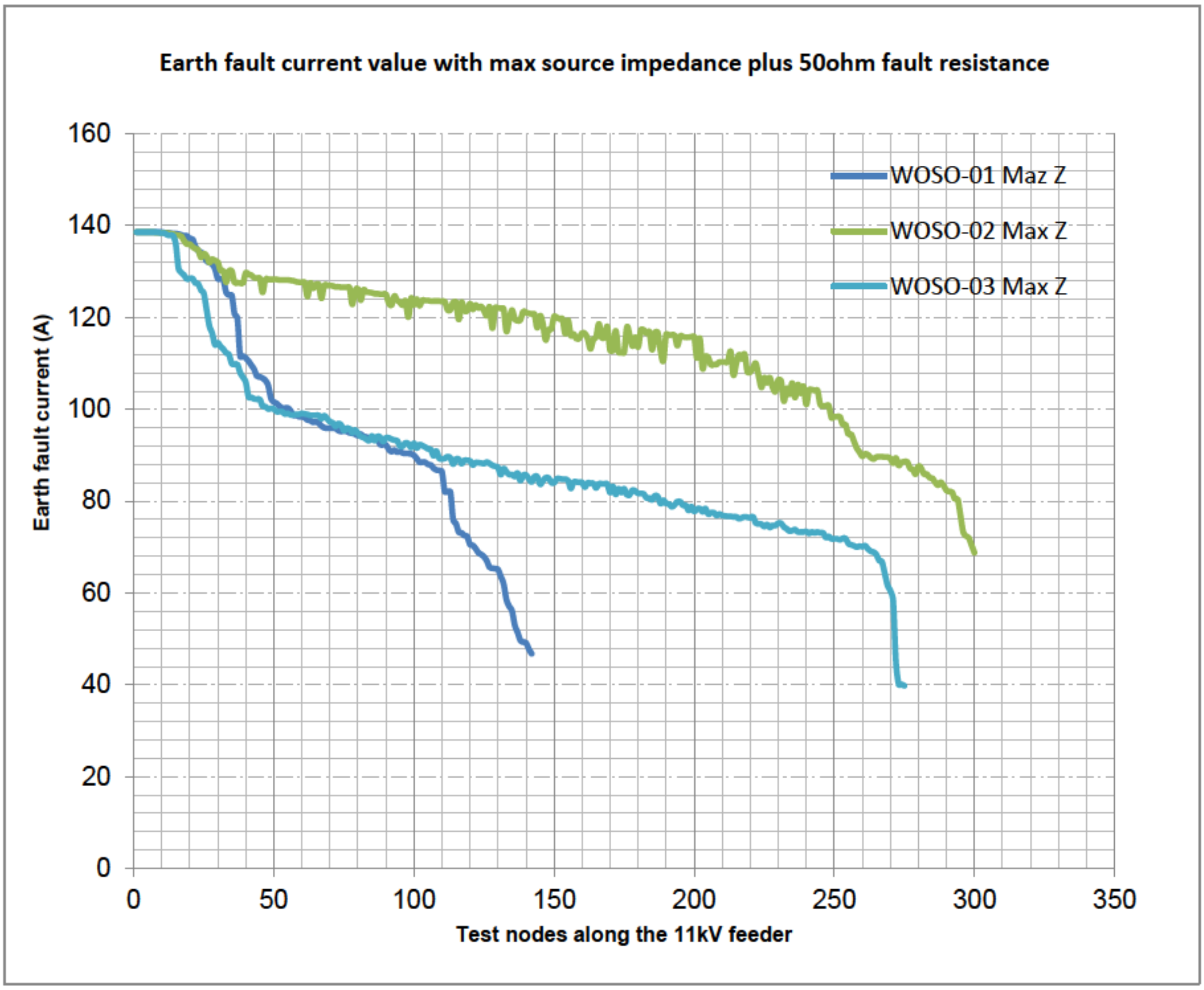


Figure 28: Solidly earth with max source impedance plus 50ohm fault resistance

Figure 29 below represents the result of analysis for a solidly earth system with minimum source impedance and 50Ω fault resistance in the network. From the results it can be seen that maximum value of earth fault current drops quite significantly to only 124A for each of the three feeders at the substation in comparison to figure 27 where the fault current at the same node was 2014A. The minimum value of fault current recorded for WOSO-01 11kV feeder was 23A in comparison to WOSO-02 feeder which was 39A and WOSO-03 feeder was 19A. When comparing these minimum values of earth fault current to figure 27, it can be noted that there was a only a small reduction of few Amps in earth fault current when fault resistance was introduced in the analysis.

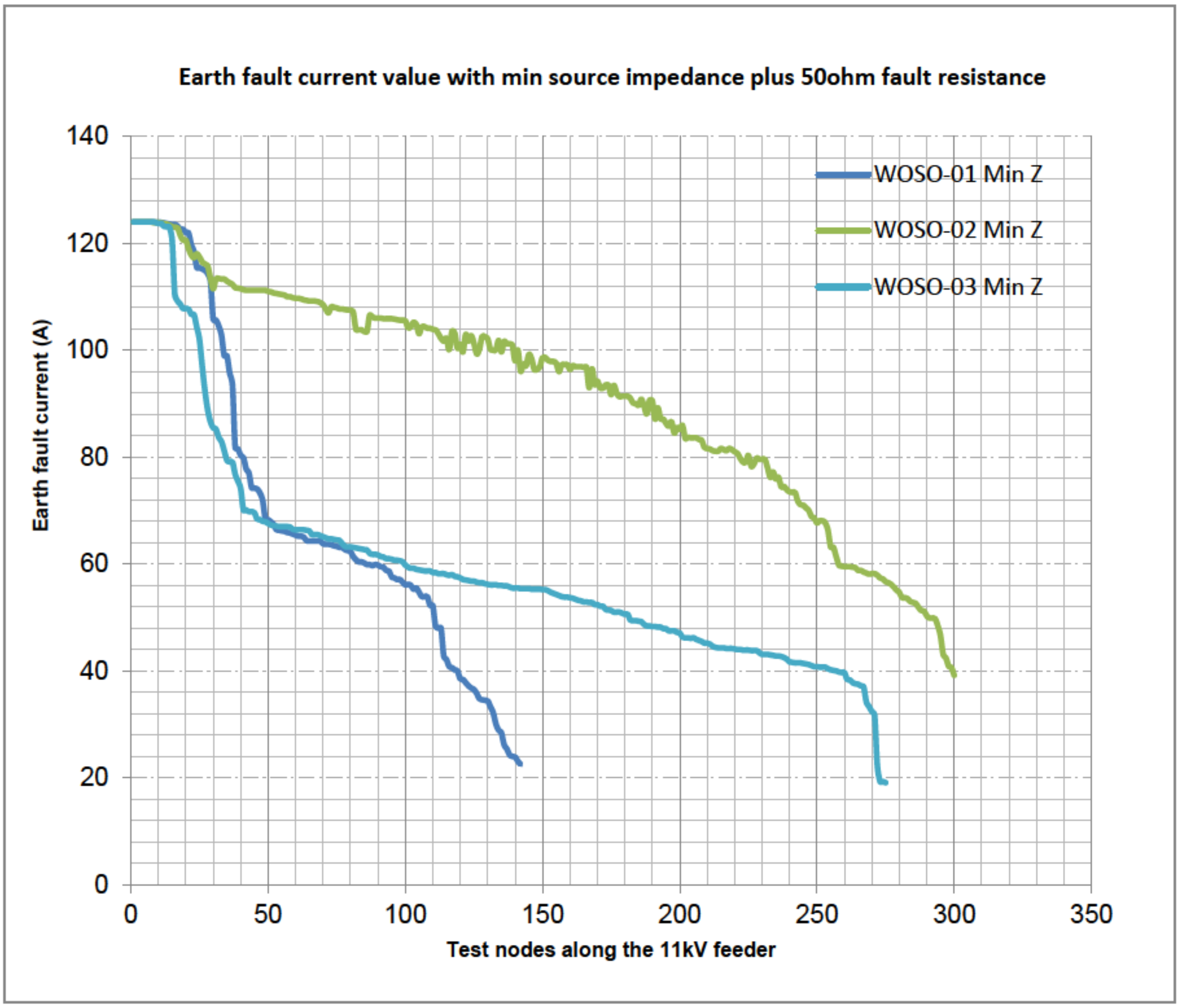


Figure 29: Solidly earth with min source impedance plus 50ohm fault resistance

Figure 30 below represents the result of analysis for an impedance earth system with maximum source impedance and no fault resistance in the network. A 6Ω Neutral Earthing Reactor (NEX) was added in the simulation to compare the earth fault current values with a solidly earth system. From the results it can be seen that maximum value of 855A earth fault current for each of the three feeders is at the substation in comparison to solidly earth system which had a value of 3212A at the same node. The minimum value of fault current recorded for WOSO-01 11kV feeder was 70A in comparison to WOSO-02 feeder which was 125A and WOSO-03 feeder was 55A. It was noted there was no change in minimum earth fault values between impedance earth system and solidly grounded system. It was also noted that WOSO-02 feeder had quite a bit of variation in magnitude of earth fault current.

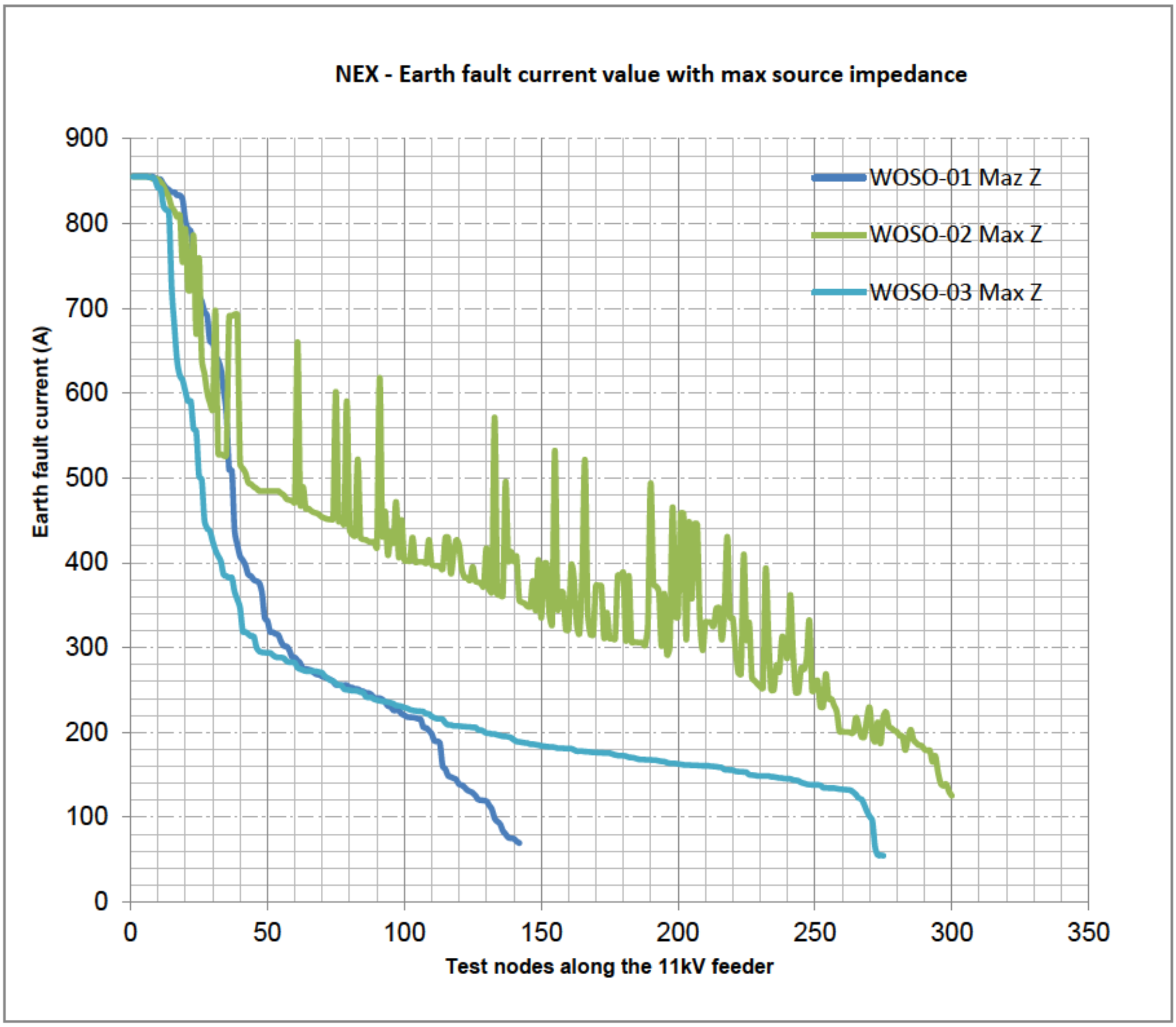


Figure 30: NEX earthing with max source impedance and no fault resistance

Figure 31 below represents the result of analysis for impedance (NEX) earth system with minimum source impedance and no fault resistance in the network. From the results it can be seen that maximum value of earth fault current was 704A for each of the three feeders at the substation in comparison to figure 30 which had fault current of 855A at the same node. The minimum value of fault current recorded for WOSO-01 11kV feeder in this case was 27A in comparison to WOSO-02 feeder which was 56A and WOSO-03 feeder was 23A. It was again noted there was no change in minimum earth fault values between impedance earth system and solidly grounded system even though there was a difference in source impedance.

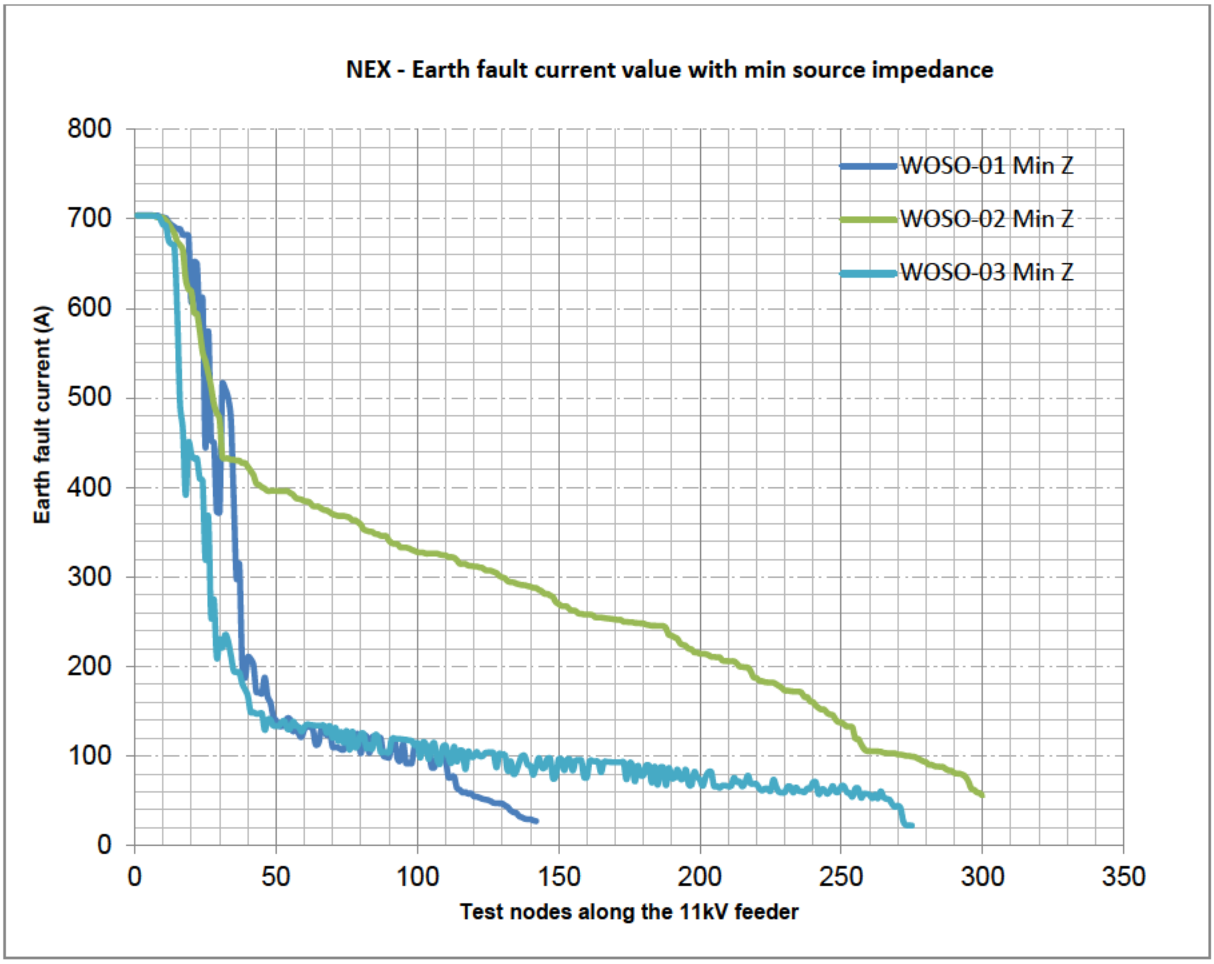


Figure 31: NEX earthing with min source impedance and no fault resistance

Figure 32 below represents the result of analysis for impedance earth system with maximum source impedance and 50Ω fault resistance in the network. From the results it can be seen that maximum value of earth fault current drops quite significantly to only 137A for each of the three feeders at the substation in comparison to figure 30 where the fault current at the same node was 855A. The minimum value of fault current recorded for WOSO-01 11kV feeder was 47A in comparison to WOSO-02 feeder which was 68A and WOSO-03 feeder was 40A. When comparing these minimum values of earth fault current to figure 30, it can be noted that there was a reduction of around 30% in earth fault current when fault resistance was introduced in the analysis.

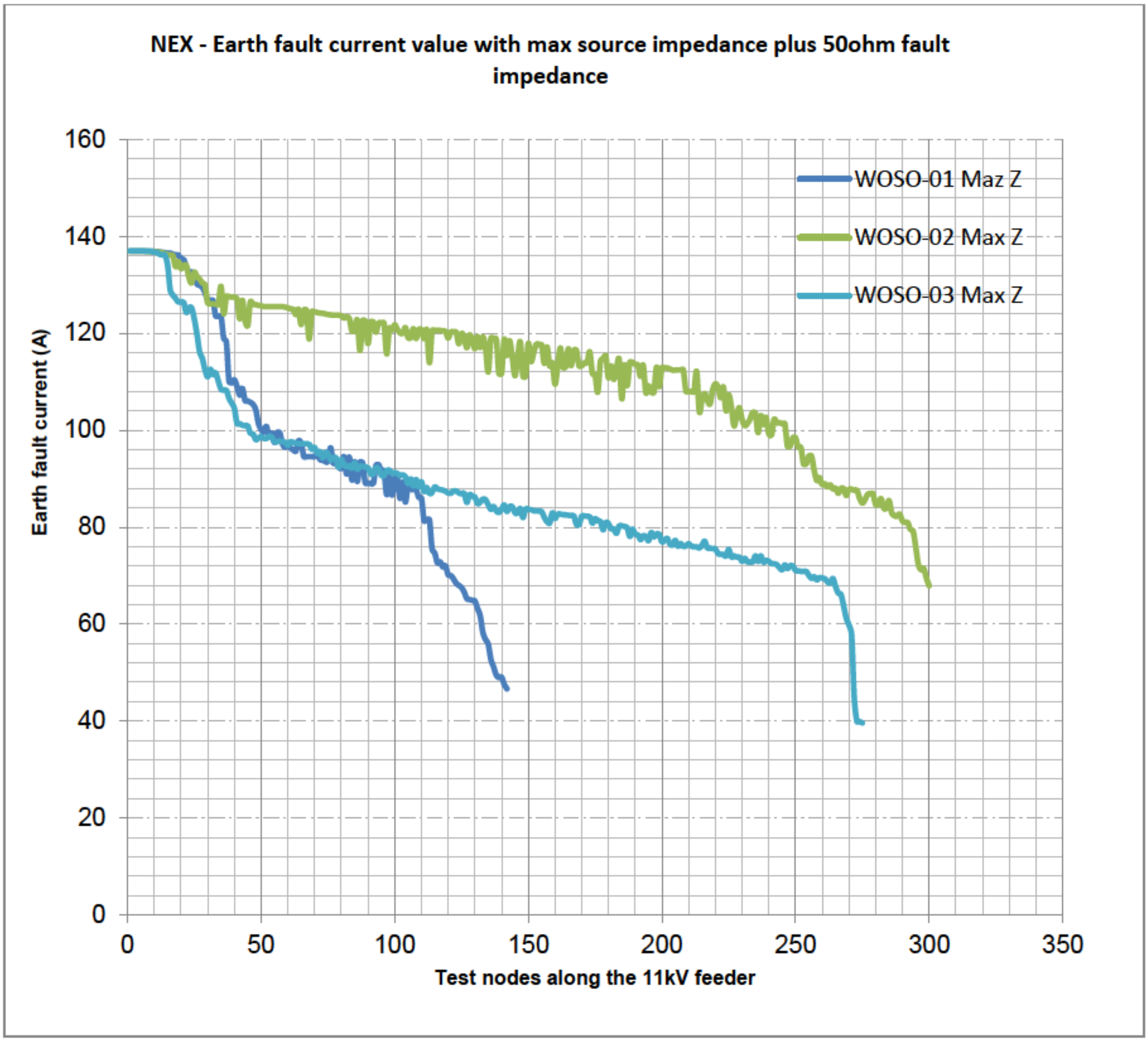


Figure 32: NEX earthing with max source impedance plus 50ohm fault resistance

Figure 33 below represents the result of analysis for impedance earth system with minimum source impedance and 50Ω fault resistance in the network. From the results it can be seen that maximum value of earth fault current drops quite significantly to only 122A for each of the three feeders at the substation in comparison to figure 31 where the fault current at the same node was 704A. The minimum value of fault current recorded for WOSO-01 11kV feeder was 23A in comparison to WOSO-02 feeder which was 39A and WOSO-03 feeder was 19A. When comparing these minimum values of earth fault current to figure 31, it can be noted that there was a only a small reduction of few Amps in earth fault current when fault resistance was introduced in the analysis.

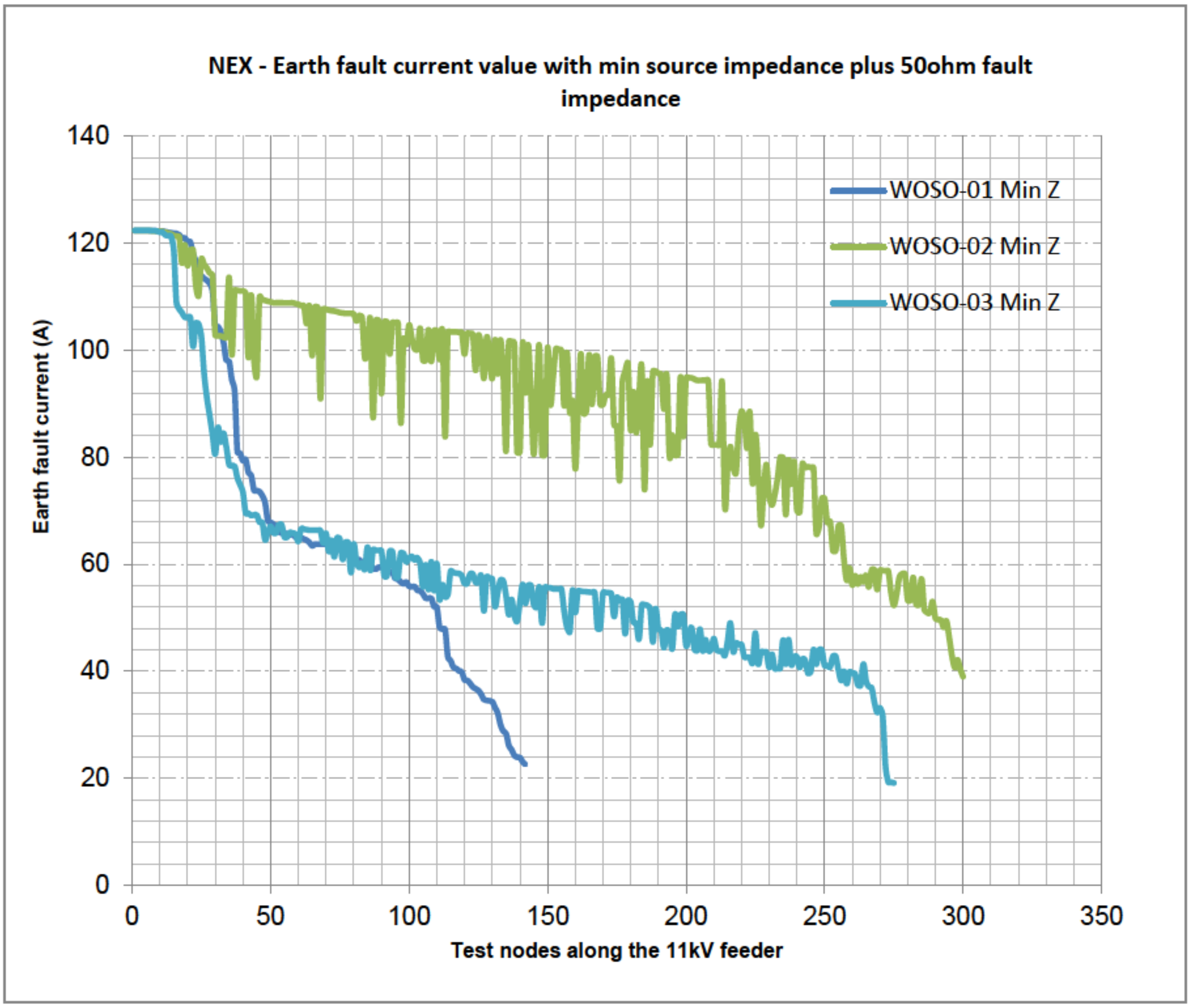


Figure 33: NEX earthing with min source impedance plus 50ohm fault resistance

6.3 Fault detection times

For each of the 11kV feeders out of WOSO-01 substation an analysis was then carried out to check the fault detection times by primary protection device for minimum faults. The minimum faults did not include those spurs which were protected by master drop out fuse. The fault clearing time will then be represented by:

$$I_{f(t)} = Fault\ Detection + Relay\ Operation + CB\ Operating(times)$$

6.3.1 WOSO-01

The primary protection device for faults along WOSO-01 feeder is a digital protection relay at WOSO substation. The following table 12 highlights the fault detection times by the protection relay for fault current at site TVS2455 in each of the simulated scenarios. The site TVS2455 had the minimum value of fault current which needs to be detected by the protection relay at the substation.

Simulated Scenarios	*Fault Level (A)*	*Detection Time(s)*
Solidly Earth + Max Source Impedance	215	1.08
Solidly Earth + Min Source Impedance	98	3.34
Solidly Earth + Max Source Impedance + 50ohm Rf	86	4.25
Solidly Earth + Min Source Impedance + 50ohm Rf	56	13.36
6ohm NEX + Max Source Impedance	198	1.20
6ohm NEX + Min Source Impedance	95	3.53
6ohm NEX + Max Source Impedance + 50ohm Rf	85	4.25
6ohm NEX + Min Source Impedance + 50ohm Rf	55	13.36
3ohm NER + Max Source Impedance	198	1.20
3ohm NER + Min Source Impedance	93	3.53
3ohm NER + Max Source Impedance + 50ohm Rf	83	4.25
3ohm NER + Min Source Impedance + 50ohm Rf	54	13.36

Table 12: WOSO-01 Fault Detection Times for Minimum Fault

6.3.2 WOSO-02

WOSO-02 feeder has a downstream Pole Mounted Recloser (PMR), therefore the PMR provides primary protection for faults beyond this PMR. The protection relay at WOSO substation provides primary protection for faults between the substation and the PMR. The following table 13 highlights the fault detection times by the protection relay for minimum fault current at site TVS37 in each of the simulated scenarios.

Simulated Scenarios	*Fault Level (A)*	*Detection Time(s)*
Solidly Earth + Max Source Impedance	592	0.67
Solidly Earth + Min Source Impedance	444	0.92
Solidly Earth + Max Source Impedance + 50ohm Rf	124	4.49
Solidly Earth + Min Source Impedance + 50ohm Rf	106	5.76
6ohm NEX + Max Source Impedance	402	1.02
6ohm NEX + Min Source Impedance	327	1.29
6ohm NEX + Max Source Impedance + 50ohm Rf	121	4.67
6ohm NEX + Min Source Impedance + 50ohm Rf	104	5.94

Table 13: WOSO-02 P142 Fault Detection Times for Minimum Fault

The following table 14 highlights the fault detection times by the Noja RC10 PMR for minimum fault current at site TVS3700 in each of the simulated scenarios. The site TVS3700 had the minimum value of fault current which needs to be detected by the PMR.

Simulated Scenarios	***Fault Level (A)***	***Detection Time(s)***
Solidly Earth + Max Source Impedance	183	0.22
Solidly Earth + Min Source Impedance	78	1.39
Solidly Earth + Max Source Impedance + 50ohm Rf	80	1.30
Solidly Earth + Min Source Impedance + 50ohm Rf	49	4.79
6ohm NEX + Max Source Impedance	172	0.25
6ohm NEX + Min Source Impedance	77	1.43
6ohm NEX + Max Source Impedance + 50ohm Rf	80	1.31
6ohm NEX + Min Source Impedance + 50ohm Rf	48	5.12

Table 14: WOSO-02 Noja RC10 Fault Detection Times for Minimum Fault

6.3.2 WOSO-03

WOSO-03 feeder also has a downstream PMR, therefore the PMR provides primary protection for faults beyond this PMR. The digital protection relay at WOSO substation provides primary protection for faults between the substation and the PMR. The following table 15 highlights the fault detection times by the protection relay for minimum fault current at site TVS2346 in each of the simulated scenarios.

Simulated Scenarios	***Fault Level (A)***	***Detection Time(s)***
Solidly Earth + Max Source Impedance	315	1.14
Solidly Earth + Min Source Impedance	140	3.18
Solidly Earth + Max Source Impedance + 50ohm Rf	99	5.47
Solidly Earth + Min Source Impedance + 50ohm Rf	67	12.47
6ohm NEX + Max Source Impedance	275	1.34
6ohm NEX + Min Source Impedance	135	3.35
6ohm NEX + Max Source Impedance + 50ohm Rf	98	5.57
6ohm NEX + Min Source Impedance + 50ohm Rf	67	12.47

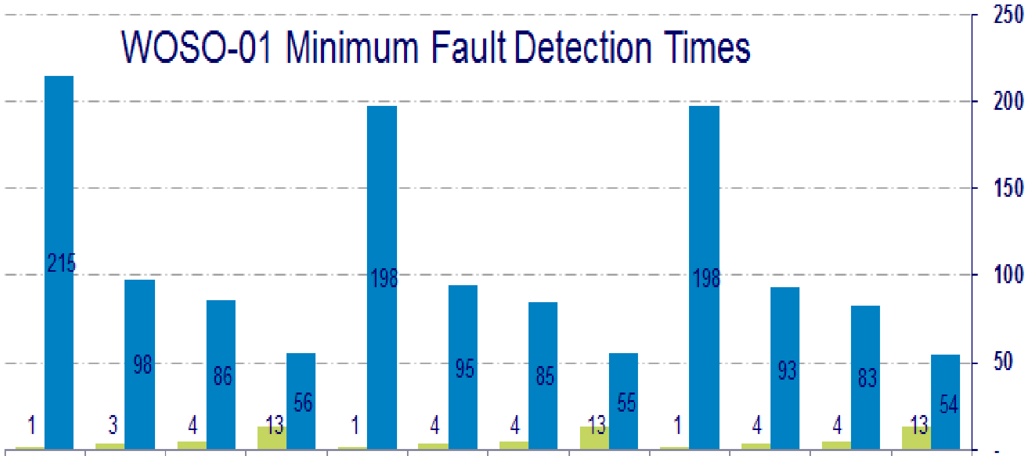
Table 15: WOSO-03 P142 Fault Detection Times for Minimum Fault

The following table 16 highlights the fault detection times by the Noja RC10 PMR for minimum fault current at site TVS73 in each of the simulated scenarios.

Simulated Scenarios	***Fault Level (A)***	***Detection Time(s)***
Solidly Earth + Max Source Impedance	136	2.04
Solidly Earth + Min Source Impedance	61	12.76
Solidly Earth + Max Source Impedance + 50ohm Rf	70	7.0
Solidly Earth + Min Source Impedance + 50ohm Rf	42	42
6ohm NEX + Max Source Impedance	130	2.25
6ohm NEX + Min Source Impedance	60	13.33
6ohm NEX + Max Source Impedance + 50ohm Rf	69	9.32
6ohm NEX + Min Source Impedance + 50ohm Rf	41	46

Table 16: WOSO-03 Noja RC10 Fault Detection Times for Minimum Fault

The observations made from the fault detection times of minimum faults, was a significant delay in detection after fault resistance is introduced in the circuit. As the fault current drops, the detection times increases with respect to the protection settings implemented in the protection relay and corresponding fault current. With SEF protection implemented in all feeders, this will keep pick up to 7A and detection time to a maximum of 7s for lower values of fault current. Figure 34 below represents the detection times of minimum fault level in WOSO-01 feeder in various simulated scenarios. When compared to the other two feeders (WOSO-02 & WOSO-03) the behaviour of fault current and detection times is similar in each of the simulated scenarios.



	Solidly Earth + Max Source Impedance	Solidly Earth + Min Source Impedance	Solidly Earth + Max Source Impedance + 50ohm Rf	Solidly Earth + Min Source Impedance + 50ohm Rf	6ohm NEX + Max Source Impedance	6ohm NEX + Min Source Impedance	6ohm NEX + Max Source Impedance + 50ohm Rf	6ohm NEX + Min Source Impedance + 50ohm Rf	3ohm NER + Max Source Impedance	3ohm NER + Min Source Impedance	3ohm NER + Max Source Impedance + 50ohm Rf	3ohm NER + Min Source Impedance + 50ohm Rf
Detection Time(s)	1	3	4	13	1	4	4	13	1	4	4	13
Fault Level (A)	215	98	86	56	198	95	85	55	198	93	83	54

Figure 34: Graphical representation of WOSO-01 detection times

The protection settings were not adjusted to improve detection times between the scenarios. Existing protection settings were utilised in each of the cases. The detection times can be improved by varying the pick-up current, time multiplier settings and curve selection. This will require checking the sizes of downstream fuses and designing the best possible protection settings for each of the scenarios.

6.4 High impedance earth fault

The following section demonstrates the characteristics of an actual high impedance earth fault and the effects it has on distribution power network. A high impedance earth fault occurred in the field past PMR as represented and shown in figure 35 below. It occurred on 11kV overhead feeder after 11kV pin insulator failed causing 11kV mains to sag down and rest on a fence.

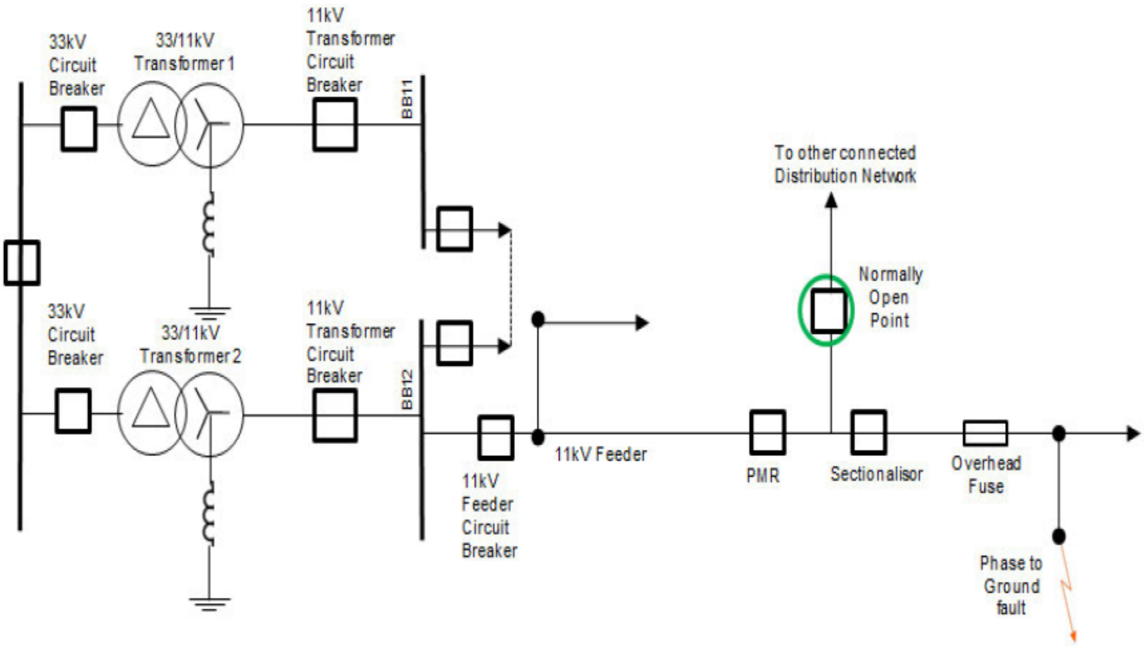


Figure 35: System Normal Configuration

Investigation of the protection devices on the faulted 11kV feeder was undertaken. It was determined that fault current was in the range of 0 – 10A and continuously fluctuated. The SEF protection on PMR would reset within its set fault reset time of 1s whenever the fault current dropped below the SEF pickup threshold of 5A. The feeder protection relay at the substation had fault reset time for the SEF element set at 2s and this was sufficient to allow the relay to operate for this fault (whilst the 1s reset time of the upstream PMR was not sufficient).

Phase to ground fault analysis at the fault location was undertaken in DINIS fault modelling software and the results are depicted in table 17 below:

Scenario	Fault Value
Phase to ground with no fault resistance	215A
Phase to ground fault with 50Ω fault resistance	85A
Phase to ground fault with 1000Ω fault resistance	6A

Table 17: Phase to ground simulation at fault location

Based on the fault analysis at the fault location, the fault resistance would have been in excess of 1000Ω, resulting in a high impedance earth fault which subsequently led to low values of fault current.

The event logs from the PMR are displayed in table 18 below. It can be observed that the SEF element in critical parameters column was picking up correctly but the fault did not persist long enough (more than 5sec) for the element to time out and issue a trip.

Date	Time	Event Title	Start / End	Source of Event	Relevant Phase	Critical Parameters
10-August-2019	9:49:37	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:38	Pickup	End	SEF+	N	Max(In), A=10
10-August-2019	9:49:38	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:39	Pickup	End	SEF+	N	Max(In), A=7
10-August-2019	9:49:40	Reset		SEF+	N	
10-August-2019	9:49:40	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:41	Pickup	End	SEF+	N	Max(In), A=5
10-August-2019	9:49:42	Reset		SEF+	N	
10-August-2019	9:49:42	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:43	Pickup	End	SEF+	N	Max(In), A=8
10-August-2019	9:49:44	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:44	Pickup	End	SEF+	N	Max(In), A=7
10-August-2019	9:49:45	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:46	Pickup	End	SEF+	N	Max(In), A=9
10-August-2019	9:49:47	Reset		SEF+	N	
10-August-2019	9:49:47	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:48	Pickup	End	SEF+	N	Max(In), A=10
10-August-2019	9:49:49	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:49	Pickup	End	SEF+	N	Max(In), A=9
10-August-2019	9:49:49	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:50	Pickup	End	SEF+	N	Max(In), A=10
10-August-2019	9:49:51	Reset		SEF+	N	
10-August-2019	9:49:52	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:52	Pickup	End	SEF+	N	Max(In), A=9
10-August-2019	9:49:52	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:53	Pickup	End	SEF+	N	Max(In), A=10
10-August-2019	9:49:54	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:54	Pickup	End	SEF+	N	Max(In), A=10
10-August-2019	9:49:54	Pickup	Start	SEF+	N	Iop, A=4
10-August-2019	9:49:56	Pickup	End	SEF+	N	Max(In), A=10
10-August-2019	9:49:57	Reset		SEF+	N	
10-August-2019	9:50:12	Reset		AR OC/NPS/EF/SEF		
10-August-2019	10:13:20	Trip		SCADA		
10-August-2019	10:13:20	Oscillography Capture	Start	OSC		Trip

Table 18: PMR Event Log

The waveforms outlined in figures 36 and 37 display the fault recorded by the digital protection relay at the substation. These are two captures of the same fault as the relay recorded twice, as the fault current was fluctuating and the protection relay was resetting. It can be observed from the two captures of the waveforms that the fault current in the earth element only reached a peak of 10A and was continuously fluctuating. It can also be observed from the earth element waveform that the fault current drops below the pickup threshold of the protective devices.

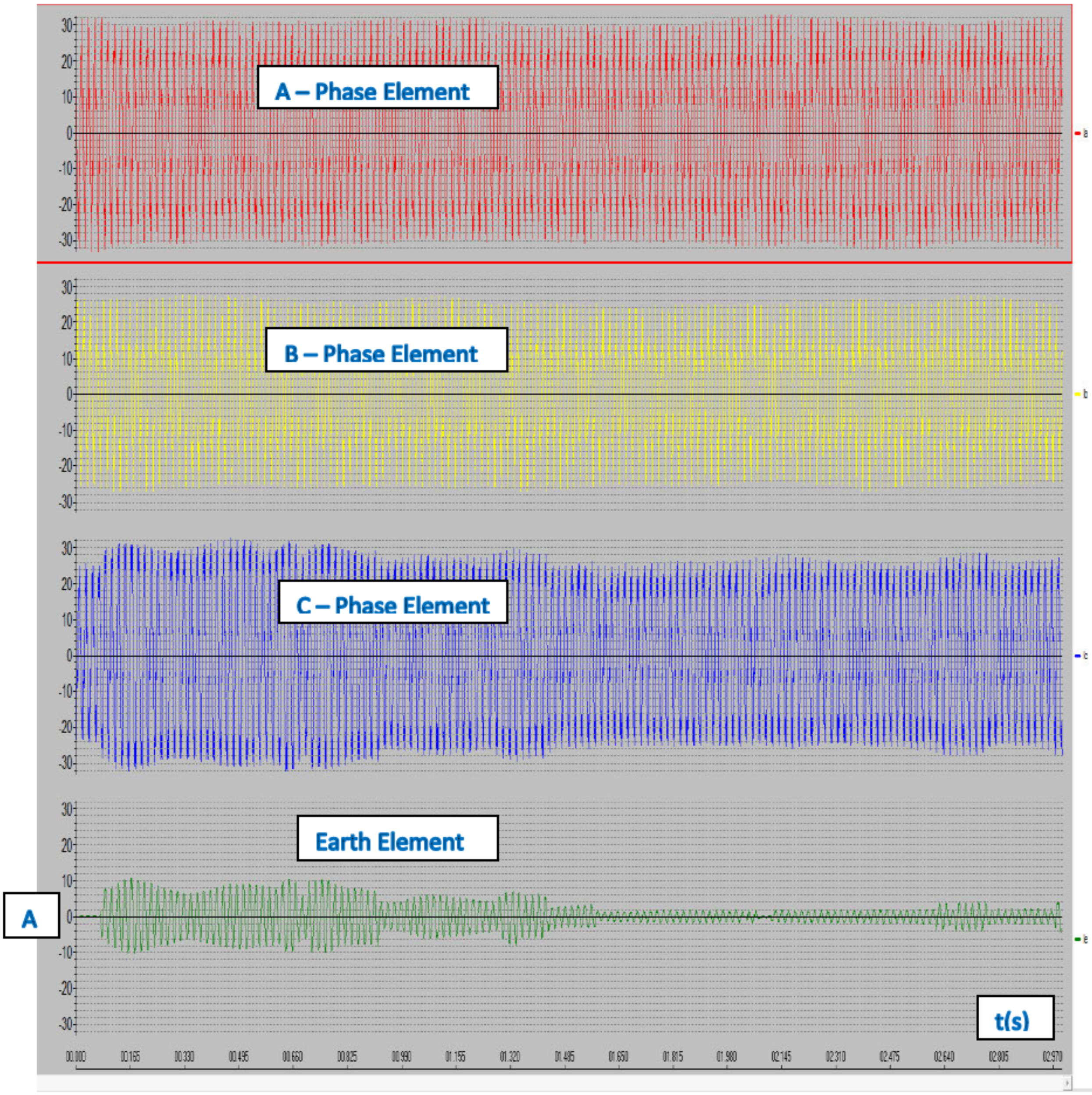


Figure 36: Substation 11kV Circuit Breaker Waveform 1

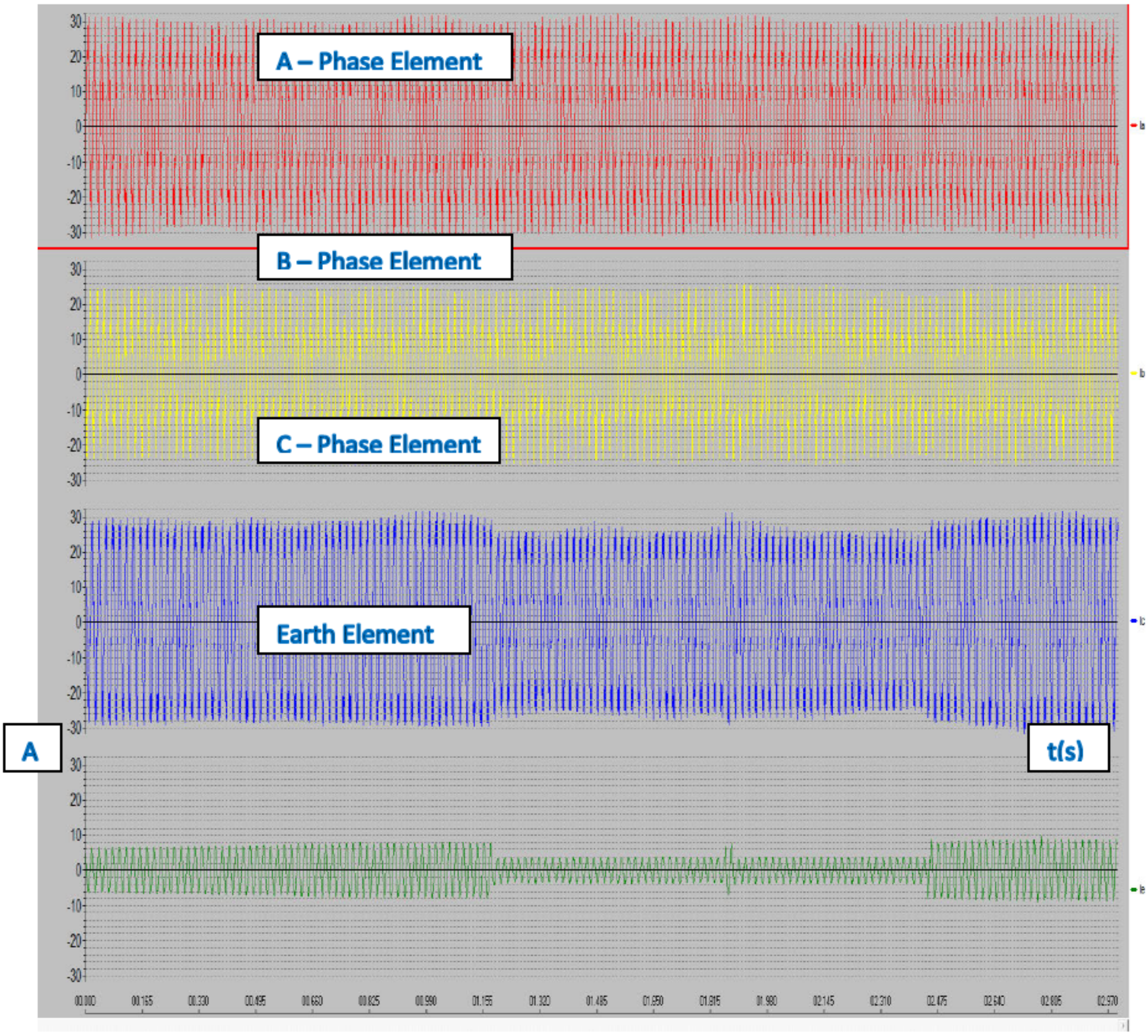


Figure 37: Substation 11kV Circuit Breaker Waveform 2

From this event it can be seen that, high impedance earth faults are bound to happen in the distribution power network. It is not a common fault that occurs in the network always but it can occur and have difficulties in being adequately detected. The fault current generated in this event was enough for Sensitive Earth Fault protection to detect and isolate the fault. In circumstances where the fault resistance is higher (greater than 1000Ω), the fault current would have been lower which would than lead to detection issues by protection relays. This fault scenario highlights the need to have high impedance earth fault detection capable devices to be introduced in the network to improve safety and assist in the detection of all types of earth faults.

Chapter 7 Proposed Earth Fault Detection

7.1 Chapter Overview

This chapter highlights the proposed earth fault detection technology which has been identified as part of this research project.

7.2 Rapid Earth Fault Current Limiter (REFCL)

REFCL's has been identified as a technology that can assist in improving safety and supply reliability in Energy Queensland's distribution power network. Literature suggests that where a bare line comes in contact with the ground or earthed object, (tree branch etc.), to avoid a fire starting the fault current needs to be limited to less than 500mA. Similarly, once a fault is detected, the circuit should not be re-energised to locate the fault with a current higher than 500mA. REFCL's offer the following benefits in comparison to existing protection devices:

- Response time of less than 60ms
- Reduces fault current to less than 500mA
- Detection capabilities of high impedance faults in the order of greater than 25kOhm
- Capabilities to reduce voltage on faulted conductor to 250V within 2s
- Reduced customer outages
- Fault location capabilities

REFCL's provides fast and complete compensation of all remaining earth fault currents – both fundamental and harmonics – by injecting a 180 degree opposite current into the neutral. In comparison to existing protective devices, REFCL's are able to reduce fault current to less than 500mA in under 3 cycles which traditional earth fault protection schemes and protective devices are not able to achieve. It is near impossible to set SEF pickup threshold down to 500mA due to feeder load and unbalanced network configurations. Accuracy of current transformers and protection relay pickup range also plays a key role in trying to achieve a pickup threshold of that low value.

The GFN employs resonant earthing with an additional residual current compensation feature which involves injecting current into an arc suppression coil at 180° out of phase with the residual fault current. The fundamental principle of resonant earthing is that in the event of a phase-to-earth fault, the tuned ASC creates a resonant circuit between the downstream network and neutral connection of the zone substation transformer resulting in a peak voltage displacement across the neutral. This leads to the faulted phase voltage becoming virtually zero, with the phase to ground voltages of the healthy phases increasing to almost phase to phase voltage in both 11kV and 22kV distribution network.

The neutral voltage displacement caused by this resonant circuit effectively leads to very low earth fault currents in comparison to non REFCL networks as the faulted phase voltage is too small to drive large currents. The power factor of the fault also approaches unity reducing arc flash risk, hence the name Arc Suppression Coil. The elevated phase to ground voltages on the healthy phase requires all equipment to be rated to withstand the overvoltage and consequently reduce the risk of cross country faults.

7.3 Network Components

Installation of REFCL's will require a shift in how the network is designed, operated and maintained as the transition from a low impedance grounded network to high impedance grounded network. As such all components of the entire 11kV and 22kV distribution network will need to be examined accordingly to understand and determine the requirements of a REFCL enabled network.

7.3.1 REFCL

The GFN is a package of products, which consist of a tuneable Arc Suppression Coil (ASC), Residual Current Compensator (RCC) and a control system. The ASC is connected to the power transformer neutral and is located in the switchyard. ASC is oil filled (hermetically sealed) consequently requiring its own bund. The ASC's purpose is to compensate for the network's capacitive coupling current during an earth fault leaving only a low residual fault current. As such the size of the ASC is determined by the size of the network. In order to compensate for the network's capacitive coupling current the ASC must be tuned to the network. The tuneable ASC is of a fixed inductance and variable capacitance type with auxiliary windings. The auxiliary windings are used for the LV tuning capacitor banks located on top of the ASC and for the RCC. The LV tuning capacitors will have capacitor banks that can be configured to offset the inductance of the ASC in order to tune the coil to the network capacitance. This adjustment enables the ASC to fully compensate for all scenarios, where feeders or sections in the network have been switched in or out. A tuning limitation will be set dictating the size of the ASC per zone substation.

The RCC is an AC-DC-AC converter that is housed in the zone substation control building or switch room. Its purpose is to neutralize the remaining residual fault current. The size of the RCC inverter is determined by the size and characteristics of the network. Because the ASC compensates the capacitive coupling current, the RCC inverter can be designed with limited power to only compensate for the residual active current. The RCC inverter also needs to compensate for capacitive coupling current caused by any mismatch of the ASC. The control system of the GFN completes the protection and control functions tying all the components together. The panel houses the Master and Slave relays and also includes the Neutral Manager (HMI) which is used for operating the device. The GFN control system is then interfaced to the station via the interface controller.

7.3.3 Substation Auxiliary Supplies

The added station alternating current load will dramatically increase due to the RCC loading demand. Typically the RCC kVA will be 10-15% of the ASC kVA rating. As such, substations that have small station service transformers will need to be upgraded in order to supply the RCC load together with the station load. The 11kV/22kV insulation of the ring main unit supplying the station service transformers must also withstand the elevated phase to ground voltages due to REFCL operation.

7.3.4 Neutral Bus

The introduction of the REFCL requires a neutral bus, enabling different earthing arrangements to be configured automatically. A neutral bus will be required on a per REFCL basis. One mode of the REFCL will automatically switch in the NER/NEX and will have a separate controller to manage the operation of each neutral bus circuit breaker. A solidly grounded earthing configuration can be achieved via the NER/NEX bypass circuit breaker or at the transformer neutral connection.

7.3.5 NER/NEX

NER’s and NEX’s does not need to be made redundant by the installation of a REFCL, rather it can be modified to ensure the NER/NEX can be switched into service by the REFCL interface controller when required as designed by the use of neutral bus.

7.3.6 Surge Arrestors

Due to the elevated phase to ground voltages during REFCL operation, 11kV and 22kV station and distribution feeder surge arrestors will need to be assessed and replaced accordingly.

7.3.7 11kV/22kV Cabling

All 11kV/22kV underground cables used in the substations that have planned REFCL implementation will be required to withstand the overvoltage during REFCL operation. Any upgrades or installation of new cables are to be rated to ensure insulation levels are sufficient and the network capacitance seen by the REFCL is kept to a minimum.

7.3.8 11kV/22kV Switchgear

Installation of new switchboards will vary from substation to substation depending on the insulation ratings of existing switchgear and the availability of accurate VT’s and CT’s to achieve compliance. An assessment will be required to be carried out on existing 11kV and 22kV switchgear in each of the nominated zone substations.

7.3.9 11kV/22kV Station VT’s

Due to the elevated phase to ground voltages during REFCL operation, VT’s will need to be assessed and replaced accordingly. Each REFCL will also require a neutral voltage measurement for the transformer/bus it is connected to.

7.4 Cost Analysis of REFCL installation

Component	Cost	Comments
ASC + RCC + Control Cubicle	$1,200,000	Cost of one set REFCL
Training + Commissioning	$85,500	Around 15 days ($5700 / day)
Developing EQL standards	Note 1	Cost of developing EQL standards
EQL's feasibility study, planning, design and site installation	Note 1	Detail feasibility study, planning, design and site installation cost's
Power system augmentation – new surge arrestors, regulators, switchboard upgrading etc.	Note 1	Cost incurred in carrying out augmentation works in the power system
On-going maintenance	Note 1	Cost in maintaining the equipment

*Note 1 – Further detail cost will be worked out if REFCL's are to be utilised

Table 19: REFCL cost analysis

Table 19 highlights the brief outline of the cost in implementing REFCL's. It can be noted that the actual cost of equipment is quite expansive which only includes one set of REFCL. There will be further cost from suppliers (Swedish Neutral) to send their staff to train EQL staff and also to assist in commissioning phases. A detail cost analysis will be required to be done as part of further work's once it is decided by EQL that REFCL's is a device that can be implemented in the distribution network to assist in improving safety of network. This will include performing a detailed feasibility study, developing EQL REFCL standards to be incorporated with existing protection schemes, planning, designing and future maintenance / replacement cost.

7.5 Other detection techniques

7.5.1 VS-SEF logic

As part of literature review, Voltage Supervised Sensitive Earth Fault has also been identified as a logic that may assist in detection of high impedance earth faults. However this logic will require rigorous testing within EQL's network to confirm its suitability. It does however require voltage inputs and not all of EQL's field protective devices have voltage transformers installed which can be a challenging factor. It further requires point of wave closing algorithm in the protective devices which will also need to be considered whilst looking into the usage of this new logic.

7.5.2 Relay Vendors

The following relay manufacturers were contacted as part of the research project to find out about the improvements they are making in the area of low earth fault detection:

- Schneider Electric
- ABB – ASEA Brown Boveri
- SEL – Schweitzer Engineering Laboratories

The relay manufacturers do not have an immediate solution that can primarily focus in low earth fault detection and are continually working around this area to have protective devices with improved detection capabilities. Whilst the protection relays have low setting range and fast processing internal timers for tripping, the CT ratio's available in primary plant is a factor that plays a part in setting the minimum current pick up of SEF protection.

EQL currently utilises Noja RC10 as a protective device in the field, which comprises of a standard OSM recloser tank and has a settings limit of 1A for SEF, but Noja power can also have special matched CT build of the OSM Recloser which allows a minimum pickup of 200mA. It does comprise of a tripping time in the range of 0 -120s with a resolution of 0.01s.

EQL can work with Noja Power to have a special matched CT tank with RC10 controller, combined with Noja's proprietary protection algorithms in the RC10 to have SEF set at 500mA on required feeders. This however does require good feeder balancing, which EQL needs to work on in-order to achieve a real low value of SEF pick up current.

Chapter 8 Conclusions and Further Work

8.1 Chapter Overview

This chapter outlines the conclusions, and further work which has been identified that is associated with the research project.

8.2 Conclusions

The primary objectives of this research project were to:

- Investigate the different earthing system's used in Energy Queensland's distribution network.
- Investigate the benefits and challenges of existing and alternate earthing systems.
- Investigate the various forms of earth fault protection currently used by distribution network service providers within Australia.
- Develop suitable distribution network models for the analysis of different earthing systems.
- Research and investigate alternate protection functions currently available in protective devices from suppliers / manufactures which can be utilised for detecting earth faults.
- Research and investigate the availability of new technologies that may provide better earth fault detection capabilities.

These objectives have been successfully accomplished and an earth fault detection method has been identified that can be utilised in Energy Queensland's distribution power network. REFCL's is a device with features that can assist further in improving safety in the distribution power network.

EQL can continue to utilise solidly and impedance / resistance neutral grounding methods as it does have advantages as highlighted in the research. Other power utilities in Australia are also investigating methods and cost benefit solutions that can further assist in low earth fault current detection. Protection relay manufacturers are also actively doing research and working with power utilities to explore opportunities to improve their product so that it is continually able to meet the requirements of adequately protected power network.

It is intended that any of the detection methods highlighted as part of this project shall be subjected to further testing to confirm its suitability and viability to EQL's distribution power network.

8.3 Further Work

The following further work has been identified as part of the research project that can be undertaken to further improve earth fault detection in EQL's distribution power network:

- Detail feasibility and cost analysis of implementing Rapid Earth Fault Current Limiter technology.
- Further laboratory and field testing of Voltage Supervised – Sensitive Earth Fault logic to confirm its suitability in distribution power network.
- Power utilities to work in-conjunction with protection relay manufacturers to keep developing algorithms which are built in protection relays which can further assist in low values of earth fault detection.

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Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For: Sanjay Narayan

Title: Analysis of Different Earthing Systems and Earth Fault Protection in Power System Distribution Network.

Major: Power Engineering

Supervisors: Andrew Hewitt*, Matthew Quinton

Sponsorship: Energy Queensland Pty Limited

Enrolment: ENG4111 – Ext S1, 2019

ENG4112 – Ext S2, 2019

Project Aim: To investigate the effects of different earthing systems on the operation and effectiveness of earth fault protection schemes, with a focus on the Energy Queensland's distribution network.

Programme: Version 3, 15th March 2018

1. Investigate the different earthing system's used in Energy Queensland's distribution network.
2. Investigate the benefits and challenges of existing and alternate earthing systems.
3. Investigate the various forms of earth fault protection currently used by distribution network service providers within Australia.
4. Develop suitable distribution network models for the analysis of different earthing systems.
5. Research and investigate alternate protection functions currently available in protective devices from suppliers / manufactures which can be utilised for detecting earth faults.
6. Research and investigate the availability of new technologies that may provide better earth fault detection capabilities.

If time and resources permit:

7. Obtain measured fault data from the field to assess and validate assumptions and/or predictions made.
8. Study and analyse the effects of fault current on substation earth grid.

Appendix B – Risk Assessment

A risk assessment was conducted to minimise risk to allow successful completion of this project. All identified risks was categorised according to:

- Risks to the safety of persons involved in the research project
- Risks to the completion of the research project
- Risks following the completion of the research project

Various control measures have been identified to eliminate the risk where it was possible to do so, or minimise the exposure to the risk where the risk was of significant danger to the work being conducted. The severity of the risks has been categorised as per Table 20 which has been extracted from Energex's risk management document M888.

Health & Safety Risks				
Risk Score	*Risk* Descriptor	Risk Tolerability Criteria and Action Requirements		
30 - 36	*Extreme Risk*	***Intolerable*** *(stop exposure immediately)*		
24 - 29	*Very High Risk*	***Risk*** must be managed in line with the **ALARP** Principles	Executive/Safety Council Approval *(required to continue risk exposure)*	May need full QRA Establish & implement appropriate mix of hard and soft controls according to the Hierarchy of *Risk* Controls and Cost-Benefit Analysis. Review their effectiveness.
18 - 23	*High Risk*		Divisional Manager/ General Manager Approval *(required to continue risk exposure)*	Establish & implement appropriate mix of hard and soft controls according to the Hierarchy of *Risk* Controls and Cost-Benefit Analysis. Review their effectiveness.
11 - 17	*Medium Risk*		Group Manager/Process Owner Approval *(required to continue risk exposure)*	Review existing controls for effectiveness Introduce new or changed *risk* controls if cost-benefit justifiable
6 - 10	*Low Risk*		Line Manager/Field Distribution Manager (or equivalent) Approval *(required to continue risk exposure)*	Continual Review of existing controls for effectiveness Introduce new or changed *risk* controls if cost-benefit justifiable
1 - 5	*Very Low Risk*		Supervisor/Coordinator Approval (or equivalent) *(required to continue risk exposure)*	Continual Review of existing controls for effectiveness

Table 20: Risk Tolerability Scale

Table 21 specifies the hierarchy of controls that was used to mitigate the hazards. The most preferred option of hazard management was applied first.

Risk Treatment / Control Hierarchy					
HARD Options - Most preferred – Consider First (less dependent on human reliability - can appear to be more costly)					
	Level	**Control Hierarchy**		**Risk Treatment**	
Highest	1	**Elimination / Substitution**	**Physical / Engineering**	**eliminating / removing exposure** to the hazardous object, material, substance, method or procedure , **or replacing it** with another that has a lower risk for the same exposure *For example, not using an EWP that has been identified as having faulty controls or using a chemical with a lower toxicity or flammability but still achieves the same function or outcome.*	**Most**
Level of Health and Safety Protection	2	**Design**	**Physical / Engineering**	better **initial design / ergonomics** and **reengineering / redesign** which introduces new methods of physical operation, barriers , safe-guards or safety devices to reduce the risk exposure *For example, design an overhead network to enable de-energised work or ergonomic redesign of tools and equipment*	**Reliability of Control Measures**
	2	**Separation**	**Physical / Engineering**	distance or time separation of hazards and exposed persons *For example, demarcation / barricading exclusion zones for fall / drop hazards*	
	3	**Administration**		improved or new rules / procedures / scheduling / maintenance / communications – better involvement of users in risk assessments / review or development of better user documents, signage, messages, notices	
	3	**Supervisor / Enforcement**		selection and preparation of personnel / behaviour reinforcement methods / fair and just culture discipline /culture	
	3	**Checking / Assessments**		Audits / Inspections / reviews / risk assessments / frequency / depth *For example, scheduling work on / near roadways outside of peak hours or improved checking on actual operations and activities. Better / different frequency maintenance inspections / servicing*	
Least	3	**Behaviour-Related Measures**		wearing PPE Personal protective equipment - providing protective clothing or equipment to exposed personnel – Training – all kinds, - Behaviour observation / interaction related programs. *For example, better Initial and refresher training for high risk activities.*	**Lowest**
SOFT Options - Least preferred (– more dependent on human reliability - can appear to be less costly)					

Notes

1) **Always use multiple controls – never rely on only 1 - the more controls the less likely that all will fail / be ineffective at the same time**

2) Always use a combination of controls from different parts of hierarchy – even HARD controls at the top of the hierarchy are not perfect

3) Always use pre-emptive controls which reduce Likelihood L as well as reactive responsive controls which primarily reduce Consequence C

4) Always consider effectiveness of control options – not just cost

5) "Better Ergonomics" means changing design and methods of use to better match human operators' capabilities and limitations

Table 21: Hierarchy of Hazard Control

Table 22 below identified the personnel hazards which were expected at various stages of the research project and appropriate control measures that was implemented to prevent any injuries and risk.

Hazard	Risk	Control Measures and Mitigation
Office Environment Hazard		
• Ergonomic Hazards	Minor / Possible (Low Risk)	• Take regular breaks • Maintain proper sitting posture • Computer screen, keyboard, mouse are correctly located • Desk and Chair are correctly adjusted
• Poor or inadequate lighting	Minor / Possible (Very Low Risk)	• Turn on all lights in the area
• Electrical hazards such as power leads	Minor / Possible (Very Low Risk)	• Cords and leads are neatly placed and clear off work areas
Field Environment Hazards		
• Manual Handling	Minor / Possible (Medium Risk)	• Site specific risk assessment • Strictly follow lifting weight limitations • Use two men lift where required • Follow good lifting techniques • Use mechanical or other forms of aid where available
• Slip Trips and Falls	Minor / Possible (Medium Risk)	• Site specific risk assessment • Beware of surroundings • Keep all equipment / leads etc away from work area • Watch step while moving around
• Extreme temperatures	Minor / Possible (Medium Risk)	• Site specific risk assessment • Plenty drinking water is available • Use sun protection (Hard hats with brim, long sleeve shirt / trousers, sunscreen lotion, sunglasses)
• Electric shock	Minor / Possible (Medium Risk)	• Site specific risk assessment • Isolate plant where necessary • Apply for permits and network access • Cleary define and delineate work area • Place work area signs
• Height	Minor / Possible (Medium Risk)	• Site specific risk assessment • Use men lifting trucks where possible • Ladders are well secured • Harnesses are correctly used

Table 22: Personal Risk Assessment

Table 23 below identified the risk to the actual research project which can potentially lead into unsuccessful completion of the study if it was not controlled or mitigated.

Hazard	Risk	Control Measures and Mitigation
• Failure of systems such as PC's and laptops	Minor / Possible (Low Risk)	• Always have backup copies of all working documents and models
• Access restrictions to data base and systems	Minor / Unlikely (Very Low Risk)	• Request access in advance • Seek assistance from personnel who already have access to systems
• Delay in response time from suppliers / manufacturers	Minor / Unlikely (Very Low Risk)	• Request for information in advance • Always follow up on correspondence

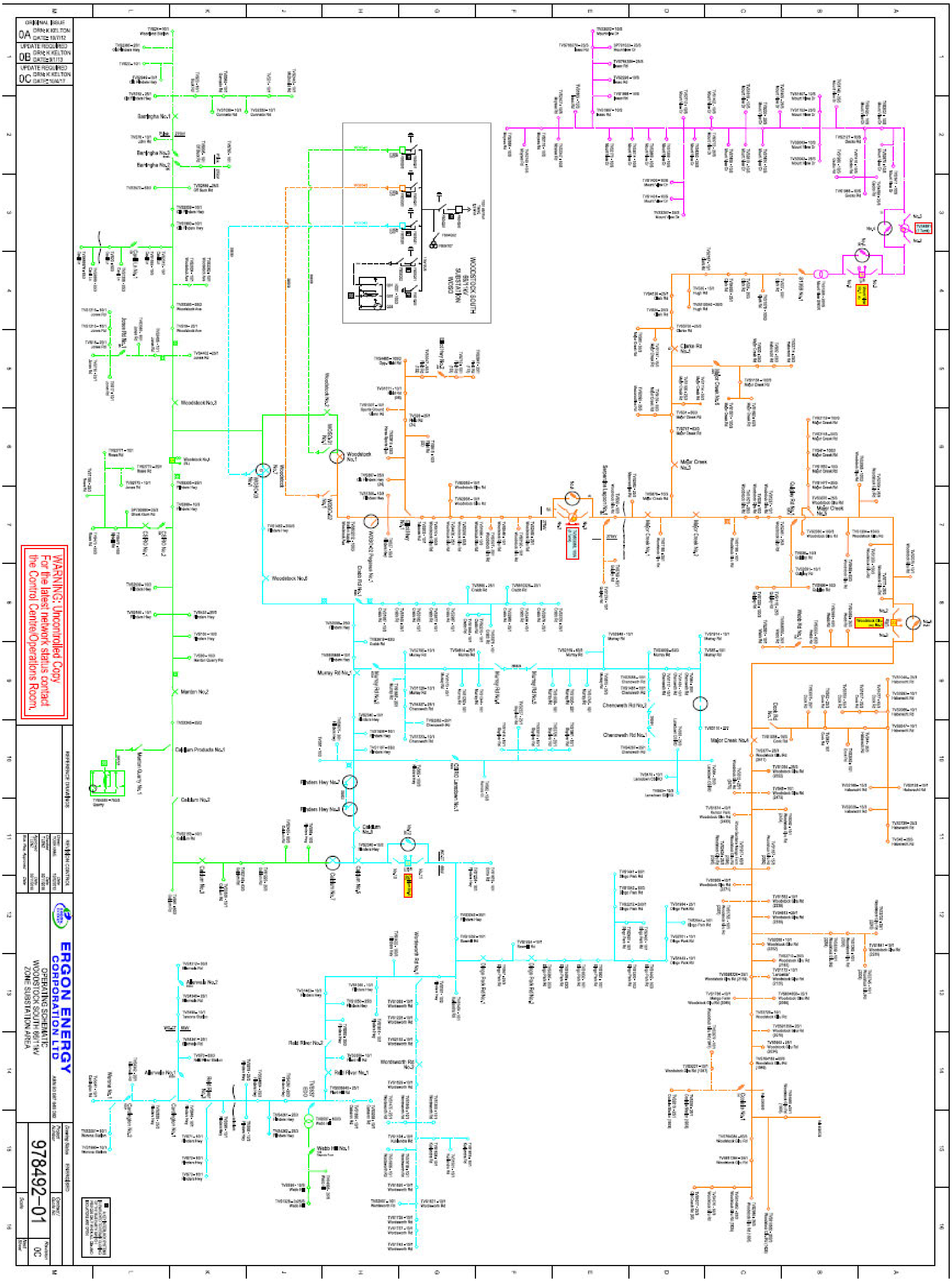
Table 23: Project Risk Assessment

Table 24 below identified the risk to the research project upon reaching completion.

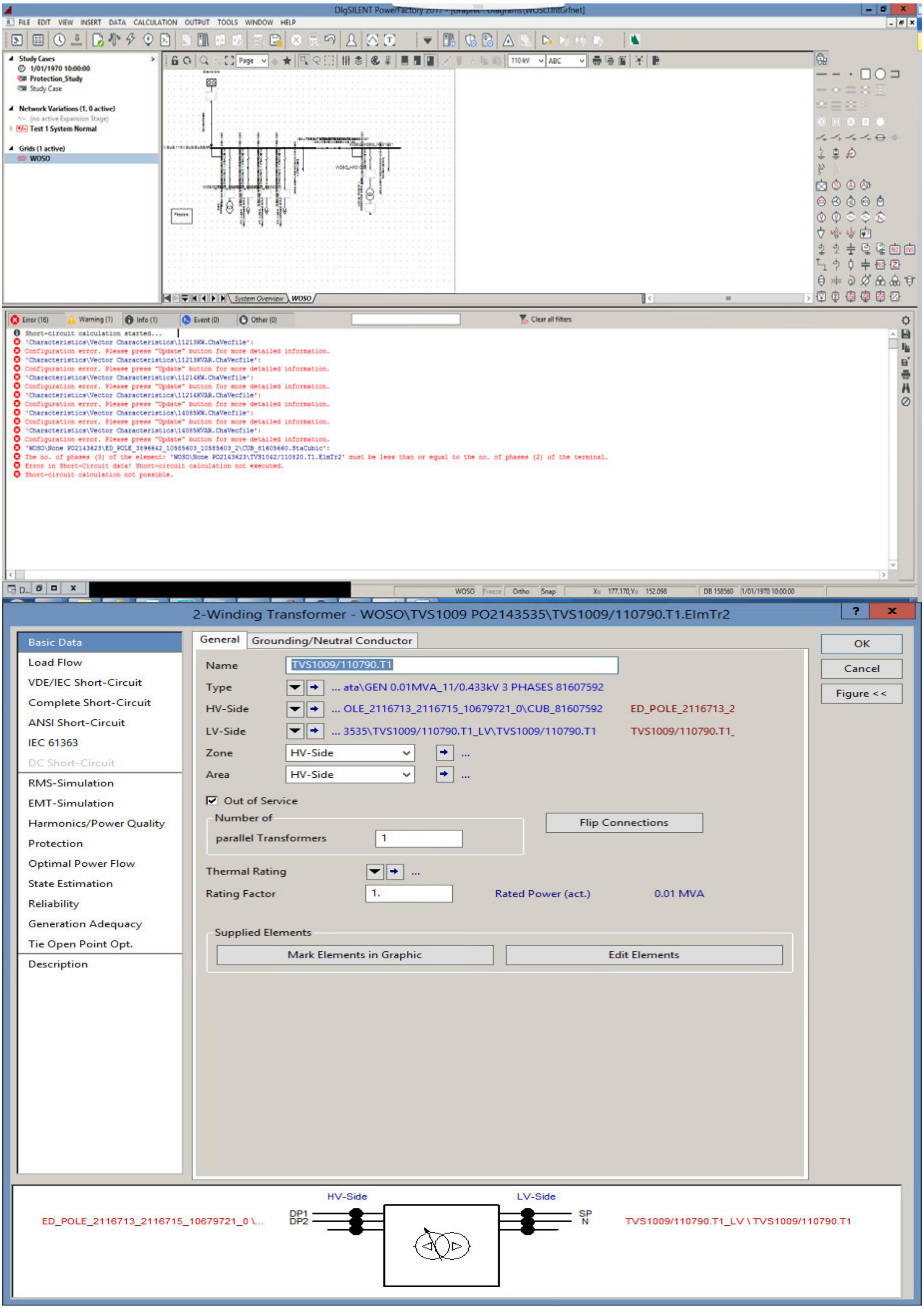
Hazard	Risk	Control Measures and Mitigation
• Implementation of alternate earthing systems and alternate detection methods	Minor / Possible (Low Risk)	• Further studies could be required by other departments • Cost analysis for a roll out program

Table 24: Post Project Risk Assessment

Appendix C – Operating Schematic of WOSO



Appendix D – Errors in WOSO Power Factory



Appendix E – Results of Earthing Systems

The following table displays measured earth fault current on A-phase in WOSO-01 11kV feeder with different earthing systems:

Maximum Source Impedance and No Fault Resistance			
Test Nodes	Solidly Earth(A)	6Ω NEX(A)	3Ω NER(A)
1	3212	856	1752
2	3212	856	1752
3	3212	856	1752
4	3212	856	1752
5	3212	856	1752
6	3212	856	1752
7	3204	856	1749
8	3204	856	1749
9	3178	854	1742
10	3164	853	1739
11	3152	852	1736
12	3072	846	1712
13	3017	842	1695
14	2983	840	1683
15	2944	837	1669
16	2943	837	1667
17	2871	833	1614
18	2871	833	1614
19	2828	828	1626
20	2422	804	1471
21	2392	794	1459
22	2215	791	1257
23	1993	763	1275
24	1940	750	1182
25	1704	717	1156
26	1347	708	883
27	1342	696	970
28	1327	691	884
29	1311	661	953
30	1306	660	876
31	1262	645	926
32	1154	639	865
33	1075	628	751
34	1071	604	749
35	958	576	717
36	748	510	587
37	733	508	574
38	534	439	437

39	511	421	425
40	504	408	420
41	497	403	411
42	490	397	410
43	458	386	387
44	448	384	378
45	446	380	376
46	441	378	373
47	434	377	367
48	417	365	355
49	375	335	324
50	367	332	318
51	356	319	310
52	351	318	306
53	350	316	305
54	350	315	305
55	347	307	304
56	338	302	296
57	331	301	291
58	325	297	286
59	322	289	284
60	321	289	284
61	317	285	281
62	315	282	278
63	310	275	275
64	307	275	274
65	304	274	271
66	301	273	269
67	299	271	266
68	296	268	263
69	296	268	263
70	288	266	259
71	288	265	258
72	288	264	258
73	288	262	258
74	288	260	258
75	286	256	255
76	285	256	254
77	283	256	253
78	283	256	255
79	281	256	253
80	280	253	251
81	279	253	250
82	279	251	251

83	278	251	250
84	276	249	249
85	275	248	248
86	270	247	242
87	268	246	241
88	268	245	242
89	266	241	241
90	260	240	234
91	256	240	231
92	256	239	232
93	256	236	231
94	250	231	226
95	246	230	224
96	245	226	222
97	244	226	222
98	241	226	220
99	241	222	220
100	241	220	220
101	240	218	219
102	239	218	217
103	239	218	217
104	239	217	217
105	227	216	207
106	226	215	206
107	225	206	207
108	224	205	206
109	220	202	202
110	215	198	198
111	198	190	182
112	198	190	182
113	196	187	181
114	166	161	155
115	162	157	151
116	153	149	144
117	152	148	143
118	150	146	141
119	149	144	140
120	142	139	134
121	141	138	133
122	139	135	131
123	135	132	128
124	133	130	126
125	132	129	125
126	128	126	121

127	123	121	117
128	123	120	116
129	122	120	116
130	121	119	115
131	116	114	111
132	111	109	106
133	101	99	96
134	96	95	92
135	93	92	90
136	85	84	82
137	81	80	78
138	77	76	75
139	76	75	74
140	76	75	73
141	72	72	70
142	70	70	68

The following table displays measured unfaulted phase voltage in WOSO-01 11kV feeder with different earthing systems:

Maximum Source Impedance and Zero Fault resistance						
	Solidly Earth		NEX		NER	
Test Points	B_Ph Magnitude (kV)	C_Ph Magnitude (kV)	B_Ph Magnitude (kV)	C_Ph Magnitude (kV)	B_ph Magnitude (kV)	C_Ph Magnitude (kV)
1	7.03	6.39	10.63	10.25	8.24	11.72
2	7.03	6.39	10.63	10.25	8.24	11.72
3	7.03	6.39	10.63	10.25	8.24	11.72
4	7.03	6.39	10.63	10.25	8.24	11.72
5	7.03	6.39	10.63	10.25	8.24	11.72
6	7.03	6.39	10.63	10.25	8.24	11.72
7	7.03	6.39	10.63	10.25	8.24	11.72
8	7.03	6.40	10.63	10.24	8.23	11.71
9	7.03	6.40	10.63	10.24	8.23	11.71
10	7.04	6.42	10.63	10.24	8.22	11.69
11	7.04	6.42	10.63	10.23	8.22	11.68
12	7.05	6.43	10.63	10.23	8.22	11.68
13	7.08	6.48	10.63	10.22	8.19	11.61
14	7.11	6.52	10.63	10.20	8.18	11.56
15	7.12	6.54	10.63	10.19	8.17	11.53
16	7.14	6.56	10.63	10.18	8.16	11.49
17	7.14	6.56	10.63	10.18	8.16	11.48
18	7.14	6.56	10.67	10.18	8.15	11.40
19	7.14	6.56	10.67	10.18	8.15	11.40
20	7.19	6.63	10.64	10.14	8.13	11.37
21	7.42	6.83	10.93	10.14	8.06	10.93
22	7.44	6.84	10.66	10.00	8.06	10.90
23	7.09	6.43	10.66	9.99	8.10	10.90
24	7.59	7.02	10.86	9.45	8.05	10.42
25	7.46	6.75	10.67	9.76	8.08	9.99
26	7.85	7.13	10.95	9.76	8.05	10.11
27	7.13	7.13	10.64	9.63	7.94	10.11
28	8.14	7.16	10.92	8.51	8.11	9.58
29	7.41	6.71	10.91	8.50	8.00	9.04
30	8.17	7.16	10.81	8.50	8.12	9.53
31	7.45	6.70	10.81	8.50	8.01	9.02
32	8.21	7.16	10.62	9.33	8.13	9.46
33	8.30	7.16	10.62	9.30	8.17	9.29
34	7.15	6.55	10.61	9.25	7.87	9.00
35	7.15	6.55	10.60	9.13	7.87	9.00
36	8.06	6.77	10.67	8.34	8.13	8.65
37	8.07	6.68	10.48	7.58	8.13	8.23

38	7.91	6.65	10.51	7.80	8.06	8.16
39	7.34	6.72	9.90	6.47	7.72	7.75
40	7.84	6.59	9.70	6.47	7.99	7.70
41	7.85	6.59	10.04	6.86	7.99	7.68
42	7.20	6.56	10.03	6.86	7.62	7.60
43	7.82	6.59	9.98	6.79	7.97	7.65
44	7.78	6.59	9.60	6.79	7.94	7.58
45	7.32	6.73	9.60	6.79	7.67	7.58
46	7.33	6.73	9.60	6.79	7.67	7.58
47	7.36	6.73	9.87	6.67	7.68	7.57
48	7.32	6.73	9.55	6.24	7.66	7.57
49	7.32	6.73	9.48	6.20	7.65	7.54
50	7.32	6.73	9.31	6.14	7.62	7.46
51	7.21	6.61	9.19	6.14	7.54	7.46
52	7.59	6.63	9.12	6.14	7.79	7.38
53	7.21	6.63	9.11	6.14	7.53	7.41
54	7.21	6.63	9.19	6.11	7.53	7.41
55	7.31	6.74	9.41	6.29	7.60	7.41
56	7.66	6.60	9.42	6.32	7.83	7.35
57	7.57	6.63	9.11	6.09	7.77	7.34
58	7.31	6.74	9.32	6.25	7.59	7.38
59	7.31	6.74	9.08	6.09	7.58	7.37
60	7.63	6.61	9.03	6.08	7.80	7.30
61	7.81	6.56	9.30	6.26	7.92	7.28
62	7.83	6.55	9.42	6.37	7.93	7.27
63	7.31	6.74	9.42	6.38	7.58	7.35
64	7.87	6.54	9.41	6.39	7.96	7.25
65	7.88	6.54	8.85	6.39	7.97	7.24
66	7.90	6.54	8.94	6.39	7.98	7.24
67	7.92	6.53	9.41	6.40	7.99	7.23
68	7.77	6.56	9.41	6.40	7.89	7.23
69	7.30	6.46	9.30	6.31	7.56	7.20
70	7.21	6.46	9.41	6.41	7.50	7.20
71	8.05	6.52	8.88	6.07	8.09	7.19
72	8.06	6.52	8.88	6.07	8.09	7.19
73	8.05	6.52	8.87	6.07	8.09	7.19
74	8.05	6.52	8.78	6.07	8.09	7.19
75	8.05	6.52	8.85	6.07	8.09	7.19
76	7.30	6.74	9.45	6.48	7.55	7.29
77	7.30	6.74	9.45	6.48	7.55	7.29
78	7.30	6.74	9.45	6.48	7.55	7.29
79	8.01	6.52	9.45	6.48	8.06	7.18
80	8.02	6.52	9.45	6.48	8.07	7.18
81	7.21	6.74	8.72	6.45	7.48	7.28

82	7.30	6.74	9.41	6.45	7.55	7.28
83	8.04	6.52	9.41	6.45	8.08	7.17
84	8.04	6.52	8.79	6.08	8.08	7.17
85	8.05	6.52	9.41	6.45	8.09	7.17
86	8.05	6.52	9.41	6.46	8.09	7.17
87	7.22	6.74	9.41	6.46	7.48	7.26
88	7.30	6.74	9.40	6.46	7.54	7.26
89	8.08	6.51	8.75	6.08	8.10	7.15
90	8.09	6.51	8.73	6.08	8.11	7.15
91	7.30	6.75	8.73	6.08	7.53	7.24
92	7.30	6.75	9.39	6.46	7.53	7.24
93	8.11	6.51	9.39	6.46	8.13	7.12
94	7.30	6.75	8.69	8.67	7.53	7.24
95	7.29	6.75	8.67	8.67	7.52	7.24
96	8.14	6.51	9.37	6.47	8.15	7.10
97	7.29	7.29	8.64	6.09	7.51	7.51
98	8.15	6.51	8.64	6.09	8.16	7.09
99	8.15	6.50	8.64	6.09	8.16	7.09
100	8.16	6.50	9.35	6.47	8.16	7.08
101	8.16	6.50	9.34	6.47	8.16	7.08
102	8.16	6.50	9.34	6.47	8.16	7.08
103	7.29	6.75	9.34	6.47	7.51	7.21
104	7.30	6.75	9.34	6.47	7.51	7.21
105	7.30	6.75	9.34	6.47	7.51	7.21
106	7.29	7.08	8.57	8.45	7.50	7.28
107	7.29	6.75	8.57	6.10	7.50	7.19
108	8.10	6.50	9.23	6.40	8.11	7.04
109	8.10	6.50	9.23	6.41	8.12	7.04
110	8.08	6.50	9.19	6.39	8.10	7.03
111	8.07	6.50	9.17	6.37	8.09	7.02
112	7.28	6.90	8.40	8.18	7.47	7.06
113	7.28	6.90	8.41	8.18	7.47	7.06
114	7.44	6.68	8.54	6.15	7.59	7.08
115	7.28	6.50	8.22	6.21	7.44	7.00
116	7.27	6.50	8.20	6.21	7.43	7.00
117	7.27	6.50	8.15	6.21	7.42	7.00
118	7.40	6.70	8.27	6.21	7.53	7.00
119	7.27	6.70	8.13	6.22	7.42	7.00
120	7.40	6.70	8.24	6.22	7.52	7.00
121	7.27	7.27	8.08	8.04	7.41	7.40
122	7.27	7.27	8.08	8.04	7.41	7.40
123	7.27	7.27	8.06	8.04	7.41	7.40
124	7.27	7.27	8.04	8.04	7.40	7.40
125	7.27	7.27	8.03	8.04	7.40	7.40

126	7.27	7.27	8.02	8.04	7.40	7.40
127	7.27	7.27	8.00	8.04	7.40	7.40
128	7.27	7.27	7.97	8.04	7.39	7.40
129	7.27	7.27	7.97	8.04	7.39	7.40
130	7.27	7.27	7.96	8.04	7.39	7.40
131	7.27	7.27	7.96	8.04	7.39	7.40
132	7.26	7.02	7.93	7.74	7.38	7.13
133	7.26	7.02	7.90	7.74	7.38	7.13
134	7.35	6.72	7.93	6.35	7.45	6.92
135	7.26	7.26	7.81	7.81	7.36	7.36
136	7.34	6.72	7.88	6.37	7.43	6.91
137	7.26	7.15	7.74	7.66	7.35	7.24
138	7.33	7.15	7.79	7.66	7.41	7.24
139	7.32	7.15	7.76	7.66	7.40	7.24
140	7.26	6.89	7.69	7.38	7.34	6.96
141	7.32	6.89	7.75	7.38	7.40	6.96
142	7.32	6.89	7.73	7.38	7.39	6.96
143	7.32	6.89	7.72	7.38	7.39	6.96

The following results shows measured earth fault current on A-phase in WOSO-02 11kV feeder with different earthing systems, varying source impedance and also adding 50Ω fault resistance:

	Solidly Earth				Neutral Earthing Reactor (NEX)			
Test Nodes	Max Z(A)	Min Z(A)	Max Z & 50Ω Rf(A)	Min Z & 50Ω Rf(A)	Max Z(A)	Min Z(A)	Max Z & 50Ω Rf(A)	Min Z & 50Ω Rf(A)
1	3212	2014	139	124	855	704	137	122
2	3212	2014	139	124	855	704	137	122
3	3212	2014	139	124	855	704	137	122
4	3212	2014	139	124	855	704	137	122
5	3212	2014	139	124	855	704	137	122
6	3212	2014	139	124	855	704	137	122
7	3203	2009	139	124	855	703	137	122
8	3174	1994	139	124	853	702	137	122
9	3174	1994	139	124	853	702	137	122
10	3162	1988	139	124	852	701	137	122
11	3112	1962	138	124	849	698	137	122
12	3045	1928	138	124	844	694	137	122
13	2953	1881	138	124	837	689	137	122
14	2869	1837	138	123	831	684	136	122
15	2733	1765	138	123	820	675	136	121
16	2676	1735	138	123	815	671	136	121
17	2598	1693	138	123	808	665	136	121
18	2396	1263	137	122	810	633	134	116
19	2241	1200	136	121	755	622	135	120
20	2089	1408	136	121	794	619	133	116
21	1988	938	135	119	722	595	134	119
22	1842	1262	135	118	722	595	134	119
23	1842	1262	135	117	786	575	132	112
24	1766	825	133	118	670	551	130	110
25	1520	1065	134	117	759	541	133	117
26	1373	972	133	117	641	527	132	116
27	1288	917	132	116	623	512	131	115
28	1283	548	133	116	601	493	130	114
29	1262	543	132	113	589	483	130	114
30	1262	543	132	112	581	477	126	103
31	1259	536	130	113	697	433	126	103
32	1259	536	130	113	528	433	126	103
33	1191	854	128	113	528	433	126	102
34	1143	822	130	113	526	431	126	102
35	1111	801	130	113	526	431	130	114
36	1102	459	128	113	691	430	124	99
37	980	443	128	112	691	430	128	111
38	950	434	127	112	693	427	128	111

39	944	386	127	112	693	427	127	111
40	927	678	130	111	517	423	127	111
41	927	678	129	111	511	419	127	111
42	921	674	129	111	506	414	123	99
43	921	674	129	111	495	405	127	110
44	891	654	129	111	493	403	123	98
45	874	642	128	111	490	400	122	95
46	857	630	125	111	488	399	127	110
47	825	608	128	111	485	396	126	109
48	823	437	128	111	485	396	126	109
49	819	604	128	111	485	396	126	109
50	811	598	128	111	485	396	126	109
51	806	325	128	111	485	396	126	109
52	805	594	128	111	485	396	126	109
53	797	588	128	111	485	396	126	109
54	797	588	128	111	485	396	126	109
55	797	588	128	110	482	394	126	109
56	797	588	128	110	480	392	126	109
57	796	588	128	110	475	388	126	109
58	796	588	128	110	474	387	126	109
59	796	588	128	110	473	386	125	109
60	796	588	128	110	471	385	125	109
61	791	527	128	110	660	384	125	108
62	789	583	125	110	469	383	125	108
63	783	578	127	109	490	379	124	105
64	771	570	126	109	464	379	125	108
65	768	568	127	109	464	379	122	99
66	765	566	127	109	461	376	125	108
67	759	562	124	109	459	375	125	108
68	754	558	127	109	459	374	119	91
69	741	549	127	109	456	372	124	108
70	740	549	127	109	454	370	124	108
71	733	544	127	108	453	369	124	107
72	728	540	127	107	451	368	124	107
73	727	539	127	108	451	368	124	107
74	721	535	127	108	451	368	124	107
75	717	417	127	108	602	367	124	107
76	714	530	127	108	449	366	124	107
77	711	333	126	108	454	363	124	107
78	711	528	123	108	446	363	124	107
79	710	284	126	108	591	361	124	107
80	709	509	126	108	440	359	124	107
81	708	526	124	107	433	353	123	105
82	708	526	126	104	432	352	123	107
83	708	526	126	104	522	351	123	106

84	702	522	126	104	430	351	120	99
85	701	432	125	103	428	348	121	100
86	694	516	125	103	427	348	123	106
87	686	274	125	107	425	346	116	87
88	679	506	125	106	425	346	123	106
89	678	420	125	106	425	346	122	105
90	664	495	125	106	418	340	118	92
91	660	492	123	106	618	338	122	105
92	656	489	123	106	433	337	122	105
93	655	437	125	106	461	337	120	99
94	653	449	124	106	409	333	122	105
95	649	484	123	106	436	333	122	105
96	649	484	123	106	424	333	122	105
97	644	480	124	106	472	332	116	86
98	643	480	120	106	406	330	121	102
99	643	480	124	106	451	329	121	101
100	639	424	123	105	403	328	122	105
101	633	421	124	104	402	327	121	102
102	633	444	123	104	403	327	120	100
103	631	397	124	105	430	326	120	100
104	631	397	124	105	401	326	121	104
105	628	250	124	103	401	326	119	98
106	628	469	124	104	401	326	119	98
107	625	393	124	104	401	326	121	104
108	614	395	124	104	400	325	119	98
109	608	455	124	104	427	324	121	104
110	601	450	124	104	399	324	121	104
111	601	370	123	104	396	322	119	98
112	597	402	122	103	396	322	121	104
113	593	445	122	102	396	322	114	84
114	592	444	123	102	392	319	121	103
115	592	444	123	102	430	315	121	103
116	589	442	120	100	430	315	121	103
117	589	442	123	103	388	315	121	103
118	589	442	121	103	410	313	120	103
119	589	442	122	100	427	312	120	103
120	587	352	123	101	421	312	119	99
121	586	439	122	100	393	312	120	103
122	584	438	123	103	383	311	120	103
123	579	434	122	102	382	310	120	103
124	579	434	122	103	380	308	118	96
125	577	350	122	101	395	307	120	103
126	577	433	120	99	379	307	119	101
127	575	228	122	100	377	306	117	95
128	571	358	118	103	376	304	120	102

129	570	428	122	102	372	301	119	100
130	569	397	122	102	417	300	117	95
131	569	355	122	100	369	299	119	102
132	567	409	122	100	365	295	117	96
133	567	226	117	100	571	294	119	102
134	566	226	119	102	363	294	117	95
135	561	321	122	100	362	293	112	81
136	560	420	120	102	361	292	119	102
137	553	223	119	101	495	291	119	102
138	552	314	119	101	402	291	119	101
139	550	413	121	101	413	290	112	81
140	550	315	121	98	401	289	112	81
141	550	222	121	100	407	288	119	101
142	550	222	121	96	356	288	115	92
143	549	412	121	97	354	286	118	101
144	543	407	118	97	352	284	115	91
145	541	299	120	99	349	281	111	81
146	541	406	119	98	349	281	115	92
147	538	404	115	96	379	279	118	101
148	535	401	117	96	344	278	111	80
149	528	295	117	97	403	272	111	80
150	527	396	120	99	335	270	118	100
151	527	343	120	99	398	268	114	90
152	523	284	120	98	399	268	116	95
153	521	391	120	98	339	267	118	100
154	519	285	116	98	328	264	118	100
155	518	301	119	97	532	263	118	100
156	517	282	116	96	346	262	114	90
157	515	203	116	97	365	259	117	100
158	515	285	115	97	365	259	113	88
159	513	385	115	97	321	258	114	90
160	510	383	117	96	321	258	110	78
161	507	381	117	97	397	258	113	89
162	505	379	115	97	381	257	117	99
163	504	295	113	97	328	255	113	88
164	503	294	115	97	317	255	113	89
165	503	294	116	97	388	255	117	99
166	496	309	119	97	521	254	113	90
167	496	308	116	93	343	254	116	99
168	495	262	116	97	316	254	116	99
169	495	372	118	94	315	253	113	90
170	490	368	113	94	373	253	113	90
171	490	260	113	93	373	252	114	92
172	487	366	117	93	373	252	114	92
173	481	189	112	93	311	250	116	98

174	480	361	112	93	341	250	112	86
175	480	361	112	92	311	250	111	86
176	478	253	118	93	311	250	108	76
177	473	249	116	92	310	249	114	94
178	472	355	114	91	385	249	115	96
179	469	321	116	91	382	248	115	98
180	461	305	114	91	388	248	111	85
181	460	333	117	91	308	247	113	92
182	457	232	117	91	385	246	111	85
183	456	299	117	90	307	246	113	91
184	455	342	117	90	307	246	115	97
185	455	179	113	90	306	246	106	74
186	441	331	117	91	306	245	113	94
187	438	313	117	90	306	245	109	82
188	438	216	113	88	303	243	114	96
189	436	218	111	91	329	235	114	96
190	436	218	116	91	493	235	114	96
191	434	242	116	87	376	233	113	95
192	432	276	116	89	372	231	111	89
193	432	240	116	87	366	226	113	95
194	429	323	114	87	302	224	108	80
195	429	323	116	86	364	223	109	84
196	422	317	116	86	291	220	108	80
197	421	230	116	87	301	219	108	80
198	419	315	116	84	465	216	113	95
199	419	229	116	85	337	216	109	84
200	419	229	116	85	336	214	113	95
201	419	229	111	86	458	214	113	95
202	418	315	115	83	458	214	113	95
203	416	202	109	84	310	213	113	95
204	414	202	112	84	448	211	112	94
205	412	226	111	84	358	211	112	94
206	412	310	110	84	446	210	112	94
207	411	309	110	83	446	210	112	94
208	411	309	110	83	331	207	112	94
209	411	161	110	82	297	206	108	82
210	409	308	110	82	330	206	108	82
211	405	305	110	82	330	206	108	82
212	404	195	110	81	330	206	108	82
213	403	303	113	81	325	204	112	94
214	403	303	107	81	346	200	104	71
215	403	303	110	82	347	200	106	78
216	402	303	112	81	309	199	108	82
217	402	303	111	81	348	199	106	78
218	397	299	112	82	431	195	105	77

219	396	243	108	81	336	188	108	85
220	389	222	108	81	335	187	110	89
221	389	264	109	81	298	184	109	87
222	387	256	110	80	271	184	107	82
223	386	183	107	79	269	183	109	88
224	382	198	105	79	410	182	104	75
225	376	235	107	80	310	182	107	84
226	374	176	106	78	329	182	105	78
227	373	259	107	79	265	180	101	67
228	369	144	105	80	261	178	103	74
229	368	202	104	80	257	176	105	79
230	364	170	106	80	254	173	102	73
231	350	162	106	80	252	173	101	71
232	346	171	102	78	392	173	101	73
233	339	186	105	76	319	172	102	76
234	335	153	103	77	250	172	104	80
235	333	205	106	76	250	172	103	80
236	330	204	103	76	279	171	100	69
237	327	180	105	74	272	166	103	79
238	325	201	103	75	312	166	101	75
239	324	156	105	74	306	161	103	79
240	321	154	101	73	289	160	99	70
241	319	199	104	73	362	156	99	70
242	314	196	104	73	297	154	102	79
243	309	192	104	72	248	152	102	78
244	307	137	104	71	248	152	102	78
245	306	193	101	71	276	148	101	78
246	304	191	101	71	274	146	101	78
247	304	191	101	70	287	146	97	66
248	301	142	101	69	332	141	97	67
249	294	164	98	69	249	138	98	72
250	294	164	98	68	252	138	98	72
251	293	145	98	68	261	135	97	68
252	289	146	98	68	231	133	96	68
253	270	124	97	68	231	133	93	63
254	270	124	97	66	269	132	93	63
255	267	141	95	63	240	119	95	67
256	267	141	95	63	240	119	95	67
257	260	117	93	61	232	114	92	61
258	249	104	92	60	224	108	90	57
259	249	112	91	60	201	106	90	59
260	243	101	90	60	201	106	89	56
261	240	107	90	59	201	105	89	58
262	238	106	90	59	201	105	88	56
263	238	102	89	59	200	105	89	58

264	233	103	89	59	199	105	88	57
265	230	107	90	59	217	104	88	58
266	227	100	90	59	207	103	87	56
267	225	110	90	58	195	103	88	59
268	225	110	90	58	195	103	88	59
269	224	109	90	58	216	103	87	55
270	224	109	89	58	229	102	88	59
271	224	98	88	58	196	102	88	59
272	223	109	89	58	189	101	88	59
273	223	109	88	57	212	100	88	59
274	220	96	88	57	187	100	86	55
275	218	95	89	57	218	99	85	52
276	218	105	89	56	224	99	86	54
277	217	107	87	56	207	97	87	58
278	217	89	87	56	205	96	87	58
279	217	107	86	55	202	94	87	58
280	212	92	88	55	201	93	85	53
281	212	92	87	54	196	90	85	53
282	210	105	86	54	196	90	86	58
283	208	90	86	53	179	89	84	53
284	208	104	85	53	192	88	84	52
285	207	90	85	53	203	88	85	57
286	202	87	84	53	192	88	83	52
287	199	86	83	52	188	86	82	51
288	198	85	84	51	185	84	82	51
289	196	91	83	51	184	84	83	53
290	193	83	82	50	180	81	81	50
291	191	82	82	50	179	80	81	50
292	191	82	82	50	179	80	81	50
293	183	78	81	50	165	79	80	48
294	178	81	80	48	172	77	79	49
295	163	73	77	47	153	72	76	46
296	148	65	73	43	140	64	72	43
297	145	60	72	42	137	62	71	41
298	145	63	72	41	139	60	71	42
299	137	59	70	41	130	59	69	40
300	131	56	69	39	125	56	68	39

The following results shows measured earth fault current on A-phase in WOSO-03 11kV feeder with different earthing systems, varying source impedance and also adding 50Ω fault resistance:

	Solidly Earth				Neutral Earthing Reactor (NEX)			
Test Nodes	Max Z(A)	Min Z(A)	Max Z & 50Ω Rf(A)	Min Z & 50Ω Rf(A)	Max Z(A)	Min Z(A)	Max Z & 50Ω Rf(A)	Min Z & 50Ω Rf(A)
1	3212	2014	139	124	855	704	137	122
2	3212	2014	139	124	855	704	137	122
3	3212	2014	139	124	855	704	137	122
4	3212	2014	139	124	855	704	137	122
5	3212	2014	139	124	855	704	137	122
6	3212	2014	139	124	855	704	137	122
7	3200	2007	139	124	854	703	137	122
8	3200	2007	139	124	854	703	137	122
9	3147	1980	139	124	851	700	137	122
10	3026	1918	138	124	842	693	137	122
11	3010	1910	138	124	841	692	137	122
12	2752	1775	138	123	821	676	136	122
13	2694	1744	138	123	816	672	136	121
14	2657	1724	138	123	813	669	136	121
15	1871	1279	136	121	726	598	134	119
16	1404	733	131	110	680	494	129	109
17	1237	674	130	109	638	465	128	108
18	1153	642	129	109	621	392	127	107
19	1097	613	128	108	615	449	126	106
20	1067	608	129	108	602	437	126	106
21	1067	608	129	108	590	432	126	106
22	1058	487	128	107	590	432	124	101
23	966	566	127	107	558	410	125	105
24	955	561	126	104	555	407	125	105
25	797	489	125	102	503	320	123	103
26	756	381	122	97	498	367	120	96
27	618	317	118	92	450	255	116	91
28	612	284	117	89	441	275	115	88
29	556	252	114	87	437	210	112	84
30	543	223	115	86	425	231	111	81
31	540	261	114	85	415	221	113	86
32	534	239	113	84	408	236	111	83
33	526	252	112	83	402	229	112	84
34	493	231	112	81	386	213	110	82
35	475	208	110	79	384	195	108	79
36	471	206	110	79	382	194	108	78
37	471	206	110	79	382	194	108	78
38	443	191	108	77	366	181	107	76

39	427	183	107	76	357	175	106	75
40	411	175	106	74	347	167	105	73
41	368	155	103	70	319	149	101	70
42	367	155	103	70	318	149	101	70
43	363	153	102	70	316	147	101	69
44	361	153	102	70	313	147	101	69
45	361	153	102	70	313	147	101	69
46	340	146	101	68	301	129	99	68
47	338	146	101	68	296	141	99	68
48	333	143	100	68	295	141	98	65
49	332	132	100	68	294	134	98	66
50	332	138	100	68	294	134	99	67
51	332	144	100	67	294	134	98	66
52	331	138	100	67	291	138	98	66
53	331	138	100	67	289	139	99	67
54	330	144	99	67	288	131	99	67
55	324	134	99	67	288	131	98	65
56	324	134	99	67	287	139	98	65
57	323	138	99	67	284	133	98	66
58	321	137	99	67	283	133	98	66
59	320	137	99	67	283	127	98	66
60	317	141	99	66	282	132	97	64
61	316	131	99	66	276	135	98	67
62	315	140	99	66	275	135	97	67
63	313	140	99	66	273	135	97	66
64	312	139	99	66	272	134	97	66
65	312	139	99	66	272	134	97	66
66	312	139	99	66	272	134	97	66
67	312	139	98	66	272	134	97	66
68	310	139	99	66	272	126	97	66
69	305	130	98	65	271	134	96	64
70	304	137	97	65	270	120	96	66
71	299	123	97	65	266	132	95	62
72	297	132	96	65	264	117	96	64
73	293	133	97	65	262	127	94	61
74	291	119	97	65	261	115	95	65
75	290	132	95	65	258	128	95	65
76	287	118	96	64	256	107	94	61
77	283	130	96	64	256	127	94	64
78	282	129	95	63	251	110	94	64
79	279	128	96	63	250	113	92	58
80	276	116	95	63	250	125	94	64
81	275	109	94	63	249	125	93	60
82	275	115	94	63	249	109	92	59
83	274	112	94	63	249	113	93	60

84	273	126	93	63	247	108	92	59
85	272	111	94	63	247	124	93	63
86	270	110	93	63	242	122	92	59
87	267	124	94	62	241	105	93	63
88	266	124	94	62	241	105	93	63
89	265	124	93	62	239	104	92	63
90	264	123	94	62	238	104	92	62
91	264	123	94	61	237	120	91	58
92	262	123	94	61	237	119	91	58
93	262	107	93	61	236	119	92	62
94	262	107	93	61	236	119	92	62
95	260	106	92	61	235	119	91	58
96	260	121	92	61	234	118	91	58
97	260	122	93	61	232	117	92	62
98	258	106	93	61	231	117	92	62
99	257	116	92	60	231	112	91	60
100	256	118	93	60	229	114	91	61
101	254	119	92	59	228	98	91	61
102	252	117	92	59	227	115	91	61
103	251	118	92	59	226	113	91	61
104	250	114	92	59	226	97	90	60
105	246	114	91	59	225	111	89	56
106	246	100	91	59	225	114	90	60
107	244	116	90	59	224	96	89	55
108	242	98	91	59	222	91	90	60
109	241	98	89	59	222	110	88	55
110	240	114	89	58	219	112	89	60
111	237	101	89	58	217	99	87	53
112	235	93	90	58	216	92	88	56
113	234	109	89	58	216	111	87	54
114	232	96	88	58	215	94	87	54
115	231	94	89	58	211	106	88	59
116	231	108	89	58	209	105	88	58
117	229	108	88	58	209	85	88	58
118	229	108	89	58	208	105	88	58
119	228	106	89	58	208	99	87	58
120	227	107	89	57	208	100	87	56
121	227	107	88	57	207	105	87	56
122	227	102	88	57	207	100	87	58
123	227	102	88	57	207	100	87	58
124	227	103	88	57	206	103	87	57
125	226	102	88	57	206	104	87	57
126	224	106	89	57	206	104	87	58
127	222	106	88	57	203	103	85	51
128	220	86	88	57	203	87	87	58

129	219	105	88	56	201	102	86	57
130	219	104	87	56	199	101	86	57
131	217	89	86	56	199	102	85	52
132	215	96	87	56	198	83	85	55
133	215	103	86	56	198	94	86	57
134	214	103	86	56	197	80	86	57
135	212	95	86	56	196	83	85	54
136	210	84	85	56	195	93	84	51
137	210	92	86	56	195	100	84	53
138	208	84	85	56	195	100	83	50
139	207	101	86	56	194	91	83	49
140	207	91	86	56	191	89	84	53
141	206	81	85	56	189	79	85	56
142	204	100	84	55	189	89	83	53
143	204	100	85	55	188	98	84	56
144	204	90	85	55	188	88	84	56
145	202	90	84	55	187	87	83	52
146	202	99	84	55	186	97	83	52
147	202	88	85	55	186	97	84	56
148	202	99	85	55	186	75	82	49
149	201	99	84	55	185	77	84	56
150	201	99	84	55	184	96	84	56
151	200	80	85	55	184	96	84	56
152	199	98	85	55	183	84	83	55
153	199	98	85	55	183	96	83	55
154	199	98	85	55	183	96	83	55
155	198	98	85	54	182	84	83	55
156	197	86	83	54	182	95	82	51
157	197	97	84	54	182	95	81	48
158	196	86	84	54	181	95	81	47
159	195	97	84	54	181	77	83	55
160	195	97	84	54	181	77	82	51
161	195	78	83	54	181	95	83	55
162	194	96	84	53	179	94	83	55
163	194	96	84	53	178	94	83	55
164	194	76	84	53	178	94	83	55
165	193	96	83	53	178	82	82	55
166	193	96	84	53	177	94	82	55
167	193	96	84	53	177	94	82	55
168	193	96	84	53	177	93	81	48
169	193	96	84	52	176	93	81	48
170	192	96	82	52	176	93	82	55
171	192	95	83	52	176	93	82	55
172	191	78	82	52	176	93	82	55
173	191	78	83	52	176	93	82	54

174	190	83	82	51	176	74	81	50
175	190	93	83	51	176	92	82	54
176	188	92	81	51	175	91	81	53
177	187	92	81	51	174	72	81	53
178	186	91	82	51	173	89	79	47
179	185	75	82	51	173	79	81	53
180	185	91	82	51	173	79	81	53
181	184	80	82	51	172	90	80	49
182	184	80	82	50	171	89	80	49
183	182	89	81	49	171	70	79	46
184	182	89	81	49	170	88	80	52
185	182	89	80	49	169	68	80	52
186	182	73	81	49	168	87	80	52
187	181	87	81	49	168	87	80	52
188	179	87	80	48	168	68	78	45
189	178	71	80	48	168	87	80	52
190	178	77	80	48	168	76	78	48
191	178	77	79	48	167	75	78	48
192	177	77	79	48	167	85	77	44
193	176	84	79	48	166	75	78	48
194	176	75	80	48	166	74	78	47
195	175	69	80	48	166	85	77	44
196	174	84	79	48	164	69	79	51
197	174	84	79	48	164	67	78	48
198	174	78	78	48	163	82	79	51
199	174	68	79	47	163	77	79	51
200	173	78	78	47	163	73	77	45
201	172	74	78	46	162	67	77	47
202	172	69	78	46	162	76	78	48
203	171	77	78	46	162	82	77	44
204	170	68	78	46	162	82	76	44
205	169	67	77	46	161	66	77	48
206	169	72	78	46	161	66	76	44
207	169	73	78	46	161	65	77	46
208	168	68	77	46	161	67	76	44
209	168	67	77	45	161	67	76	44
210	168	68	77	45	161	66	77	46
211	168	67	77	45	161	66	76	44
212	168	80	77	45	160	76	76	44
213	167	71	77	44	160	71	76	44
214	167	67	77	44	160	72	76	43
215	167	67	77	44	159	66	76	46
216	167	65	76	44	159	71	77	49
217	166	67	76	44	156	78	76	44
218	165	71	77	44	156	70	76	45

219	164	70	77	44	156	69	76	45
220	164	70	76	44	156	69	76	45
221	161	65	77	44	154	64	75	43
222	160	75	75	44	154	62	74	43
223	160	64	75	44	154	64	74	43
224	160	64	75	44	153	64	74	42
225	159	62	75	44	153	61	75	47
226	158	62	75	44	150	74	74	41
227	157	67	74	44	150	66	74	44
228	156	66	75	44	149	60	74	44
229	156	66	75	43	149	59	74	44
230	155	66	75	43	149	59	73	41
231	155	72	75	43	149	66	74	43
232	155	72	74	43	149	66	73	41
233	154	60	74	43	149	59	73	41
234	153	62	74	43	148	65	73	41
235	153	60	74	43	148	61	74	46
236	153	60	74	43	147	61	73	41
237	153	65	73	43	146	60	74	46
238	153	60	73	43	146	64	73	41
239	153	61	73	42	146	64	73	43
240	152	64	73	42	145	71	73	43
241	151	60	73	42	145	71	72	41
242	150	64	73	42	144	57	72	42
243	149	63	73	42	144	63	72	42
244	148	58	73	42	143	62	72	40
245	147	68	73	41	141	58	71	40
246	146	67	73	41	140	61	72	44
247	146	67	72	41	139	66	71	41
248	146	61	72	41	138	60	72	44
249	146	58	72	41	138	60	72	44
250	144	61	72	41	138	66	71	41
251	144	61	72	41	138	66	71	41
252	144	60	72	41	138	60	71	41
253	142	65	72	41	135	59	71	43
254	142	65	72	40	135	55	71	43
255	140	59	71	40	134	64	70	40
256	139	59	71	40	134	64	69	38
257	139	55	70	40	134	53	70	40
258	139	58	70	40	134	58	69	38
259	138	58	70	40	133	58	70	40
260	138	54	70	40	133	57	69	40
261	138	57	70	38	133	53	69	40
262	136	61	70	38	132	57	69	37
263	136	53	69	38	132	53	68	37

264	135	53	69	38	130	61	69	41
265	131	55	68	38	127	54	68	38
266	127	53	67	37	122	52	66	37
267	126	52	67	37	121	52	66	37
268	118	47	64	34	115	47	64	34
269	109	43	62	33	107	43	61	32
270	104	45	61	32	101	45	60	33
271	98	42	58	32	96	42	58	32
272	66	27	45	22	65	27	45	22
273	56	23	40	19	55	23	40	19
274	56	23	40	19	55	23	40	19
275	55	23	40	19	55	22	40	19