University of Southern Queensland

Faculty of Health, Engineering & Sciences

Locating Low Voltage Underground Power Cable Faults Using Infrared Technology

A dissertation submitted by

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ENG4111 and ENG4112 Research Project

towards the degree of

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Abstract

There are many ways to locate low voltage underground cable faults, however most of these require access to the cable to be tested. Networks need to have staff that can respond to faults in a timely manner in order to restore supply to homes and businesses quickly. Thermography uses a camera to detect different levels of infrared radiation in order to construct an image of the heat detected on a surface being surveyed. This process has been used primarily on objects that give off heat directly, such as overhead lines and open switchboards.

This project has proposed a method to combine thermography with underground cable fault location techniques. The proposed method differs from the traditional use of a thermal camera since the target being surveyed is generally 600 to 800 millimetres below the ground. It is theorised that the heat generated from the fault current will heat the ground and thermally conduct to the surface, where the infrared radiation will be given off and detected by the camera.

To determine the viability of using this new technique, surveys were performed on low voltage distributors that had recently failed. These thermal images were then compared to the traditional fault locations to determine how accurate they were in locating the low voltage faults.

There can be enough heat generated in certain circumstances to detect a thermal hot spot on the ground. This method, like many traditional methods, does have its limitations. Rain, wind and amount of fault current all play vital roles in the ability of this technology to perform accurately.

The surveys performed showed that the technology can be used to locate underground faults in this manner. It has also highlighted the need for further research and experimentation in these fields. Having a safer method of locating faults will always be of benefit to all stakeholders.

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Limitations of use

Certification of Dissertation

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

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

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Signature

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I would also like to thank my friends and study group, Matthew, Nick, Stefan and Harrison. Thank you for the assistance and keeping the motivation up, without your help, I would not have reached this point.

I would especially like to thank my wonderful wife, Erin. Your support and encouragement have allowed me to continue with my degree. Thank you for spurring me on when I needed it the most. Without your love and support, this project would never have been possible.

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Table of Contents

Table of Figures

Abbreviations and Acronyms

The following abbreviations and acronyms have been used within this thesis:

CIG	Cable Identification Generator
CIR	Cable Identification Receiver
DC	Direct Current
EPR	Ethylene Propylene Rubber
HAC	Hazard Assessment Checklist
HV	High Voltage
LV	Low Voltage
PILC	Paper Insulated Lead Covered
POPIE	Pool of Potential Indicating Equipment
PPE	Personal Protective Equipment
SCC	Sydney County Council
SIM	Secondary Impulse Method
MIM	Multiple Impulse Method
TDR	Time Domain Reflectometry
TSB	Thermally Stable Bedding
Vp	Propagation Velocity
XLPE	Cross Linked Polyethylene

Chapter 1 Introduction

1.1 Background and Justification

Ausgrid's network was originally a conglomeration of the individual county councils around Sydney and the Central Coast. It included Sydney County Council, Mackellar County Council, and St George County Council to name a few. Each of these councils had their own way of installing cabling and adopted different ways of terminating and distributing power. These councils were all merged together in 1996 to form EnergyAustralia (Sydney County Council, 2007), that was later rebranded to Ausgrid once the retail arm was privatised.

Today, Ausgrid's network spans 22,275 square kilometres and encompasses Sydney, the Central Coast, Newcastle and the Hunter Valley (Ausgrid, 2023). There are thousands of kilometres of underground cables connecting substations and customers at various voltage levels and installation types. Faults on this network occur on a daily basis and can be caused by many factors. The age of the cable, external damage to cables and moisture ingress are all common factors to underground cable faults.

Since the application of an infrared camera for the purposes of locating underground faults on the low voltage network has not been widely documented, this thesis can be used to determine the feasibility of using the current technology in a new method. The data collected from the thermal survey will be compared to traditional fault location equipment and used to determine the suitability of using infrared cameras for this purpose.

If this project can successfully determine that the use of the infrared camera can be utilised to locate underground low voltage cable faults, then the process of fault location can be completed more efficiently. This will enable customers to have their power restored quicker, reducing outage times and potential fines for electricity distribution network owners.

This technology can also be used proactively. Once a faulty section has been identified, before the fuses have operated, a survey can be completed and if successful, a planned outage can be undertaken to repair the damaged cable. This has the added advantage of alerting customers to the issue before a major outage and ensuring the resources are available to repair the fault in a timely manner.

This project will look at both reactive and proactive use of the infrared camera and determine the feasibility in both scenarios. It is intended that this research will be a starting point in this area of fault location and further research can be conducted on this topic.

1.2 Project Outline

Locating underground cable faults has been required since the first cables were laid in the 1880s. Since this time, fault location techniques have evolved from simple resistance methods to sophisticated computerised and automated processes. These improvements have allowed cable faults to be detected, repaired and returned to service much quicker than previously possible (HV Technologies Inc, 2023). By speeding up this process the outage time can be reduced, saving cost for the organisation and the affected customers.

This dissertation will explore the use of thermal imaging to locate underground cable faults on the low voltage network. Experimental data with a thermal camera can be gathered and compared with the results of traditional cable fault location techniques to determine the accuracy and reliability of using this equipment for pinpointing faults (Elkateb, 1978). This form of fault locating relies on the premise that a large amount of heat energy is generated from the ongoing fault current, and a temperature difference can be detected above the location of the fault.

1.3 Current Problems with Access to the Network

Due to the variation of cable types and installation styles utilised on Ausgrid's network, it is impossible to have one method to locate all types of faults (Elkateb, 1978). Due to this, there are multiple techniques used to find underground cable faults and various pieces of equipment can have varying degrees of success locating faults. To ensure a correct fault location is given, it is best practice to prove the location with multiple pieces of equipment and, if practicable, different fault location techniques (Clegg, 2004).

With so many different types of faults that can be encountered on the network, it is vital that adequate test equipment is available on the job site. It is also necessary for the fault to be diagnosed correctly from the start. This can be achieved by having experienced staff on site to accurately perform the fault diagnosis and apply the correct equipment and methodology (Elkateb, 1978).

Accessing the low voltage network has its own set of issues. Although the faulty cable is isolated, adjacent cables in link boxes and pillars are still energised. Application of temporary insulation is required to ensure unintentional contact by people or equipment does not occur (Ausgrid, 2022). Access permits for testing are required before any work can commence. This ensures the isolation of the faulty cable has been completed and documented for the fault location crew.

These processes around accessing the network and issuing permits, take time before the fault location process can occur (Ausgrid, 2022). By not having to access the network or having to come within minimum safe working distances, fault locations can be sped up and cables can be returned to service quicker than the current processes. Being able to locate faults in this manner eliminates the requirements to isolate the network and issue the required permits.

1.4 The Aim of the Project

This project aims to determine the feasibility of using infrared technologies to locate low voltage underground faults. To determine the feasibility, data will be gathered by surveying the route above a faulted low voltage cable on Ausgrids' low voltage network. The intention of performing these surveys on the different cable type and installation types, is to determine the suitability of this technology under the different scenarios.

It is hypothesised that the heat generated by the fault should create a "hot spot", or temperature gradient, above the fault. The infrared camera will then be able to detect a difference in temperature along the route of the cable. This point can then be checked against the network plans to determine if a faulty joint could be responsible for the fault. This data will then be recorded and collated in a table format as shown in Chapter 4.

Traditional fault location methods can then be used to determine the fault location, which will then be compared to any hot spots discovered during the thermal imaging survey. This method will confirm the accuracy of the thermal survey compared to the traditional fault location techniques, which will be used as a baseline. If the traditional fault location methods and the thermal survey provide the same fault location, then this data will also be recorded in the data table in Chapter 4.

1.5 Objectives of the Project

The proposed objectives for this project are:

- Conduct research on fault location techniques currently utilised on Ausgrid's low voltage network.
- Conduct research on thermal imaging and how it is currently utilised in the fault location industry.
- Record and table the collected data from the infrared camera survey.

- Analyse the data and determine the effectiveness of the infrared camera for locating low voltage cable faults.
- Determine suitability of thermal imaging as a standalone fault location technique.

1.6 Thesis Outline

Chapter 1 in this thesis outlines the aims and objectives of this project. It also outlines the reasons why this research is important and the current issues with traditional fault location methods. These include accessing the network in a timely manner and a requirement to access the network live.

Chapter 2 includes a literature review of the current fault locating methods and how they are applied in industry. It also includes a literature review of infrared thermography and how it is currently used in locating faults on the transmission and distribution networks.

Chapter 3 explains the test methodology used within this project. This chapter also documents how sites are selected and the different types of faults that are being examined in this project. Chapter 3 also looks into the protection devices used on the low voltage network and the operating capabilities.

Chapter 4 documents the data collected from the surveys and the analysis of this data. This chapter analyses the sites surveyed and compares the infrared camera images with the traditional fault location results. This section delves into the use of the camera and discusses the benefits and limitations of using this type of fault location.

Chapter 5 discusses the data and how it can be applied to the industry. It also considers the safety applications and how it can reduce costs to businesses by reducing the risk of performing these tasks.

Chapter 6 of this thesis discusses further work that can be carried out by other researchers in this field. It covers topics and additional data points that were not covered in this project and discusses areas of improvement that were found whilst undertaking this thesis.

Chapter 2 Literature Review

2.1 Overview

To further understand the subject material, a literature review has been conducted on the topics of Fault Location and Infrared Thermography. This literature review intends to gather supporting evidence for this project in order to justify this project and further the research in fault location of underground cables.

This literature review will show a dearth of literature on current fault location techniques and infrared thermography. The use of infrared thermography has not been documented for finding underground cable faults due to the limitations of the infrared radiation and how it is detected and processed by the infrared camera.

Research will be conducted on current fault location methods and the processes and procedures currently employed. Research will also be conducted on the installation methods of low voltage underground cables and how these installation methods can affect the heat transfer through the ground.

The construction of low voltage cables and the various types of cables used within Ausgrid's low voltage network will be researched. This will allow this project to examine how the type of cable can help or hinder the transfer of heat from the fault to the ground for the infrared camera to capture. The causes of cable faults and the variety of cable faults can also be examined to determine if a link exists between the fault type and the heat generation.

The current uses of infrared thermography and how it currently applies to Ausgrid's high voltage and low voltage networks will be examined. This will create an understanding of the limitations of this technology in order for it to be appropriately applied to locating faults on the low voltage network.

2.2 Identification of a Knowledge Gap

Initial research on locating underground faults using infrared technology, have shown that there is very little information on this method of fault location. Infrared technology is used in many industries and used to determine the temperature of any object. In the electrical industry it is used to determine high resistance connections on apparatus, such as:

- Open covered switchboards.
- Overhead power lines.
- Overhead air break switches.
- Exposed underground links.

These situations all utilise the camera's ability to have direct visibility of the apparatus to be surveyed, in order to capture the infrared radiation emitted from the target. This project differs in this approach, as the target will be buried, and the infrared measured will be radiated through the ground. Figure 1 below shows how the heat gradient is detected by the thermal camera. The bar on the right of the image shows the maximum and minimum temperatures. The white patch in the image indicates a temperature of 16.8^{o}C. As the colours change down the spectrum the temperature drops to approximately 12^{o}C. This colour gradient indicates a heat source under the ground and, in this situation, has conducted through the concrete to the surface.

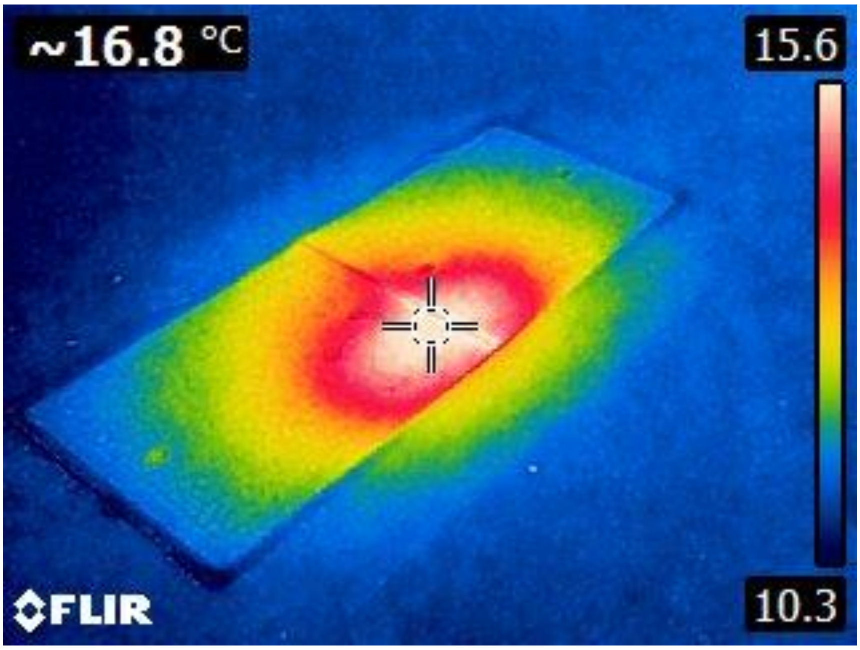

Figure 1 Surveying Area Above Fault for Heat Differential

2.3 Low Voltage Cable Design and Installation

To ensure a reliable network, underground cables are required to be constructed to appropriate standards. Low voltage polymeric cables must comply with AS/NZS 5000.1-2005 Electric cables – Polymeric insulated – For working voltages up to and including 0.6/1 (1.2) kV (Standards Australia, 2017). This standard specifies the construction, dimensions and test requirements for single core and multicore cables (SAI Global, 2005).

The conductor material for underground cables is usually copper or aluminium. These materials are readily available and are easy to work with since they are two of the most malleable materials available. Copper has traditionally been used since it has a low resistivity, is readily available, easy to work with, and more cost effective than other materials. In recent years, aluminium has become popular due it being lighter than copper. Since the resistivity of aluminium is higher than copper, the conductor size is much larger to allow for the same current carrying capacity. Table 1 below shows the comparison of different conductor metals resistivity and conductivity (Helmenstine, 2019). Although silver has a much lower resistivity, to use a rarer material would make the cost of cable construction too prohibitive.

Table 1 Resistivity and Conductivity of Conductor Metals (Helmenstine, 2019)

Material	ρ (Ω•m) at 20 °C Resistivity	σ (S/m) at 20 °C Conductivity
Silver	1.59×10^{-8}	6.30×10^{7}
Copper	1.68×10^{-8}	5.96×10^{7}
Annealed copper	1.72×10^{-8}	5.80×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminium	2.82×10^{-8}	3.5×10^{7}
Iron	1.0×10^{-7}	1.00×10^{7}
Platinum	1.06×10^{-7}	9.43×10^{6}
Lead	2.2×10^{-7}	4.55×10^{6}

Heat is a major factor in deciding the conductor size and installation method. Ausgrid requires that any cable directly buried into the ground are backfilled with thermally stable bedding (TSB) (Ausgrid, 2020). This thermally stable bedding is used to help the cable evenly distribute the heat generated within the cable to the surrounding earth. This should also reduce hot spots forming within the cable and help prolong the life of the distributor.

2.4 Construction of Underground Cables

Underground power cables are generally constructed to ensure a conductor is wrapped in insulating material, bundled together with other phases and surrounded with another insulating material. In some cases a metallic wire or screen can be used to provide mechanical strength to the cable (Amprion GmbH, 2023).

The main cores can be either copper or aluminium, depending on the current requirements, weight restrictions, or physical size of the cable restrictions. Since copper has better thermal properties than aluminium, and conducts power better than aluminium, an aluminium conductor needs to be significantly larger for the same rating as a copper conductor (Pellew, 2020).

Aluminium cables also have a greater voltage drop compared to copper cables. This factor is the reason why aluminium cables are much larger than the copper conductors for the equivalent ratings. Figure 2 below shows the voltage drop for copper and aluminium conductors and emphasises the difference between them over 100 metres.

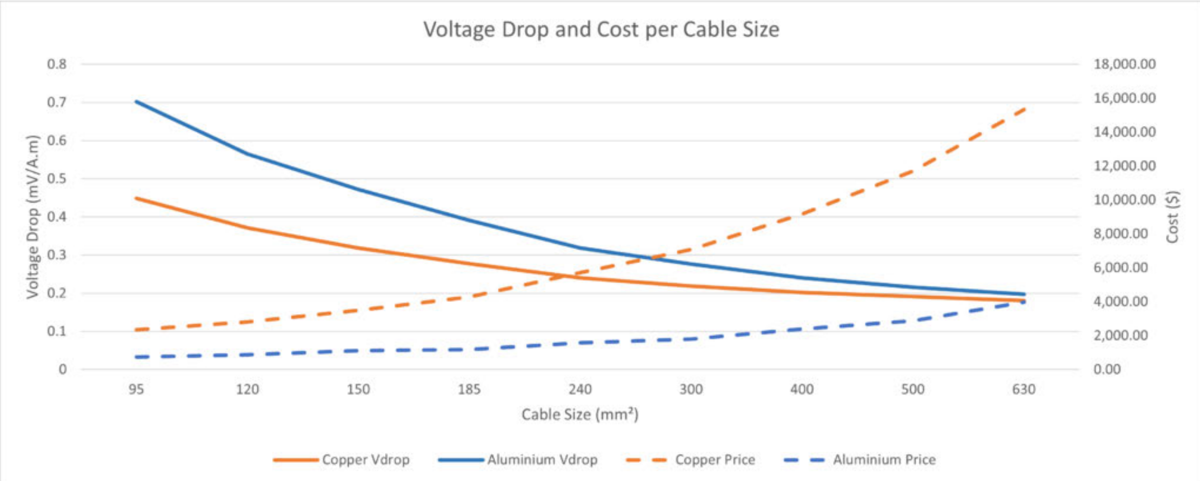

Figure 2 Voltage Drop for Copper and Aluminium Cables (Pellew, 2020).

The two main insulation mediums used on low voltage underground cables are:

- Oil impregnated paper with a lead sheath.
- Plastic insulated, either unsheathed or with a copper wire sheath.

Paper Insulated Lead Covered (PILC) cables were first installed in 1890, and have been used until 1960 when Ethylene Propylene Rubber (EPR) and Cross-linked poly-ethylene (XLPE) cables were first produced (de Kock & Strauss, 2004). Many paper cables are still in service on Ausgrid's network and the cable type will be recorded in this project.

The metallic sheath found on some low voltage cables can be solid aluminium, solid lead or stranded copper. In some cases the low voltage cables can have three conductors and the aluminium sheath is used as the neutral. A filler material such as hessian tape is used to fill gaps usually between the cores. This allows the outer sheath to be rounded and produce a more uniform cable (Clegg, 2004).

2.5 Types of Underground Cable Faults

A cable fault can be described as a weakness or defect that effects the overall function and reliability of the cable (Clegg, 2004). There are a variety of different types of cable faults, which are dependent on the type of cable installed. Some of these fault types include:

- Contact Fault – A short circuit between a core and another core or the metallic sheath (Elkateb, 1978).
- Ground Fault – A failure in the outer sheath which allows the main cores to come into contact with the earth. This occurs when cable do not have a metallic sheath (Clegg, 2004).
- Open Circuit – A failure in the core, where the conductor is no longer continuous between the ends. Usually a sizable resistance is measured across the gap created by the break (Elkateb, 1978).
- High Resistance – A failure in the cable where the resistance of one conductor is significantly different from the others. This can happen when a cable is pulled or strands on the conductors are broken (Clegg, 2004).
- Transitory Faults – These failures are more commonly found on low voltage networks, where a fuse will operate and upon reinstatement will hold. This type of fault can be caused due to intermittent arcing, which will draw excessive current (Clegg, 2004).

It is also possible to have combinations of these faults. An open circuit fault may also have burnt through to ground, creating an open circuit and an earthed contact fault. In these situations, different fault location techniques can be used. Figure 3 below shows the different fault arrangements that can be found on a low voltage network.

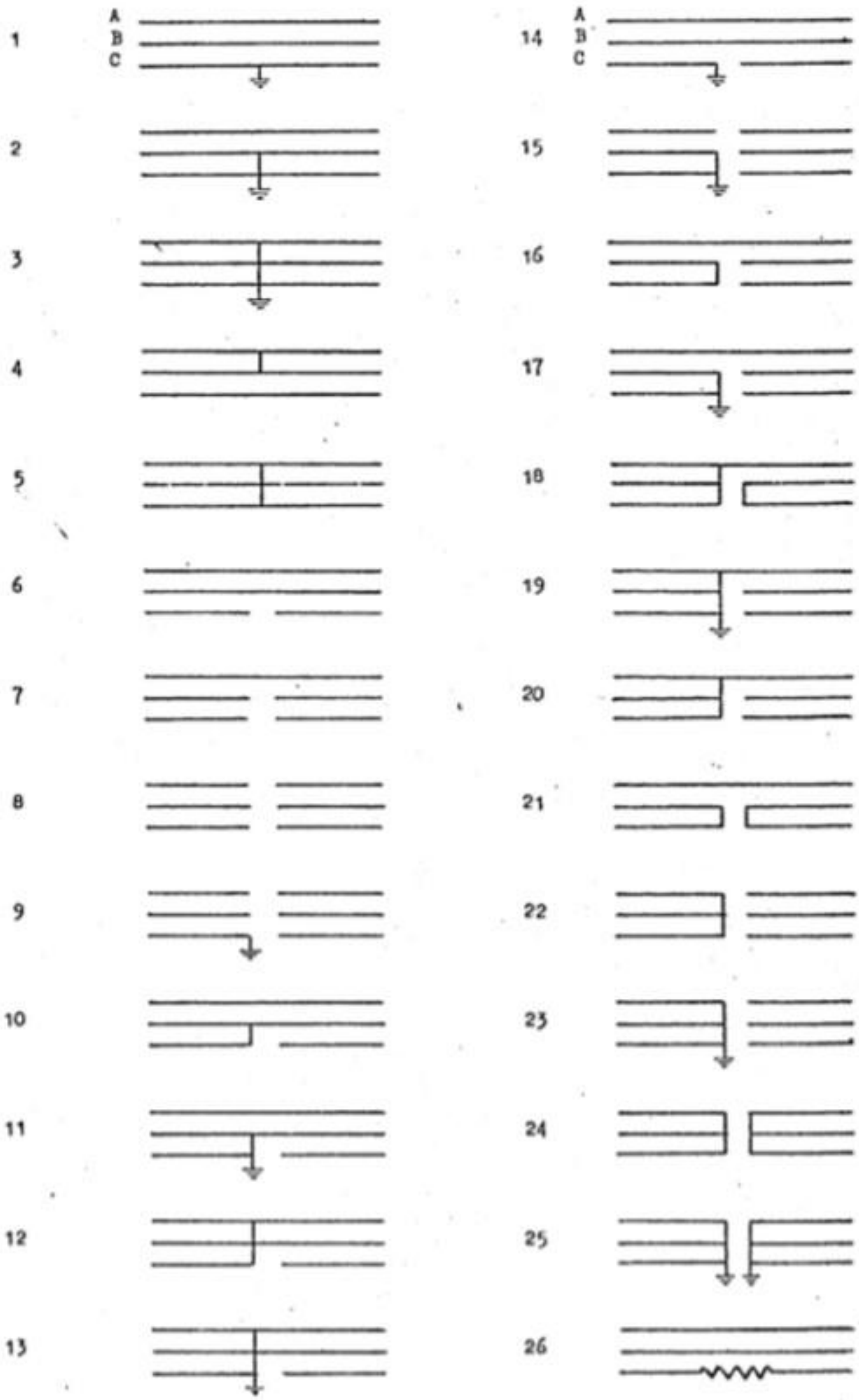

Figure 3 Arrangement of Cable Faults (Elkateb, 1978)

2.6 Reasons for Cable Faults

There are many reasons underground cables fail and understanding theses helps to identify potential issues and may allow the faults to be repaired and returned to service quickly. Cable failures can occur at various times during the cable's life and can be caused naturally and from external influences. Some of these factors include:

- Damage during cable installation – Cables can fail before they are energised. When cables are installed in conduits, care must be taken to ensure the conduits are clear of small stones and dirt, and no sharp edges at the conduit connections. Tension on the cable being pulled, must not exceed the manufacturer's specifications as these factors can cause faults in the outer sheath creating earth faults or high resistances in the screen or cores (Clegg, 2004).

- Poor jointing kits or techniques – Faulty jointing kits or using the wrong type of kit can lead to failures within the joint or in the cable. If the kits do not seal the cable fully, water can ingress to the joint causing a failure. Water can also seep into the cable, requiring extended lengths of cable to be replaced. Poor jointing techniques can also lead to similar failures. Heat shrink must be installed to correctly seal the cable and no sharp edges must be left as this will cause earth faults.

- Environmental effects – The location of the cable is a factor in the longevity of the cable. It is important to ensure cables are installed to minimise impacts from tree roots, vibration, termites and other animal damage, along with the weather where the cable is terminated (Clegg, 2004).

- Poor Network Control – The low voltage network will often be placed in parallel. This means a different substation will provide power to another substation's distributor. This is achieved through switches, links or bonds on the network, and usually happens when part of the network fails. In some situations, parallels can be left in circuit after a fault is repaired and may cause two or more substations to supply the same distributor. If a fault starts to occur on the distributor it will draw current from all points of supply, meaning that excessive current will be supplied to the fault before the protection will operate. Faults that develop like this can burn large lengths of cable, particularly paper insulated cables, where the oil dries out and the paper insulation becomes brittle.

- Third Party Damage – Underground cables are laid in the public space and can easily be damaged when connecting to electrical services or other nearby services in the ground. A common cause of damage is from directional borers and excavations. In these scenarios, a fault location is not usually required. Occasionally the cable will remain in service and will fail at a later time due to moisture ingress (Clegg, 2004).

2.7 Low Voltage Protection Device

Low voltage distributors are protected by 400A HRC fuses which are designed to operate under fault conditions. These fuses protect the low voltage distributor by operating when the current exceeds the fuse rating. The point of fuse operation is dependant on the amount of current flowing over a length of time.

Figure 4 below shows the time current curves for different size fuses. This project will be looking at the 400A fuses and this image shows how the more current flowing through the fuse, the faster the fuse will operate. If a fault draws 1000A for 100 seconds, the power of the fault can be calculated to be:

$$P = VI = 240 \times 1000 = 240kW$$

This power would be heating the ground for 100 seconds before the fuse was to operate, which may cause a hot spot for the thermal camera to detect.

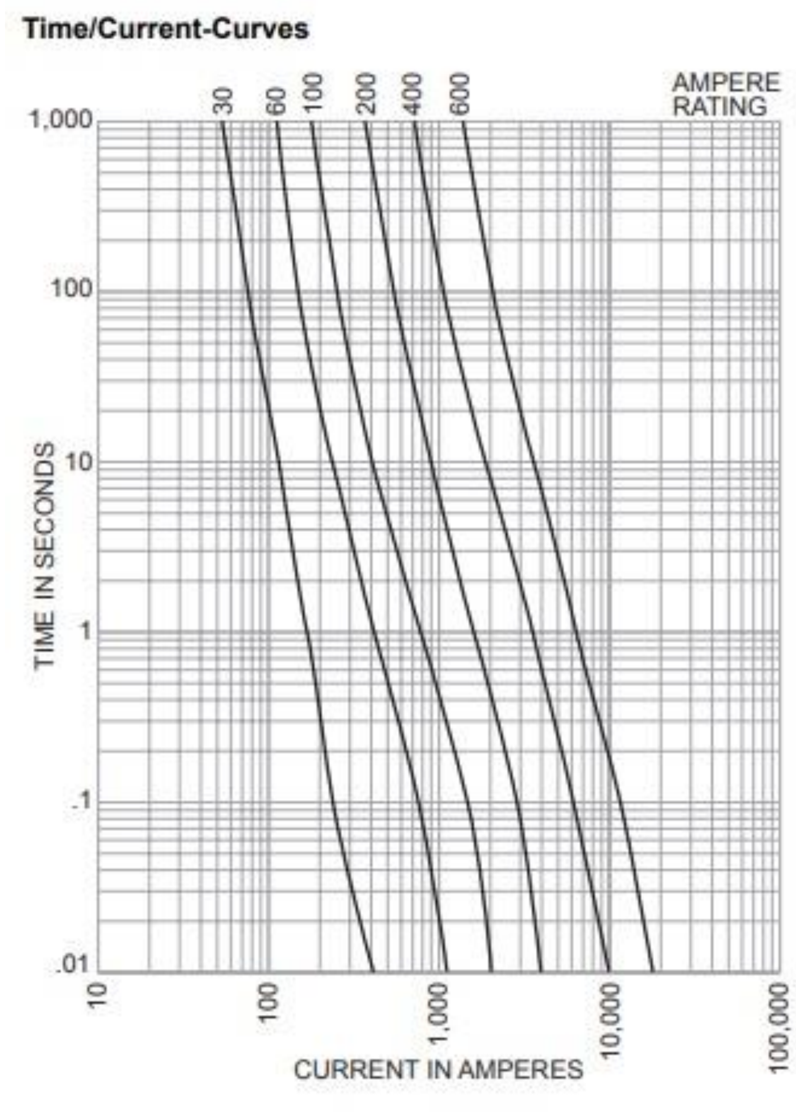

Figure 4 Time/Current Curves for HRC Fuses (Cooper Bussman, 2018)

2.8 Traditional Fault location

The traditional fault location process can be broken down into several logical steps. Following a process helps to ensure a correct method is followed and no incorrect assumptions are made. These steps include:

- Diagnosis
- Primary Location
- Secondary Location

2.8.1 Diagnosis

The first step in locating a fault is to determine the type of fault that has formed on the cable. Using an insulation resistance tester (IRT) and multimeter can help determine the continuity of the conductors and the insulation of the cable. A continuity test will determine if there is an open circuit or high resistance fault. An insulation test can determine if the fault is to earth or between cores, and the value of the fault resistance. This step will determine which fault location methods can be applied.

2.8.2 Primary Fault Locations

Primary fault locations are used to narrow down the search for a fault. Cables can be any length from metres to hundreds of kilometres. Locating a fault on these cables would be impossible without being able to narrow down the search area. The following primary fault location methods are the most common techniques used on underground cables.

2.8.2.1 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) is based on the measurement of time between an electrical pulse and the reflections of the pulse from changes of impedance along the length of the cable (Camufffo, 2019). By measuring these changes, primary fault locations can be undertaken on faults that have insulation properties that are significantly different from the other conductors within the cable. It is a particularly good method of locating open circuit faults and faults with an insulation resistance of less than 50 ohms.

If the length of the conductor is known, a measurement can be taken to determine the propagation velocity of the cable under test. This velocity will be the average speed a pulse takes to travel from the unit to the end of the cable and return. The equation below shows how the propagation velocity (V_p) can be calculated.

$$V_p = \frac{2L}{t}$$

In this formula, L is the length of the cable and t is the time of the pulse. For a cable of 100 metres, and a time measured of 1.25 µsec, the propagation velocity can be calculated to be 80 m/ µsec. This velocity would then be used on any time based fault location (Camufffo, 2019).

The propagation velocity is dependent on the dielectric of the cable under test, which is why it is important to measure the velocity of each cable before commencing any fault location. Since cables can be jointed together with a variety of different cable sizes, insulation types, and lengths, the velocity will rarely be the same for any two cables. The table below shows common propagation velocities for different dielectrics.

Table 2 Propagation Velocities for Cable Dielectrics (Clegg, 2004)

Dielectric	**Velocity of Propagation (m/µs)**
Oil Impregnated Paper	150 - 171
Dry Paper	216 - 264
Polyurethane	Approx. 200
XLPE	156 - 174
PVC	152 - 175

Figure 5 below shows typical traces obtained from a time domain reflectometer. From these traces, open circuit faults can be identified from the sharp rise of the trace. This shows how large impedance rises are indicated by peaks, where lower impedances and indicated by troughs in the trace.

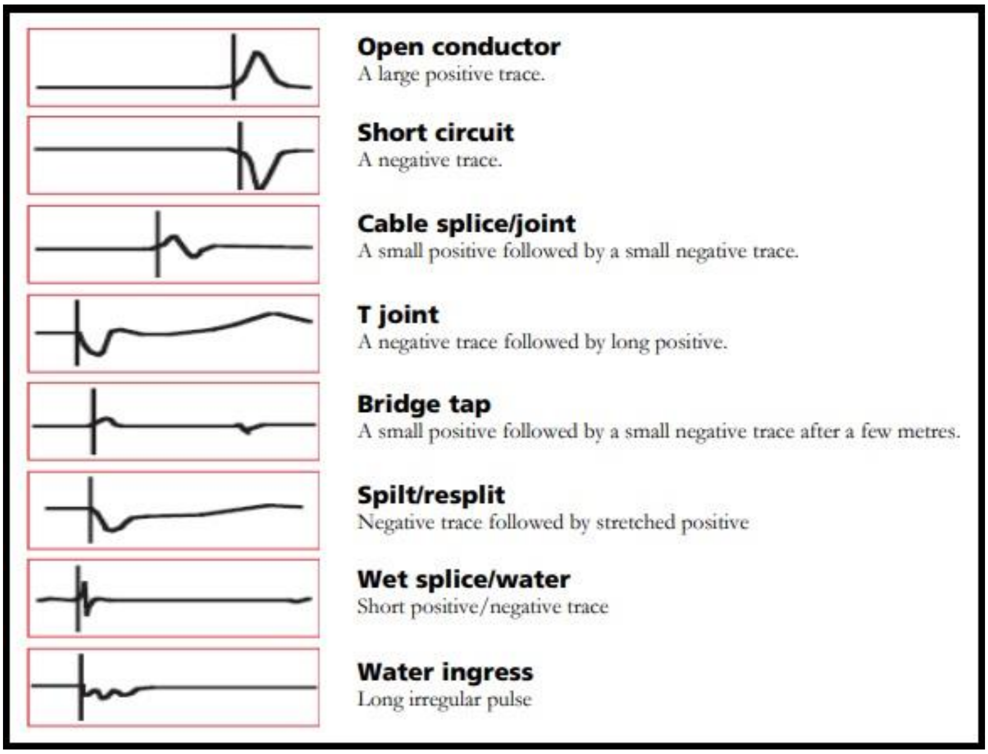

Figure 5 Typical Traces Using a Time Domain Reflectometer (Megger.com, 2023)

Although a time domain reflectometry is excellent at finding open circuit and short circuit faults, the trace can be distorted due to many factors. Multiple tee joints in a short space can create overlaps in the trace which can be summative and make accurately reading the trace nearly impossible. The length of the cable under test can also cause the signal injected by the reflectometer to degrade before it reaches the fault. This can be particularly true on long transmission cables (Clegg, 2004).

2.8.2.2 Arc Reflection Methods

Arc reflection methods or impulse methods, couple time domain reflectometry and the application of high voltage to obtain a fault location. Impulse methodology relies on an arc being produced at the fault site. For this to occur, the insulation resistance must be higher than the 50 ohms required from the time domain reflectometry method.

The first step in performing an impulse method fault location is to gain an initial trace of the cable. This trace should show the initial impedance change from the test lead to the cable under test and the cable terminations at the far end. It may also show joints along the route of the cable as shown in Figure 5 above.

A high voltage pulse is then sent along the cable which triggers either one or multiple low voltage pulses to be sent from the time domain reflectometer. The high voltage pulse will arc at the fault site and the low voltage pulses will reflect a short circuit to the reflectometer unit. These traces can then be overlayed and the distance to the fault can be measured, using the same techniques as the time domain reflectometry method.

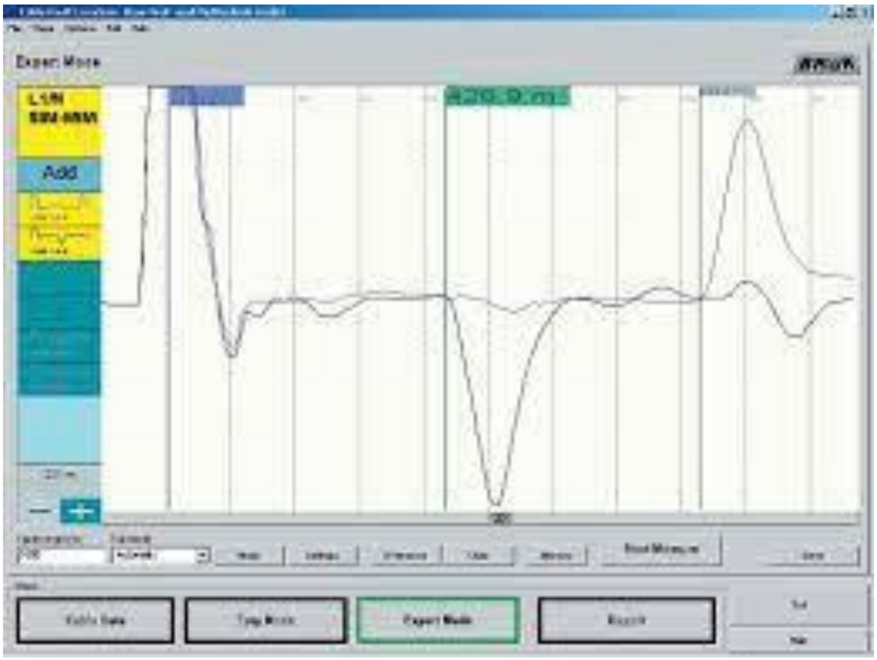

Figure 6 Fault location Using Impulse Method

Figure 6 above, shows the positive reflection indicating the end of the cable from the initial trace, and the negative reflection at the fault site, caused from the high voltage pulse.

2.8.2.3 Resistance Methods

Resistance or bridge locations were used to locate faults since the first cables were installed. These methods are based on the Wheatstone bridge circuit and are modified to locate cable faults instead of an unknown resistance. Figure 7 below shows how the Wheatstone bridge circuit is arranged. This circuit is balance when V_{out} is 0 Volts. This indicates that the current flow through R_1 and R_2 is equal to R_3 and R_4 and this only occurs when the resistances on either side of the voltmeter are also equal.

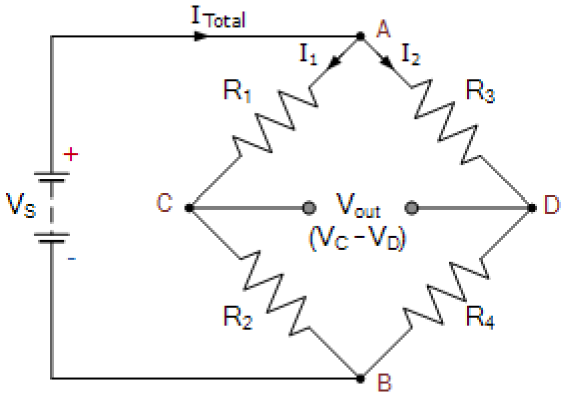

Figure 7 Wheatstone Bridge Circuit (Storr, 2022)

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} = 1\ (Balanced)$$

To locate faults with this circuit, R_1 and R_3 can be changed to a slide wire with a counter attached while R_2 and R_4 are cable lengths either side of the fault. By balancing the galvanometer, a ratio between the health core and the faulty core can be established and used to calculate the distance to the fault. This process can be seen in figure 8 below (EEEGuide.com, 2023).

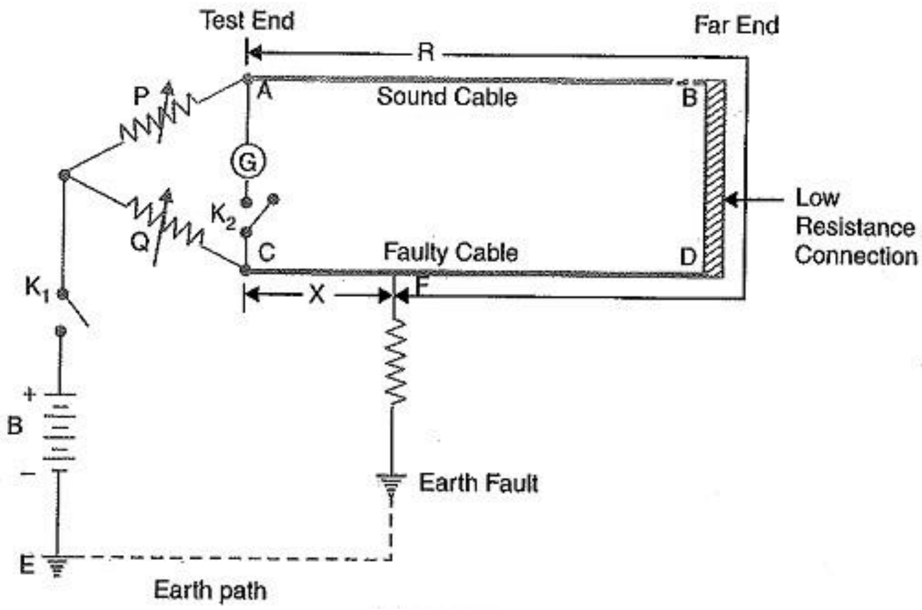

Figure 8 Murray Loop Circuit Diagram (EEEGuide.com, 2023)

This circuit is known as a Murray Loop circuit, and is used primarily to locate earth faults. There are three requirements to utilise this method.

- Continuity of the conductors to be used.
- The insulation resistance of the healthy conductor needs to be at least five times greater than the faulty conductor.
- Fault resistance low enough for stable current to flow.

Continuity is required for the current to pass from the test end of the cable to the far end of the cable and back to the fault on the healthy core, and from the test end to the fault on the faulty core. If current cannot flow, a location cannot be achieved.

To achieve an accurate fault location, the insulation resistance of the healthy conductor is required to be at least five times greater than the faulty conductor. This ensures maximum current flows through the fault intended to be located and a parallel path is not formed through the healthy conductor. Figure 8 above shows that current flows through X to reach the fault. If the insulation resistance of the health core (R) is too low, current will flow through both paths and the fault location obtained will be the average of both faults.

Stable current is required to be able to accurately locate a fault with this method. Unstable currents can be caused be heating of the fault due to current flow, movement of the fault causing fault resistance changes, or faults that are arcing when a high voltage supply is used to apply current. In these circumstances the balancing circuit will not be able to be balanced and an accurate location will not be achieved.

2.8.3 Secondary Fault locations

Secondary fault location methods are used to pin point a fault and determine a course of action to repair the fault. This may be to simply cut out an existing joint and piece in a new section of cable, or may require further work, including a road crossing or network upgrades to help reduce outages in the future.

2.8.3.1 High Voltage Impulse

This method of pinpointing a fault requires a capacitive discharge into the faulty cable to create an arc at the fault site. This method often uses a high voltage supply to charge a capacitor bank, which is discharged through a timed contact. This process is repeated to provide a constant pulse rate, usually 1 pulse for every 1 to 2 seconds. Depending on the nature of the fault, the pulse can sometimes be heard above the ground and can easily be located. Other times, acoustic equipment is required to hear the fault and to be able to pinpoint the fault accurately (Clegg, 2004).

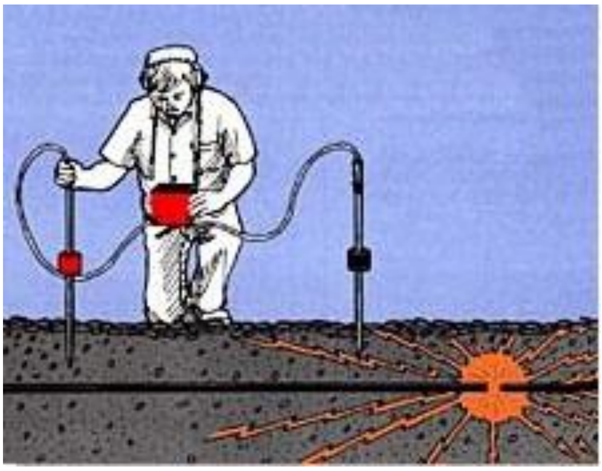

Figure 9 Pinpointing an Underground Fault (Unitest Instruments, 2023)

Figure 9 above shows how a fault will arc, creating an audible discharge at the fault site. The acoustic equipment will detect the magnetic pulse from the surge generator and also this discharge. The unit will then determine the direction to the fault from the time it takes for the sound to travel from the fault to each of the probes. In figure 8, the fault is closer to the black probe and the unit will indicate this, leading the fault locator in this direction until the unit gives the opposite direction (Unitest Instruments, 2023).

2.8.3.2 Pool of Potential Indicating Equipment (POPIE)

Pool of potential fault locating methods are only used on cables that are unscreened and where there is a direct path between the fault and the general mass of earth. This method of pinpointing faults requires the fault locator to have knowledge of the cable type and installation method of the cable under test. To successfully pinpoint a fault using this method, current is applied to the faulty conductor and pulsed to create an intermittent pool of potential at the fault site.

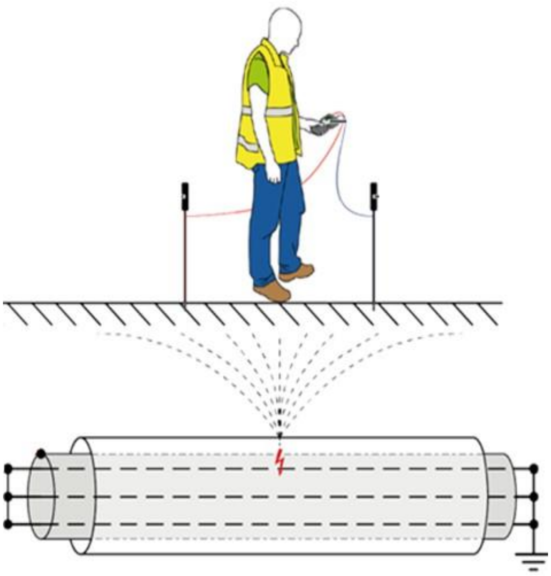

Figure 10 Pool of Potential Indicating Equipment (POPIE) (HV Technologies Inc, 2023)

At the fault site, the current applied creates a voltage differential from the fault. This voltage can be measured with a centre orientated voltmeter. When the fault is on the left of the fault locator, the voltmeter will swing to the left indicating a higher voltage on that side. When the fault locator is directly on top of the fault, the voltmeter will not move indicating zero volts across the probes (HV Technologies Inc, 2023). This method is particularly useful on cable sheath faults since there is only a PVC outer layer on the cable.

2.8.3.3 Audio Frequency Method

The audio frequency method is similar to the pool of potential method, except it uses an 8kHz frequency to create the potential difference. This method has the advantage of using battery operated equipment and is therefore inherently safer than using a high voltage test set. Since it is battery operated, it is more portable than traditional high voltage test sets and can be used in difficult to access areas.

This method can also be used to locate phase to phase short circuits. An audio frequency can be injected into the cable which will return through the short circuit fault. A detection coil can be used to pick up the maxima and minima in the magnetic field created by the twist in the cable (HV Technologies Inc, 2023). This pattern will continue from the location of the generator to the fault location where the volume of the fault will increase. In cases where there is substantial cable after the fault, a capacitive effect may cause the signal to continue at a lower volume. Figure 11 below shows how this method is utilised in the field.

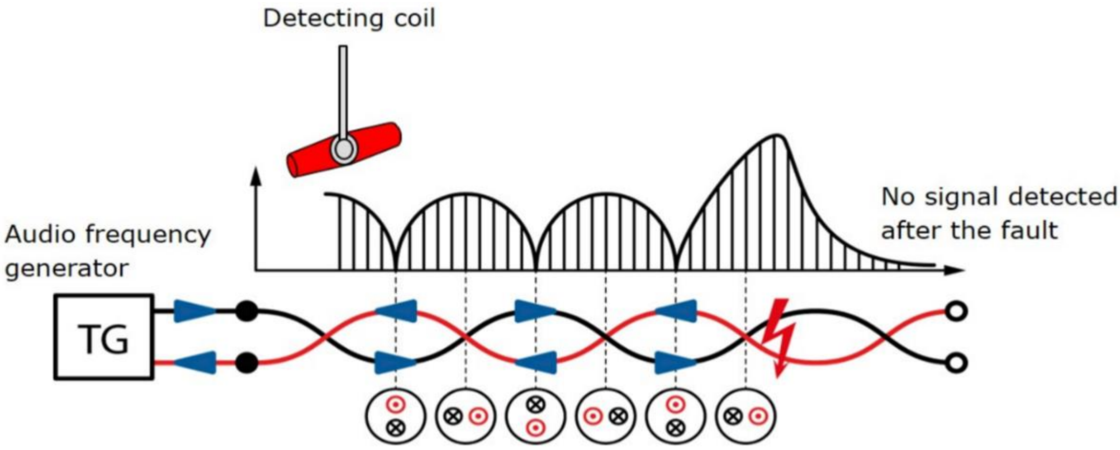

Figure 11 Audio Frequency Twist Method (HV Technologies Inc, 2023)

2.9 Infrared Thermography

Thermal analysis and thermography have been used in some way since 400BC where Hypocrites used the sense of touch to determine fever in unwell patients. In more recent times, thermal analysis is used to measure the temperature of faulty equipment, calculate melting points or freezing points of materials and to ensure food is cooked and maintained at a safe temperature.

Infrared thermography is defined as the collection and analysis of radiated electromagnetic energy in the infrared portion of the electromagnetic spectrum using a thermal infrared imaging device (Ruddock, 2006). Infrared cameras measure the infrared energy given off from the top 1/1000 inch of the surface being surveyed and although they do not measure temperature, it can be calculated from the radiation measured.

Since infrared radiation is only given off by the first 1/1000 inch of a material, in general, it will not pass through any solids or liquids. Any heat generated under a surface will transfer through objects and give off infrared radiation at the surface point. This is the basis of the experiment used in this project to locate faults in underground cables.

The infrared camera converts the infrared energy emitted by an object into electrical impulses by using a detector system built into the camera. The software then converts the electrical impulses into a colour chart of the different levels of radiation it has measured and shows them on the screen. In 1946, the first infrared line scanner was used to produce an infrared image of an overhead line and took one hour to develop the image (Ruddock, 2006). With modern electronics and computing power, an infrared image can be seen immediately after taking the picture.

There are three main laws and formulas concerning infrared radiation which are all based on the performance of a theoretical object called a “black body”. These laws include the Stephan-Boltzmann Law, Wein’s Law and Plank’s Law.

2.9.1 The Stephan-Boltzmann Law

Joseph Stephan and Ludwig Boltzmann determined that the amount of energy given off by any object is proportional to the object’s temperature, in degrees Kelvin, to the 4^{th} power. This explains why infrared cameras are very sensitive to small changes in temperature, since a small change in temperature gives a large change in radiated energy. This can be seen in the formula below, where Q is the radiated energy (Kingston, 1995).

$$Q = 5.67 \times 10^{-8} \times T^4$$

2.9.2 Wein’s Law

Most objects emit energy at many wavelengths, however, there is one specific wavelength that produces a maximum amount of energy. This wavelength can be found by applying Wein’s Law to any temperature in degrees Kelvin. This law is very helpful in thermographic surveying as it allows the operator to obtain the maximum sensitivity and accuracy for the survey being conducted.

$$\lambda = \frac{2898}{T \times Kelvin}$$

2.9.3 Plank's Law

Planks Law describes the spectral density and distribution of electromagnetic energy radiated by a black box at a given temperature over all the wavelengths. Plank showed how different atoms and molecules reflect or absorb different wavelengths. It is this principle that allows different lighting to be generated. The temperature of the LED bulb allows a warm or cooler light to be produced. Figure 12 below shows the relationship of the temperature of an object to the wavelength of the energy given off from the object.

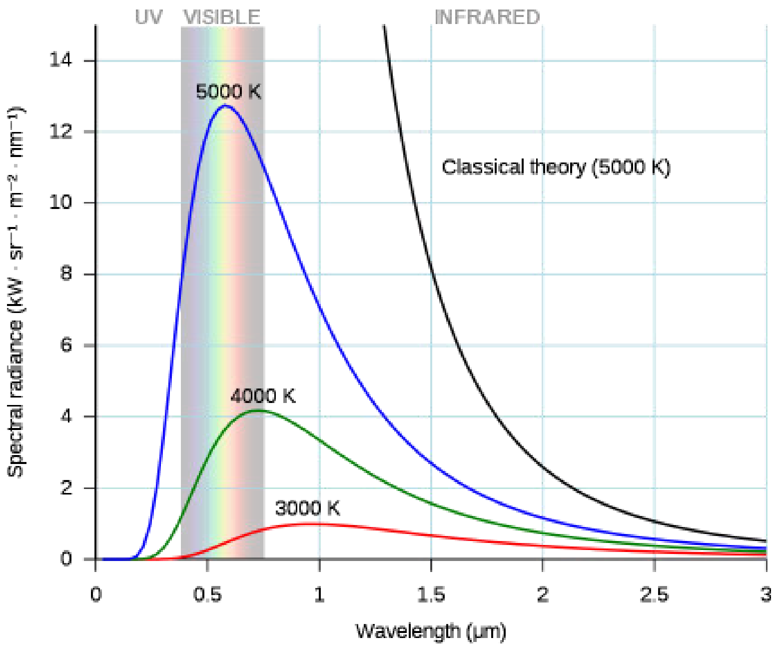

Figure 12 Plank's Quantum Theory (Study.com, 2023)

Planck's equation, below, shows that the energy of a particle is proportional to the frequency of the particle. Where E is the energy of the particle and v is the frequency of the radiation. In this equation h is Planck's constant of 6.626×10^{-34}.

$$E = hv$$

2.9.4 Overhead Lines

Overhead lines are scanned regularly as part of a maintenance program. The joints and connections are surveyed with a thermal camera to determine if any hot spots are forming, and to track the condition of the hot spots found previous surveys. This data can then be used to prioritise repairs on the different feeders and allow for outages to the network.

For overhead feeders that are difficult to access, helicopters can be used to fly alongside the feeder and survey the lines. While the helicopter is following the line, it is very easy to lose sight of the line and the joints. To help keep track of the line, a navigator and a watcher is also used. This process also uses a wide angle lens, that allows the surveyor easier viewing of the joints at a distance (Ausgrid, 2022).

Figure 13 Overhead Feeder Surveying (Ausgrid, 2023)

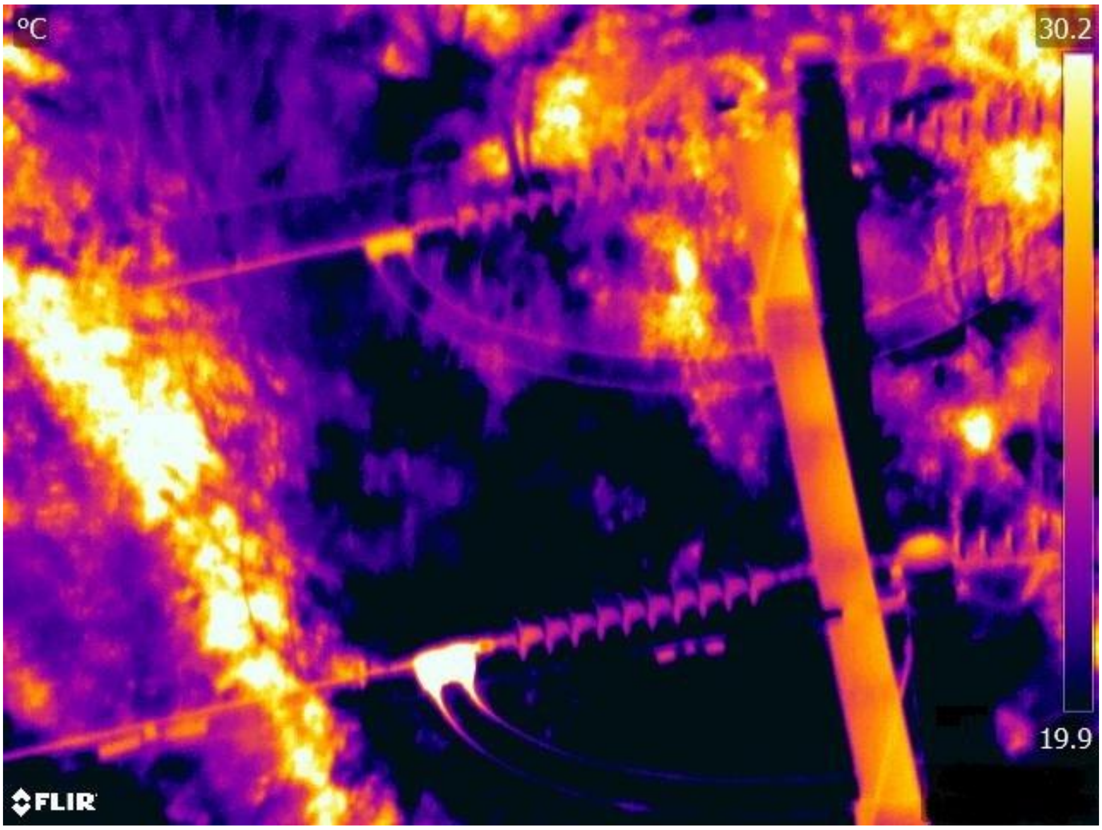

Figure 14 Hot Spot found on Overhead Connection (Ausgrid, 2023)

It is important to note that, while surveying overhead conductors, the wind can significantly influence the results of the thermal survey. Surveying overhead conductors with wind or rain will cool the faults, making them difficult or impossible to locate. In the case of thermal surveys being performed from a helicopter, additional care needs to be taken to ensure the rotor wash does not have a cooling effect on the conductors and joints being surveyed. This is accomplished by flying to one side of the line, ensuring the rotor wash does not affect other lines and appropriate clearances can be kept from adjacent in service feeders (Ausgrid, 2022).

2.9.5 Switchboards

Low voltage switchboards are also scanned on a regular basis. This can be helpful to reduce the likelihood of electrical fires starting from high resistance joints or overloading of circuits. It is important to consider the safety of workers while these surveys are being undertaken. Most industrial switchboards have a metal cover over the exposed copper busbars and care must be taken to ensure the cover does not make contact with any live conductors when it is being removed or replaced (Ausgrid, 2023).

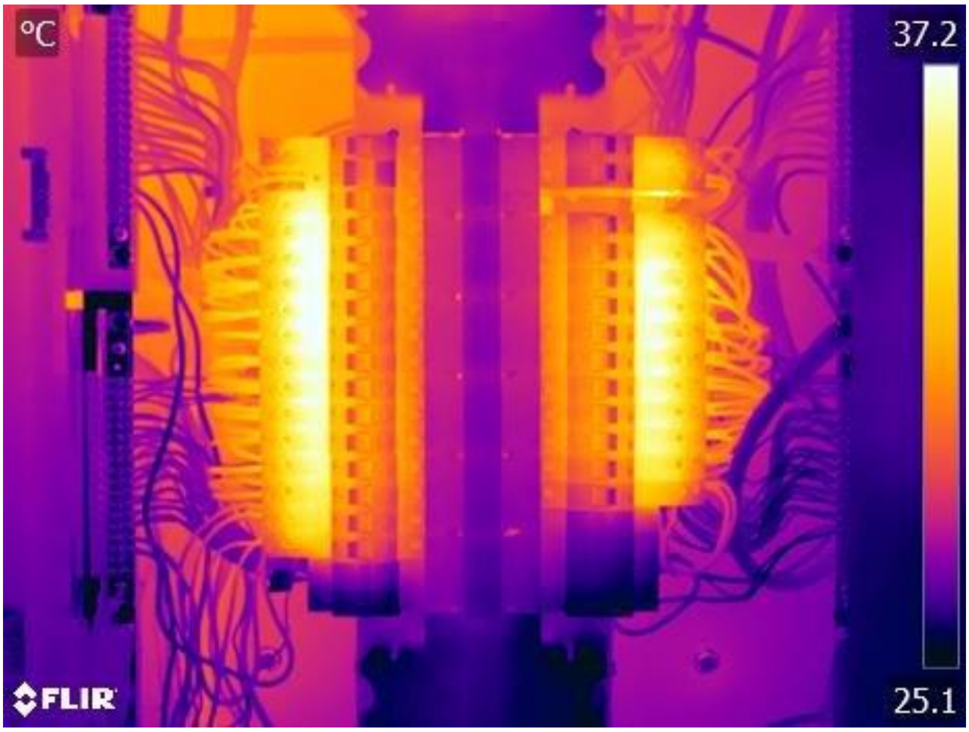

Figure 15 Overloaded Switchboard

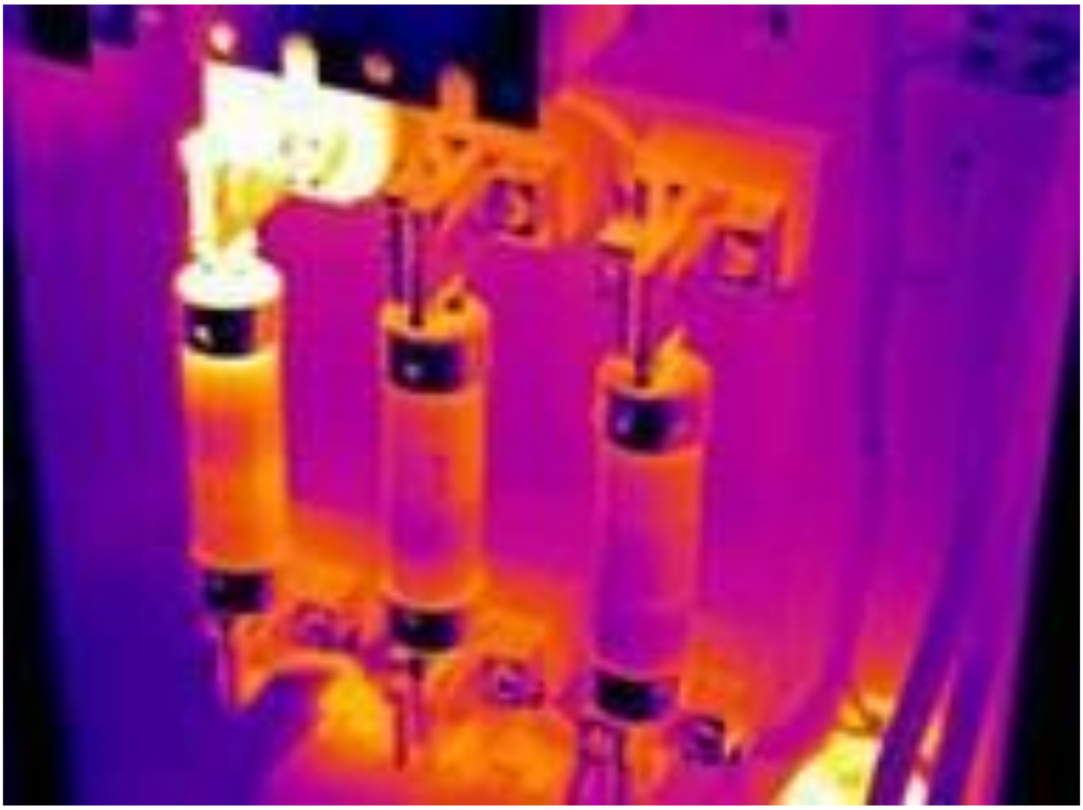

Figure 16 High Resistance Connection

Figure 15 and 16 above show two switchboards that have issues that has the potential to lead to failures. Figure 15 shows a board that could be overloaded. This board would need to have the currents checked on each of the subcircuits to determine the load and the rating of each breaker. Figure 16 shows a high resistance connection on the top of the A phase fuse. This additional heat generated will be using more power from the supply and has the ability to cause an electrical fire if it is not picked up in time (Revolution Electrical, 2023).

Companies can perform infrared surveys to reduce business costs. Some insurance companies give discounts to companies that perform these surveys on a regular basis since it can reduce the risk of fire and damage to buildings. Infrared surveys identify faults which can reduce power consumption, saving in electricity costs.

2.9.6 Low Voltage Pillars

Low voltage pillars are a connection point for underground cables. They form an accessible location where connections can be made to homes and businesses from the low voltage mains. Due to the number of connections within these pillars, there is a possibility for faults to develop and for the pillar to melt or catch on fire. This can pose a serious risk to the public and the electrical network.

Pillars installed on the network must comply with Ausgrid's network standards (Ausgrid, 2018). This document details the requirements of low voltage pillars to ensure faults occurring on the network do not cause damage to the mains and apparatus. NS224 sets out the specifications to allow for 400A fuses to supply the low voltage network and peak fault currents of 35kA (Ausgrid, 2018).

To ensure the low voltage pillars are safe for the public and the network they are surveyed on a five yearly basis, mainly due to the number of pillars in Ausgrid's area. These pillars are surveyed in two phases. Step one is to survey the outside temperature of all the pillars in a given area with an infrared thermometer. If the outside temperature is greater than the ambient temperature it is recorded. Step two is to follow up with an infrared camera to determine if there is an internal fault to the pillar.

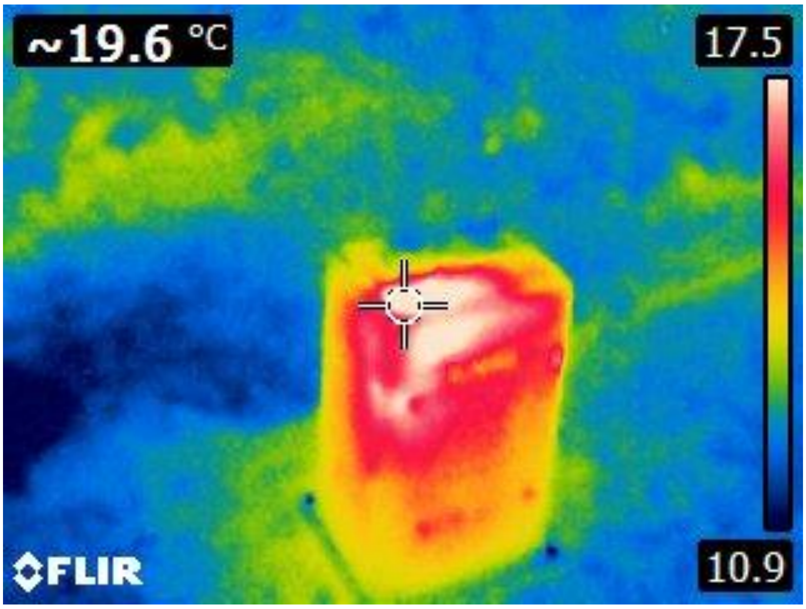

Figure 17 Low Voltage Pillar With Fault Under the Cover

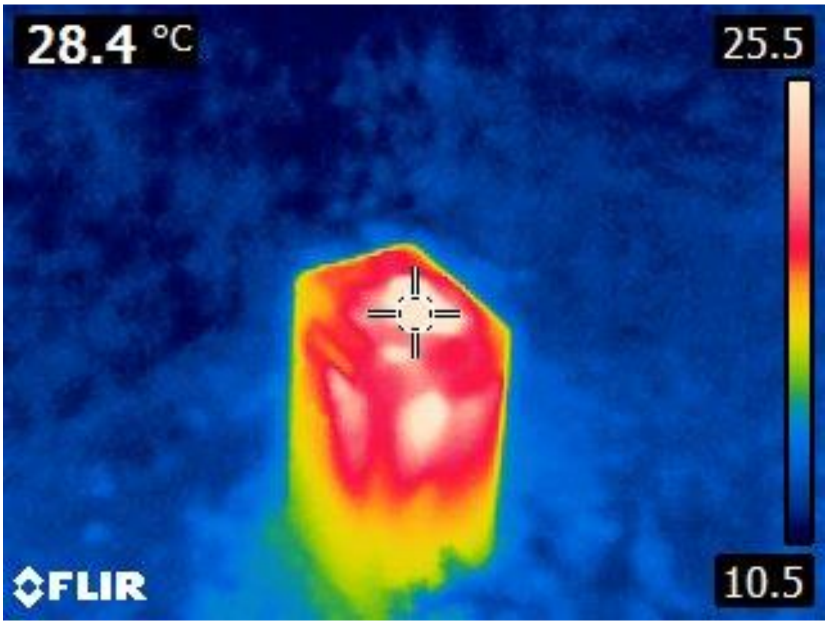

Figure 18 Low Voltage Pillar Above the Ambient Temperature

Figures 17 and 18 above show how the thermal imaging camera can detect a hot spot on the pillar. These will be recorded and a follow up will be performed to check the internal connections and correct any defects within the pillar.

2.9.7 Heat Sources

Infrared cameras will detect radiated energy from three specific sources. These include:

- Emitted energy from the object being surveyed. Such as a high resistance connection on a low voltage switchboard (Ruddock, 2006).
- Energy from a different source reflecting from the object being surveyed. The sun reflecting off metallic components can make the object being surveyed appear hotter than it actually is (Ruddock, 2006).
- Energy transmitted through the object being surveyed (Ruddock, 2006). This is the scenario where heat from the faulty joint, buried in the ground, will transmit heat energy to the surface and then be emitted from the ground.

The rate at which energy is emitted from an object is known as the emissivity. The emissivity of an object is determined by five distinct features. These include:

- Material of the object
- Surface condition
- Temperature
- Wavelength
- Geometry of the area to be viewed

The material and surface condition of the target to be surveyed are the most crucial to the emissivity value and these are the factors that will be considered in this report. Below is a table outlining the long wave emissivity of different materials. For this project, the materials being surveyed are soil, asphalt, bricks and concrete. Since these materials all have an emissivity of between 0.9 and 0.95, the infrared camera will be set to 0.95 as this setting will be suitable for all materials being surveyed.

Table 3 Long Wave Emissivity Chart (Ruddock, 2006)

Material	Emissivity
Aluminium – Foil/New, Polished	0.04
Aluminium – Old, Oxidised, Discoloured	0.9
Asphalt	0.93 to 0.95
Ceramics and Bricks	0.8 to 0.95
Cloth	0.95
Concrete	0.94 to 0.95
Copper - New	0.04
Copper – Oxidised	0.4 – 0.98
Electrical Tape	0.95
Glass	0.76 to 0.85
Painted Surfaces	0.74 to 0.96
Paper	0.5 to 0.95
Rubber	0.95
Sand	0.90
Soil	0.90 to 0.98
Steel, Iron, Oxidised	0.65 to 0.95
Steel, Stainless	0.1 to 0.8
Water	0.93
Wood	0.89 to 0.94

Chapter 3 Test Methodology

3.1 Sites to Survey

The current process of restoring power to customers after a cable failure is to replace the 400A fuses and use a tong ammeter to check the distributor load does not exceed the 400A HRC fuse rating (Ausgrid, 2018). If the fuses are holding, and the current does not exceed 400A, then the distributor is left energised. This process is repeated every time the HRC fuse operates until the fuse operates immediately after being replaced. At this point a fault location is required to locate the fault and repairs are initiated to the distributor.

This project intends to find sites that have had the HRC fuses replaced on at least two occasions so a survey of the underground cable can be undertaken in an attempt to locate a temperature gradient above the fault. This would then enable a controlled outage to occur, and traditional fault location can be used to pinpoint the fault.

In order to determine sites that can be surveyed, data of all low voltage faults from 2015 to February 2023 has been collected. This data will then be collated and filtered to produce a list of substations and distributors that have regular failures, with decreasing timeframe between each failure. These sites can then be surveyed to determine if any faults can be detected with the infrared camera.

This project will attempt to reach 20 sites of different environmental, installation and cable types across the Sydney region, in order to determine the optimal conditions for the infrared survey to locate a fault. The time of day will also be recorded to determine how the ambient temperature affects the ground temperature and the effect on the hotspot generated above the fault.

3.2 Cable Types

Due to the construction type of most underground cables, faults usually fail to the general mass of ground before failing to another conductor. It is also common for these ground faults to have a resistive path to ground. Since this is the case in most faults, this project will be focusing on the ground faults.

Figure 19 Low Voltage PVC Cable Cross Section

Ausgrid uses many different types of low voltage cables. This is mainly due to the amalgamation of many smaller county councils into, what is now, Ausgrid's network area. Advancements in technology have also helped to make cables more resilient to degradation while buried directly in the ground. PVC and XLPE cables are able to withstand more water ingress than the older paper insulated cables.

Advances in safety factors have also forced a change in cable types. The paper lead cables are largely phased out due to the hazard of working with lead. Joining lead cables together requires heating of solders and lead wipes to ensure a smooth and water tight fit is established. The heating of these materials produces hazardous fumes that can be detrimental to the health of these workers.

Figure 19 above shows a newer style solid aluminium PVC cable. This particular style has a steel wire armouring around the outside to provide additional mechanical strength for the cable. Figure 20 below shows the older paper insulated cable. This cable has an aluminium sheath that is used as the neutral conductor and solid aluminium cores for the three phases.

Figure 20 Paper Insulated Lead Cable

These cables were used in the 1960s and 70s and are still in use today. They utilise the aluminium sheath for both the mechanical protection and for the neutral conductor, allowing for a smaller overall cable size. The paper insulation is impregnated with an oil to insulate the lead conductor. When this type of cable fails, the paper can dry out due to the heat generated by the fault. This can cause water to enter the cable and require large sections to be removed before it can be returned to service.

3.3 Limitations

3.3.1 Infrared Survey Limitations

Some of the limitations around surveying distributors will include factors such as ambient temperature, time of day and weather conditions. These factors will be recorded in the data collection table in Chapter 4 of this thesis.

When dealing with thermal properties in an outdoor environment, factors such as wind, rain and sunlight directly affect the results of the thermal survey. Factors like rain and wind will remove a portion of the radiated heat and can make it hard or impossible to determine a temperature differential above the faulted distributor. Having an additional heat source, such as the sun, may heat the ground more than the fault, also making it difficult to detect any differences between the ambient ground temperature and the heat generated by the fault.

Where faults have occurred and fault locations are required immediately, thermal surveys may be less than optimal depending on the time taken to get to site. Since the fuses will no longer be supplying the fault, heat will no longer be generated and the existing heat in the ground will be dissipating through the ground and into the air. As the time of fuse failure is not always known, it is difficult to measure this quantity.

3.3.2 Traditional Fault Location Limitations

Each type of fault location method has its own set of limitations. The fault locator needs to be aware of these limitations to ensure the most appropriate method is used in each circumstance. Using a time domain reflectometer has the limitation of only being able to detect short circuits and open circuits. This is due to the way the TDR unit traces large impedance changes along the route of the cable.

SIM/MIM is one of the more reliable fault locations methods, however it still has issues when trying to locate faults on cables without a screen. The SIM/MIM method relies upon the high voltage pulse being able to arc from the conductor. When the cable does not have a screen, the pulse tends to partially conduct which will fail to show on the trace.

The resistance loop bridge method is extremely accurate when applied correctly. It does however have its own set of limitations. The bridge method requires continuity on the conductors from end to end. The insulation resistance between the healthy core and the faulty core needs to have a minimum ratio of 1:5. To ensure current can flow in the faulty core, the fault resistance must be less than 1 MΩ. If these three factors are not met, the resistance loop bridge method cannot be used.

3.3.3 Project Constraints

This project has been limited to the low voltage network since the 400A HRC fuses located at the distribution substation allow current to flow and generate heat at the fault site for an extended period of time. High voltage faults are controlled by relays and circuit breakers that operate much faster to reduce the fault current and fault times on the high voltage network. High voltage faults therefore do not generate enough energy to create a hot spot on the ground above a fault meaning an infrared camera will not be able to locate the fault.

The time between the operation of the HRC fuse and the point the infrared survey is completed, has not been measured as part of this project. This has not been considered due to the difficulties in knowing the exact time of the failure in most circumstances. It is a constraint of this project because once the HRC fuse has operated and supply is removed from the fault, heat will no longer be generated at the fault site. Further to this, any heat in the ground will also be radiating into the air and also dissipating through adjacent services.

3.4 Thermal Imaging Survey

A thermal survey will be conducted on suspected faulty cables from November 2022 through to September 2023. The survey will gather data from twenty suspected fault sites and populate the table in Chapter 4 below. The project will attempt to capture data to determine the suitability of using infrared technologies in varying capacities. These include cable type, cable installation, varying weather conditions, and time of day.

Risk assessments will be conducted for each survey site. The most common hazards expected to be identified will be:

- Traffic
- Sun exposure
- Trip hazards
- Lack of lighting

A risk assessment for this project has been included in Appendix E of this dissertation, which includes the listed hazards above, as well as some more specific hazards. It also shows the controls for each identified hazard.

Chapter 4 Data Collection and Analysis

4.1 Data Collection

Due to the mild weather conditions less faults occurred than expected. This meant that only 15 sites were able to be surveyed instead of the proposed 20 sites. This data has been obtained from two sources, including historical data and network failures. Historical data was used from previous outages that were logged into an outage database and data from network failures was sourced from direct failures on the network where power was lost to homes and businesses.

The data collected from network failures have been collected at the time of arrival on site. The survey of the distributors usually takes 10 to 15 minutes to complete and can have multiple tees, customers and connections to overhead mains. The network plans were on site to confirm the route of the distributors and the location of the joints. Additional time was spent surveying the joint locations since faults are more commonly found at these locations.

The historical data has been collected and sorted to find substations that have had multiple failures on the same distributors. The timeframe between failures was assessed in an attempt to determine the probability of the next failure. In some of these instances cables have been in service for up to 12 months between fuse operations. Due to the large number of fuse operations over the time period, distributors that had failed in the first half of 2023 were considered for surveying.

If this project was to be ongoing, it would track these outages, and surveys would be conducted after the second or third outage depending on the time between fuse operations and customers affected by the outage. Tables 5, 6 and 7 below capture the data gathered from the infrared surveys. They show the data from the distributors, environmental data at the time of surveying and the fault locations performed to confirm the infrared camera location. Distributors that are still in service do not have fault location details, however this information will be stored and compared if the distributor fails in the future.

The historical data was acquired through Ausgrid's outage management system. This system collects all the outages on Ausgrid's network and stores them into the database. The data collected has been sorted to only show faults on the low voltage network and then further sorted to find multiple occasions where faults have occurred on the same substation distributor.

Table 4 Excerpt From Outage Management Database

17/10/2022	North	MEADOWBANK	ZN4545:PA2	S2707:FL4	Equipment Failed in Service	U/G Cable
17/07/2021	North	MEADOWBANK	ZN4545:PA4	S2707:FL4	Equipment Failed in Service	U/G Cable
11/08/2020	North	MEADOWBANK	ZN4545:PA4	S2707:FL4	Equipment Failed in Service	U/G Cable
1/02/2023	CBD	CITY SOUTH	ZN3288:PA41 42DEF	S1013:FL6	Equipment Failed in Service	U/G Cable
31/01/2023	CBD	CITY SOUTH	ZN3288:PA41 42DEF	S1013:FL6,SY61936	Equipment Failed in Service	U/G Cable
12/12/2022	CBD	CITY SOUTH	ZN3288:PA41 42DEF	S1013:FL6	Self Clear (No Cause Found)	Feeder/Distributor U/G
29/06/2022	CBD	CITY SOUTH	ZN3288:PA41 42DEF	S1013:FL6	Self Clear (No Cause Found)	Feeder/Distributor U/G
3/07/2023	North	NORTH SYDNEY	ZN35400:PA110	S36005:FL1	Self Clear (No Cause Found)	Feeder/Distributor U/G
15/05/2023	North	NORTH SYDNEY	ZN35400:PA110	S36005:FL1	Self Clear (No Cause Found)	Feeder/Distributor U/G
13/04/2023	North	NORTH SYDNEY	ZN35400:PA110	S36005:FL1	Self Clear (No Cause Found)	Feeder/Distributor U/G
26/11/2022	North	NORTH SYDNEY	ZN35400:PA110	S36005:FL1	Self Clear (No Cause Found)	Feeder/Distributor U/G
15/12/2022	South	KOGARAH	ZN10999:PA38	S10786:FL3	Self Clear (No Cause Found)	Feeder/Distributor U/G
23/12/2022	South	KOGARAH	ZN10999:PA38	S10786:FL3,KO8829	Equipment Failed in Service	U/G Cable

Table 4 above shows an excerpt from Ausgrid's Outage Management Database. An example of the filtering process shows four faults occurred on distributor 6 from substation 1013. This site was surveyed and added in as site 12 below. Other historical data was collected and filtered in the same way. All of these sites shown were filtered to show a repeating pattern of faults on the network. This data can be used to determine where the next faults may occur and plan an outage, rather than waiting for customers to lose power and require other works to be cancelled in order to get crews to attend these outages.

Table 5 Low Voltage Distributor Data

Location	Substation	Installation Type	Cable Type	In Service
1	S7999	Pit and Duct	PVC	Yes
2	S10786	Direct Buried	PILC	Yes
3	S3269	Direct Buried	PILC	No
4	S35442	Conduit/ Direct Buried	PVC	Yes
5	S1990	Direct Buried	PILC	Yes
6	S47274	Direct Buried	PILC	No
7	S7725	Direct Buried	PILC	No
8	S6020	Direct Buried	PILC	Yes
9	S6963	Pit and Duct	PILC	Yes
10	S5296	Direct Buried	PVC	No
11	S36005	Direct Buried	PILC	Yes
12	S1013	Pit and Duct	PVC	Yes
13	S1231	Direct Buried	PVC	Yes
14	S1048	Pit and Duct	PVC	Yes
15	S2707	Direct Buried	PVC	Yes

Table 6 Environmental Data for Each Location

Location	Ambient Temperature	Weather Conditions	Ground Cover
1	19.0^{o}C	Sunny	Concrete
2	23.0^{o}C	Sunny	Pavement
3	18.0^{o}C	Night/Rain	Grass/Pavement
4	20.7^{o}C	Day/Overcast	Concrete/Bitumen
5	14.0^{o}C	Night/Wet	Concrete
6	28.8^{o}C	Day/Shady	Concrete
7	14.0^{o}C	Night/ Shady	Grass
8	11.0^{o}C	Night	Concrete/Bitumen
9	11.0^{o}C	Night	Concrete/Bitumen
10	12.0^{o}C	Wet	Grass/Dirt
11	16.0^{o}C	Sunny	Concrete
12	11.0^{o}C	Night	Concrete/Bitumen
13	13.0^{o}C	Night	Gravel/Dirt
14	12.0^{o}C	Night	Concrete
15	16.0^{o}C	Sunny	Concrete

Table 7 Fault Location Data

Location	Temperature of Ground Above Fault Location	Fault Confirmed by Traditional Methods	Methods Used
1	27.8°C	Yes	Visual Identification
2	N/A	No	In service
3	18.0°C	No	Arc Reflection
4	21.3°C	Yes	TDR
5	12.2°C	Yes	TDR
6	29.1°C	Yes	Arc Reflection
7	N/A	No	Arc Reflection
8	N/A	No	In service
9	N/A	No	In service
10	N/A	No	TDR
11	N/A	No	Visual Damaged
12	N/A	No	In Service
13	15.2°C	No	In Service
14	N/A	No	In Service
15	N/A	No	In Service

4.2 Successful Survey Sites

From the data collected, sites 1, 4, 5, 6 and 13 successfully identified a fault location and was able to be confirmed by a traditional fault location. All of these sites were located under a hard surface, either concrete or bitumen, although sites 1 and 5 are located in a pit and duct arrangement. Site 13 was under dirt, but was heavily compacted since the location was near a busy shopping centre and carpark.

4.2.1 Site 1

Site 1 is located in a pit and duct arrangement and the survey was conducted on a sunny day with an ambient temperature of 19°C. In this case the fault was found in a pit. It was still in service and current was passing through the PVC insulation to ground. This current path caused burning of the PVC and generated enough heat within the pit to cause the lid to become hotter than the surrounding tiles above ground.

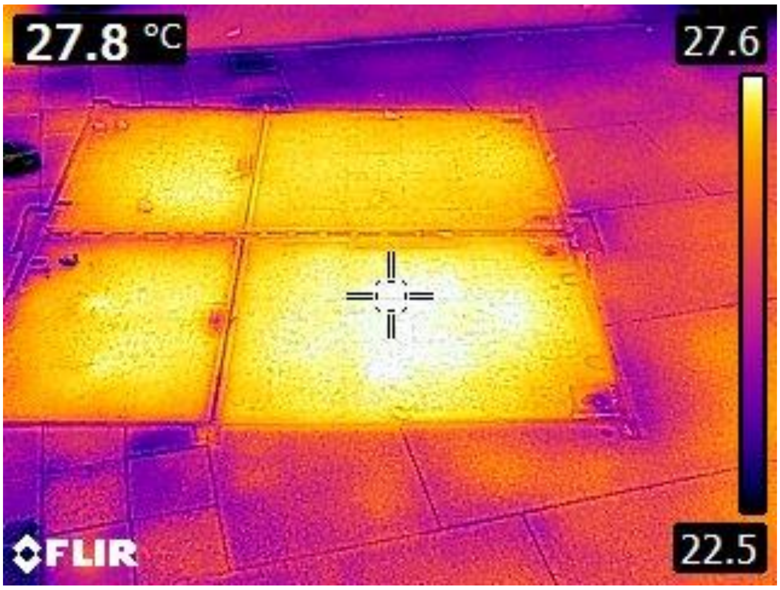

Figure 21 Thermal Image of Site 1

Figure 21 shows the hot spot generated on the pit lid caused by the fault within the pit. The heat has radiated from the cable into the free air. This temperature difference had then conducted through the concrete pit lid and can be detected by the infrared camera.

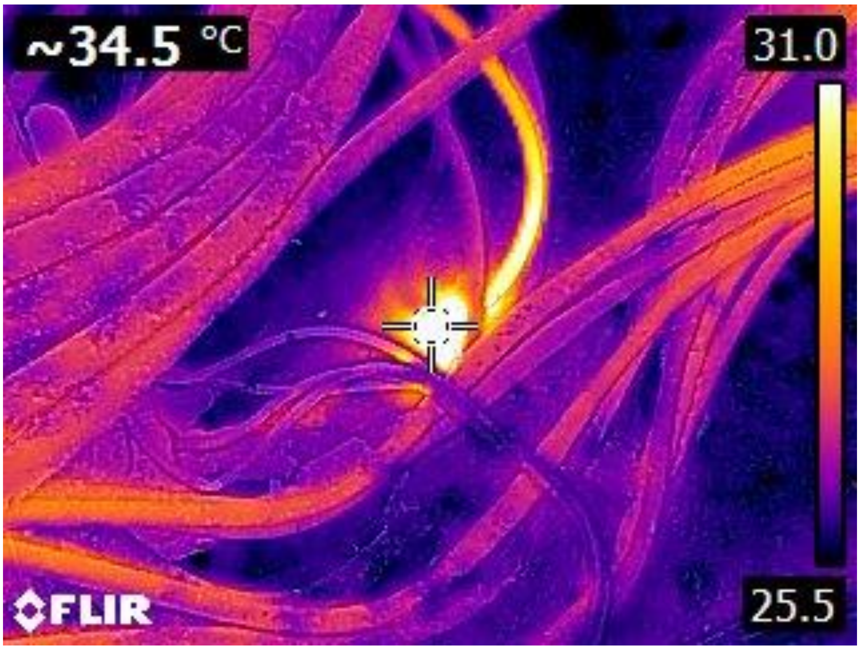

Figure 22 Thermal Image of the Fault at Site 1

The temperature inside the pit is much higher than detected on the pit lid. The fault is still heating the air and is fairly low at 34.5°C. This type of fault would be burning for a while without the 400A HRC fuse operating. Figure 22 shows the infrared image of the fault and the heat conducting up the cable and radiating into nearby cables.

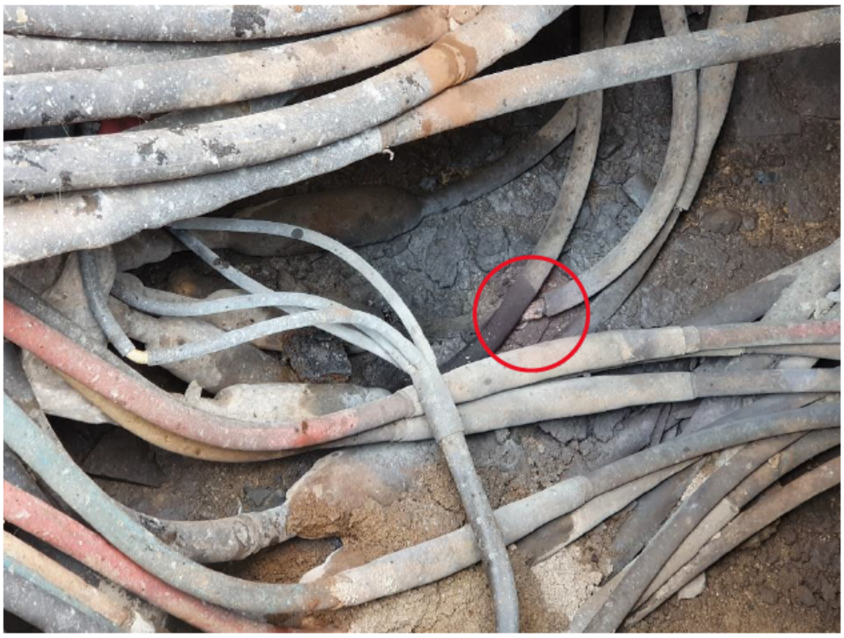

Figure 23 Photograph of Fault Within Pit for Site 1

The red circle in Figure 23 shows the location of the fault. This photograph shows the missing PVC insulation where the fault current has been burning the insulation away. The infrared camera works well in these situations since the hot air within the pit has been trapped and can easily transfer through the pit lid via heat conduction.

4.2.2 Site 4

The fault detected at site 4 was located on the mouth of a duct line underneath the driveway to a residence. At the time of the survey, the cable was still in service and heat was still being generated by the fault current. Figure 24 below shows the thermal image of the fault location. The heat from the fault was radiating out the end of the duct line creating the hotspot shown.

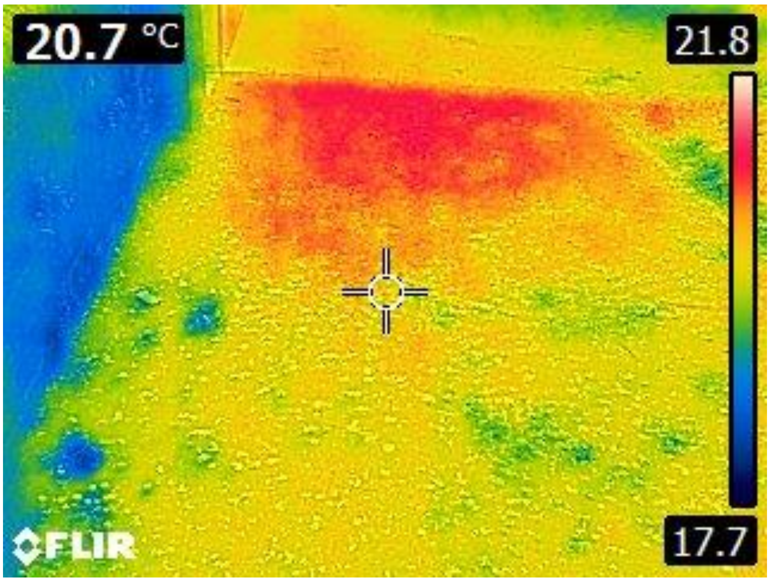

Figure 24 Site 4 Thermal Survey Image

In this image there is no thermal radiation given off from the driveway. This would be due to the thicker slab and reinforcing bars laid into the driveway compared to the relatively thin bitumen foot path. The footpath will be able to conduct the heat enabling this location and emphasising the difference in thermal properties between the two materials.

This fault was proven by the use of time domain reflectometry. A trace of the cable was taken from either end of the cable. These traces were then compared to the overall length of the cable and the fault could be measured from either direction giving a location that matched the thermal image above.

A secondary fault location method was then used to pinpoint the fault. By applying high voltage pulses and using the Aquatronics listening equipment, an accurate fault location was then achieved. This fault was then excavated and the joint repaired, allowing the affected customers to have power restored.

4.2.3 Site 5

The fault at site 5 was located after initial investigations determined the fault was located in a different section of cable. This meant the fault had been re-energised and had been able to continue to generate heat at the fault location. The fault was located on the service tee to a customer's premises, which only affected one property. Supply was still available at all the network points and at all the remaining properties.

Figure 25 Site 5 Fault location

This fault was pinpointed on the property boundary between the concrete footpath and the customer's tiled area. It had been raining during the day but the ground had started to dry up. Having the ground wet would have made a successful thermal survey nearly impossible since the water would have removed any heat from the ground.

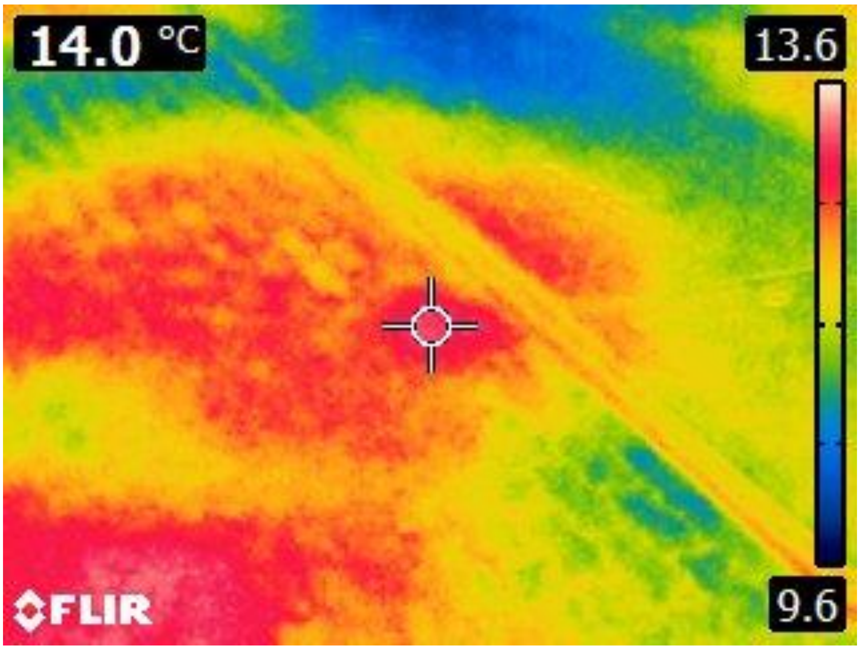

Figure 26 Thermal Image of the Fault Location at Site 5

Figure 26 shows the thermal image of the fault location at Site 5. The drain running through the centre of the image is affecting the conduction of the heat. Since the ground was still damp from the earlier rain the thermal survey was much harder to detect. In this instance the hot spot was much larger than normally expected. This may have been due to the tiles allowing heat to conduct through the gaps and spreading out much further than under a continuous piece of concrete. This effect can be seen on the right side of the image where the hot spot is more condensed. The lower right portion of the image also shows the temperature difference between the tiles and the gaps around the tiles.

From this site, faults located under this type of surface may have larger hotspots than normally expected due to the different rates of heat conduction in the ground. This fault also required knowledge of the cable routes. By having an understanding of the cable and joint locations, an accurate survey was conducted and a successful location achieved.

4.2.4 Site 6

Figure 27 below shows the fault location site identified through an arc reflection method and pinpointed using the audio frequency equipment. The thermal image shown in Figure 28, shows a hot spot under the scar in the bitumen footpath. This type of scar is indicative of a previous fault repair, and in this situation a joint is located at the end of the scar.

Figure 27 Photograph of Fault Located Adjacent to Low Voltage Pillar

This survey was completed on a sunny day, however the fault was in the shade. This made the survey harder to detect since there was reflected infrared radiation detected on the left side of the image in Figure 28. To determine the extent of the reflected infrared radiation, this survey was performed from multiple angles to ensure the fault was correctly identified.

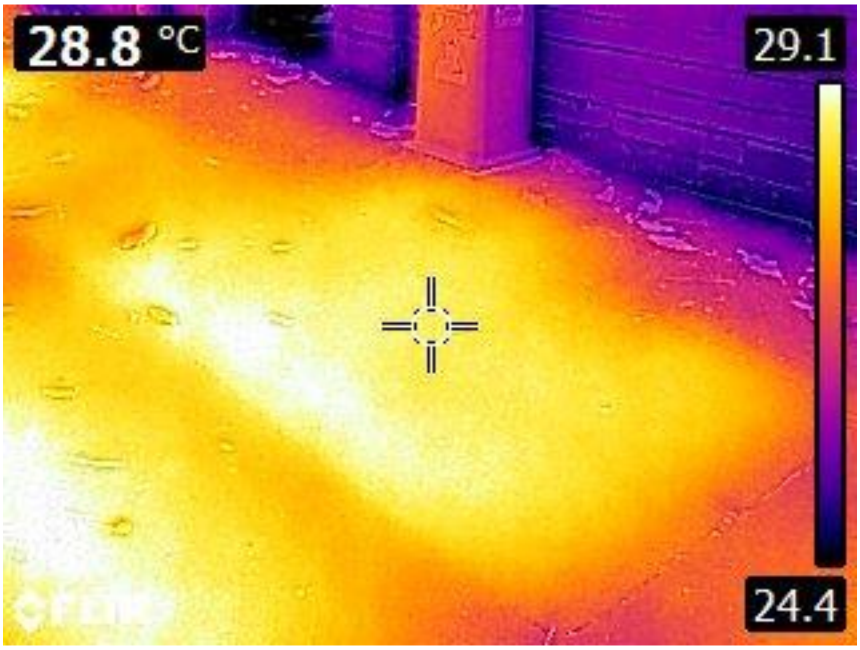

Figure 28 Infrared Image of Fault Location

This site highlights the importance of understanding how the reflected infrared radiation can affect the process and the importance of following approved techniques to achieve a successful fault location. Using the traditional fault location methods to confirm this fault also adds certainty to the fault location process. Having multiple fault location techniques that all give the same location allows the fault locator certainty in proceeding with an excavation.

To ensure this location was correct, a SIM/MIM was also used as a primary fault location method. This confirmed the fault location at the pillar and was pinpointed using the Aquatronics listening equipment. The fault was located in a 4 to 1 joint. This joint is where a multicore cable is connected onto four single cables which allows for ease of access into the terminations of the low voltage pillar. These joints are prone to failure as there are many voids created by the round cables being combined into a square shape.

Figure 29 below shows the faulty 4 to 1 joint located adjacent the low voltage pillar. This joint was cut out and replaced with new joints before being returned to service.

Figure 29 Faulty 4 to 1 Joint

4.2.5 Site 13

Distributor 4 from this substation developed on open circuit fault on A phase which was able to be supplied from another distributor until an outage could be arranged. In this scenario, the fault is being supplied from both sides of the open circuit from two separate substations. This allows current to flow from both sides which in turn generates additional heat.

S1231 is located against an east facing brick wall that was exposed to the sunlight during the day, as seen in Figure 31. The low voltage cables have been installed between the substation and the wall. Figure 30 shows the infrared image of the area. The fault can be seen between the wall and the substation in the dull yellow area. This does not stand out as much as the other successful sites due to the radiated infrared radiation from the substation and the wall. A survey was also completed on the adjacent substation in a similar location that also showed no signs of heat between the wall and the substation, ruling out any form of reflection in this situation, also shown in Figure 30 below.

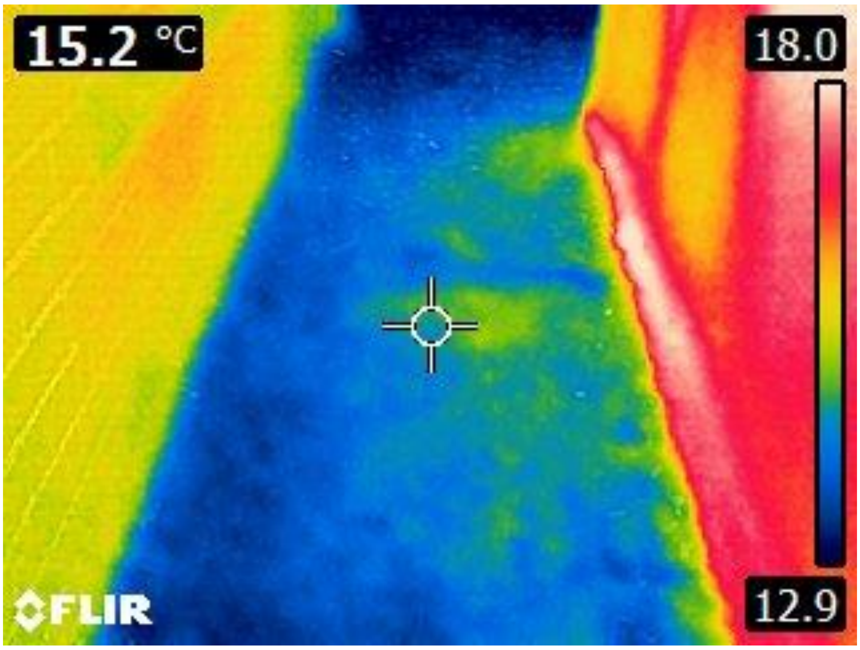

Figure 30 Infrared Image of Site 13

The heat generated by the fault could also indicate the cable has failed in two places. This can be inferred due to the hot spot generated where the cable turns into the substation. This can be seen in a yellow colour as well as the hotspot under the cursor of the camera. These yellow hot spots are fairly wide, probably due to the concentration of cables in the vicinity of the substation.

Once the outage had been arranged, a traditional fault location was completed on this distributor to prove the faut location. Having this survey completed before gaining access to the network provides additional confidence in determining the correct fault location. This image also shows how experience in using an infrared camera and knowledge of the job site are vital in accurately determining a correct fault location.

Figure 31 Location of Site 13

4.3 Unsuccessful Survey Sites

There are many reasons why the infrared survey of the remaining sites were unable to detect a fault. In some cases the reason the fault location could not be located was easy to ascertain. In other cases there were a combination of factors that resulted in an unsuccessful thermal survey. These reasons include the following factors:

- Weather Conditions
- Fault Conditions
- Reflective Surfaces
- Ground Conditions

4.3.1 Weather Conditions

The weather conditions at the time of an infrared thermal survey can have a significant impact on the results. In the scenarios this project has been experimenting with, the hot spots have been over a large area, approximately 2 square metres and in some cases larger. Any wind blowing across the survey area will quickly dissipate any heat conducting through the ground making a thermal image difficult to locate.

Wet weather can also reduce the effectiveness of the thermal survey. The rain will cool the ground significantly, reducing the chance of detecting an underground cable fault. Since the infrared radiation is only detected in the first 1/1000th of an inch of the object being surveyed, the infrared camera will detect any water on the surface of the object being surveyed. The infrared camera will detect the temperature of the water on the surface of the object and not detect any temperature gradient. This is apparent in sites 3 and 10 where the ground was wet due to light rain throughout the day.

Even sunny weather conditions can cause issues for the infrared camera. On sunny days infrared radiation can be reflected from surfaces that can be picked up by the infrared camera. To ensure the reflected radiation does not affect the survey it is important to view the target from multiple angles. This technique can be used to show the operator where the reflected infrared radiation is originating and what the true reading of the target area is.

4.3.2 Fault Conditions

The condition of the fault plays a vital role in generating the initial heat in the ground. The ideal scenario is for the fault to be pulling enough current to generate sufficient heat and transfer this heat into the ground without operating the 400A HRC fuse. In some cases the current drawn by the fault will not be enough to generate heat in the ground which will make a successful survey unlikely. This can be seen in a number of sites including sites 2, 7, 8, 9, 14 and 15, where no temperature gradient could be found along the route of the cable.

While this heat is being generated, the cable insulation will also be deteriorating, increasing the heat in the ground. This will continue until enough current flows to operate the HRC fuse at the substation. This phenomena is known as thermal runaway. If the thermal runaway is not stopped in a reasonable amount of time the fault can cause the cable to overheat and damage the cable along the length and not just at the point of the failure. This can be particularly damaging to paper insulated cables as the paper insulation has an oil impregnated into it. As the cable heats up this oil will dry out, leaving the paper insulation dry and brittle. At this point the cable will need to be replaced, costing thousands in excavation works and installation of new cable.

4.3.3 Reflective Surfaces

Reflective surfaces can reflect the infrared camera signal onto another object or can detect infrared radiation from other nearby surfaces. This is seen during nighttime surveys where metal poles can bounce the infrared cameras signal and detect the temperature of the night sky. This can cause a very low reading depending on the accuracy of the camera and needs to checked by the operator.

The opposite is true for sunny days, the infrared radiation from the sun can reflect from shiny surfaces or given off from bricks that have warmed up during the day. This radiation is then given off and reflected from the target to the infrared camera. Figure 30 above, shows an example of the walls on either side of the fault giving off heat that was absorbed by the walls during the day. This can make the thermal image difficult to interpret due to the higher infrared radiation emitted from the adjacent walls. Although the infrared camera was successful in locating the faults at Sites 6 and 13, they highlight how the reflected infrared radiation can make it difficult to obtain an adequate thermal image on the camera under these conditions.

4.3.4 Ground Conditions

The ground around the fault can determine how well the heat can permeate through the ground to the surface. In highly built up areas, such as Sydney city, there are many other utilities that are buried next to the electrical network. Metallic water pipes, gas pipes, communication networks and other utilities cause heat to dissipate in different ways. This can create difficulties in accurately locate faults using the infrared camera.

In some cases a thermally stabilised backfill can be used to increase the heat conduction from the cable. This reduces the heating effect and can increase the current carrying capacity of the cable. Most low voltage installations, that are direct buried, are backfilled with clean sand. This also allows for a consistent heat transfer but at a much lower cost to the installation.

Pit and duct installation methods can also cause heat to dissipate in different ways. Conduits can direct heat to openings such as breaks in the conduit or to pits. Faults in pits can also heat up causing additional damage to adjacent distributors that have been layered on top or around the faulty cable. Sites 11 and 12 were both located in Sydney city, and installed in a pit and duct method. The infrared camera was unable to detect the heat from these faults. This could be due to the heat being drawn away from the pit lids through the adjacent conduits, removing heat from these sites.

The moisture within the ground can also affect the current flow and therefore the heat generated by the fault. Areas that have high water content in the ground can have increased fault currents, and therefore higher heat generation, than areas that are much drier. This has been seen in areas closer to the beach where there is a greater water content. In some fault locations the ground can become so hot steam can be seen from the excavation whilst digging is occurring.

Chapter 5 Discussion of Data

5.1 Benefits of Fault Locating with Infrared

This research intended to utilise existing technologies in a new way, in order to locate underground faults in a safer and more efficient manner. It also intended to find a method to proactively locate faults while a distributor is still in service, and reduce the number and length of outages to customers connected to Ausgrid's network. Although there are many types of faults, the majority of faults located on the low voltage network consist of resistive earth faults, which has been the main focus of this project.

From the sites surveyed, there is potential for this technology to be used in the manner proposed in this project. This can be seen specifically in site 1, as the hot spot detected, and the cable fault in the pit clearly showed signs of damage. This site was surveyed while the distributor was in service, but after the fuse had been replaced. In this situation heat was still being generated and had radiated enough heat to show a thermal difference on the pit lid. Although this method has been successful on a pit and duct system directly after a fuse has operated, the data collected shows that this method was not as successful on direct buried faults. On the occasions where faults were detected, the hot spot was much larger expected and required a follow up fault location with traditional fault locating methods. The infrared survey did, however reinforce the location with traditional methods. This also shows that although a survey may not provide a positive location on its own, it can still be helpful as a secondary method, and reinforce other methods.

Another benefit of using an infrared camera is the improved safety of the staff working on site. This new method completely removes the user from having to approach live low voltage mains and apparatus, making this method much safer than traditional fault locating methods where access to the cable is required. Secondary fault location methods use probes and stakes to receive signals in order to pinpoint the location of the fault. The thermal survey does not penetrate the ground and therefore has eliminated the risk of damaging underground assets.

5.2 Consequences of Locating with Infrared

Although there are many positive aspects of locating faults with an infrared camera there are a few issues that need to be addressed. Training staff to use the infrared camera is an important factor in achieving an accurate fault location. This training would need to be conducted by an individual that has experience in using and interpreting infrared information.

The thermal image can be easily misread, either in a false positive or a false negative way. If the operator determines there is a fault by misinterpreting the image and provides an incorrect fault location, a crew will excavate the suspected fault, increasing the risk of damage to a healthy section of cable. This is an additional cost and further disruption to customers that would not need be taken had an experienced thermal operator located the fault.

It should also be noted, that from the data collected above, the camera was only able to detect a fault in 5 out of the 15 sites. Some of these sites were used to determine how the different weather conditions and different types of ground cover would affect the heat conduction from the fault to the surface. The installation methods were also considered within this research project and a variety of different installations were chosen to determine if a correlation could be found. If the ideal site conditions had been used for this project, the success rate of this method may have been much higher.

One of the factors not considered at the time of surveying was the time taken between the operation of the 400A fuse to the start of the infrared survey. If this time is too long any heat generated by the fault will have dissipated and will no longer be captured by the camera. Any further investigation into this form of fault location methodology would benefit from measuring this time and determining a point where the infrared camera can no longer locate a hot spot on the ground.

5.3 Analysing Thermal Images

Thermal images are not always easy to read, and the settings on the camera can be the difference between detecting a hot spot and missing a potential fault on the network. It is important to understand the thermal properties of the objects being surveyed and of the objects in the vicinity of the survey. This was evident in site 13, where the radiated energy drowned out the heat generated from the fault. In this scenario, it can be very hard for a surveyor to detect a fault using this method.

The thermal image needs to be taken to maximise the infrared radiation emitted from the target being surveyed. This can be difficult when surrounding objects are very close and the infrared camera is detecting radiated energy reflected from these objects. Appropriate training and experience in the use of the camera, coupled with the knowledge of infrared radiation, can ensure the surveyor is successful in locating the fault.

5.4 Comparison of Fault Locating Techniques

From the 15 sites surveyed, 8 sites had traditional fault locations performed. Of these locations, three were completed by time domain reflectometry, two were located visually, and three by arc location methods. All 15 sites were completed using the infrared survey.

Table 8 Comparison of Fault Location Methods

Location Method	Number of Faults Located	Success Rate
Visual Damage	2	25%
Arc Reflection	3	37.5%
Time Domain Reflectometry	3	37.5%
Thermal Imaging	5	33%

$$Success\ Rate = \frac{Number\ of\ faults\ located}{Number\ of\ sites\ where\ traditional\ methods\ were\ used} \times 100$$

$$Success\ Rate = \frac{Number\ of\ faults\ located}{Number\ of\ sites\ where\ thermal\ imaging\ was\ used} \times 100$$

The success rates have been calculated as percentages using the above formulas in order to compare the data between the fault location methods. For the three traditional fault location methods utilised, the success rate was calculated based on the 8 sites where traditional fault location techniques were required. To determine the suitability of the thermal camera, it has been used on all 15 sites, including cables that have failed causing outages and sites identified from historical data.

Table 8 above compares the different fault location methods used and the success of each method. The thermal survey method was used on all fault types in order to specifically compare the different installation types and determine its suitability. The other fault location methods were used in their ideal situations and cannot be used when the cable is still in service, unlike the thermal surveys.

Even under non-ideal scenarios, the calculated success rate of the thermal survey shows it is comparable to the success rates of the traditional fault locating techniques. This shows that thermal imaging can be used in certain cases to assist with the fault location process. All these methods are used in conjunction with each other to ensure a successful fault location is achieved.

5.5 Cost Benefit Analysis

This form of fault location requires no contact with the low voltage network, eliminating the need for the application of temporary insulation to live exposed mains and apparatus. By maintaining distance from the network, this fault location can be completed safer and more efficiently than by using traditional fault locating methods that require isolations and direct access to the cable to be tested.

To perform a thermal survey of a distributor can take between 10 to 15 minutes, depending on the length and complexity of the circuit. A traditional fault location method can take up to an hour to locate a fault. This is after the isolation of the network has been completed and a permit has been issued. The infrared survey does not require any isolations and can be performed while other works are progressing since it is a non-intrusive test method.

The cost of a thermal camera can range from $3,000 to $5,000, depending on the resolution of the camera and the additional functionality. Comparing this cost to some traditional fault locating equipment, this is fairly inexpensive. A high voltage test set can start at around $20,000 and other equipment would be required to ensure an accurate fault location is performed.

For the short time taken, and the minimal cost incurred, and the added safety benefits, this type of fault location has many advantages and very low overall costs. It is an additional tool to be used in fault locating of underground cables and can provide additional confidence when used with other methods.

Below is a cost benefit table showing the cost associated with purchasing and maintaining an infrared camera. These costs can be variable depending on the level of cost that a company is willing to undertake. A cheaper infrared camera may be purchased to reduce the initial cost, however this may result in poorer image quality and lead to faults being misdiagnosed.

A false positive reading with the infrared camera can be extremely costly to a business, both financially and in reputation. Excavations that are not required are time consuming and costly to a company. Restoration of concrete pavements can cost upwards of $10,000 and can have negative impacts on the community, including a safety risk for pedestrians walking around these sites. If too many sites are excavated on a repeated basis, it can also make the company appear inefficient in its processes as well as wasting money. This can lead to irate customers and additional complaints regarding disruptions and ongoing outages.

It is important to maintain the calibration of the equipment being used. Equipment that has not been regularly calibrated and maintained can shorten the life of the equipment and can unknowingly give false readings. Although this is an ongoing cost to the company, it is minor compared to unnecessary excavations and a poor reputation within the community.

Table 9 Costs of Using Thermography for Fault Locating

Costs	
Cost of Infrared Camera	$5000 to purchase new camera.
Time Taken to Survey Low Voltage Distributor	15 Minutes of survey time. Approximately $100.
Calibration of Camera	Annual cost of calibrating camera. Approximately $500 per year.
Training Staff	1 hour of training for 3 staff. A one-off cost of approximately $1000.
Fuse replacement	Approximately $400 per fuse.

Table 10 Benefits of Using Thermography for Fault Locating

Benefits	
Improved Safety for Workers	Reduction of lost time injuries or potential fatalities.
Reduce number of unplanned outages for customers	Reduces fines associated with unplanned outages.
Advanced warning of faults	This increases efficiency by allowing crews to be planned to respond to network faults rather than cancelling planned work to attend an emergency outage.
Reduce costs of low voltage fuse replacement	By attending faults earlier, there will be less fuses that are replaced saving costs on fuses.

Although the benefits are difficult to be quantified, they provide a substantial benefit to any company that is prepared to improve safety and reduce costs within the business. Staff currently have to be trained to apply temporary insulation in order to access the low voltage network in order to complete the fault location process. The thermal camera eliminates this requirement by not needing direct access to the low voltage terminations. From the number of low voltage faults that occur, it would be reasonable for a company to recoup the cost in approximately 6 months. This may be even quicker if large fines can be avoided by tracking these faults and attending sites before the fuses are operating immediately.

Chapter 6 Recommendations and Conclusions

6.1 Recommendations for Further Research

From the research and experimentation conducted whilst undertaking this project, it is evident that further research is needed to gain further insight into locating underground faults with thermal imaging. The following factors can help determine the optimal conditions for an infrared survey to be completed:

- Time Factors
- Time of Day
- Network Load
- Network Installation

The time between the fuse operating and the time of the infrared survey can make a difference to the heat generated in the ground, and also how much heat remains for the infrared camera to pick up. This time factor can be the difference between finding the fault or missing it. There is scope for further research in this area to determine the viability of using the thermal camera to detect temperature gradients. This could be graphed to show the heat dissipation over time and a reduction of the thermal gradients over the timeframe.

The time of day that the survey is completed can also make a large difference to the success of the survey. During a sunny day there is additional infrared radiation being reflected from adjacent surfaces that will make detecting a temperature gradient more difficult. From the data collected, surveys that were completed on days that were not as sunny or at night time, had an improved chance of being successful in locating a fault. Although this project did consider the time of day the surveys were completed, there were not enough sites surveyed to gain a conclusive outcome to determine if this was a major factor in the success of this fault locating method. Additional sites surveyed at different times combined with the data collected in this study would allow for a greater understanding of the capabilities of the infrared method.

The load of the distributor was not considered during this project. This was due to the lack of visibility of the network as these loads are not recorded. Fault currents were also not available at the time of surveying the distributors, making it difficult to determine the heat generated by the fault compared to the load of the distributor. The use of load measuring equipment could help in determining these currents and assist in determining the heat generation at the point of failure in future research.

The installation of the cables also impacted the success of the infrared survey. Pit and duct style installations held the heat better than the direct buried installations. The pit wall insulated the pit, forcing the hot air upwards to the pit lid. This heat then radiated through the lid and created a temperature gradient on the surface that the thermal camera could detect. Since there were only two sites that were surveyed that had a pit and duct system, it would be advantageous to explore more of this type of installation method to further the research in this style of cable installation.

6.2 Conclusions

A review of the literature was conducted on the types of traditional fault location methods and on the use of infrared thermography in industry. The literature review showed that there was a lack of research in using the infrared thermography techniques for locating underground cable faults. This study has combined these two areas by examining traditional fault location techniques and use of the infrared camera to detect temperature gradients near the surface of underground cable faults.

This project proposed that 20 sites were to be surveyed with the infrared camera, however due to the milder weather conditions which in turn caused a reduced number of faults, only 15 sites could be surveyed. From these 15 sites, the infrared camera was able to successfully detect five faults. This resulted in a 33% success rate for this type of fault location method.

This project has examined the feasibility of locating underground low voltage cable faults using an infrared imaging camera and determined there is a place for this type of fault location method. Although this method is not suitable in all scenarios, it has a unique capability to detect faults without having to access the low voltage network. From the data collected, this method was successful in locating the fault in one third of the sites visited.

An analysis of the collected data shows that there is an improved likelihood of locating a fault within a pit and duct system with the thermal camera. This type of installation lends itself to the fact that the heat is trapped in a confined area. This heat will then radiate through the pit lid and can then be found by the infrared camera. The pit lid construction is thinner than the surrounding concrete and will heat up faster than the surrounding area forming a better temperature gradient than a direct buried cable installation.

The success rate of the thermal camera is comparable to the success rates of the traditional fault locating methods. Each traditional method was used in only a few of the sites visited and multiple methods were used to confirm each location. The thermal survey can be used to ensure an accurate fault location is given in conjunction with the traditional fault location methods.

The thermal survey is most useful on days where there is little sun or at night time. This reduces the infrared radiation from the surrounding materials and allows the fault to radiate heat into the environment for the infrared camera to detect. The time after the fault had occurred also played a large part in the detection of the fault. This would certainly be an area for further research.

A cost benefit analysis shows how the benefits of using the thermal imaging technique far outweigh the costs of purchasing a camera, training and calibration. The ongoing safety improvements and the efficiencies that can be gained are difficult to place a value on, since these costs will be different in each workplace. The ability to eliminate the low voltage hazards ensures a safe workplace for all stakeholders.

The findings from this study show that infrared thermography surveys, when coupled with traditional methods, will improve safety and accuracy while performing low voltage fault locations. Infrared thermography offers unique opportunities to industry, and this thesis has demonstrated that it will play a key role in the safe and effective location of underground power cable faults.

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Appendix A Project Specification

ENG4111/ENG4112 Research Project

Project Specification

Student: Gregory Mansell

Title of Project: Locating Low Voltage Underground Power Cable Faults Using Infrared Technology

Major: Power Engineering

Supervisor: Tony Ahfock

Enrolment: ENG4111 – Ext S1, 2023

ENG4112 – Ext S2, 2023

Aim: When a fault occurs on the low voltage network, the fault current will be in excess of 1000 Amps and, in most cases, this current will flow for an extended period of time before the HRC fuses operate. This fault current will generate heat in the ground which will rise to the surface and heat an area above the fault before the HRC fuses operate and remove the source of the heat.

It is my intention to utilise the Flir infrared camera to survey the route of the cable and detect these hotter patches of heat. The cable route will be confirmed from the network plans as part of the job discussion for the team locating the fault. Infrared images of the suspected faulty areas can then be taken along with normal photographs to show the location.

Traditional fault location methods can then be used in most circumstances to determine to accuracy of the infrared location process. These processes can then be analysed and determine the feasibility of the new fault location method.

Programme: Version 1, 15th March 2023

1. Conduct background research on fault location techniques and procedures currently utilised on Ausgrids' low voltage network.
2. Conduct research on the advantages and disadvantages of using infrared technology for locating low voltage underground faults.
3. Utilise current training and documentation of the infrared camera. If an upgraded model is to become available, then further training may be required.
4. Record the effectiveness of the camera for fault locating purposes. This will require additional information, such as ambient temperature, cable type, Time of fuse operation.
5. Determine the safety implications or improvements to the fault locating process as a whole.
6. Analyse the experimental data collected and determine if the infrared technology is a feasible method of accurately locating low voltage underground faults.

Appendix B Risk Assessment

Project Risk Assessment

This project will require the application of High Voltage to underground cables and also a requirement to work within minimum safe working distances of live electricity. These hazards, and others, warrant a risk assessment to be undertaken on the experiments being undertaken and the risks to the research project. Below is a risk assessment completed on the experiments being undertaken and work in the field, and also a risk assessment on the project itself.

		CONSEQUENCE				
		Insignificant	Minor	Moderate	Major	Severe
LIKELIHOOD	Almost certain	11	16	20	23	25
	Likely	7	12	17	21	24
	Possible	4	8	13	18	22
	Unlikely	2	5	9	14	19
	Rare	1	3	6	10	15

Risk ranking			
EXTREME	HIGH	MEDIUM	LOW

Figure 32 Risk Assessment Matrix (Ausgrid, 2021)

Table 11 Risk Assessment of Thermal Surveys

Hazard	Risk Rating	Control	Adjusted Risk Rating
Insufficient fault data	21	Start collecting data early	14
Unable to collect data due to other commitments	24	Arrange for other team members to help collect data.	15
Allowing time to write results of experiments	17	Start writing early and follow timetable	6
Uncontrolled discharge of electricity	23	Follow testing procedures and maintain appropriate distances	10

Motor Vehicle Accidents	16	Driver Training, Awareness	5
Slips and Trips	12	Use cable covers and be aware of surroundings	3
High Voltage Testing	20	Use earth stick after testing, ensure equipment is working properly, follow procedures	6
Manual Handling	21	Wear gloves, Two-person lift, Training	14
UV Exposure	17	Wear PPE, Hats, Sunscreen, Additional Shade if Applicable	9
Vehicular Breach of Worksite	23	Traffic Control, Hi-Vis Clothing,	14

Appendix C Ethics

The code of ethics and guidelines on professional conduct of Engineers Australia will be adhered to.

Appendix D Timeline and Resources

Appendix D.1 - Timeline of Project

			Semester 1 - ENG 4111															Break					Semester 2 -ENG 4112														
	Task	Duration	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24	Week 25	Week 26	Week 27	Week 28	Week 29	Week 30	Week 31	Week 32	Week 33	Week 34	Week 35
1	Approval of Project	1 Week																																			
2	Completeing Additional Documentation	2 Weeks																																			
3	Collection of Data	8 Weeks																																			
4	Varifying Results	8 weeks																																			
5	Analyse Data	8 Weeks																																			
6	Analyse Fault location Techniques	8 Weeks																																			
7	Draft Dissertation	24 Weeks																																			
8	Proof Reading and Editting Dissertation	2 Weeks																																			
9	Present Results at Professional Practice	2 Weeks																																			
10	Complete Dissertation and Submit	2 Weeks																																			

Appendix D.2 - Resources Required

All required fault locating equipment is readily available at my workplace and listed below.

Item/Equipment	Quantity	Owner	Cost	Description
Laptop	1	Student	Nil	Laptop with operating software
Microsoft 365 Package	1	Student	Nil	Software Installed on Laptop
Insulation Resistance Tester	1	Ausgrid	Nil	For Measuring Insulation Resistance of Cable Faults
Flir Infra-Red Camera	1	Ausgrid	Nil	Used to locate Hot spots above suspected Faults
Baur IRG 3000 /4000	1	Ausgrid	Nil	Time Domain Reflectometry for Pre-Fault Location Methods
Baur SSG 3000	1	Ausgrid	Nil	High Voltage Surge Generator for Pinpointing Cable Faults
Baur SA 32	1	Ausgrid	Nil	Coupling Unit for Pre-Fault Location
Aquatronics Super D.A.D Acoustic Detector	1	Ausgrid	Nil	For Pinpointing Cable Faults
Fault Locating Truck	1	Ausgrid	Nil	Used for Transporting Test Equipment
General PPE	Various	Ausgrid	Nil	Hi-Vis Clothing, Cut Resistance Gloves, Safety Glasses, Steel-Capped Boots, etc
Office Supplies	Various	Student	$50	Pens, Paper, etc
Mapping Software	1	Student	Nil	Used to map Ausgrid's low voltage network in various areas

Appendix E