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Prevention Of Electrical Accidents With Safe Personal Protective Bonding And Earthing

A dissertation submitted by

Andrew Pratt

in fulfilment of the requirements of

ENG4112 Research Project

towards the degree of

Bachelor of Engineering (Power)

Submitted: September, 2014

Abstract

Working on powerlines is an inherently dangerous occupation. Powerline construction and maintenance can be performed whilst the power line is energised or de-energised. Although working with the powerline switched off is logically safer, a lineworker may still be exposed to lethal electrical hazards with causes such as lightning, induction or accidental energisation. Sadly, there are numerous examples where line workers have been electrocuted working on de-energised powerlines.

The title of this project is “Prevention of electrical accidents with safe personal protective bonding and earthing”. Personal Protective Bonding and Earthing (PPBE) is a safety technique employed by line workers to protect themselves against the the risk of an electric shock. The technique aims to ensure the worksite is maintained at equipotential conditions at all times. This is attempted by the installation of bonding cables at or near the work area to ensure all conductive surfaces are electrically connected together.

The project aim is to identify unsafe conditions that may exist for the application of PPBE. If unsafe conditions are identified it may be possible to determine solutions which will make working on powerlines safer.

The electrical principles which underpin the use of PPBE can be applied to all forms of electrical work. However, the focus of this project is on high voltage distribution powerlines.

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Acknowledgments

I would sincerely like to thank Mr Leith Elder for his expert advice and personal encouragement for me to fulfil my goal in becoming an engineer. Leith has been a source of inspiration for me over many years.

I would also like to thank my supervisor Dr Bob Burgess for his guidance. Bob's expert advice provided me the confidence I needed to keep progressing and complete the project.

Andrew Pratt

University of Southern Queensland
September 2014

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Nomenclature

Total impedance of the human body - The vectorial sum of the internal impedance and the impedances of the skin (AS/NZS 60479)

Threshold of perception - The minimum value of touch current which causes any sensation for the person through which it is flowing (AS/NZS 60479)

Threshold of reaction - The minimum value of touch current which causes involuntary muscular contraction (AS/NZS 60479)

Threshold of let-go - The maximum value of touch current at which a person holding electrodes can let go of the electrodes (AS/NZS 60479)

Threshold of ventricular fibrillation - The minimum value of touch current though the body ventricular fibrillation (AS/NZS 60479)

Ventricular fibrillation - The condition when the heart assumes an uncontrolled vibration and stops beating. This condition can be caused by current flowing across a person's chest. Ventricular fibrillation is the most common cause of death by electrocution. (IEEE 1048)

Electric shock- A sudden discharge of electricity through a part of the body (Oxford dictionary)

Electrocution - Death caused by electric shock

Touch potential (or touch voltage) - The voltage difference between a grounded metallic structure or equipment and a point on the earth's surface separated by a distance equal to one normal horizontal reach, approximately 1.0m (IEEE 1048)

Step potential (or step voltage) - The potential difference between two points on the earth's surface separated by a distance of 1.0m. (IEEE 1048)

Worksite ground - The technique where the ground set installed at the structure where the work is to be performed. Also known as personal ground, working ground, personal protective ground (IEEE 1048)

Bracket grounding - The grounding method where temporary ground sets are installed on both sides of the worksite, eg. at the adjacent structures. (IEEE 1048)

Accessible voltage drop - The voltage difference between any two points accessible to workers at the worksite. (IEEE 1048) For example, the two points could be the ground or work platform a worker is standing on and a conductor they are touching. (IEEE 1048)

Conductor - A wire (or combination of wires) suitable for carrying electric current (IEEE 1048)

De-energised - Free from any electrical connection to a source of potential difference and from electric charge; not having a potential different from that of the earth (IEEE 1048)

Energised - Electrically connected to a source of potential difference, or electrically charged to have a potential different from that of the earth in the vicinity (IEEE 1048)

Equipotential - An identical state of electrical potential for two or more items. For the purposes of electrical grounding, a near identical state of electrical grounding (IEEE 1048)

Ground or grounded - A conducting connection,whether intentional or accidental, by which an electrical circuit or equipment is connected to earth, or to some conductive body of relatively large extent that serves in the place of earth, resulting in the circuit or equipment to be grounded. Also known as 'earthed' (IEEE 1048)

Ground potential rise - also known as 'earth potential rise' - The maximum voltage that a station ground grid (or earth) may attain relative to a distant point assumed to be at the potential of remote earth (IEEE 1048)

Isolated - Physically separated, electrically and mechanically, from all sources of electrical energy. Such separation may not eliminate the effects of electromagnetic induction. (IEEE 1048)

Isolation Point - a location in the powerline where the supply is switched off, and the downstream section of line is isolated. For example, an air break switch or circuit breaker

Magnetic field induction (inductive coupling) - The process of generating voltages and/or currents in a conductive objective or electric circuit by means of time varying magnetic fields (IEEE 1048)

Access Permit - A form of authorisation which allows access to work on, or near, or to test electrical apparatus (CEOP8030)

Access Permit Earths - a set of temporary earths and short circuits applied to the de-energised section line in the immediate vicinity of the isolation point

Working Earths - a set of temporary earths and short circuits applied to the de-energised line at or near the worksite when the Access Permit Earths are not in view.

Abbreviations

APE - Access Permit Earths

AS or AS/NZS - Australian Standards or Australian Standards and New Zealand Standards

IEC - International Electrotechnical Commission

IEEE - Institute of Electrical and Electronic Engineers

EPR - Earth Potential Rise

ESR - Electrical Safety Rules

ENA - Energy Network Association

ENO - Energy Network Operator

ESAA - Electricity Supply Association of Australia Limited

HV - High Voltage

LV - Low Voltage

PPBE - Personal Protective Bonding and Earthing (includes temporary short circuit cables and earth conductors)

PPBE - Personal Protective Bond only

USQ - University of Southern Queensland

WE - Working Earths

11kV - 11000 Volts

Chapter 1

Introduction

1.1 Introduction

In the modern world, the use of electricity has become an integral part of peoples life. Many of the activities that people undertake, or the products that people use, would not be possible without a reliable and readily available electricity supply. The electrical energy that consumers use is supplied via an established power network. The power network comprises a system of generators, transmission and distribution lines, and substations. The transmission and distribution lines which transport power from the generation station to the consumer may be constructed overhead or underground.

Energy Network Operators (ENO) are the network businesses responsible for the operation and maintenance of these power networks. In order to maintain a safe and reliable electricity supply, ENO must perform regular maintenance on their assets. ENO also perform work to enhance their networks to cater for future development by constructing new assets including powerlines and substations.

The construction and maintenance of powerlines requires the work of skilled trade persons known as lineworkers. Powerline work is a specialised construction activity where workers must be able to avoid the hazards of working with electricity. Powerlines are operated at extremely high voltages. For example, typical distribution high voltage lines operate at 11,000 or 22,000 Volts. Transmission lines operate at voltages as high as 500,000 Volts. The worrying reality is that lineworkers cannot see the presence of electricity or the imminent danger it poses. Contact with an energised high voltage line can be lethal, and therefore, inadvertent contact is always a concern.

To keep their workers safe, and mitigate the hazards of electricity, ENO enforce strict rules and procedures on how work must be done. Some companies use a document known as the 'Electrical Safety Rules' (or a similar name), to specify their requirements. The rules provide a systematic approach to work designed to put in place protections which keep the workers safe.

Powerline work can be undertaken under either energised or de-energised conditions. Energised or 'live line' work is performed when the social or economic costs of isolating a powerline are too high. For example, de-energising the electricity supply to a central business district can cause loss of trading for many businesses. This subsequently would cause angst amongst the community and might damage the reputation of the ENO.

Logically, working on a de-energised powerline is the safer option and is the preferred approach where the impact of de-energising the network is not too great.

This research project focuses on a safety technique as known as Personal Protective Bonding and Earthing (PPBE). The technique may also be referred to as ‘protective grounding’ or ‘equipotential bonding and earthing’. PPBE is applied by lineworkers when working on de-energised powerlines. Although a powerline might be turned off and seemingly safe to access, the lineworkers must be protected against an unplanned energisation of the line. Such an event could be lethal, and sadly there are many tragic cases where workers have been fatally injured.

A powerline can be unintentionally energised by causes including voltage induction, lightning strikes, accidental contact with other nearby lines, and network switching errors. PPBE is to applied to the powerline so that in the event of an unplanned energisation, equipotential conditions are maintained at the linesman’s worksite.

Chapter 2

Literature Review

2.1 What is Personal Protective Bonding and Earthing?

Broadly speaking, Personal Protective Bonding and Earthing (also known as 'protective grounding') is the practice of short circuiting and connecting to earth the electrical conductors of a powerline. This procedure is undertaken by lineworkers prior to commencing work on de-energised lines. PPBE is a safety measure aimed at mitigating the risk of an electric shock caused by unplanned energisation of the powerline.

The Institute of Electrical and Electronics Engineers (IEEE) states "the primary purpose of protective grounding is to limit the voltage difference between any two accessible points at the worksite to an acceptable value" (IEEE 1048) In other words the voltage difference at any two points a worker might simultaneously touch must be small enough that it does not cause a harmful electrical shock. An acceptable value will limit the current through the human body to an amount that will not cause ventricular fibrillation of the heart (IEEE 80, p13). The effects of current upon the human body is discussed in greater detail in Section 6.3.

Another explanation of PPBE is the provision of an alternative low resistance path for fault current to flow and safely bypass the worker. The concept is that the majority of fault current will take the path of least resistance through the earth cables and not the worker. However, it is important to remember that if a worker forms a parallel path with the fault current, then at least some current will flow through the worker. It is the magnitude of this current which determines the risk to the worker.

Simply stated, the goal of protective grounding is to ensure is that equipotential conditions are maintained at all times at the site of the lineworker.

2.2 Sources of electrical hazards

To appreciate the purpose and use of protective bonding, it is necessary to understand the sources from which an electrical hazard might arise.

When a powerline is de-energised for work, it is isolated from its normal sources of supply, or in other words simply 'turned off'. This is usually achieved by opening a circuit breaker and creating a visible isolation by then opening an air break switch or outdoor links. However, it is still possible that the line may be energised accidentally, or subjected to induced voltages and currents caused by electric or magnetic induction (IEEE 1048). Any of these circumstances are dangerous, and if not successfully mitigated, may cause a lethal hazard for a lineworker whether they be at the pole top or standing on the ground. If this occurs, a worker may be subjected to step or touch voltages, which if large enough could result in a serious electric shock.

Accidental energisation of a powerline can occur in a number of ways. Sometimes the cause can be human error. For example, a line may be mistakenly turned on before a linesman has completed work. Or, the lineworkers themselves can be at fault if they cause an accidental contact between their de-energised line and a nearby live circuit. This possibility is a particular hazard with powerlines supporting multiple circuits and where only one circuit is isolated from supply. Vandalism has also been known to cause an unintended energisation of powerlines, and an example of this is detailed in Section 2.6.3.

A direct strike on the line by lighting may result in a surge of fault current traveling along the line. This current will quickly dissipate to earth but its path may include a line worker in contact with the powerline. This is an extremely dangerous event given the enormous amount of energy that lighting can generate.

Induced voltages and currents are a concern when a de-energised powerline is located within close vicinity of other nearby powerlines which remain energised. The Australian Standard "AS/NZS 4583:2012 - Electrical hazards on metallic pipelines" provides excellent information on magnetic induction (or low frequency induction), and the hazard it creates. When a powerline is isolated, its electrical conductors can be compared to the metallic pipelines described in this standard. That is, they are metallic objects suspended in air and fully susceptible to the magnetic fields of nearby powerlines.

AS/NZS 4853:2012 explains "alternating current on a high voltage powerline can induce a voltage on an adjacent pipeline. This induction results in a voltage over the exposure length due to the electromagnetic field from the current. The induction is caused by the alternating magnetic field intersecting the pipeline, causing the pipeline to act as a secondary core of an air core transformer. The voltage is proportional to the length exposed to the magnetic field".

The magnitude of the induced voltage is also influenced by other factors. This includes the physical distance between the de-energised conductors of the isolated line, and each phase conductor of the live powerline, as well as the magnitude and phase relationship of the load currents of the energised line. The induction effects of a nearby powerline with relatively balanced load currents will be relatively small as the "overall induced voltage is the phasor sum of the voltage induced by each power line phase current" (AS/NZS 4583). Thus, in a balanced load situation, the magnetic fields caused by each phase effectively cancel each other out. However, the effects of induction can be more severe when a nearby powerline which suffers a single phase to ground fault. This results in a relatively larger flow of unbalanced fault current whose magnetic fields are not canceled by current in the other phases.

AS/NZS 4853:2012 defines capacitive coupling as "the condition whereby the capacitance between the phase conductors or any metal object forms an electrical path to earth". The standard explains the electric field created by an energised powerline causes the flow of a small continuous current to earth. When a de-energised line intercepts the electric field, a portion of the current is distributed along its conductors which then flows from the conductors to earth. The earth current can be by its own capacitance to earth, or, by a direct electrical connection. Potentially this could be via a lineworker if they form a circuit to earth.

If protective bonding is not employed to maintain equipotential conditions at the worksite, lineworkers can be exposed to lethal voltages. A safety alert titled "Fatality of Power Line Rigger" published on the Queensland Government Electrical Safety website, outlines a tragic incident where a lineworker was electrocuted whilst constructing a new line adjacent to an existing 275kV transmission line. Whilst the precise details of the accident are not specified, the article indicates that voltage induction was the cause (Dieckmann 2009).

2.3 Effect of current on the human body

Unfortunately, it is not possible to achieve absolute equipotential conditions at a worksite. Under fault conditions, a worker will be exposed to some voltage and current even if the amount is very small. When considering the potential hazards of de-energised work, and the application of PPBE, it is therefore important to have understanding of the magnitude and duration of current a person can safely withstand.

AS/NZS 60479.1:2010 provides a thorough reference “on the effects of shock current on human beings and livestock”. In fact, this standard was created for use in determining electrical safety requirements. Other standards such as IEEE Std-1048 also include literature on this subject due to its relevance in the safety context of those standards.

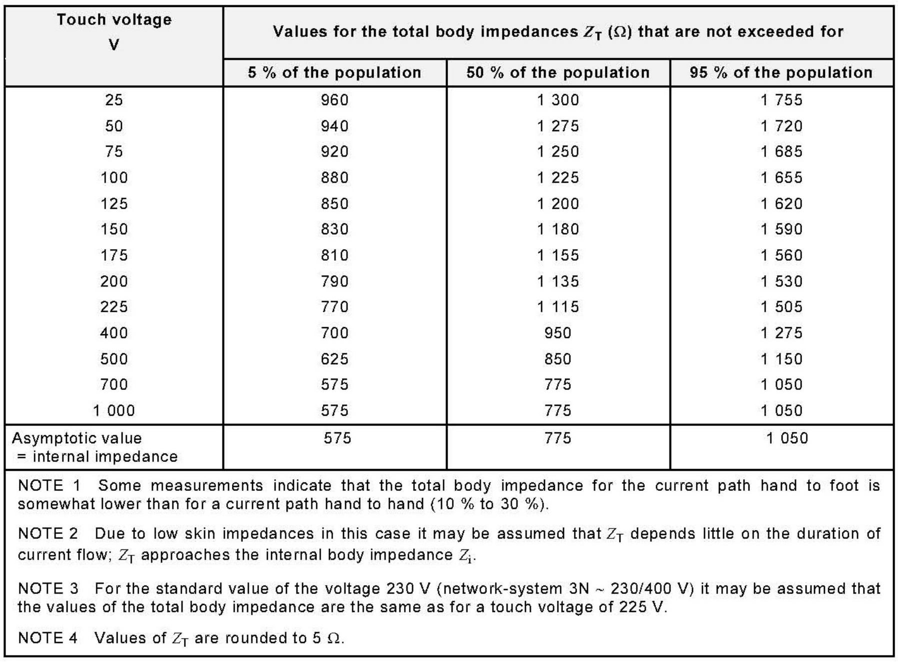
The danger of an electric shock to a person depends upon the magnitude and direction of current. Current will flow through a person’s body from an entry point to an exit point, or simply between the two conductive points of which a person is touching. Applying Ohm’s Law, the magnitude is dependant upon the voltage difference between these two points, and the Total Impedance of the Human Body (TIHB) for this given path (e.g. hand to hand). The value of TIHB will vary between different individual persons involved, the contact points on their body, and the environment in which a person is working.

AS/NZS 60479.1:2010 provides a great deal of tabular data which illustrates how different conditions affect a persons resistance, and therefore, how much current will flow. After inspecting the information, it can be seen that the TIHB is affected by the:

- current path through the body (eg. hand to hand, or hand to foot, or hand to both feet)
- size of the ‘touch voltage’
- duration of the current flow
- frequency of current
- degree of moisture and salt content of the skin
- contact surface area at the entry and exit points of the body
- contact pressure exerted and temperature

Tables 1 to 9 of the AS/NZS 60479.1:2010 show experimental measurements of the TIHB value when tested under the different conditions above. It can be seen that the TIHB decreases with higher values of touch voltage, surface contact area, moisture and salt content. Thus under such conditions, higher current will flow and the severity of the shock will be greater.

For a lineworker working on a warm day, it would be reasonable to expect they would have a relatively low value of TIHB. They likely make good surface contact as they grab a conductor, and would do so with moist and salt affected hands due to their perspiration. Therefore, the nature of their work will possibly make them more susceptible to touch voltages than other people. Figure 1 indicates the total impedance of humans could be in the range of 525 Ohms to 1050 Ohms for a touch voltage of 1000V.



Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	960	1 300	1 755
50	940	1 275	1 720
75	920	1 250	1 685
100	880	1 225	1 655
125	850	1 200	1 620
150	830	1 180	1 590
175	810	1 155	1 560
200	790	1 135	1 530
225	770	1 115	1 505
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value = internal impedance	575	775	1 050

NOTE 1 Some measurements indicate that the total body impedance for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

NOTE 2 Due to low skin impedances in this case it may be assumed that Z_T depends little on the duration of current flow; Z_T approaches the internal body impedance Z_i.

NOTE 3 For the standard value of the voltage 230 V (network-system 3N ~ 230/400 V) it may be assumed that the values of the total body impedance are the same as for a touch voltage of 225 V.

NOTE 4 Values of Z_T are rounded to 5 Ω.

Figure 2.1: Total Body impedances for a current path hand to hand A.C 50/60Hz, for large surface areas of contact in saltwater-wet conditions. Source: AS/NZS 60479.1:2010

The seriousness of electric shock current to a person is dependant upon the magnitude of shock current and its duration. The magnitude of current also affects a persons ability to react and free themselves from their danger. AS/NZS 60479.1:2010 different degrees of severity from the ‘threshold of perception’, to the ‘threshold of ventricular fibrillation’. The threshold of perception is the the minimum amount of current flowing though a persons body for them to be able to sense the shock. When ventricular fibrillation occurs the hearts normal rhythm is disrupted and cardiac arrest can occur which may lead to death. A safe level of current might be the ‘threshold of let-go’. At this threshold, a person experiencing a shock still has enough muscular control to free themselves from the circuit.

Table 11 from AS/NZS 60479.1:2010 provides a summary of ‘time/current’ zones and their physiological effects. (See Figure 2.2)

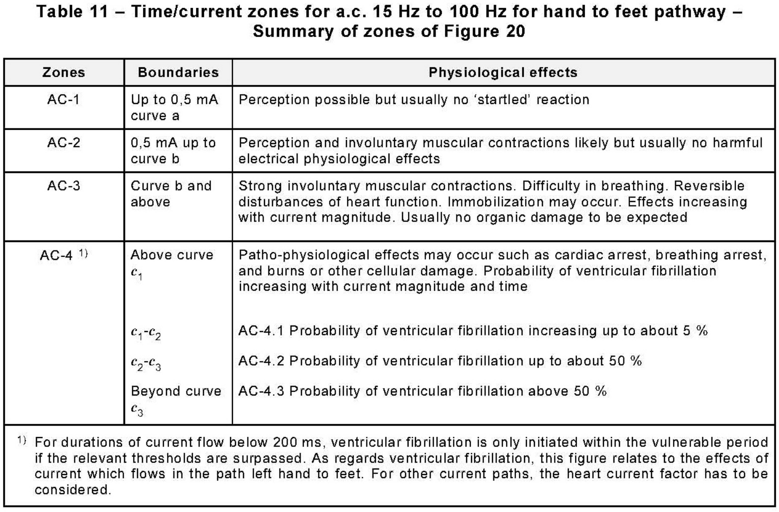


Table 11 – Time/current zones for a.c. 15 Hz to 100 Hz for hand to feet pathway – Summary of zones of Figure 20

Zones	Boundaries	Physiological effects
AC-1	Up to 0,5 mA curve a	Perception possible but usually no ‘startled’ reaction
AC-2	0,5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects
AC-3	Curve b and above	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected
AC-4 [1]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	AC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2-c_3	AC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	AC-4.3 Probability of ventricular fibrillation above 50 %

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

Figure 2.2: Time/current zones for a.c.15 Hz to 100 Hz for hand to feet pathway Source: AS/NZS 60479.1:2010 - Table 11

Figure 20 from AS/NZS 60479.1:2010 provides an illustration of these zones.

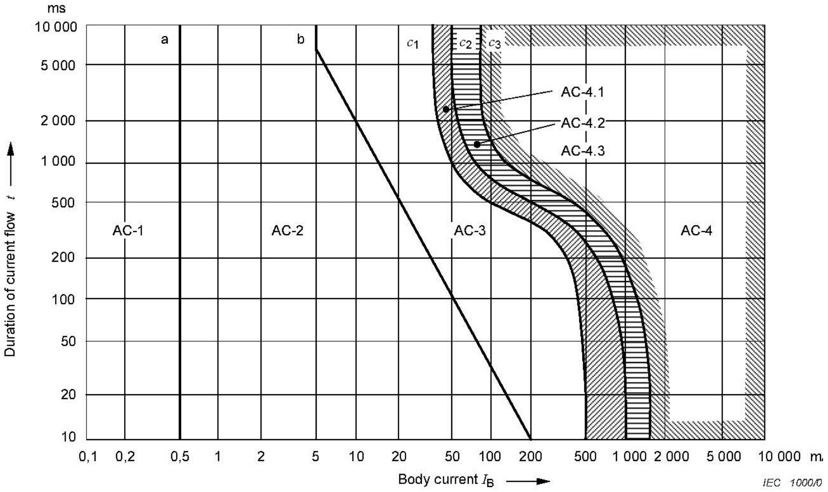


Figure 2.3: Conventional time/current zones of effects of a.c.currents (15 Hz to 100 Hz) on persons for a current path corresponding to left hand to feet. Source: AS/NZS 60479.1:2010 - Figure 20

In Figure 2.3, it can be seen that ventricular fibrillation may occur with as little as 50mA of current. IEEE Std-1048 suggests a minimum of 67mA will cause fibrillation. The actual amount will depend on the person and duration of the shock. However, when compared with large fault currents which can be thousands of amps, either amounts seem very minuscule indeed.

2.4 Selection of appropriate protective grounding equipment.

The goal in applying protective grounding is to maintain equipotential conditions for the line worker. If this is achieved, then the line worker will be safeguarded against the possibilities of an electric shock. Careful consideration of the equipment used and how it is installed is needed to ensure a safe work environment.

A one approach fits all approach will not necessarily work all the time. Failure to properly plan a project, recognise potential hazards at a site, or select the right equipment may see the PPBE fail in its duty. To make matters worse, poor implementation of PPBE can actually increase the risk of harm to lineworkers under fault conditions.

There are a number of standard guidelines available to network businesses and lineworkers to enable them to make good PPBE selections. IEEE Std 1048-2003 "Guide for Protective Grounding of Power Lines" is a thorough and specific reference on the topic of protective grounding. The purpose of the document is "to provide guidance for protective grounding in job sites during de-energised maintenance of powerlines". (IEEE 1048)

IEEE 1048 offers balanced advice, including assessment of the benefit and risks, on specific scenarios requiring use of protective grounding. For example, in cases where a structure contains both HV and LV de-energised conductors, the standard suggests connecting the worksite earths to the LV neutral conductor. The benefit of this is an assured low resistance connection to earth as the neural conductor is solidly grounded at a nearby substation. However, IEEE 1048 also discusses risks which must be taken into account by the work crew before deciding upon this approach. These include the possible transferred earth potential caused by a ground fault through the portable earths to the LV conductors supplied from the substation. This could place other workers simultaneously working on the LV mains at risk of severe touch voltages. A suggested mitigation measure is the use of rubber insulation mats on the LV conductors to safeguard against this event. This is but one example of many scenarios discussed in the standard. The example is evidence of the importance of crews considering all the risks before deciding the most appropriate application of PPBE.

IEC 61230 “Live working - Portable equipment for earthing and short circuiting” is a standard which covers the actual equipment used for protective grounding. This is an important standard as the design and component manufacture must be of high quality if it is to be relied upon when subjected to a severe fault. The design of the portable bonding and earthing equipment, including the components such as the clamps and cables, as well as the equipment test procedures, are covered by this standard.

“EC 5 Guide to Protective Earthing” is a document with comprehensive information on power system earthing. A solid understanding of earthing principles is imperative in analyzing potential hazards associated with personal protective grounding. The document is written for permanent earthing installations, but the information it contains makes it a valuable resource for this research subject. The standard provides much information on earthing design including solid explanations of soil resistivity and electrode resistance.

“IEEE Std 80:2000 Guide for Safety in AC Substation Grounding” serves a similar purpose to the EC 5 Guide to Protective Earthing and is an alternative reference for earthing design.

Many network businesses have their own rules aimed at ensuring a safe approach to working with electricity. One example is the Essential Energy policy document CEOP8030 “Electrical Safety Rules”. This document’s purpose is to “provide a uniform set of safe work requirements which persons must comply with when involved with work on or near electrical apparatus”. The document provides explicit instructions for all types of electrical work on Essential Energy’s assets.

Essential Energy has another document CEOP2377 “Equipotential and Personal Protective Bonding” which supplements the safety rules, and provides specific instructions for the application of personal protective bonds. In the case of overhead line work, the document offers five different methods in which protective bonding can be applied. The choice of method depends on the type of pole and whether a permanent earth is established at the pole. Figures 4 to 8 illustrate the different methods as per the document.

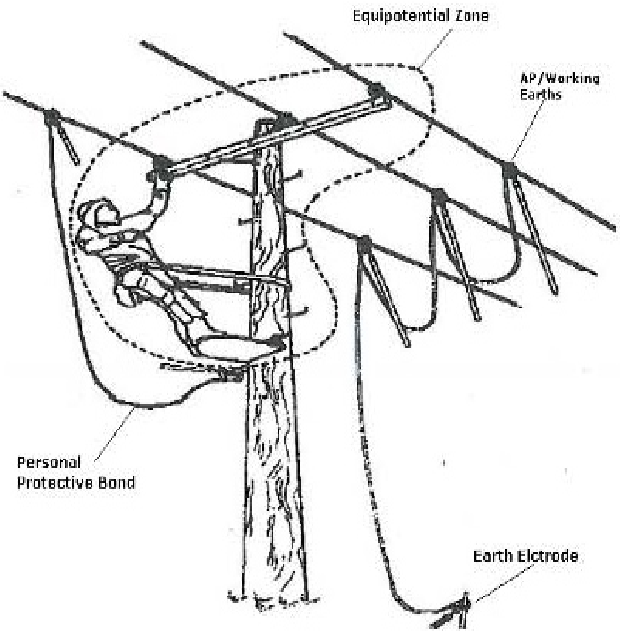


Figure 2.4: Bond installed on timber pole with earthing and short circuiting in view of the worksite. Source: EE2377

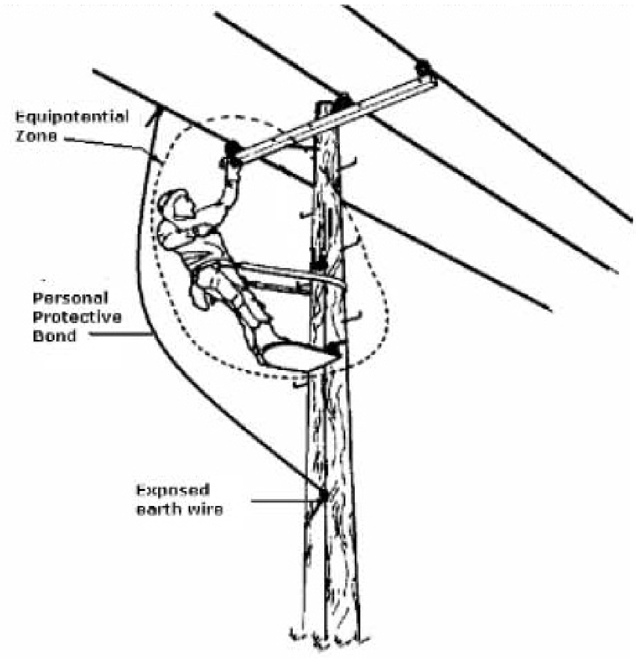


Figure 2.5: Personal Protective Bonding using known permanent earth on a timber pole. Source: EE2377

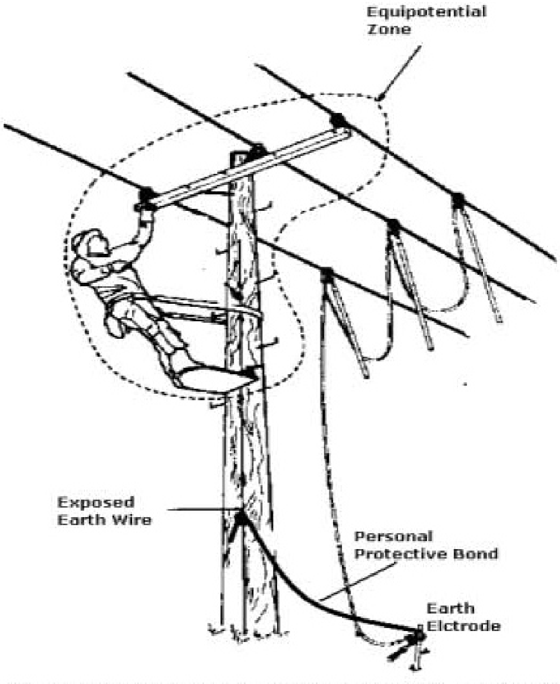


Figure 2.6: Personal Protective Bond using known permanent earth and Access Permit/working earths on a timber pole. Source: EE2377

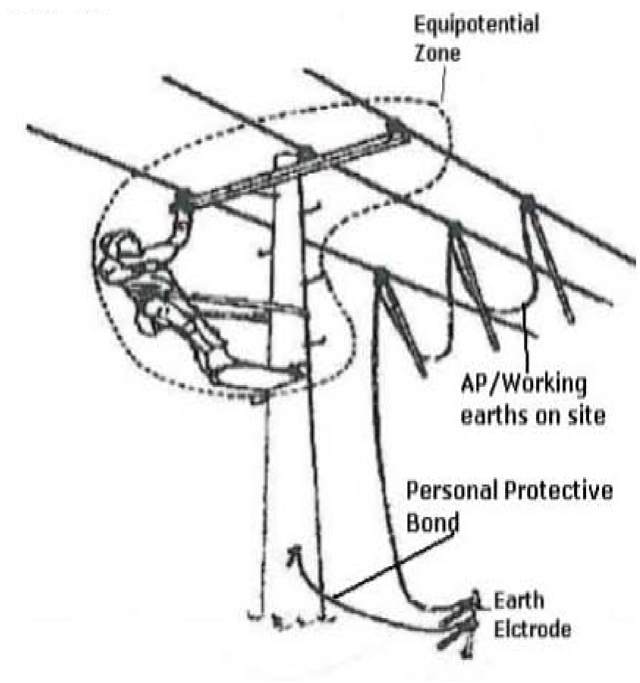


Figure 2.7: Personal Protective Bond installed with Access Permit/ working earths on steel or concrete structure. Source: EE2377

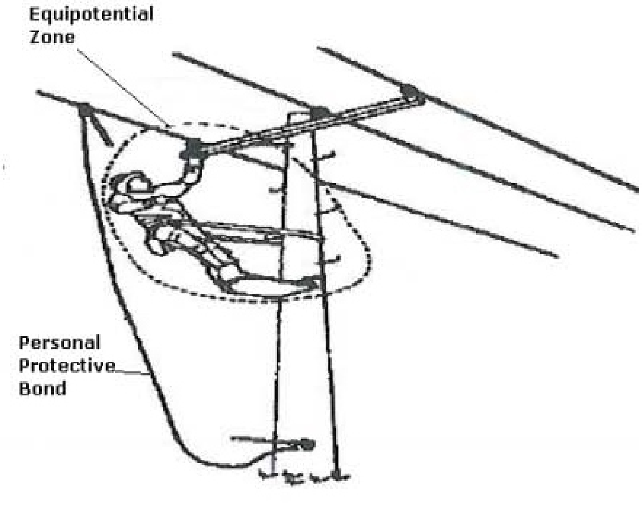


Figure 2.8: Steel or Concrete pole or structure with personal protective bond installed. Source: EE2377

2.5 What can go wrong with Personal Protective Bonding and Earthing?

The correct implementation of PPBE can the difference between life and death for a lineworker. However, if not applied correctly, it can actually increase the chance of harm, not just for the workers, but also unsuspecting members of the public.

In his paper “Transferred Potential - A hidden killer of many linemen”, Suresh discusses the dangers of Earth Potential Rise (EPR) to lineworkers in contact with de-energised lines. Suresh examines the particular case of 3 wire distribution lines which don’t have an overhead earth wire but are supplied from a star secondary transformer with a solidly earthed neutral. Suresh criticizes the practice of earthing the de-energised line at the source end as well as applying earths at the worksite. Instead he argues that a safer outcome will be achieved by placing protective grounds and equipotential bonds at the worksite only. Suresh demonstrates the danger caused by earthing at the source end. He shows that voltage rise (i.e EPR) experienced on the substation earth grid can be transferred along the powerline to the worksite. Suresh discusses a case where a lineworker was fatally injured by this phenomenon. The worker was electrocuted when a ground fault occurred on a separate energised feeder from the same substation, at the same time work was taking place on a de-energised line.

The issue of earth potential rise is also discussed by Harrington although in a different context. Harrington’s paper is focused on ’bracket earthing’, or the practice of applying a set of earths one span either side of the worksite. Harrington quotes rules from many utilities which highlight a philosophy to protect workers by having them “work between grounds”. With a simple example, Harrington demonstrates how a worker may not be protected at all by this approach and how they can be subjected to a severe touch voltages. In his article he explains the voltages are proportional to the fault current times the ground resistance and this can leave a line worker exposed to several kV. Harrington says the solution to protective grounding is “to create by any practical means an equipotential zone for the man to work in”.

The principles behind the findings of Harrington and Suresh provide much food for thought for many worksite scenario’s a lineworker might encounter. For example, if a fault occurs and worksite earths are installed close to the pole, then hazardous step potentials may form on the ground where an assistant linesman might be standing. On the other hand, if the worksite earths are applied a significant distance from the pole, the linesman aloft on the pole might be subject to very high touch voltages. There are two important questions about this. Firstly, is there is an location to apply the earths, and how can this be determined? Secondly, do present day line workers understand these issues and can they consider these risks before starting the job?

Zipse discusses another hazard in the form of 'stray current'. He defines stray current as current that enters the earth and flows uncontrolled back to its source. Unlike current flowing though cables, once current enters the earth, we lose the ability to control where it goes. As electric current will choose the path of least resistance, it will sometimes flow through areas which create hazards for humans or animals. This could include, for example, swimming pools, and buried metallic pipelines. In his paper "Death by Grounding", Zipse explains how the use of multi-grounded neutral systems exacerbate this problem. By providing multiple entry points to the earth, we allow the current to flow uncontrolled and through nearby objects on its way back to its source. In his paper, Zipse emphasises the problem by referring to real electrocution cases including fatalities in swimming pools, and cows killed by the stray current from underground bare concentric neutral cables.

A sad case in Australia also shows the significance of the hazard posed by stray current. In 2005, a Sydney Water employee was electrocuted when repairing a broken water pipe in Sydney's West (SMH 2005). The cause of the accident was stray current caused by a faulty earth or neutral system either on the premises or somewhere nearby. (Workcover NSW). A report published following this incident by Werda et al offers excellent insight into how faulty electrical neutral or earth systems can cause stray current to flow through water pipes and other places it is not expected. It is easy to understand how the danger experienced by the plumber can also affect a lineworker in both overhead and underground line work. The frightening aspects of scary aspect of stray current is that it cannot be seen, nor simply controlled by turning off the main switch of an installation. Current may still flow uninhibited from a faulty installation on the property next door, or further somewhere further beyond.

The significance of Zipse and Werda et al's reports is that stray current will flow through de-energised lines unexpectedly, and therefore, pose a lethal risk to lineworkers. Once a power line has earths applied, it may then provide a low resistance path for stray current to travel its source. A very dangerous example would be the result of an earth fault on a nearby powerline which may cause a current of hundreds of Amps to flow through the earth. Some of this might flow back into the de-energised line creating a sever risk of electric shock. Lineworkers must be mindful of this risk when planning how they manage their use of equipotential bonding and earthing.

2.5.1 Potential safety problem with bonding method shown in Figures 2.6 and 2.7

There have been doubts raised about the safety of the bonding method shown in Figures 2.6 and 2.7.

If the overhead line becomes energised unintentionally, fault current will flow from the overhead conductors through the portable earths to the ground. However, as can be seen in both figures, the line worker is forming a parallel path through which fault current can also flow to ground. Whilst it is often stated that current will follow the path of least resistance, in a parallel circuit there will always be some current flowing in each branch.

It is expected that the low resistance of the portable earths would cause current to flow through the equipment and down to earth via both connections at the pole and temporary earth stake. However, it is conceivable that the voltage at the connection on the pole could be greater than the voltage at the earth stake due to the resistance ratios of the pole. If so, this would cause current to flow from the pole towards the earth stake rather than the other way round. Any current flowing in this direction would have to flow from the conductors and through the linesman.

Should this occur the lineworker may be subject to a far more significant, and possibly lethal, shock than anyone would have expected. A thorough analysis of this bonding method is required to determine if there is a lethal flaw with this PPBE method.

2.6 Case studies

2.6.1 Introduction

The following case studies are real examples which highlight the dangers that lineworkers are sometimes exposed to. Cases 1 and 2 demonstrate the value of PPBE in achieving a safe outcome. In Case 3, it is possible that a fatality may have been avoided had proper PPPE was established at the site prior to the operation of the air break switch.

2.6.2 Case study - Lightning discharge incident

Incident details

In December 2013, three overhead line crews were working on an 11kV rural distribution feeder in the Glen Innes region of New South Wales. The work was required for pole replacements and other unspecified maintenance. The powerline the crews worked on was de-energised by opening, locking and tagging an Air Break Switch(ABS). After the line was proven de-energised, a set of Access Permit (AP) earths were established one span downstream of the isolation point (i.e ABS). (EEWI 2013)

At approximately 12.30pm, the crew coordinator and an apprentice arrived at a pole which was due to be replaced. As the access permit earths were remote and out of site, in accordance with their Electrical Safety Rules, they applied a set of worksite earths on the southern side of the pole and a set of equipotential bonds on the other side. The bonds were applied in a similar fashion to the arrangement shown in Figure 6. The old pole was removed and the new pole was sited in position ready for its foundation to be backfilled and rammed. (EEWI 2013)

Around this time, the crew coordinator observed a storm approaching from the west and stopped work to allow it to safely pass. Whilst waiting for the storm to clear, the crew coordinator received a call from the local network operator. He was told that there were high voltage fuses blown about three km's west of the work location. It is a common occurrence for high voltage fuses to blow during storms as a result of lighting causing surges on the powerline. The crew coordinator waited a further ten minutes until he was satisfied that the storm had safely passed. At this point he decided to ascend the pole so they could complete the work. This involved tying the conductors to the insulators on the new pole. (EEWI 2013)

Whilst tying off the conductors, the crew coordinator heard and saw an arc from the worksite earth where it was clamped to the overhead conductor. The crew coordinator did not receive a shock but was frightened by the arcing. The apprentice on the ground also saw and heard the arc. The crew coordinator sat back in his harness and analyzed in his mind what had happened. He concluded that the arc was caused from induction due to lightning. Sometime later, he finished tying off the conductors, descended the pole, removed the worksite earths and moved on to the next job location. (EEWI 2013)

At the end of the day, the crew coordinator reported the incident to his supervisor.

Outcome

The supervisor insisted the crew coordinator attend hospital for a medical assessment. An ECG and physical examination was made, and the crew coordinator was cleared with out any signs of illness or injury. The apprentice who was on the ground at the time did not suffer any injuries either. (EEWI 2013)

A worksite investigation was launched to determine the cause of the incident. At this point in time, the investigation into the incident is not yet complete. The preliminary findings from the investigation are:

- Data obtained from the Bureau of Meterology confirmed that lightning was recorded in the area at approximately the same time the incident occurred.
- The worksite earths, and equipotential bonds were installed in accordance with recommended procedures.
- On the balance of probabilities, the arcing was caused by a lightning discharge on the powerline.

Comments

This incident is a positive example of PPBE doing its job and keeping the workers safe. With the benefit of hindsight, the best outcome would have been for the workers to have waited longer before resuming work. The preliminary report does not state what other forms of personal protection the line workers were wearing (eg. gloves) but this may have also been of benefit in this case.

There are, however, several questions that arise from this incident had the circumstances been different. For instance, had a permanent earth been available on the pole, and the worksite earths applied in the configuration shown in Figure 6, would the crew coordinator still have been safe?

2.6.3 Case study - Energisation caused by vandalism

Incident details

In May 2001, a line crew was working aloft from an Elevated Work Platform (EWP) on a de-energised 11kV line. Their task was to replace a faulty crossarm at an existing pole in an urban area. The 11kV line was isolated by opening ABSs on either side of the worksite, access permit conditions were established, and the crew installed two set of worksite earths on either side of the pole (ESAA 2001). This application of worksite earths is known as ‘bracket earthing’.

Whilst removing the last high voltage conductor from the old crossarm, the crew members noticed arcing on the line from one of the worksite earths. The crew immediately stopped work and moved their work platform clear of the line. It was later confirmed there was a successful 'trip and reclose' on an 11kV feeder connected to one of ABSs which isolated supply to the site (ESAA 2001).

An inspection was made of all the isolation points to determine the cause of the trip and reclose. A piece of fencing wire was found hanging from one ABS and later upon closer inspection, burn marks were visible on one phase of the switch. Another piece of fencing wire was found hanging on a fence adjacent to the pole which supported this ABS. The investigation team concluded that the fencing wire was too long and heavy to have been carried by birds, and therefore, vandalism was the cause. Consequently the police were notified of the incident (ESAA 2001).

Outcome

No one was injured in the incident although the crew member who was holding the wire was sent to hospital as a precaution (ESAA 2001).

The unintended energisation of the site caused an 'intermix' between the 11kV circuit and LV mains which reside below them on the pole. An intermix is when the high voltage circuit makes direct contact with the low voltage circuit and causes a large over-voltage in the LV circuit. Exactly how this occurred is not stated in the incident report. However, some domestic switchboards and appliances were damaged as a result.

Comments

It is apparent that this incident was the direct result of vandalism. The incident report does not make any suggestion of fault on the part of the work crew, or provide any indication of poor weather. This event emphasizes that danger is always present despite proper planning and responsible actions of the work crews. The line crew was exposed to a lethal risk of electric shock in a manner of which they had no control. The use of protective grounding was proved vital in the safe outcome for the workers.

Considering the reported intermix, it can be surmised that the worksite earths were connected to the neutral conductor of the LV system. This is a valid method of obtaining an earth connection in accordance with IEEE 1048 (2003). However, this method is not without danger. The damage caused to domestic switchboards and appliances is evidence that dangerous voltages were impressed upon the connected consumer installations. Potentially, this decision has endangered the lives of unsuspecting members of the community (IEEE 1048 2003).

A cause for concern is whether lineworkers are actually considering the pros and cons of different earthing methods? Are they equipped with enough expertise to make the safest choices, or do they simply rely on the same approach for all job sites? A failure to properly assess the risks is a root cause of an accident. Work supervisors, lineworkers, and network operators need to ensure they consider each site on its merits.

2.6.4 Case study - Worker electrocuted operating Air Break Switch

Incident details

An electrical fitter/mechanic employed by the South East Queensland Electricity Board (SEQEB) received a fatal electric shock whilst operating a pole mounted ABS (Bevan 2005).

Earlier a fault had occurred in the network when a 33kV crossarm failed and the 33kV conductors dropped into an 11kV circuit below them. The over voltage caused by the intermix of 33kV and 11kV caused an 11kV surge arrestor to fail. This resulted in the surge arrestor forming a permanent short circuit from the 11kV mains to earth via a steel surge arrestor cable saddled down the outside of the same pole as the ABS. The metal operating handle of the switch, which was mounted at ground level, was earthed by a connecting cable to the surge arrestor downlead (Bevan 2005).

After the 33kV fault had been identified and dealt with, the fault caused by the surge arrestor was still present on the 11kV circuit, and this caused the protection devices to trip. At this stage, staff were unaware of what was causing the fault or its location, so they were switching sections of line on and off to test and isolate the faulty line section. When the SEQEB employee closed the switch, he unknowingly connected the faulty surge arrestor to the 11kV which energised everything connected to it 6.35kV (phase voltage of the 11kV system). Therefore, the surge arrestor downlead and metal operating switch handle were also energised and the worker formed part of the fault current circuit to earth (Bevan 2005).

Outcome

The SEQEB worker who was only 24 years old, was electrocuted and died instantly (Bevan 2005).

Comments

This tragedy demonstrates the dangers on not maintaining equipotential conditions as a work site. The provision of an ‘equipotential mat’ at the ABS site may have prevented the worker’s death when he closed the switch. The use of insulated gloves when switching may also have saved the life of the SEQEB employee. It is not clear whether it was a requirement at the time of this incident. However, is now a mandatory requirement of many ENO's that insulated gloves must be warn when switching.

2.6.5 Case study: Fatality cause by voltage induction

Incident details

In December 2009, a power construction crew were working on the construction of a new 275kV transmission line. As construction of the line was not complete, the work would be undertaken under de-energised conditions. The project was located near the town of Kelso in North Queensland.

The task for the day was the installation of spacers between phase conductors of the new transmission line. Due to the height of conductors being approximately 30m, a suspended mobile trolley was to be used to install spacers at the required locations. An elevated work platform would be used to lift the trolley and the workers into position.

The work contained significant safety risks including working from heights and voltage induction from adjacent powerlines. At the worksite, an energised 275kV transmission line resided just 15m away. Risk management procedures adopted by the company included the preparation of an Activity Method Statement (AMS), a work permit for working at height activity, a Task Risk Assessment, and a mandatory pre-start safety meeting.

The AMS was prepared two days prior to the work and accepted and signed by all members of the work crew. Therefore, it would reasonable to assume the risks involved with the work would be understood by all team members. The permit for working at heights was obtained the day before the work. Work procedures document in the AMS mandated that the line conductors be earthed via the adjacent towers. The document specified the use of insulated gloves and line stick for the purpose of applying these earths.

On the day of the planned work, work commenced but a number of safety requirements were totally disregarded. The mandatory pre-start discussion was not held and some vital tools and safety equipment was not available at the site. The crew supervisor instructed his colleague to attach the earth cable to the EWP rather than the towers as they lacked the proper attachment clamp. Also, the insulated line stick which was needed to safely apply the earths was also not available.

Instead of stopping work to address the safety problems, the crew supervisor elected to push ahead. The supervisor attempted to attach the earth clamp to the overhead conductors using his hands. At the time he was doing so, he was wearing one insulated glove and one riggers glove which does not provide adequate insulation.

Outcome

The crew supervisor who was in the work trolley received a fatal electric shock. The co-worker, who was in the EWP, also received 4 separate shocks. The co-worker survived but unfortunately sustained severe injuries. The electric discharge which harmed the workers was caused by voltage induction from the adjacent energised transmission line. The primary cause of the accident was attributed to a failure to properly earth the line in accordance with the AMS procedures.

Comments

This tragic incident highlights some key issues relating to workers safety on de-energised powerlines.

It is unquestioned that had the workers followed the documented procedures of the AMS, the incident would not have occurred. The workers involved would have been protected and remained safe. It is therefore the tragic result of this incident which highlights the importance of Personal Protective Bonding and Earthing. The incident also demonstrates why planned mandatory control measures are so important to ensure a safe work outcome.

The incident also demonstrates how humans from time to time make poor decisions which can have tragic consequences. What is known is that the crew supervisor, a 29 year old engineer, had considerable experience and was well aware of the risks caused by induction. What is not certain is why he elected to ignore safety procedures and proceed with the project.

Chapter 3

Methodology

3.1 Research Methodology

3.1.1 Aim of the research

Power companies place an enormous emphasis on the safety of their workforce. Strict procedures exist for construction activities on powerlines. In an ideal world, a well planned project will ensure that all risks for the line worker are mitigated, and the project proceeds safely and without incident. However, as the case studies in Section 2.6 show, situations occur from time to time where lines are energised unexpectedly and lineworkers are placed at risk. In these cases, PPBE provides a vital last line of defence for the lineworker, and its effective performance is crucial to the final outcome from an incident.

The overall aim of my research is to achieve two important outcomes. Firstly, to accurately examine current PPBE techniques and identify any potential shortcomings which may exist. Should problems be found then potential solutions will be recommended. Secondly, to increase awareness and emphasise the dangers of working on de-energised lines. It is hoped that my findings will serve to reduce complacency that may exist amongst current line workers. if these two objectives are met, then my findings will be of benefit in reducing serious accidents in the future.

3.1.2 The process for research

A real high voltage 11kV distribution feeder was selected for analysis to examine the likely performance of PPBE at several locations along its route. The selection of a real powerline ensures the parameters used in the analysis are realistic real world values. This ensures the results have greater credibility than a project based on purely hypothetical information.

A further benefit of using real world information is the multitude of scenarios that can be envisaged when visiting several sites. There are a number of factors that will influence the performance of PPBE, a few of which include the fault level, number of isolation points, their proximity to the worksite, pole conductivity and size, and site soil resistivity. Conducting several site surveys assisted in developing a broad range of scenarios, which in turn meant a more thorough analysis.

The research approach is outlined in the following 4 steps.

Step 1

The first step was the collection of site data and network information. In total five sites along the feeder were selected for the project. At each site, information was collected for later use in the project analysis. The typical information obtained at each site included:

- Pole details including material, height, and pole top configuration.
- Details of the permanent earth (if existing) including the conductor size and noting if the conductor was bare or insulated.
- Earth resistivity test including a note on the level of moisture in the soil (eg. dry or recent rain).
- Alternative options for earthing of PPBE equipment (eg. LV neutral conductor)?
- Presence and location of underground services such copper phone lines or metallic water pipes
- Note of the likelihood of work site being frequented by members of the public

Step 2

To conduct an electrical analysis of PPBE performance, information about the local 11kV distribution network was required. For example, to determine the maximum fault levels at a site under analysis, information to calculate the upstream network impedance must first be obtained. The information required was obtained from Essential Energy's substation records, Graphical Information System (GIS), original powerline survey plans, and by field inspections to verify the data.

A factor which may significantly influence the outcomes of the research the selection of electrical resistance values for timber, steel and concrete power poles. Detailed information is included in Section 3.2.4.

Step 3

Determine the PPBE technique which would be applied at each site. The study area is located within the jurisdiction of Essential Energy, the local network service provider. As such, the application of PPBE is influenced by the requirements within Essential Energy documents CEOP2377 (Personal Protective Bonding and Earthing) and CEOP8030 (Electrical Safety Rules). Factors affecting the selection of PPBE include the type of pole, the availability of a permanent earth, the proximity of the upstream electrical isolation point(s), and whether or not the isolation point(s) is within view of the work site.

Step 4

Provide a thorough electrical analysis of the PPBE system at the work site. The goal is to predict whether the PPBE would adequately protect the line workers in the event of an unexpected energisation. The PPBE performance is determined as part of an overall system of protection provided by the electrical isolation points, and the provision of access permit earths at those points.

The electrical analysis includes the following steps:

- An appraisal of all possible electrical risks at each site (e.g. accidental energisation, transferred potential).
- Preparation of appropriate electrical connection diagrams, and sequence diagrams for analysis purposes.
- Determination of the maximum prospective fault current that may flow through the work site.
- Determine the possible step and touch voltages and currents a line worker may be exposed to, and whether these outcomes are within safe limits.
- Earth surface voltage analysis to examine step potential or transferred potential risks at the locality.
- Analysis of alternative PPBE application options to identify if an improved level of safety can be achieved.
- Document results and make recommendations based on the key findings.

3.2 Analysis and results

3.2.1 Details of 11kV feeder to be used for analysis

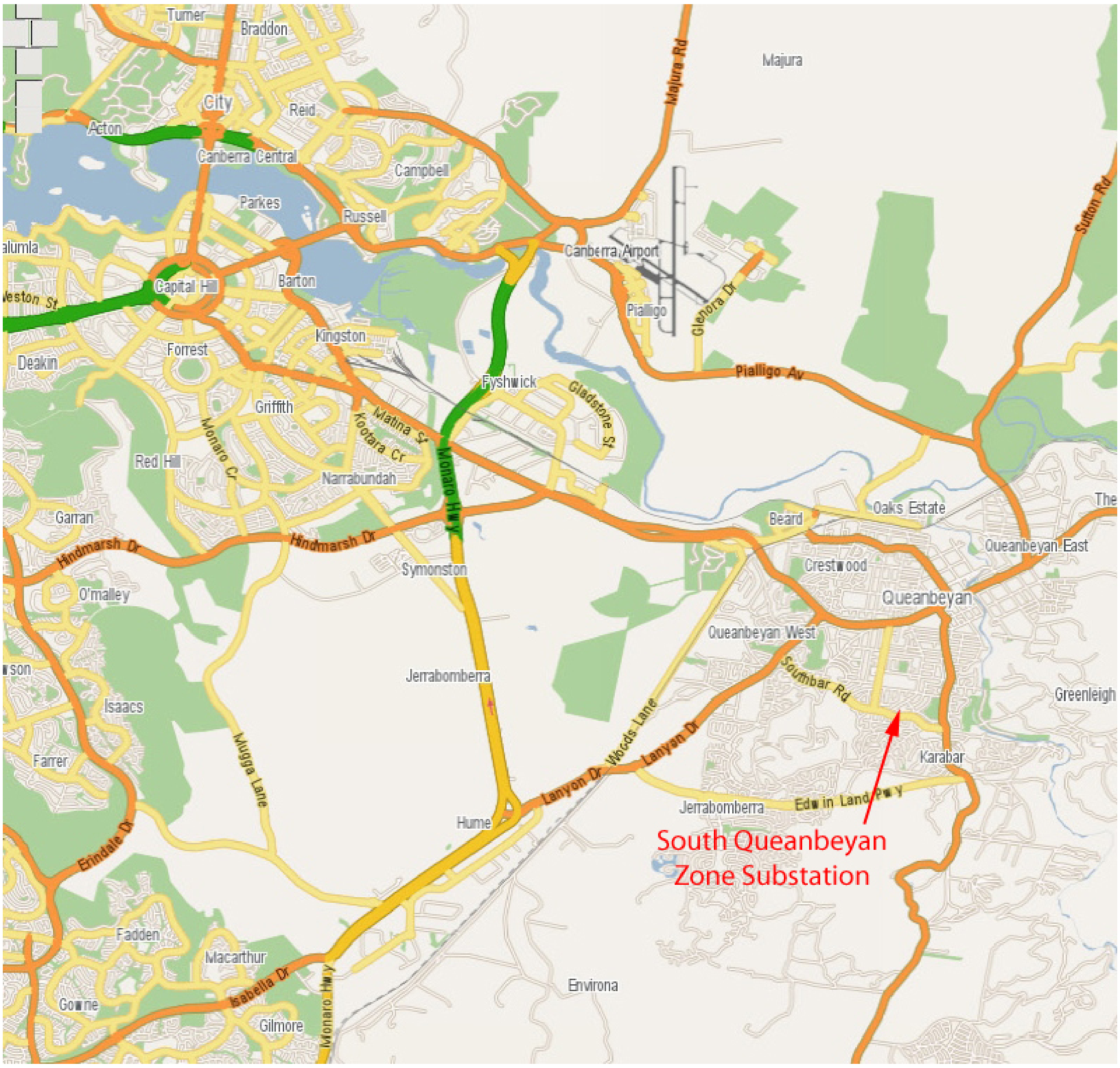
An 11kV distribution feeder located in the Queanbeyan region of NSW was used for analysis in this project. The feeder selected is known as the “Southbar Road 11kV feeder” (Feeder). The Southbar Road feeder commences at the South Queanbeyan Zone substation in an urban area of Queanbeyan, before leaving the city and supplying customers in the rural surrounds. As such, this feeder provided a useful cross section of work sites from both urban and rural locations. A locality diagram for the substation and Southbar Road feeder is shown in Figure 3.1.

The South Queanbeyan Zone Substation (Zone Substation) is one of two substations that supply power to the city of Queanbeyan. The Zone substation is supplied via two 66kV overhead sub-transmission lines originating at the Transgrid 132kV/66kV Oaks Estate substation located to the north of the city. The Zone Substation has two main 66kV/11kV Dy1 power transformers both rated at 20/25/30MVA.

Under normal operating conditions, the 66kV bus is energised by both 66kV feeders connected in parallel. A 66kV bus bar isolator is kept ‘normally open’ which in turn leaves one transformer in service whilst the other is de-energised but available on standby. An automatic changeover system is available should there be a fault with the in service transformer or incoming 66kV supply. It is possible for the two transformers to operate in parallel, however, it would require an unusual circumstance for this to occur.

The Zone Substation has 10 outgoing 11kV feeders to supply Queanbeyan and the surrounding area. Some of these feeders can be paralleled with feeders from other zone substations to allow back feeding when required. The Southbar Road feeder can be can connected to the Googong Zone Substation located to the south of Queanbeyan via the Michelago 11kV feeder from that substation.

The No.1 and No.2 main transformers are of identical make with impedances of 10.21% and 10.11% respectively. The transformer ratings are 20MVA , 25MVA and 30MVA depending upon the operation of cooling fans and oil pumps.



South Queanbeyan Zone Substation

Figure 3.1: South Queanbeyan Zone Substation locality

A single line schematic diagram of the Southbar Road 11kV feeder is shown in Figure 3.2.

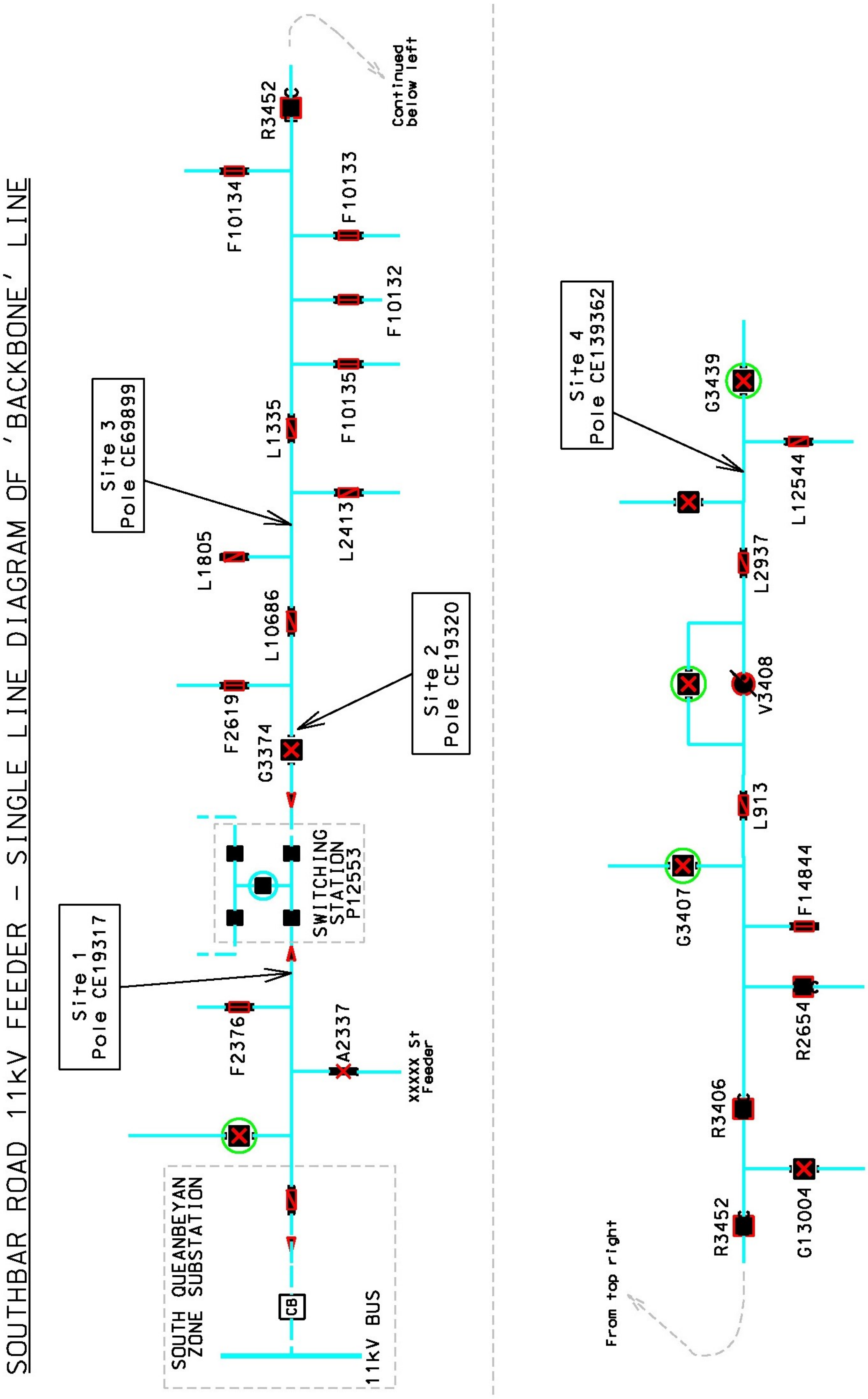


Figure 3.2: Southbar Road 11kV Feeder Network Diagam

3.2.2 Information required in project analysis

Source impedance values

To accurately calculate prospective fault levels at each site, it was necessary to consider the impedance of the upstream 66kV network. To determine values of source impedance, fault current levels at the Zone Substation 66kV bus were obtained from Essential Energy's protection engineers. The fault level information has been obtained for two possible scenarios. The first is the 66kV bus is in its 'normal' configuration whereby the 66kV bus bar isolator is open, and the supply to the substation is via one of two 66kV feeders. The second is with the 66kV bus tie closed and the substation supplied by the two 66kV feeders operating in parallel. The fault current levels at the 66kV bus are shown Table 3.1 below.

Fault description	Normal Configuration	Maximum Configuration
Three phase fault	4.51kA	5.15kA
SLG fault	4.10kA	5.15kA

Table 3.1: Queanbeyan South Zone Substation fault levels at 66kV Bus

The presence of access permit or work site earths on a powerline which is re-energised create a fault situation on this line. The analysis of the fault current flowing from such a fault is made easiest by the use of symmetrical sequence components.

Using the known fault level information, for the 66kV source, the positive sequence impedance Z^{+} of the source can be determined by the equation:

$$X^{+}_{source} = \frac{V_{an}}{I_{fault_{3ph}}} \tag{3.1}$$

Given the Zone Substation is electrically a long way from the system power generators, it is assumed the negative sequence impedance of the source is not influenced by the effect of rotating machinery. Therefore Z^{-} is equal to Z^{+}.

A Single Line to Ground (SLG) fault is the type of fault which will cause the most current to flow to earth. It is this type of fault which provides the greatest hazard to the safety of the line workers. As such, the SLG fault is a key focus of the project research. When the SLG fault is analysed using symmetrical components, the positive, negative and zero sequence networks are connected in series. It can therefore be shown be shown that the SLG fault level is be determined from the Equation 4.19:

$$I_{fault_{SLG}} = \frac{3V_{an}}{X^{+} + X^{-} + X^{0} + 3R_f} \tag{3.2}$$

With transposition, this equation becomes:

$$X^{0}_{source} = \frac{3V_{an}}{I_{fault_{SLG}}} - X^{+} + X^{-} - 3R_f \tag{3.3}$$

When determining the zero sequence impedance value X^0, the fault resistance should not be considered and therefore, the term $3R_f$ cancels from Equation 3.3.

Essential Energy's engineers also advised that a the Zone Substation earth grid resistance value was measured at $0.3\,\Omega$ a few years ago.

Using the above fault level information, the source impedance values are calculated using Equations 3.1 and 3.3 below.

$$X^{+}_{source} = \frac{1}{\sqrt{3}} \times \frac{66000V}{4.51kA} = 8.449\,\Omega \tag{3.4}$$

$$X^{-}_{source} = Z^{+}_{source} = 8.449\,\Omega \tag{3.5}$$

$$X^{0}_{source} = \frac{1}{\sqrt{3}} \times \frac{66000\,V}{4.10\,kA} - 8.449\,\Omega - 8.449\,\Omega = 10.984\,\Omega \tag{3.6}$$

To use these values to determine fault levels in the 11kV system, it is necessary to convert the impedances to per unit values.

Using a 25MVA base, the base current is found:

$$I_{base66} = \frac{25\,MVA}{\sqrt{3} \times 66kV} = 218.7\,A \tag{3.7}$$

The base impedance is found:

$$Z_{base66} = \frac{66000\,V}{\sqrt{3} \times I_{base66}} = 174.7\,\Omega \tag{3.8}$$

The 66kV source per unit values are determined by dividing the results of Equations 3.4, 3.5 and 3.6 by Z_{base66}. Thus,

$$X^{+}_{sourcepu} = j0.038634\,pu \tag{3.9}$$

$$X^{-}_{sourcepu} = j0.038634\,pu \tag{3.10}$$

$$X^{0}_{sourcepu} = j0.050224\,pu \tag{3.11}$$

Transformer impedance values

To determine the available fault levels at the 11kV bus, the impedance of the zone substation transformers must also be considered. Whilst the two transformers are of identical make and rating, the No.1 transformer has an impedance of 10.21% and the No.2 transformer an impedance of 10.11%. The Southbar Road Feeder can be supplied by either transformer depending upon which one is left in service. The impedance percentages are converted to a per unit value by simply dividing by 100, thus giving $X_{Tx_{pu}} = 0.1021\,pu$ and $X_{Tx_{pu}} = 0.1011\,pu$ respectively. The fault level will be slightly higher when the No.2 transformer is in service.

Line impedance

Conductor and cable information for the Southbar Road 11kV feeder has been obtained from Essential Energy's Geographic Information System (GIS) and historical construction plans. The information was verified during field visits to obtain information to be used in the project analysis. A summary of the cable and conductor information is shown in the Table 3.2 below.

Section	From	To	Cable and Conductor type	Distance (m) (m)	Notes
1	Zone sub	CE19301	3c 240mm PASS Alum	35	
2	CE19301	CE19313	Lemon (30/7/3.00 ACSR)	612	
2A	CE19313	CE19265	Mercury (7/4.50 AAC)	20	
3	CE19313	CE19297	Lemon (30/7/3.00 ACSR)	15	
3A	CE19297	CE19ZZZ	Mercury (7/4.50 AAC)	29	33-A2337
4	CE19XXX	CE19099	Lemon (30/7/3.00 ACSR)	112	
5	CE19099	CE19317	Mercury (7/4.50 AAC)	260	Site 1
6	CE19317	CE19319	Mercury (7/4.50 AAC)	345	
7	CE19319	P12553	3c 240mm sq Al UG cable	72	
8	P12553	CE6152	3c 240mm sq Al UG cable	348	
9	CE6152	CE19320	Mercury (7/4.50 AAC)	122	Site 2
10	CE19320	CE19325	Mercury (7/4.50 AAC)	660	
11	CE19325	CE69894	Mercury (7/4.50 AAC)	162	
12	CE69894	CE69899	Lemon (30/7/3.00 ACSR)	511	Site 3
13	CE69899	CE138673	Lemon (30/7/3.00 ACSR)	1174	
14	CE138673	CE138710	Neon (19/3.75 AAAC)	1837	33-R3452
15	CE138710	CE138712	Neon (19/3.75 AAAC)	211	33-R3406
16	CE138712	CE138870	Neon (19/3.75 AAAC)	3936	L913
17	CE138870	CE139310	Hydrogen (7/4.50 AAAC)	2146	L2937
18	CE139310	CE139362	Neon (7/4.50 AAAC)	1534	Site 4

Table 3.2: Southbar Road 11kV feeder cable and conductor details

A single line diagram of the feeder showing relevant conductor sections, isolation points, and the work sites to be analysed, is shown in Figure 3.2. The diagram can be used to correlate the section information in Table 3.2.

The values of impedance used in calculations have been obtained from sources including conductor and cable catalogues, and Essential Energy's Overhead Design Manual. The per unit impedance information is summarised in Table 3.3.

Cable or Conductor	Z Positive (Ω/km)	Z Negative (Ω/km)	Z Zero (Ω/km)
3c 240mm PASS Alum	0.162 +j0.095	0.162 +j0.095	0.74 +j0.047
Lemon (30/7/3.00 ACSR)	0.167 + j0.228	0.167 + j0.228	0.167 + j0.684
Mercury (7/4.50 AAC)	0.315 + j0.259	0.315 + j0.259	0.315 + j0.777
UG cable 3c 240mm sq Al	0.162 +j0.095	0.162 +j0.095	0.74 +j0.047
Neon (19/3.75 AAAC)	0.173 + j0.235	0.173 + j0.235	0.173 + j0.705
Hydrogen (7/4.50 AAAC)	0.323 +j0.259	0.323 + j0.259	0.323 + j0.777

Table 3.3: Overhead conductor and underground cable impedance values

To calculate the prospective fault currents at each work site, the cable and conductor information must first be converted to per unit values. To simplify this process a script was developed in Matlab. The Matlab script imports the data from a Microsoft Excel file, and then multiplies the data by the line section distances. Finally, the Ohmic impedance information have been converted to per unit values by dividing by the 11kV base impedance.

The value of the 11kV base impedance is found as follows:

$$I_{base11} = \frac{25MVA}{\sqrt{3} \times 11kV} = 1312.2\,A \tag{3.12}$$

$$Z_{base11} = \frac{11000V}{\sqrt{3} \times I_{base11}} = 4.84\,\Omega \tag{3.13}$$

A summary of the per unit section impedance values is shown in Table 3.4 below.

Section	Positive sequence Z (pu)	Negative sequence Z (pu)	Zero sequence Z (pu)
1	0.0012 + j0.0007	0.0012 + j0.0007	0.0054 + j0.0003
2	0.0211 + j0.0288	0.0211 + j0.0288	0.0211 + j0.0865
2A	0.0013 + j0.0011	0.0013 + j0.0011	0.0013 + j0.0032
3	0.0045 + j0.0061	0.0045 + j0.0061	0.0045 + j0.0184
3A	0.0019 + j0.0016	0.0019 + j0.0016	0.0019 + j0.0047
4	0.0158 + j0.0130	0.0158 + j0.0130	0.0158 + j0.0389
5	0.0225 + j0.0185	0.0225 + j0.0185	0.0225 + j0.0555
6	0.0024 + j0.0014	0.0024 + j0.0014	0.0110 + j0.0007
7	0.0116 + j0.0068	0.0116 + j0.0068	0.0532 + j0.0034
8	0.0079 + j0.0065	0.0079 + j0.0065	0.0079 + j0.0196
9	0.0430 + j0.0353	0.0430 + j0.0353	0.0430 + j0.1060
10	0.0105 + j0.0087	0.0105 + j0.0087	0.0105 + j0.0260
11	0.0176 + j0.0241	0.0176 + j0.0241	0.0176 + j0.0722
12	0.0405 + j0.0553	0.0405 + j0.0553	0.0405 + j0.1659
13	0.0657 + j0.0892	0.0657 + j0.0892	0.0657 + j0.2676
14	0.0075 + j0.0102	0.0075 + j0.0102	0.0075 + j0.0307
15	0.1407 + j0.1911	0.1407 + j0.1911	0.1407 + j0.5733
16	0.1432 + j0.1148	0.1432 + j0.1148	0.1432 + j0.3445
17	0.1024 + j0.0821	0.1024 + j0.0821	0.1024 + j0.2463

Table 3.4: Southbar Road 11kV feeder section impedances in per unit

3.2.3 Type of fault for analysis

Prior to working on a line, the powerline is isolated, proven de-energised, and then short circuiting and earthing is applied. When APE or WE earths are applied, all three phases of the line are securely bonded together and then bridged to earth. Should the line be re-energised by an accidental three phase switching, the short circuiting of the line presents a balanced three phase fault. In this situation, practically all the fault current flows back to its source via the phase conductors of the powerline, and there is no significant amount of current flowing to earth.

The most dangerous type of fault for a work site is the single line to ground fault. In this case, all the fault current flows via the powerline to the worksite, and then returns to the source via the earth. This can occur if only one of the phases in the powerline is energised. This could possibly occur in a number of ways. For example, if the powerline was mistakenly energised using single phase switching (with links or fuses), or is there is contact made with another nearby circuit either by accident, or by an act of vandalism.

As the single line to ground fault is the most dangerous type, the SLG fault level will be determined and used in the project analysis.

3.2.4 Verification of parameters

Resistance of timber, steel and concrete poles

Bonner, Erga, Gibbs & Gregorius (1989) describes how the electrical conductivity of wood varies depending upon a number of factors. The resistance of timber will vary depending upon the amount of moisture in the timber, and particularly the surface moisture. The electrical resistance is less when measured along the grain rather than across it. The resistance from one pole to the next is also affected by the species and preservative treatment. Bonner et al. (1989) states that that test results indicate a pole's resistance ranging from 2500 Ohms when wet, to several megohms when dry. Their paper, being a discussion of results from actual field tests, says three 40 foot poles measured under different conditions had resistances in the range of 18000 Ohms to 2 megohms.

Ragon, Shupe, Wu, Donohoe & Freeman (2010) performed a clinical study into the effects of different preservative treatments on the conductivity of timber power poles. The study was performed with the assistance of ABB who provided facilities and equipment for the testing. The focus of the study was modern day preservative treatments including creosote, Chromated Copper Arsenate (CCA), pentachlorophenol, and copper napthenate. Their findings support Bonner et al. (1989) by verifying how the electrical resistance of a pole varies wildly depending upon its moisture content, and to a lesser degree, its species and type of preservative treatment. In their paper, Ragon et al. (2010) quote Stamm, a researcher on the topic from the 1930s, who said “a change in moisture content from zero to about 30% of the weight of wood, the conductivity increases a million fold".

The electrical conductivity measurements from their tests, and conducted on one foot long pole samples, are listed below in Table 3.5. For ease of interpretation, and for my calculations, the conductivity values have been converted to an equivalent resistance per metre value. This resistance value is based on a 12.5m 6kN preservative treated timber pole which is a commonly used size in overhead distribution powerlines. According to Essential Energy's construction standards, this sized pole has an average diameter of 285mm.

	Chemical treatment	Conductivity (σ/m)	Resistivity (Ω.m)	Resistance/metre (Ω/m)
Oven dry	Creosote	1.60E-11	6.25E+10	9.80E+11
	Penta	7.20E-12	1.39E+11	2.18E+12
	CuNap	6.06E-12	1.65E+11	2.59E+12
	CCA	4.40E-12	2.27E+11	3.56E+12
	Untreated	1.60E-12	6.25E+11	9.80E+12
20% Moisture	Penta	8.50E-07	1.18E+06	1.84E+07
	Untreated	6.80E-07	1.47E+06	2.31E+07
	CCA	6.40E-07	1.56E+06	2.45E+07
	CuNap	6.30E-07	1.59E+06	2.49E+07
	Creosote	5.00E-07	2.00E+06	3.14E+07
Saturated	Untreated	3.10E-03	3.23E+02	5.06E+03
	CCA	2.60E-03	3.85E+02	6.03E+03
	CuNap	2.00E-03	5.00E+02	7.84E+03
	Creosote	1.30E-03	7.69E+02	1.21E+04
	Penta	1.10E-03	9.09E+02	1.43E+04

Table 3.5: Timber pole conductivity and resistance data

Sokolowski, Dwivedi, Pathak, Buratto & Yu (2008) refer to a publication of the Electricity Authority of NSW, "Electrical Hazards Associated with Conductivity of Australian Hardwood Power Line Poles", which demonstrates "that seldom does a wooden powerline pole exposed to natural weather conditions reach a moisture level exceeding much more than 20%"

Whilst timber poles are the most common type used in distribution powerlines, the use of steel and concrete poles is becoming more common. In comparison to timber, steel is a very conductive material. The resistivity of steel used for power poles is 190×10^6 Ω.m (Gillespie 2013). It is shown in Section 4.2.4 that a standard 12.5m 12kN straight steel pole with diameter of 273mm and wall thickness 4.7mm, will have a resistance of $46.9\mu\Omega/m$.

Concrete is a semi conductive material. However, most concrete poles are reinforced with steel which greatly affects the practical resistance of the pole. A line worker for instance might be using a pole step to stand on whilst working aloft. These steps are bolts screwed into ferrules embedded in the pole, which are welded to the steel reinforcing. Whilst this might not always be the case, it is reasonable to treat concrete poles as conductive similar to steel poles.

Specifications of short circuiting and earthing equipment

Portable earths are designed and rated to withstand the electrical energy flowing by a specific level of current for a minimum amount of time. For example, the rating of a particular portable earthing set may be 6kA for 1.0 second. As explained by Australia (n.d.), it is imperative that the set chosen for a task is rated to a higher fault level than the maximum sized fault that can occur at the worksite. If an underrated set of earths are used, they could fail for two reasons. Firstly, the high fault current may cause excessive temperature rise in the cables and they may be melt. Secondly, the high fault current can generate large magnetic fields causing the cables to move violently. In this case, the cables may tear or even break away from their lugs or connection clamps.

Portable earthing sets are available with either aluminium or copper conductors. The benefit of aluminium conductors is the reduced weight, and therefore, less strain for the line worker who must apply them (Australia n.d.). Table 3.6 below has examples of commercially available portable earthing sets and their ratings. The electrical resistance information provided in column 4 has been obtained from AS/NZS 3008.1.1:2009. The lead which connects the earth electrode to the short circuit bonds is normally supplied at a maximum length of 20m.

Current rating	Time rating (s)	Conductor type	Conductor area (mm sq)	Cable resistance (Ω/m)	20m lead resistance (Ω)
10kA	0.5	Al	55	0.000704	0.01408
16kA	0.5	Al	85	0.000419	0.00838
25kA	0.5	Al	130	0.000276	0.00552
45kA	0.5	Al	2 x 130	0.000138	0.00276
3.5kA	1.0	Cu	16	0.00147	0.0294
6kA	1.0	Cu	25	0.000949	0.01898
8kA	1.0	Cu	35	0.000674	0.01348
12kA	1.0	Cu	50	0.000470	0.0094
16kA	1.0	Cu	70	0.000332	0.00664
20kA	1.0	Cu	95	0.000252	0.00504
30kA	1.0	Cu	120	0.000197	0.00394
40kA	1.0	Cu	150	0.000159	0.00318

Table 3.6: Common portable earthing sets

Soil resistivity and earth electrode resistance

When a powerline is de-energised for work, the line is isolated from the supply and then short circuited and earthed prior to line workers commencing their work and making contact with the conductors. In many cases, a permanently installed earthing conductor is not available at the site. Therefore, the line workers must install a temporary earth electrode for this purpose. This is usually achieved by driving an electrode into the ground to a depth of approximately 0.5m.

The electrical resistance of the temporary electrode will be dependent on the soil resistivity of the earth, the depth to which it is installed, and the moisture level of the soil. Resistance readings taken at the site can be used to calculate the resistivity of the soil, and to predict the resistance of the temporary electrode to earth.

Soil resistivity is determined by the equation (AS/NZS 4853 n.d.):

$$\rho = 2\pi \times a \times R \tag{3.14}$$

Where:

$$a = horizontal\ spacing\ of\ test\ electrodes\ (m)$$

$$R = the\ resistance\ measurement\ obtained\ (\Omega)$$

The predicted earth electrode resistance is then calculated by the equation (AS/NZS 4853 n.d.):

$$R = \frac{\rho}{2\pi l} log(\frac{4l}{r} - 1) \tag{3.15}$$

Where:

$$l = proposed\ depth\ of\ electrode\ (m)$$

$$R = the\ expected\ resistance\ of\ electrode\ (\Omega)$$

3.2.5 Essential Energy documents - Electrical Safety Rules and Equipotential and Personal Protective Bonding

When preparing for work on de-energised lines, staff must consider the requirements of two important documents. In Essential Energy's jurisdiction, these are CEOP8030 - Electrical Safety Rules (ESR), and CEOP2377 - Equipotential and Personal Protective Bonding. These documents outline mandatory requirements for the application of short circuit bonds and temporary earths, as well as personal protective bonds at the worksite. In some cases, there will be multiple sets of temporary earths applied to the de-energised section of line before work commences. As such, the protective bonding applied at the worksite is just one component of a larger system of protection for the line workers.

The requirements of both CEOP8030 and CEOP2377 have been taken into account in the project analysis. Some specific requirements of these documents relevant to the analysis is outlined below.

CEOP8030 - Electrical Safety Rules

- Access permit earths must be applied between all points of High Voltage (HV) isolation and the work area.

- When Access Permit Earths (APE) are not in view, a set of Working Earths (WE) shall be installed at the work site. It is a requirement that at least one set of earths shall be in view, and where practical, close to the persons working on the conductors.
- When applying earths, if a known permanent earth is available, then it should be used. If not, a metal stake of minimum 12mm diameter must be driven into the ground ensuring that it is firmly anchored. (The document does not specify a minimum depth or maximum earth electrode resistance).
- The Low Voltage (LV) neutral shall not be used as part of the HV earthing system.
- Equipotential bonding must be applied to ensure there no possibility that persons can form a bridge between two points of different potential.

CEOP2377 - Equipotential and Personal Protective Bonding

The purpose of this document is to ensure employees work under equipotential conditions. The document outlines the procedures for installing PPB when working on de-energised lines. For work on overhead powerlines, the selection of PPB technique is dependent upon a number of conditions.

- If a permanent earthing conductor is available at the pole site.
- Whether the pole is timber, or, steel or concrete.
- If Access Permit Earths have been installed and whether these are in view of the work site.
- the type of work being conducted and whether the task includes opening bonds or dividing conductors.

On projects where APE earths are applied, and are within view of the worksite, additional sets of earths are not required at the pole being worked on. However, the procedure requires the installation of a personal protective bond from the overhead conductor to a 'bonding point' located below the workers feet. The bonding point must be located a minimum 2.4m above ground level.

The procedure does not specify minimum cable sizes for personal protective bonds. Instead it requires that PPB must be ”rated similarly to earthing and short circuiting equipment”.

Chapter 4

Analysis and results

4.1 Individual site analysis

4.1.1 Site 1 - Pole CE19317 Cooma Street, Queanbeyan

The first site analysed was pole number CE19317 located on Cooma Street, Queanbeyan. The pole is located approximately 1.03km in line distance from the 11kV bus at the zone substation.

Pole CE19317 is a 55’ (16.7m) timber pole treated with creosote preservative. The pole is part of a dual circuit section of powerline supporting 66kV and 11kV overhead conductors. A permanent earth cable is installed on the pole but is not connected to any hardware at the pole top.

Figure 4.1: Pole CE19317 located at Cooma Street, Queanbeyan

Given the urban location of pole CE19317, the 11kV section of powerline can be energised from a number of alternative supply points. If the Southbar Road feeder is disconnected at the Zone Substation, the line section can be supplied from the adjacent Queenbar Road or Karri Crescent feeders. It is also possible to supply the site via the Michelago Feeder from Googong Zone Substation. Pole CE19317 has four possible points of supply in total, none of which are within sight of the pole.

For de-energised work to occur at pole CE19317, the Electricity Safety Rules require access permit earths to be installed at each point of isolation. As the isolation points are not in view of the worksite, a set of portable working earths at the pole will also be required. A permanent earth is available at the pole so therefore, the bonding configuration of Figure 2.6 of Section 2.4 must be used. The nearest upstream isolation point on the Southbar Road 11kV feeder is at the Zone Substation, and therefore, the access permit earths would be electrically connected to the substation earth grid.

Figure 4.2 is a connection diagram detailing the worksite connections, and its position in relation to the other isolation points, and access permit earths.

The 11kV powerline at pole CE19317 could be at risk of three types of unexpected energisation. The line could be energised by an accidental switching error, a transferred potential rise from the zone substation, or by contact with the 66kV conductors located above the 11kV circuit on the pole. An analysis of the PPBE performance in each of these situations is following.

Resistance values of the worksite

The resistance values of the worksite must be known to evaluate the flow of fault current caused by an accidental line energisation. The parameters shown in the worksite area of Figure 4.2 are influenced by the pole size and timber type, the soil resistivity, cable size of the PPB and permanent earth, as well as some other factors. The work site resistance values used in the following analysis are listed in Table 4.1. A pole diagram illustrating some of the important dimensions is shown in Figure 4.3. Other network values including line impedances to be used in the calculations are summarised in Table 4.2.

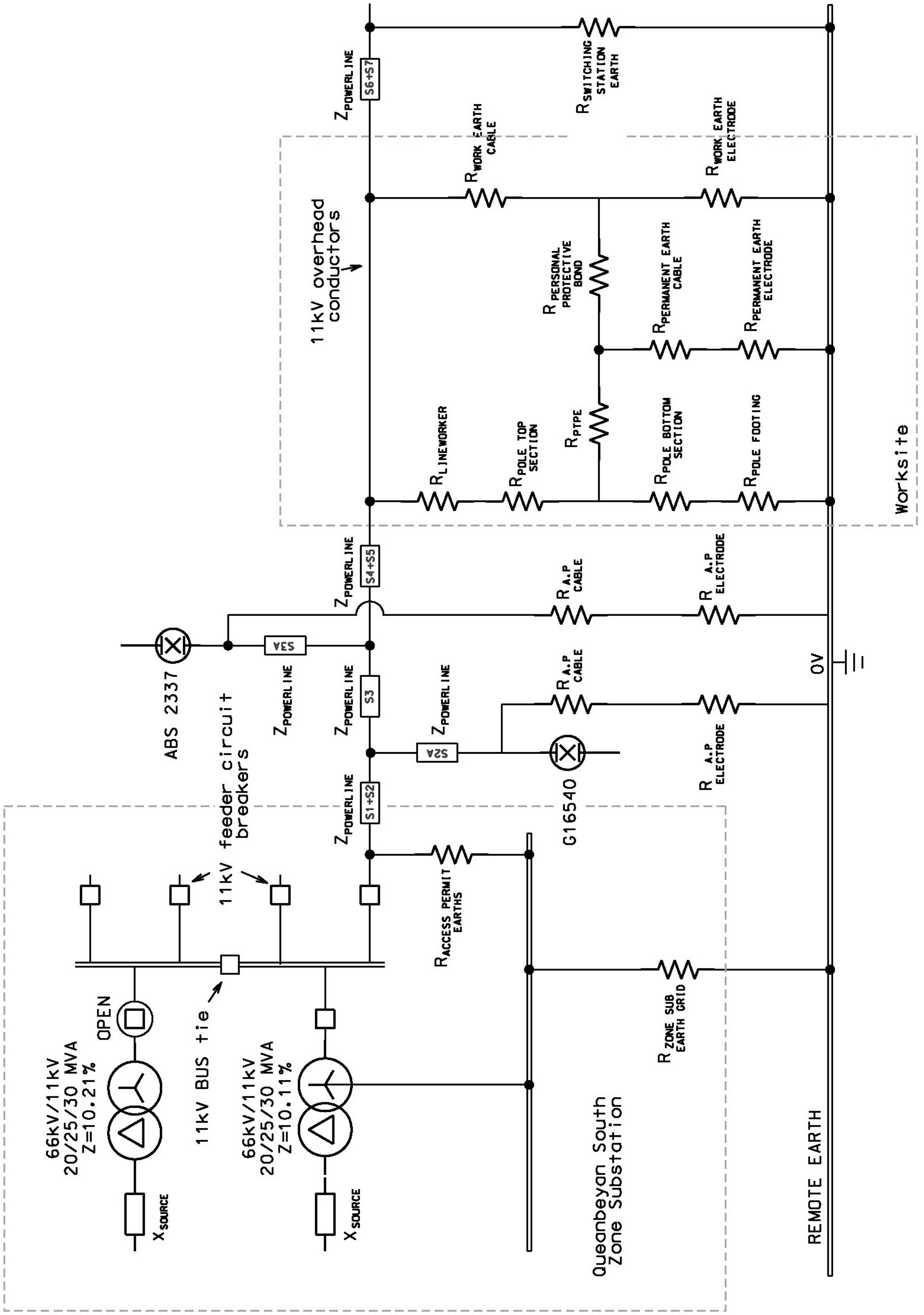


Figure 4.2: Connection diagram for de-energised worksite at pole CE19317 including isolation locations and Access Permit Earths

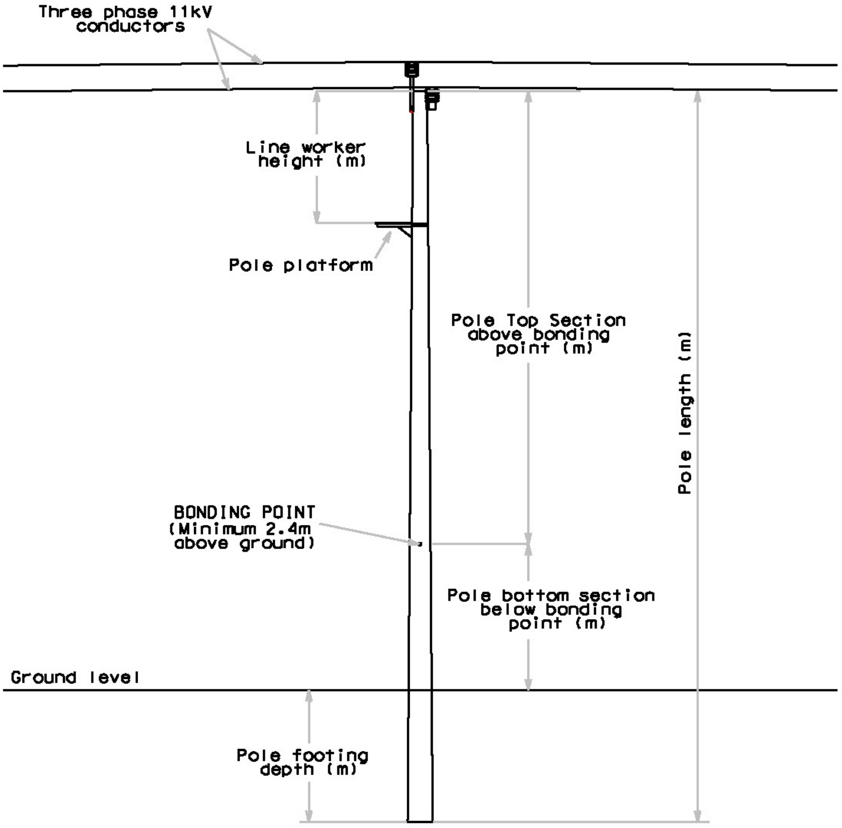


Figure 4.3: Dimensions of pole CE19317 at Site 1

The value R_{PTPE} represents the contact resistance between the permanent earth cable and the pole surface. At pole CE19317, the permanent earth cable is bare and making contact with the pole. Therefore, the value of R_{PTPE} will be relatively low. A more modern practice is the use of insulated cables for permanent earths. In these cases, a cable loop is made off the pole to allow an easily accessed connection point for test lead or earth connections. When a connection is required, the line worker strips the insulation in the loop and makes the connection.

Essential Energy's CEOP2377 document does not explicitly state whether the PPB should be in contact with the pole. Therefore, it is reasonable to anticipate in some cases where the PPB is connected to an insulated cable, that there will be no electrical contact between the PPB and pole surface. In the project analysis R_{PTPE} can be made very high (or practically infinite) to represent this situation.

Input	Value	Notes
Pole length	16.8m	55' obtained from pole button
Embedment	2.5m	$Estimated - Polelength \times 0.1 + 0.8m$
H_{11kV}	9.1m	11kV conductor height
H_{LW}	2.2m	Line worker height including reach above head
BP_{attach}	2.4m	Bonding point - Minimum 2.4m required by ESR
$Pole_{topsection}$	4.5m	$H_{11kV} - H_{LW} - BP_{attach}$
$Pole_{bottomsection}$	4.9m	$BP_{attach} + Embedment$
$R_{lineworker}$	900Ω	Estimate from AS60479
R_{timber}	$31.4M\Omega/m$	Creosote treated timber at 20% moisture level
$R_{poletop}$	$141.3M\Omega/m$	$R_{timber} \times Pole_{topsection}$
$R_{polebottom}$	$153.9M\Omega$	$R_{timber} \times Pole_{bottomsection}$
$R_{polefooting}$	37Ω	Calculated with Equation 3.15
R_{PTPE}	∞	Permanent earth not in contact with pole
R_{PPB}	0.0023Ω	$5m \times 50mmsqCucable$
$R_{P.Ecable}$	0.0017Ω	35mm sq Cu cable
$R_{P.Eelectrode}$	88Ω	Measured at site
$R_{W.Ecable}$	0.0071Ω	$15m \times 35mmsqCucable$
$R_{W.Eelectrode}$	433Ω	Calculated with Equation 3.15

Table 4.1: Values used to determine equivalent resistance of worksite

Input	Value	Notes
Z_{p1}	Ω	Sum of line section impedances S1 and S2 from Table 3.4
Z_{p2}	Ω	Line section impedance S3 from Table 3.4
Z_{p3}	Ω	Line section impedances S4 and S5 from Table 3.4
Z_{p4}	Ω	Sum of line section S6 and S7 impedances from Table 3.4
Z_{p5}	Ω	Line section impedance S2A from Table 3.4
Z_{p6}	Ω	Line section impedance S3A from Table 3.4
R_{ap1}	Ω	Resistance of portable earthing cables used at Zone sub isolation
$R_{ap2_{cable}}$	Ω	15m x 50mm sq Cu cable
$R_{ap2_{electrode}}$	Ω	Nominal value
$R_{ap3_{cable}}$	Ω	15m x 50mm sq Cu cable
$R_{ap3_{electrode}}$	Ω	Nominal value

Table 4.2: Line impedance and access permit earth values used in worksite analysis at pole CE19317

Due to the network complexity of Site 1, the analysis is simplified if the worksite is reduced to a single value. To determine an equivalent single value, loop analysis based on Kirchoff's Voltage Law has been used. For simplicity, the resistance values of the worksite area in Figure 4.2 are combined as follows:

$$R_1 = R_{lw} + R_{poletop}$$

$$R_2 = R_{polebottom} + R_{polefooting}$$

$$R_3 = R_{ptpe}$$

$$R_4 = R_{ppb}$$

$$R_5 = R_{PEcable} + R_{PEelectrode}$$

$$R_6 = R_{WEcable}$$

$$R_7 = R_{WEelectrode}$$

The circuit for the loop analysis is shown in Figure 4.4.

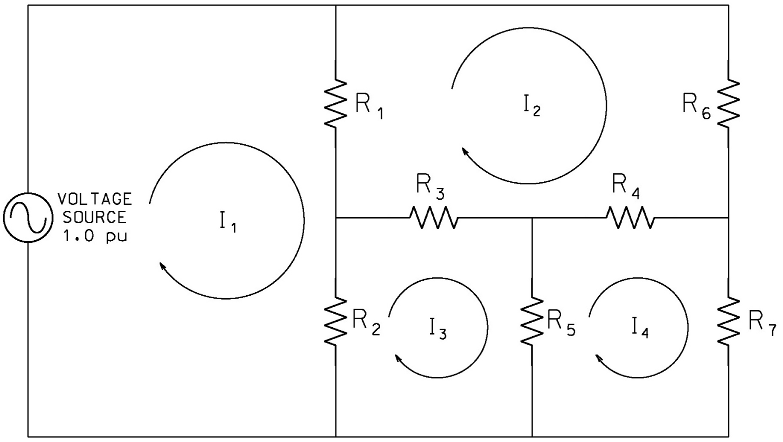


Figure 4.4: Simplified resistance network to determine total worksite resistance at pole CE19317

A system of equations is determined as follows:

$$(R_1 + R_2)I_1 - R_1 I_2 - R_2 I_3 = V_s \tag{4.1}$$

$$-R_1 I_1 + (R_1 + R_3 + R_4 + R_6)I_2 - R_3 I_3 - R_4 I_4 = 0 \tag{4.2}$$

$$-R_2 I_1 - R_3 I_2 + (R_2 + R_3 + R_5)I_3 - R_5 I_4 = 0 \tag{4.3}$$

$$-R_4 I_2 - R_5 I_3 + (R_5 + R_4 + R_7)I_4 = 0 \tag{4.4}$$

The system of equations can be presented in Matrix form $ZI = V$. This has been done for implementation into Matlab.

$$\begin{bmatrix} (R_1 + R_2) & -R_1 & -R_2 & 0 \\ -R_1 & (R_1 + R_3 + R_4 + R_6) & -R_3 & -R_4 \\ R_2 & -R_3 & (R_2 + R_3 + R_5) & -R_5 = 0 \\ 0 & -R_4 & -R_5 & (R_5 + R_4 + R_7) = 0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Matlab has been used to solve the equations and determine the loop currents. The currents are found with the equation:

$$I = Z^{-1} \times V \tag{4.5}$$

The equivalent resistance of the worksite is equal to V divided by I_1. With the input values listed in Table 4.1, the total equivalent worksite resistance is calculated as 73.1 Ohms.

4.1.2 Pole CE19317 - Single phase energisation from zone substation

Analysis

The switching devices at the supply (and isolation) points for pole CE19317 all have three phase operation. That is, when the device is opened or closed, all three phases are switched simultaneously. The upstream protection device is the zone substation circuit breaker, whilst the three other supply point devices are a enclosed Gas Switch (GS), Air Break Switch (ABS), and switching station Ring Main Unit(RMU). Although a set of single phase overhead links exist at the zone substation (at the overhead to underground cable pole), it is unlikely these would be used as the primary method to de-energise or re-energise the line. Therefore, the likelihood of a single phase energisation from the substation occurring is relatively remote. However, whilst still technically possible, and if it occurred it would be a worst case scenario, an analysis of such an event is worthwhile and justified.

If a single phase energisation occurs, the fault current will flow back to the star point of the zone substation transformer secondary winding. The presence of access permit earths connected directly to the substation earth grid provide a very low impedance path for the fault current to flow. Therefore, it is reasonable to expect that the majority of the fault current will flow through this path, and that the risk posed to a lineworker at pole CE19317 will be greatly reduced.

Figure 4.5 is the sequence diagram which models the flow of fault current should a single phase energisation occur. From the figure it can be observed that the negative sequence and zero sequence networks are effectively bypassed by the application of access permit earths at the zone substation.

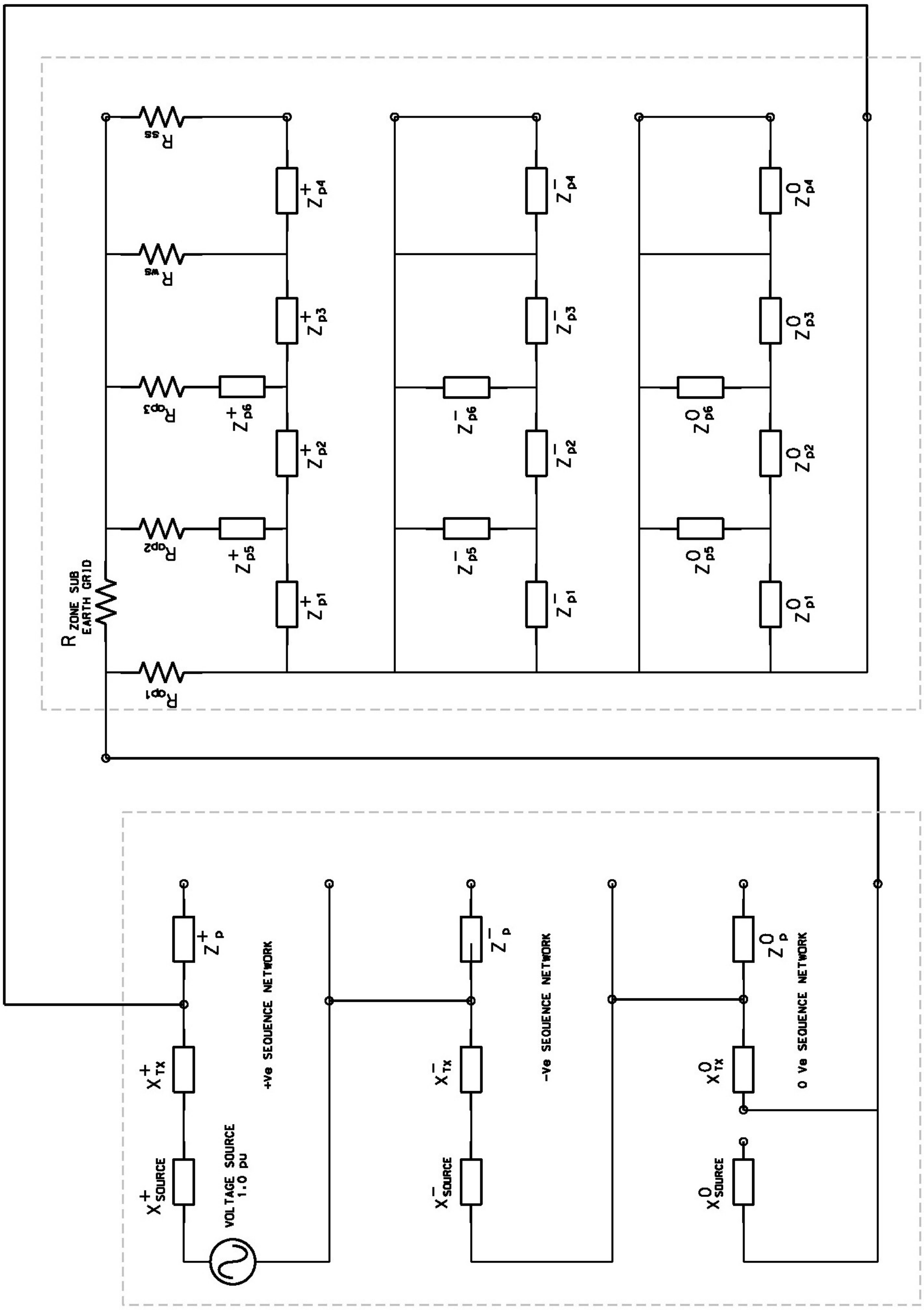


Figure 4.5: Sequence diagram for fault analysis of accidental energisation from Zone Substation

In understanding the seriousness of the hazard caused by a single phase energisation, it is important to know the maximum fault current that can flow. This emphasizes the level of danger a line worker can be exposed if allowed to contact the line without the proper protection. In this situation, the fault is caused by the sudden connection of the earthed section of line to the energised system operating normally. To simplify the calculation, the positive sequence network of the earthed section of line (see Figure 4.5) is first reduced to a single impedance.

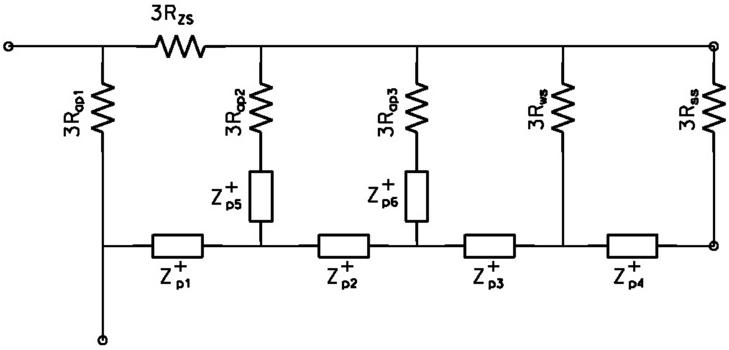


Figure 4.6: Simplified sequence diagram of earthed section of powerline

Let

$$Z_a = \frac{3R_{ws}(Z_{p4} + 3R_{ss})}{3R_{ws} + Z_{p4} + 3R_{ss}} = 7.732 + j0.0137pu$$

Let

$$Z_b = \frac{Z_6(Z_{p3} + Z_a)}{Z_a + Z_{p3} + Z_{p6}} = 5.168 + j0.0147pu$$

Let

$$Z_c = \frac{Z_5(Z_{p2} + Z_b)}{Z_5 + Z_{p2} + Z_b} = 3.877 + j0.0091pu$$

Let

$$Z_d = \frac{3R_{ap1}(Z_{p1} + Z_c + 3R_{zs})}{3R_{ap1} + Z_{p1} + Z_c + 3R_{zs}} = 0.00436 + j0.0000pu$$

The equivalent sequence circuit is shown in Figure CE19317SPEZSSeq2a. The zero sequence current can now be determined.

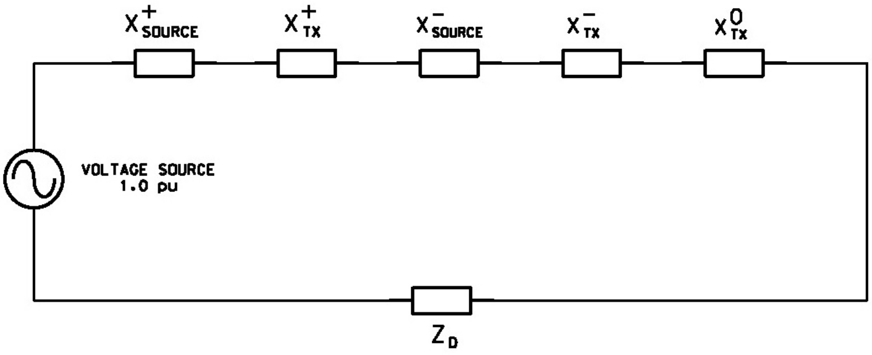


Figure 4.7: Equivalent sequence circuit to determine maximum fault current

The maximum fault current which can flow as a result of the fault is:

$$I_f = 3 \times I_O \tag{4.6}$$

$$I_f = X_s^+ + X_t^+ + X_s^- + X_t^- + X_t^0 + Z_d \tag{4.7}$$

$$I_f = 9834.2A$$

For a single phase energisation from the substation, the current flowing through the worksite has been determined using loop analysis. A system of equations have been developed to solve the currents in the circuit shown in Figure 4.8.

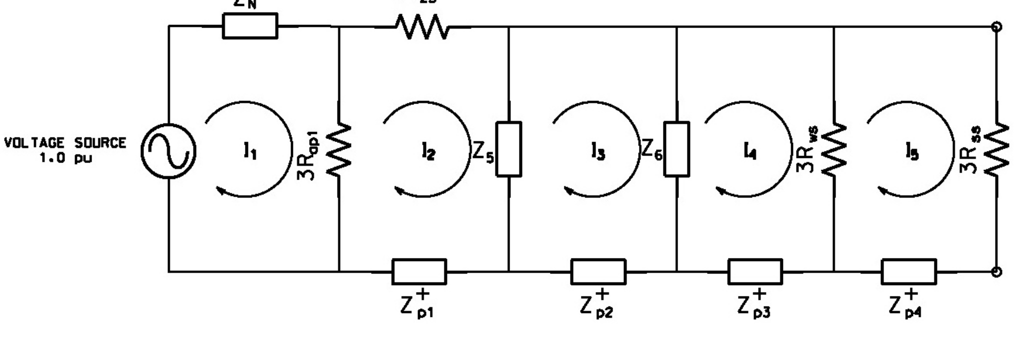


Figure 4.8: Simplified circuit to determine total fault current flowing as a result of accidental energisation from Zone Substation

Let

$$Z_n = X_s^+ + X_t^+ + X_s^- + X_t^- + X_t^0 \tag{4.8}$$

$$Z_n I_1 + 3R_{ap1}(I_1 - I_2) = V_s$$

$$(Z_n + 3R_{ap1})I_1 - 3R_{ap1}I_2 = V_s \tag{4.9}$$

$$R_{ap1}(I_2 - I_1) + 3R_{zs}I_2 + Z_5(I_2 - I_3) + Z_{p1}I_2 = 0$$

$$-3R_{ap1}I_1 + (3R_{ap1} + 3R_{zs} + Z_5 + Z_{p1})I_2 - Z_5 I_3 = 0 \tag{4.10}$$

$$Z_5(I_3 - I_2) + Z_6(I_3 - I_4) + Z_{p2}I_3 = 0$$

$$-Z_5 I_2 + (Z_5 + Z_6 + Z_{p2})I_3 - Z_6 I_4 = 0 \tag{4.11}$$

$$Z_6(I_4 - I_3) + 3R_{ws}(I_4 - I_5) + Z_{p3}I_4 = 0$$

$$-Z_6 I_3 + (Z_6 + 3R_{ws} + Z_{p3})I_4 - 3R_{ws}I_5 = 0 \tag{4.12}$$

$$3R_{ws}(I_5 - I_4) + 3R_{ss}I_5 + Z_{p4}I_5 = 0$$

$$-3R_{ws}I_4 + (3R_{ws} + 3R_{ss} + Z_{p4})I_5 = 0 \tag{4.13}$$

Matlab was used to solve the equations. To simplify the implementation in Matlab, Equations 4.10 to 4.10, have been converted to the matrix form $ZI = V$.

$$\begin{bmatrix} (Z_n + 3R_{ap1}) & -3R_{ap1} & 0 & 0 & 0 \\ -3R_{ap1} & (3R_{ap1} + 3R_{zs} & -Z_5 & 0 & 0 \\ & +Z_5 + Z_{p1}) & & & \\ 0 & -Z_5 & (Z_5 + Z_6 + Z_{p2}) & -Z_6 & 0 \\ 0 & 0 & -Z_6 & (Z_6 + 3R_{ws} + Z_{p3}) & -3R_{ws} \\ 0 & 0 & 0 & -3R_{ws} & (3R_{ws} + 3R_{ss} \\ & & & & Z_{p4}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The loop currents are found with equation 4.14:

$$I_f = 3 \times Z^{-1} \times V \tag{4.14}$$

Referring to Figure 4.8, the total worksite current is equal to I_4 - I_5 times the 11kV base current. The worksite current has been calculated as

$$I_{ws} = 0.9A$$

.

The current flowing through the substation Access Permit Earths connected is equal to I_1 - I_2 times the 11kV base current. This current is

$$I_{Rap1} = 9823.2A$$

Conclusion

The analysis proves that the majority of fault current will flow back to the source transformer via the APE at the substation. The APEs will effectively shield the worksite should such a fault occur. The fault current of 0.9A at the work site is too low to be dangerous, and is practically negligible. The lineworker will be safe in the event of a single phase energisation.

4.1.3 Pole CE19317 - Transferred potential from zone substation to work site

Analysis

Examples highlighting the danger of Earth Potential Rise (EPR) are presented in Section 2.5. For the isolation of the 11kV powerline for work on pole CE19317, APE's must be applied at the zone substation. The APE's must therefore be directly connected to the substation earth grid. It is therefore possible, a transferred potential from the earth grid may energise the 11kV conductors at pole CE19317.

A dangerous situation can arise if a SLG fault occurs on another feeder supplied from the substation. The ground fault will cause current to return to its source transformer via the substation earth grid. A fault close to the substation will result in the highest magnitude of current due to the absence of line impedance. Under normal operating conditions, the maximum SLG fault current is approximately 9.1kA. The returning fault current will cause a rise in the potential of the earth grid. The magnitude of this potential rise is a function of Ohm's Law. The installation of APE's will result in potential of the disconnected Southbar Rd 11kV feeder rising to the potential as the earth grid. Therefore, this voltage will also be transferred to the worksite.

The connection diagram representing the transferred potential hazard is shown in Figure 4.9. The significance of the hazard can be seen by calculating the EPR of the substation. The worst case will occur when the maximum possible level of fault current flows. To model this situation, the fault resistance R_{fault}, as shown in the figure, will set to 0Ω.

The EPR of the substation grid is calculated by using Ohm's Law. The EPR is the product of the fault current magnitude and zone substation earth grid resistance. The maximum level of fault current $I_{fault_{SLG}}$ is determined using Equation 4.19 and impedance values representative of the 11kV bus.

$$X_{bus}^{+} = X_{S}^{+} + X_{Tx}^{+} \tag{4.15}$$

$$X_{bus}^{+} = 0.038634 + 0.1011\,pu$$

$$X^{+}_{bus} = 0.139734\,pu$$

$$X^{-}_{bus} = Z^{-}_{S} + X^{-}_{Tx} \tag{4.16}$$

$$X^{-}_{bus} = 0.038634 + 0.1011\,pu$$

$$X^{-}_{bus} = 0.139734\,pu$$

$$X^{0}_{bus} = Z^{0}_{S} + X^{0}_{Tx}pu \tag{4.17}$$

$$X^{0}_{bus} = 0.050224 + 0.1011\,pu$$

$$X^{0}_{bus} = 0.151324\,pu$$

$$I_{fault_{SLG}} = \frac{3V_{an}}{X^{+}_{bus} + X^{-}_{bus} + X^{0}_{bus}} \tag{4.18}$$

$$I_{fault_{SLG}} = \frac{3 \times 1.0}{0.139734 + 0.139734 + 0.151324} \times I_{base11}$$

$$I_{fault_{SLG}} = 9136\,A$$

The magnitude of EPR is determined:

$$GPR = I_f \times R_{Zs} \tag{4.19}$$

$$GPR = 9136\,A \times 0.3\,\Omega$$

$$GPR = 2740\,V$$

To assess the danger of EPR to the line worker at pole CE19317, an analysis of the resulting fault current flow is required. Figure 4.10 shows the sequence diagram representing the transferred potential situation. In Figure 4.10 it can be seen that the negative sequence and zero sequence networks are effectively short circuited by the fault on the alternative feeder. A simplified sequence diagram is shown in Figure 4.12. Loop analysis has been used to determine the current flowing in each part of the network.

Input	Value	Notes
R_{ap1}	0.00146 pu	Resistance of access permit earths applied at ZS (50mm cable only)
$R_{ap2_{cable}}$	0.00146 pu	Resistance of APE cable at G16540 (50mm cable)
$R_{ap2_{electrode}}$	5.165 pu	Permanent earth electrode resistance at G16540 (from EE records)
R_{ap2}	5.166 pu	Total resistance of access permit earths ($R_{ap2_{cable}} + R_{ap2_{electrode}}$)
$R_{ap3_{cable}}$	0.00146 pu	Resistance of APE cable at A2337 (50mm cable)
$R_{ap3_{electrode}}$	5.165 pu	Permanent earth electrode resistance at G16540 (from EE records)
R_{ap3}	5.166 pu	Total resistance of access permit earths ($R_{ap2_{cable}} + R_{ap2_{electrode}}$)
R_{ss}	3.099 pu	Switching station earth grid resistance (from EE records)

Table 4.3: Resistance values of temporary earths applied at isolation locations

Using values from Tables 3.4, 4.1 and 4.3, the circuit can be analysed and the total fault current determined. The parallel network formed by the temporary earths can be reduced to a single equivalent value as follows:

Let

$$Z_a = \frac{3R_{ws}(Z_{p4} + 3R_{ss})}{3R_{ws} + Z_{p4} + 3R_{ss}} = 2.588 + j0.0137pu \tag{4.20}$$

Let

$$Z_b = \frac{(Z_a + Z_{p3})(Z_{p6} + 3R_{ap3})}{Z_a + Z_{p3} + Z_{p6} + 3R_{ap3}} = 1.734 + j0.0147pu \tag{4.21}$$

Let

$$Z_c = \frac{(Z_b + Z_{p2})(Z_{p5} + 3R_{ap2})}{Z_b + Z_{p2} + Z_{p5} + 3R_{ap2}} = 1.299 + j0.0091pu \tag{4.22}$$

Let

$$Z_d = \frac{3R_{zs}(Z_{p1} + Z_c)}{3R_{zs} + Z_{p1} + Z_c} = 0.0592 + j0.0007pu \tag{4.23}$$

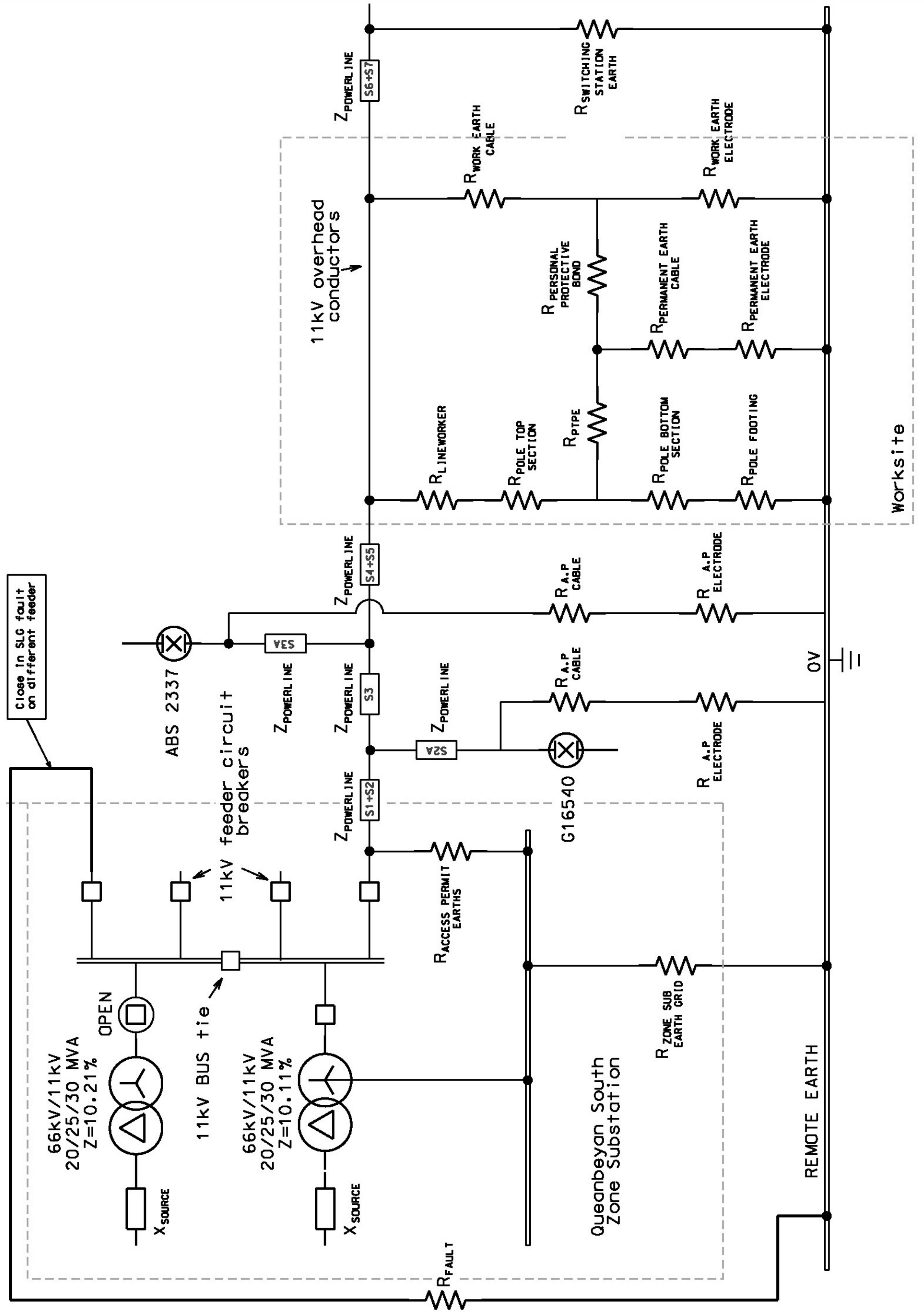


Figure 4.9: Connection diagram for Transferred Potential case caused by close in SLG fault on an adjacent feeder

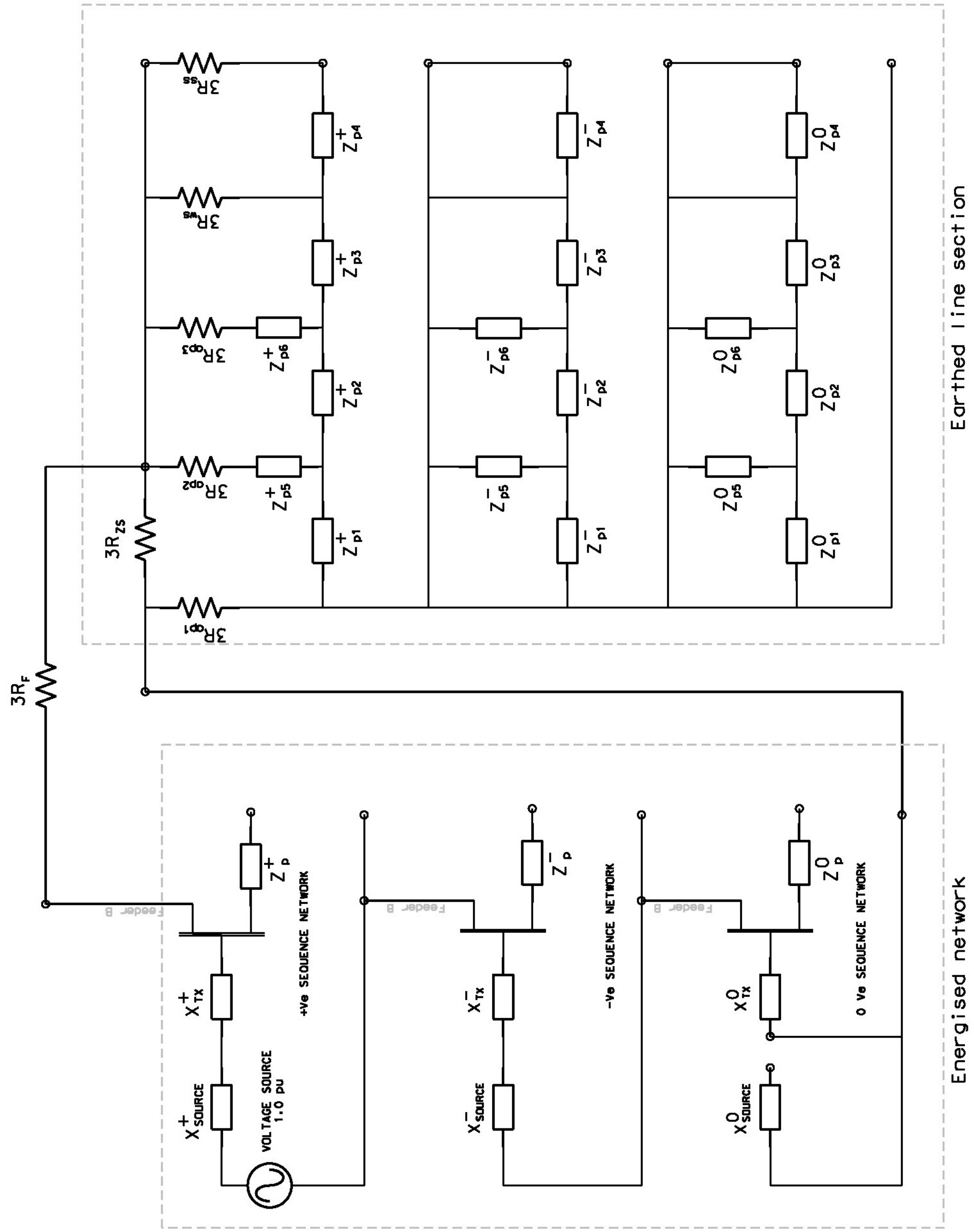


Figure 4.10: Sequence diagram for current flow analysis of Transferred Potential case

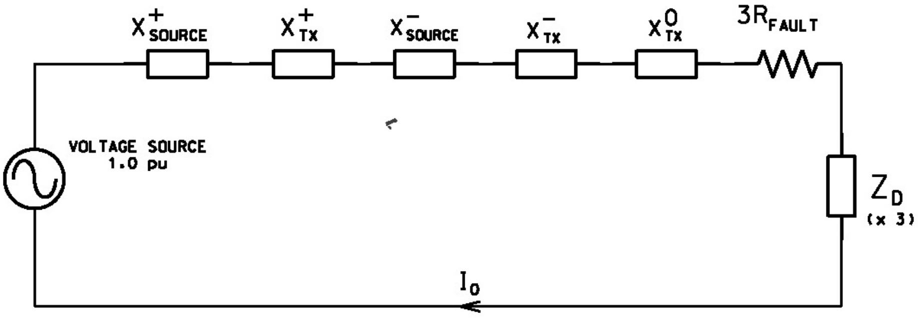


Figure 4.11: Sequence diagram for current flow analysis of Transferred Potential case

The magnitude of the fault current caused by the ground fault on the adjacent feeder is calculated using equation 4.24:

$$I_f = \frac{3 \times V_{an}}{X_s^+ + X_T^+ + X_s^- + X_T^- + X_T^0 + 3 \times Z_d + 3 \times R_f} \tag{4.24}$$

$$I_f = \frac{3 \times 1.0}{j0.0485 + j0.011 + j0.0485 + j0.011 + j0.011 + 3(0.0605 + j0.0000355) + 3 \times 0)}$$

$$I_f = 8984.6A$$

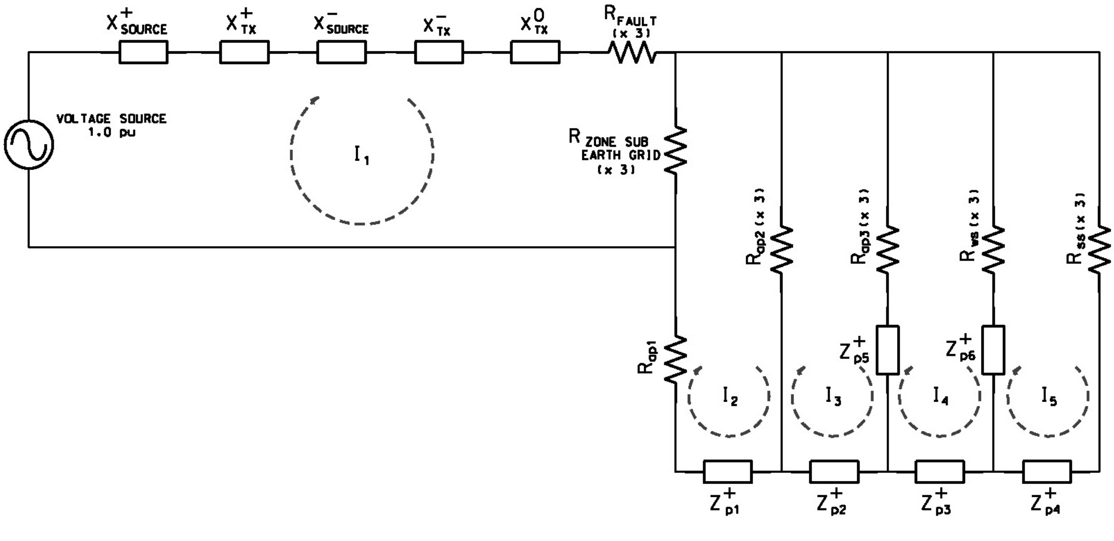


Figure 4.12: Simplified circuit diagram for use in solving current flow in event of transferred potential case

Now that the total fault current I_f is known, loop analysis can be used to determine the portion of current which would flow through the worksite. Figure 4.12 is a simplified sequence circuit used for this analysis. To simplify the calculations,

Let

$$Z_n = X_s^+ + X_T^+ + X_s^- + X_T^- + X_T^0 + 3 \times R_f$$

Let

$$Z_5 = (Z_{p5} + 3R_{ap2})$$

Let

$$Z_6 = (Z_{p6} + 3R_{ap3})$$

Referring to Figure 4.12, a system of equations is developed:

$$Z_n I_1 + 3R_{zs}(I_1 - I_2) = V_s$$

$$(Z_n + 3R_{zs})I_1 - 3R_{zs}I_2 = V_s \tag{4.25}$$

$$3R_{zs}(I_1 - I_2) + Z_5(I_2 - I_3) + Z_{p1}I_2 = 0$$

$$-3R_{zs}I_1 + (3R_{zs} + Z_5 + Z_{p1})I_2 - Z_5 I_3 = 0 \tag{4.26}$$

$$Z_5(I_3 - I_2) + Z_6(I_3 - I_4) + Z_{p2}I_3 = 0$$

$$-Z_5 I_2 + (Z_5 + Z_6 + Z_{p2})I_3 - Z_6 I_4 = 0 \tag{4.27}$$

$$Z_6(I_4 - I_3) + 3R_{ws}(I_4 - I_5) + Z_{p3}I_4 = 0$$

$$-Z_6 I_3 + (Z_6 + 3R_{ws} + Z_{p3})I_4 - 3R_{ws}I_5 = 0 \tag{4.28}$$

$$3R_{ws}(I_5 - I_4) + 3R_{ss}I_5 + Z_{p4}I_5 = 0$$

$$-3R_{ws}I_4 + (3R_{ws} + 3R_{ss} + Z_{p4})I_5 = 0 \tag{4.29}$$

The equations are converted to the matrix form $ZI = V$. This allows for implementation into Matlab which will be used to determine the currents.

$$\begin{bmatrix} (Z_n + 3R_{zs}) & -3R_{zs} & 0 & 0 & 0 \\ -3R_{zs} & (3R_{zs} + Z_5 + Z_{p1}) & -Z_5 & 0 & 0 \\ 0 & -Z_5 & (Z_5 + Z_6 + Z_{p2}) & -Z_6 & 0 \\ 0 & 0 & -Z_6 & (Z_6 + 3R_{ws} + Z_{p3}) & -3R_{ws} \\ 0 & 0 & 0 & -3R_{ws} & (3R_{ws} + 3R_{ss} + Z_{p4}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The zero sequence loop currents are found by multiplying the inverse of the impedance matrix by the voltage matrix. That is, $I_0 = Z^{-1} \times V$. The zero sequence currents are converted to the real fault currents by multiplying by three I_0. Thus, $I_f = 3 \times I_0$.

Results

Referring to Figure 4.12, the total worksite current I_{ws} is equal to the difference between currents I_4 and I_5. After using the values listed in Tables 4.1, 4.2, and 4.3, and solving in Matlab, the calculated worksite current is 34.9 Amps. The PPBE of the worksite is configured as per Figure 4.31 of Section 2.4. With this bonding configuration, 34.9A is a safe level of worksite current. This will be proven in Section 4.2.3.

Referring to Figure 4.12, the actual EPR of the substation grid, and the voltage appearing across the worksite, can be calculated. The substation grid EPR is calculated as shown in equation 4.30:

$$V_{ws} = I_4 \times 3R_{zs} \tag{4.30}$$

$$EPR = 2573.9V$$

The voltage transferred to the worksite is calculated as shown in equation 4.31:

$$V_{ws} = (I_4 - I_5) \times (I_{p6}^{+} + 3R_{ws}) \tag{4.31}$$

$$V_{ws} = 2555.6V$$

Therefore, almost the entire EPR of the substation grid has been transferred to the worksite. Given the small size of the worksite current and the applied protective bonding, the lineworker would be safe should if scenario eventuates. However, a transferred potential of 2555V could be deadly if past protective bonding methods were used instead.

In Section 2.5, the practice of 'bracket earthing' was discussed in the review of a paper by Harrington & Martin (1954). Bracket earthing describes the practice of installing temporary bonds and earths at poles either side of the worksite. In this syste, no bonding is installed at the worksite itself. It was believed that the worker would be shielded against any current flow by the earths on either side of the worksite. Had the bracket earthing method outlined by Harrington been applied for pole CE19317, and the pole been of a conductive material(such as steel), then the hazard for the lineworker would be lethal. A fatality would be a reasonably likely possibility.

4.1.4 Intermix of 66kV and 11kV circuits near worksite

Analysis

Pole CE19317 supports two high voltage overhead circuits. The top circuit is a 66kV sub-transmission powerline, whilst the bottom circuit is the Southbar Road 11kV feeder. The 66kV and 11kV dual circuit configuration exists for a line section of approximately 2.0km along the Cooma Road. No overhead earth wires are installed along this section of dual circuit line.

A hazardous situation would occur if there was a clash, or 'intermix', between the 66kV and 11kV conductors. The powerline is designed with large spacing between the circuits to ensure this does not happen under normal operation. However, there is a real risk of such an event whilst construction activities are taking place. For example, the uncontrolled movement of the 11kV conductors during a project to repair or replace them.

The following analysis is of a 66kV and 11kV intermix close to the worksite location. The first task is to determine the maximum prospective fault current that may flow. Figure 4.13 shows the sequence diagram representing the intermix fault situation.

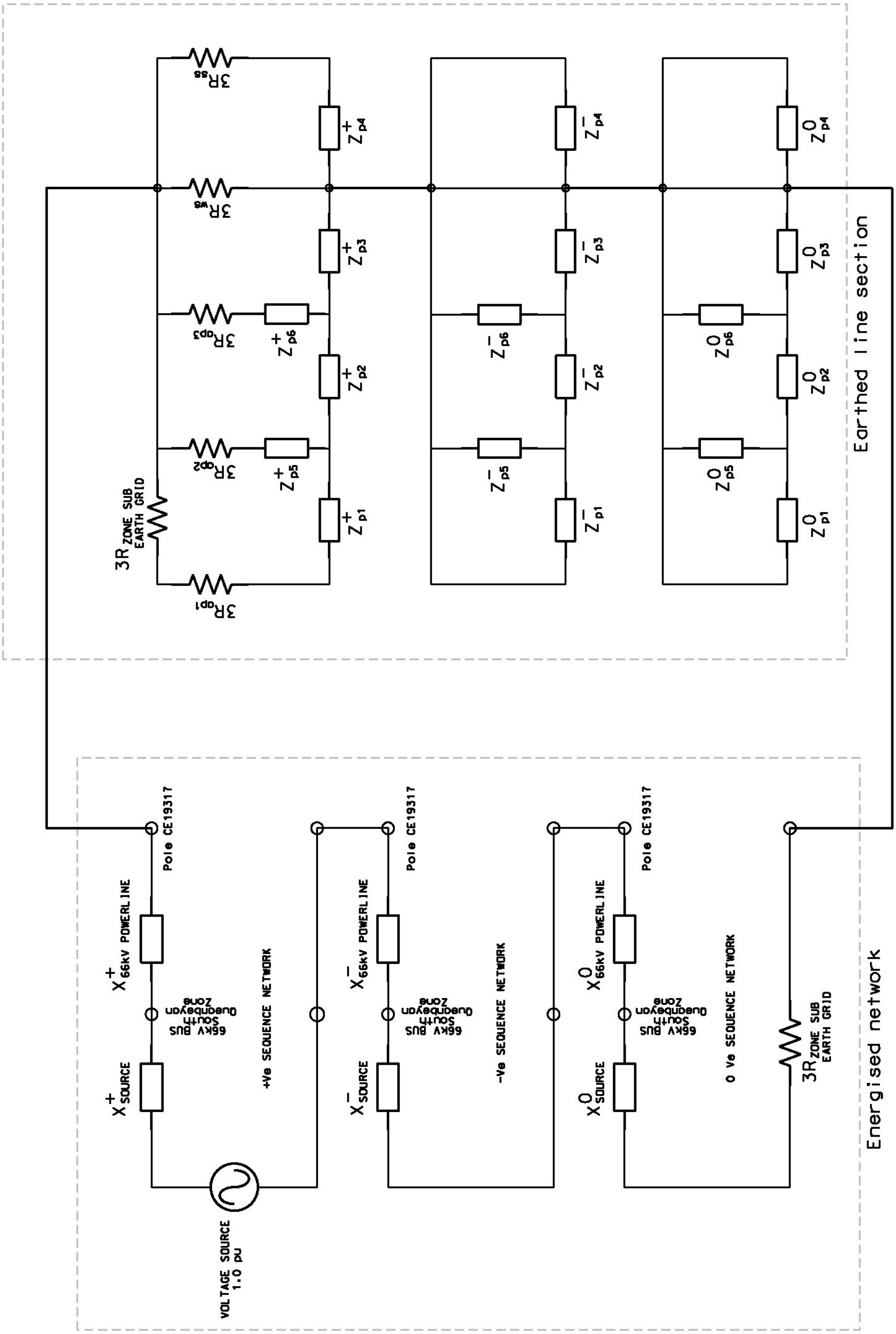


Figure 4.13: Sequence diagram for fault analysis of a 66kV and 11kV 'intermix' near the worksite

The equivalent upstream 66kV source impedance is known at the 66kV busbar at South Queanbeyan Zone substation. The 66kV fault level at the busbar was provided by Essential Energy's protection engineers. The 66kV source impedances are calculated in Equations 3.9, 3.10, and 3.11. The 66kV line distance from the substation to pole CE19317 is 1.1km. The 66kV conductors are 7/4.50 AAC 'Mercury'. Therefore the 66kV line impedance values are:

$$X^{+}_{L_{66kV}} = 1.1\,km \times (0.315 + j0.259)\,\frac{\Omega}{km} = 0.3465 + j0.2849\,\Omega \tag{4.32}$$

$$X^{-}_{L_{66kV}} = 1.1\,km \times (0.315 + j0.259)\,\frac{\Omega}{km} = 0.3465 + j0.2849\,\Omega \tag{4.33}$$

$$X^{0}_{L_{66kV}} = 1.1\,km \times (0.315 + j0.777)\,\frac{\Omega}{km} = 0.3465 + j0.8547\,\Omega \tag{4.34}$$

The impedance values are converted to per unit by dividing by $Z_{base_{66}}$:

$$X^{+}_{L_{66kV}} = 0.00198 + j0.00163\,pu$$

$$X^{-}_{L_{66kV}} = 0.00198 + j0.00163\,pu$$

$$X^{0}_{L_{66kV}} = 0.00198 + j0.00489\,pu$$

To determine the magnitude of the resulting fault current, the earthed section sequence impedances will be reduced to a single equivalent value Z_d. For the purpose of determining a maximum current value, the fault contact resistance R_f is assumed to be zero.

Let

$$Z_a = \frac{(3R_{ap1} + 3R_{zs} + Z_{p1})(Z_{p5} + 3R_{ap2})}{3R_{ap1} + 3R_{zs} + Z_{p1} + Z_{p5} + 3R_{ap2}}$$

Let

$$Z_b = \frac{(Z_a + Z_{p2})(Z_{p6} + 3R_{ap3})}{Z_a + Z_{p2} + Z_{p6} + 3R_{ap3}}$$

Let

$$Z_c = \frac{(Z_b + Z_{p3})(3R_{ss} + Z_{p4})}{Z_b + Z_{p3} + 3R_{ss} + Z_{p4}}$$

Let

$$Z_d = \frac{(3R_{ss} \times Z_c)}{Z_c + 3R_{ss}}$$

The zero sequence current is determined with Equation **??**.

$$I_0 = \frac{1.0}{X_s^+ + X_{L_{66kV}}^+ + X_s^- + X_{L_{66kV}}^- + X_s^0 + X_{L_{66kV}}^0 + 3R_f + Z_d} \tag{4.35}$$

The total fault current is three times the zero sequence current.

$$I_f = 3 \times I_O \tag{4.36}$$

Using the above source values from Equations 3.9, 3.10, and 3.11, and the line impedance values calculated above, the fault current I_f flowing as a result of the 66kV and 11kV intermix 2460.7A.

The worksite current can be determined by using Loop analysis. Figure 4.14 represents the fault current circuit. Z_c is the equivalent resistance of all the isolation access permit earths which surround the worksite.

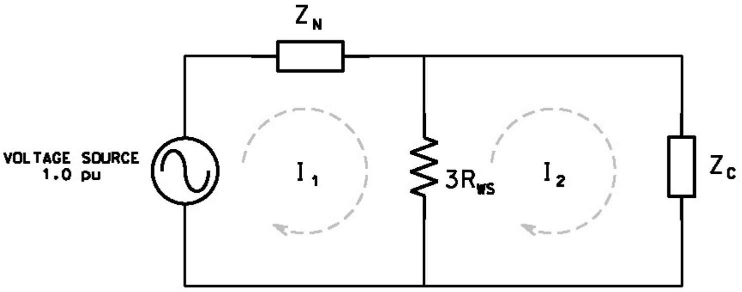


Figure 4.14: Simplified circuit diagram for determination of work site current

$$Let Z_N = X_s^+ + X_s^- + X_s^0 + X_{L_{66kV}}^+ + X_{L_{66kV}}^- + X_{L_{66kV}}^0 + 3R_f \tag{4.37}$$

To determine the loop current values I_1 and I_2, a system of equations has been developed:

$$Z_n I_1 + 3R_{ws}(I_1 - I_2) = V_s$$

$$(Z_n + 3R_{ws})I_1 - 3R_{ws}I_2 = V_s \tag{4.38}$$

$$R_{ws}(I_2 - I_1) + Z_c I_2 = 0$$

$$-3R_{ws}I_1 + (3R_{ws} + Z_c)I_2 = 0 \tag{4.39}$$

The equations are presented in the matrix form $ZI = V$ for easy solution in Matlab.

$$\begin{bmatrix} (Z_n + 3R_{ws}) & -3R_{ws} \\ -3R_{ws} & (3R_{ws} + Z_c) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \end{bmatrix}$$

The zero sequence currents I_1 and I_2 are found by Equation 4.40. The actual fault currents is equal to three times the zero sequence currents.

$$I = Z^{-1} \times V \tag{4.40}$$

Referring to Figure 4.14, the worksite current is equal to I_1 - I_2 times the 66kV base current (see Equation 3.7). Using Matlab, the worksite current has been calculated $I_{ws} = 12.3$

The equivalent worksite resistance was evaluated in Section 4.1.1 as 73.13Ω. Using Ohm's Law, the voltage appearing across the work site is:

$$V_{ws} = I_{ws} \times R_{ws} = 12.3 \times 73.13\Omega = 901.8V \tag{4.41}$$

Results

Whilst a large amount of fault current (2460A) flowed due to the contact between the 66kV and 11kV circuits, only a very small portion (12.3A) flowed through the worksite. The installation of APEs at the multiple isolation points provided a low impedance path for the majority of current to bypass the worksite.

A worksite fault current of 12.3A is not large enough to risk injury to the line worker. The current would have passed through the working earths and PPB applied at the worksite setup as per Figure 2.6. It is concluded the line worker would have remained safe in the event of the circuit 'intermix'. More analysis on the PPB technique of Figure 2.6 is provided in Section sec:CEOP2377Fig3.

4.1.5 Pole CE19321 - Old Cooma Road, South Queanbeyan

Pole CE19321 was selected as the second site for analysis. Pole CE19321 is located on a hill top just outside the urban area of Queanbeyan. The pole is located 1.97km in line distance from the Zone Substation. The pole location is on a radial section of powerline and beyond the alternative supply points of other 11kV feeders.

Figure 4.15: Pole CE19321 located at Old Cooma Road near Queanbeyan

Pole CE19317 is a 60’ (18.3m) timber pole treated with creosote preservative. The pole supports both 66kV and 11kV overhead conductors. The 11kV circuit is strained at the pole with a enclosed gas switch installed. The gas switch is used to isolate supply to the downstream section of line. A permanent earth cable is available on the pole.

The following analysis is for work occurring on one side of the pole with the gas switch used as the only the network isolation. The ESR require a set of APE earths to be applied to the conductors at the worksite. In accordance with CEOP2377, the temporary earthing and personal protective bonding would be applied as per Figure 2.6 of Section 2.4. With this configuration, the APE must be bonded to the pole’s permanent earth with a personal protective bond.

Figure 4.16 provides details the worksite connections, and the upstream 11kV network. The analysis is of a SLG fault which would be the most hazardous type for the line worker. In this case, the fault current flows through the earth and possibly through the worksite and line worker. It is acknowledged that a SLG fault would be considerably unlikely to occur at this site. This is because the gas switch provides three phase operation and can be locked open. However, the purpose of the analysis is to determine whether the application of PPB will protect the worker. The results have relevance for other similar work sites further along the powerline where the occurrence of a SLG is more likely.

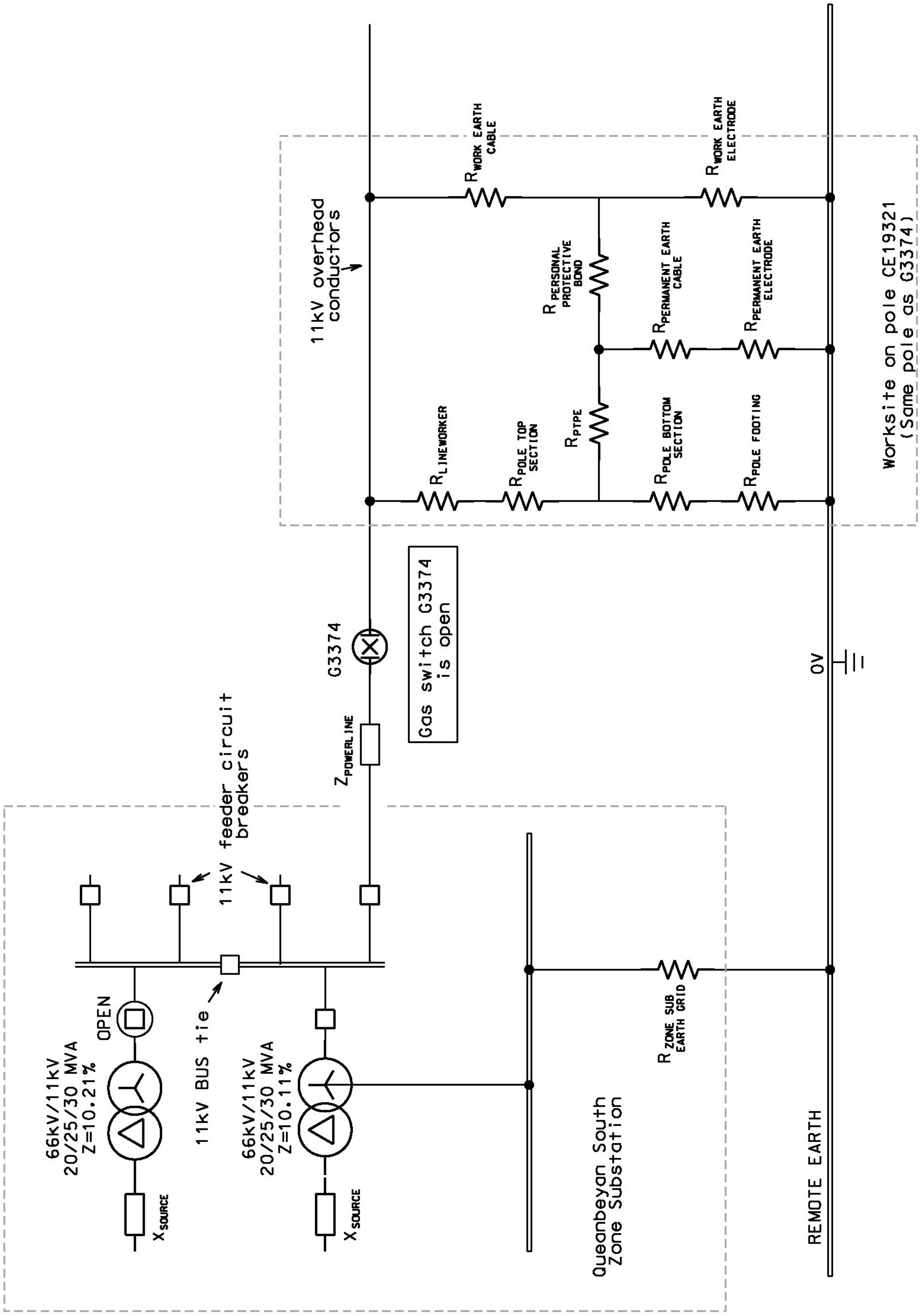


Figure 4.16: Connection diagram for de-energised worksite at pole CE19321

The performance of the applied PPB has been assessed by determining the magnitude and path of fault current through the worksite. This has been done using the method of symmetrical components as described in AS 3851 (AS 3851-1991 n.d.). A sequence diagram representing the faulted circuit is provided in Figure 4.17. The line impedance Z_p represents the line impedance between the substation and pole site, and is equal to the sum of line section impedances 1 to 9 of Table 3.2.

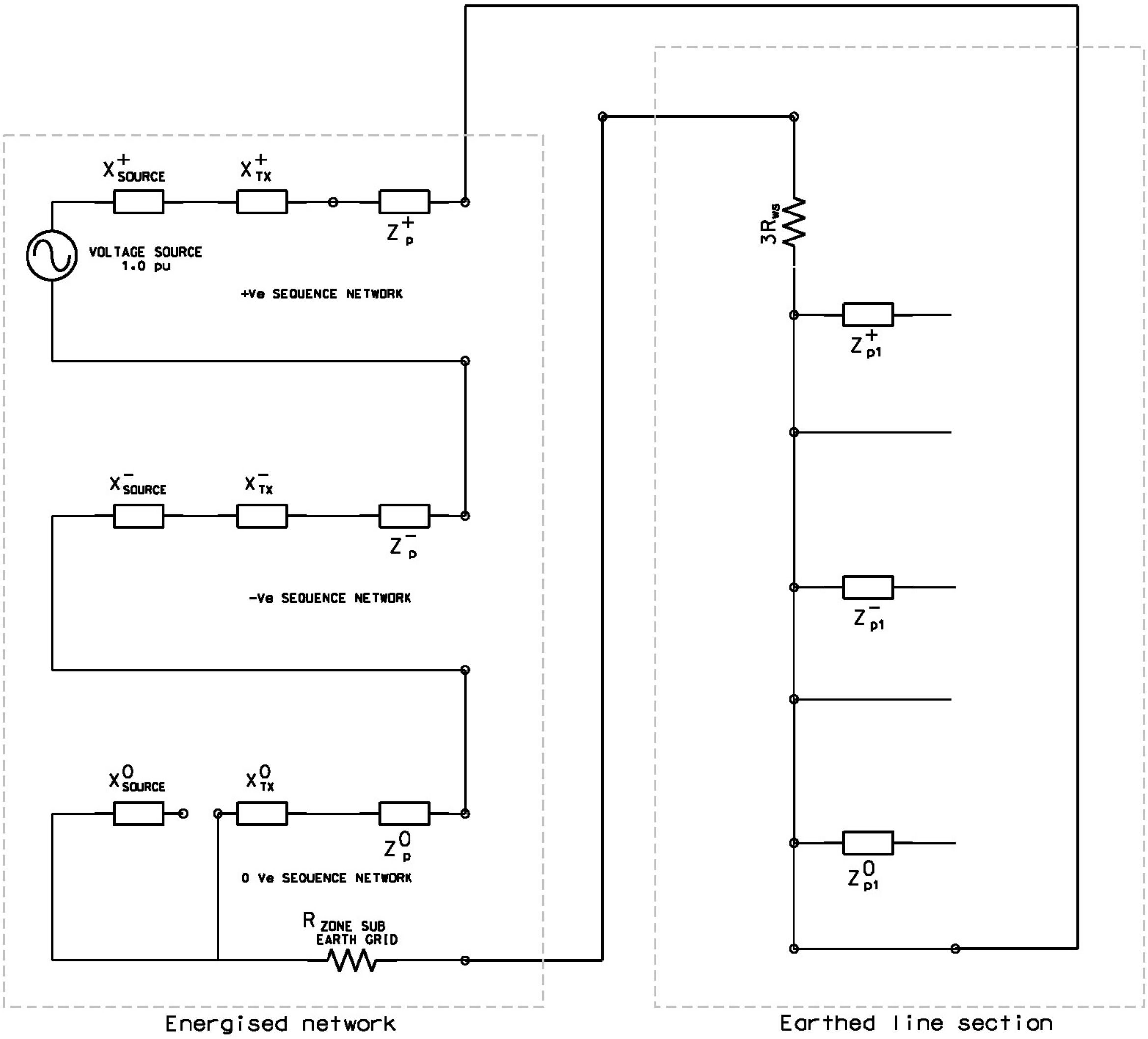


Figure 4.17: Sequence diagram for de-energised worksite at pole CE19321

To simplify calculations, the sequence impedance values of the energised network shown in Figure 4.17, are combined to one equivalent value Z_N.

$$Z_N = X^+_S + X^+_T + X^-_S + X^-_T + X^0_T + Z^+_p + Z^-_p + Z^0_p + 3R_{ZS} \qquad (4.42)$$

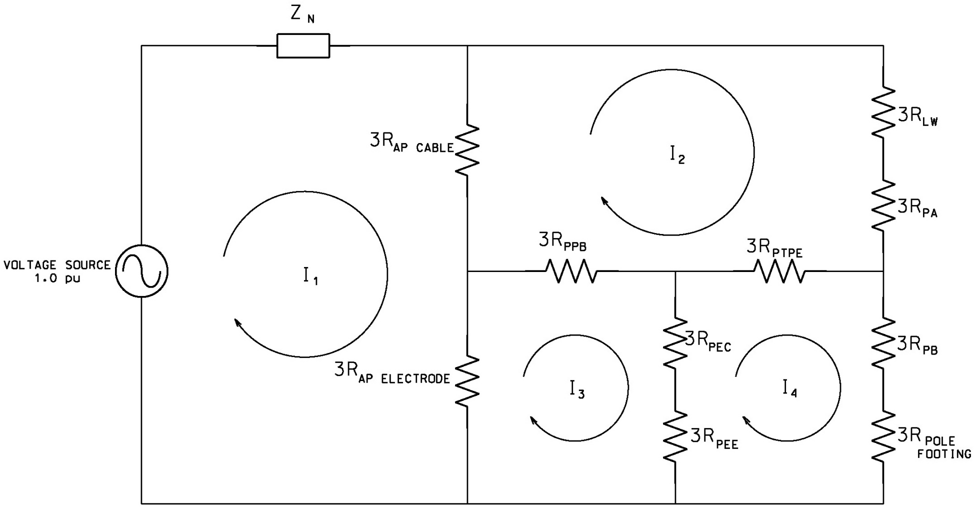


Figure 4.18: Simplified diagram for loop analysis of fault current for worksite of CE19321

Figure 4.18 is the circuit diagram used for loop analysis of the fault situation. To determine the currents I_1 to I_4, a system of equations have been developed.

$$(Z_n + 3R_{apc} + 3R_{ape})I_1 - 3R_{apc}I_2 - 3R_{ape}I_3 = V_S \tag{4.43}$$

$$-3R_{apc}I_1 + (3R_{apc} + 3R_{lw} + 3R_{pa} + 3R_{ppb} + 3R_{ptpe})I_2 - 3R_{ppb}I_3 - 3R_{ptpe}I_4 = 0 \tag{4.44}$$

$$-3R_{ape}I_1 - 3R_{ppb}I_2 + (3R_{ape} + 3R_{ppb} + 3R_{pec} + 3R_{pee})I_3 - (3R_{pec}I_3 + 3R_{pee})I_4 = 0 \tag{4.45}$$

$$-3R_{ptpe}I_2 - (3R_{pec} + 3R_{pee})I_3 + (3R_{pee} + 3R_{pec} + 3R_{ptpe} + 3R_{pb} + 3R_{polefooting})I_4 = 0 \tag{4.46}$$

The equations are now presented in matrix form for input into Matlab. Matlab was used to solve the equations and determine the loop currents.

$$\begin{bmatrix} (Z_n + 3R_{apc} & -3R_{apc} & -3R_{ape} & 0 \\ +3R_{ape}) & & & \\ -3R_{apc} & (3R_{apc} + 3R_{lw} + 3R_{pa} & -3R_{ppb} & -3R_{ptpe} \\ & +3R_{ppb} + 3R_{ptpe}) & & \\ -3R_{ape} & -3R_{ppb} & (3R_{ape} + 3R_{ppb} & \\ & & +3R_{pec} + 3R_{pee}) & -(3R_{pec} + 3R_{pee}) \\ 0 & -3R_{ptpe} & -(3R_{pec} + 3R_{pee}) & (3R_{pee} + 3R_{pec} + 3R_{ptpe} \\ & & & +3R_{pb} + 3R_{polefooting}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

As shown in equation 4.47, the loop currents I_1 to I_4 are found by multiplying the inverse impedance matrix with the voltage matrix. These currents are the zero sequence currents. The actual fault currents have been determined by multiplying the zero sequence currents by three as per equation 4.48.

$$I_0 = Z^{-1} \times V \tag{4.47}$$

$$I_f = 3 \times I_0 \tag{4.48}$$

Referring to Figure 4.18, the critical worksite voltage and currents have been determined. The total fault current I_f is equal to I_1. The total work site current I_{ws} is also equal to I_f. The current flowing in the PPB I_{ppb} is equal to the difference between I_2 and I_3.

The worksite voltage V_{ws} is equal to $(I_2 - I_3)$ times R_{apc} plus $(I_1 - I_3)$ times R_{ape}. The touch voltage experienced by the line worker is the voltage difference between the overhead conductors, and the contact position on the pole. V_{touch} is calculated as V_{ws} minus $I_4(R_{pb} + R_{polefooting})$.

Finally, the current that would flow through the line worker is equal to loop current I_2.

A script to perform the analysis was prepared in Matlab. A representative Matlab script is included in Appendix B. A summary of the work site values used in the calculations is provided in Table 4.4. A pole diagram illustrating important dimensions of the pole is seen in Figure 4.3.

Input	Value	Notes
Pole length	18.3m	60' length obtained from pole button
Embedment	2.63m	$Estimated - Polelength \times 0.1 + 0.8m$
H_{11kV}	9.1m	11kV conductor height
H_{LW}	2.2m	Line worker height including reach above head
BP_{attach}	2.4m	Bonding point - Minimum 2.4m required by ESR
$Pole_{topsection}$	4.5m	$H_{11kV} - H_{LW} - BP_{attach}$
$Pole_{bottomsection}$	4.9m	$BP_{attach} + Embedment$
$R_{lineworker}$	900Ω	Estimate from AS60479
R_{timber}	$31.4M\Omega/m$	Creosote treated timber at 20% moisture level
$R_{poletop}$	$141.3M\Omega/m$	$R_{timber} \times Pole_{topsection}$
$R_{polebottom}$	$135.0M\Omega$	$R_{timber} \times Pole_{bottomsection}$
$R_{polefooting}$	37Ω	Calculated with Equation 3.15
R_{PTPE}	1Ω	Permanent earth not in contact with pole
R_{PPB}	0.0023Ω	5m x 50mm sq Cu cable
$R_{P.Ecable}$	0.0017Ω	35mm sq Cu cable
$R_{P.Eelectrode}$	30Ω	Obtained at site
$R_{W.Ecable}$	0.0071Ω	15m x 35mm sq Cu cable
$R_{W.Eelectrode}$	1527.7Ω	Calculated with Equation 3.15

Table 4.4: Values used to in calculation of equivalent resistance of worksite

A summary of the critical work site currents and voltages determined in Matlab are in Table 4.5.

I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{TOUCH} (V)	I_{LW} (A)
209.62	209.62	205.6	6170.6	2.60	0.00000

Table 4.5: Voltage and current values for energisation of work site at pole CE19321

Conclusion

The results in Table 4.5 show a touch voltage of only 2.60V and zero current passing through the path of the lineworker. The results prove the application of this PPB technique will ensure the safety of the lineworker.

4.1.6 Pole CE69899 - Quarry Road, South Queanbeyan

Pole CE69899 was selected as the third site for analysis. Pole CE69899 is located on Quarry Road in the rural area to the south of Queanbeyan. The pole is located 3.26km in line distance from the Zone Substation. The pole location is on a radial section of powerline and beyond the alternative supply points of other 11kV feeders.

Figure 4.19: Pole CE69899 located at Quarry Road near Queanbeyan

Pole CE69899 is a 12.5m timber pole treated with CCA preservative treatment. The pole supports 11kV overhead conductors only. The pole can be isolated from the 11kV supply by opening the upstream links L10686. Pole CE69899 does not have a permanent earth cable available on the pole.

The upstream links L10686 used to isolate the supply are not in view of the worksite. Therefore, the ESR require APE earths to be applied at the pole where the links are installed. In accordance with CEOP2377, a set of temporary working earths and a personal protective bond are required at pole CE69899. The PPB would be attached between the conductor being worked on and the pole below the workers feet. The worksite would be set up as per Figure 2.4 of Section 2.4.

Figure 4.20 details the worksite connections, and the upstream 11kV network. The analysis is of a SLG fault which would be the most hazardous type for the line worker. The links L10686 offer only single phase operation. It is plausible that a SLG fault would occur in the event one link was closed by way of a switching error.

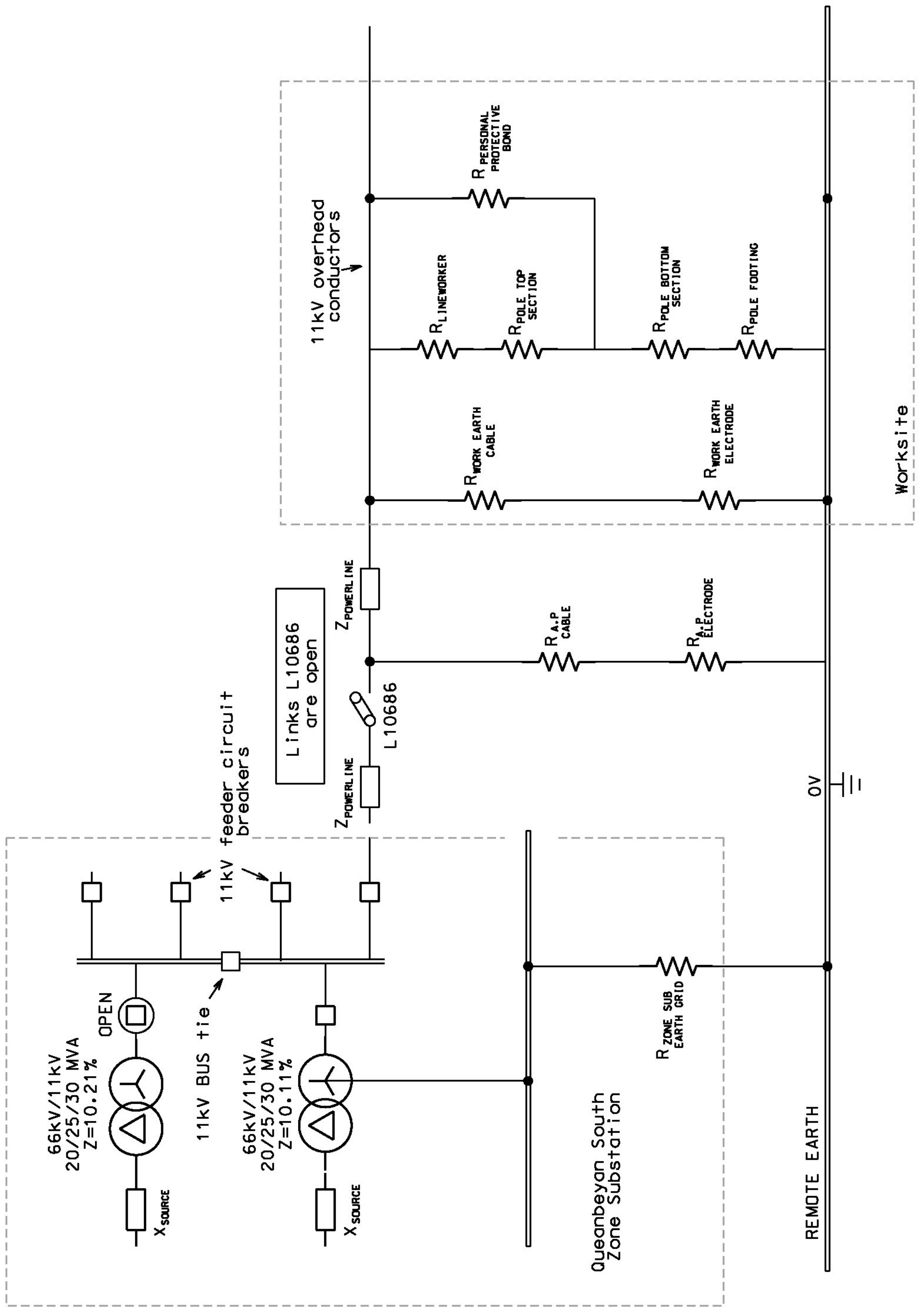


Figure 4.20: Connection diagram for de-energised worksite at pole CE69899

The performance of the applied PPB will be assessed by first determining the magnitude and path of fault current through the worksite. This is done using the method of symmetrical components in accordance with AS 3851 (AS 3851-1991 n.d.). A sequence diagram representing the fault circuit is provided in Figure 4.21. The line impedance Z_p represents the sum of line section impedances 1 to 12 of Table 3.2.

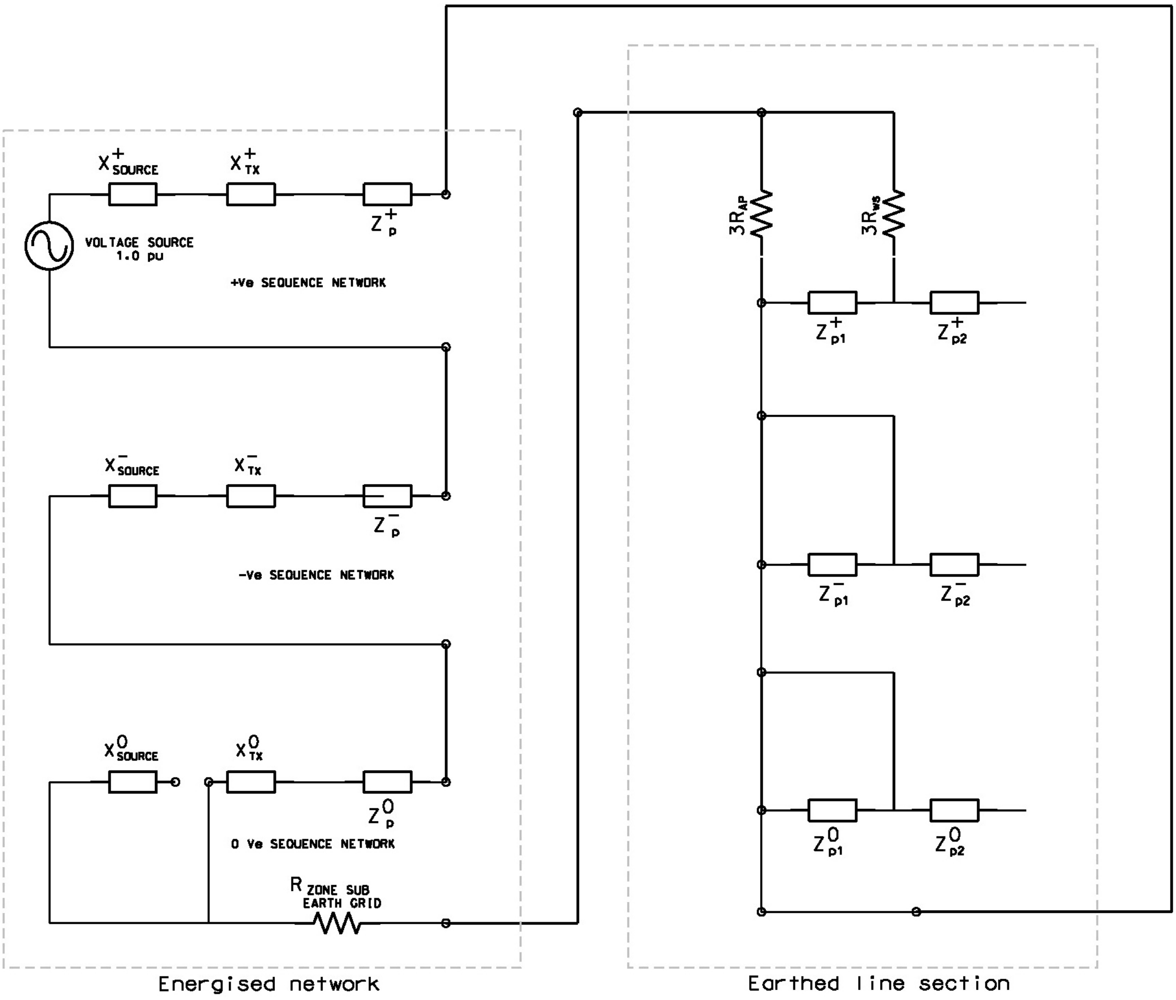


Figure 4.21: Sequence diagram for de-energised worksite at pole CE69899

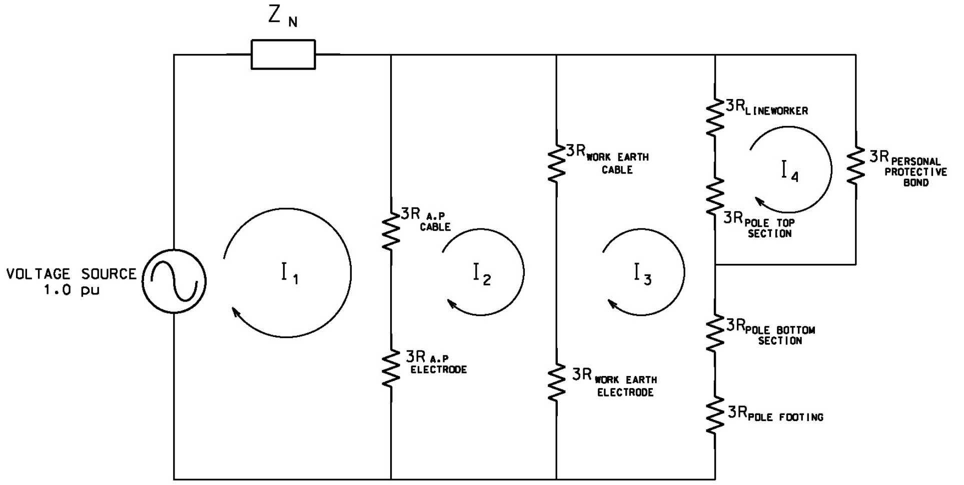


Figure 4.22: Simplified diagram for loop analysis of fault current for worksite of CE69899

To simplify calculations, the sequence impedance values of the energised network shown of Figure 4.22, have been combined to one equivalent value Z_n.

$$Z_n = X_S^+ + X_T^+ + X_S^- + X_T^- + X_T^0 + Z_p^+ + Z_p^- + Z_p^0 + 3R_{ZS} \tag{4.49}$$

Figure 4.18 is the circuit diagram for loop analysis of the fault situation. To determine the currents I_1 to I_4, a system of equations has been developed.

$$(Z_n + 3R_{apc} + 3R_{ape})I_1 - (3R_{apc} + 3R_{ape})I_2 = V_S \tag{4.50}$$

$$-(3R_{apc}+3R_{ape})I_1+(3R_{apc}+3R_{ape}+3R_{wec}+3R_{wee}+Z_{p1})I_2-(3R_{wec}+3R_{wee})I_3 = 0 \tag{4.51}$$

$$-(3R_{wec}+3R_{wee})I_2+(3R_{wec}+3R_{wee}+3R_{polefooting}+3R_{pa}+3R_{pb}+3R_{lw})I_3-(3R_{lw}+3R_{pa})I_4 = 0 \tag{4.52}$$

$$-(3R_{lw} + 3R_{pa})I_3 + (3R_{lw} + 3R_{pa} + 3R_{ppb})I_4 = 0 \tag{4.53}$$

The equations can be expressed in matrix form ready for input into Matlab. Matlab has been used to solve the equations and determine the loop currents.

$$\begin{bmatrix} (Z_n + 3R_{apc} + 3R_{ape}) & -(3R_{apc} + 3R_{ape}) & 0 & 0 \\ -(3R_{apc} + 3R_{ape}) & \begin{matrix}(3R_{apc} + 3R_{ape} + Z_{P1} \\ +3R_{WEC} + 3R_{WEE})\end{matrix} & -(3R_{wec} + 3R_{wee}) & 0 \\ 0 & -(3R_{wec} + 3R_{wee}) & \begin{matrix}(3R_{wec} + 3R_{wee} \\ +R_{polefooting} + 3R_{pa} \\ +3R_{pb} + 3R_{lw})\end{matrix} & -(3R_{lw} + 3R_{pa}) \\ 0 & 0 & -(3R_{lw} + 3R_{pa}) & \begin{matrix}(3R_{lw} + 3R_{pa} \\ +3R_{ppb})\end{matrix} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

As shown in equation 4.54, the loop currents I_1 to I_4 are found by multiplying the inverse impedance matrix with the voltage matrix. These currents represent the zero sequence currents. The actual fault currents are equal to three times the zero sequence currents as shown in Equation 4.55.

$$I_0 = Z^{-1} \times V \tag{4.54}$$

$$I_f = 3 \times I_0 \tag{4.55}$$

Referring to Figure 4.22, critical worksite voltage and currents can be determined. The total fault current I_f is equal to loop current I_1. The worksite current I_{ws} is equal to I_2. The current flowing through the PPB I_{ppb} is equal to I_4.

The worksite voltage V_{ws} is equal to $(I_2 - I_3)$ times $(R_{WEC} + R_{WEE})$. The touch voltage experienced by the line worker is the voltage difference between the overhead conductors, and the contact position on the pole. V_{touch} is calculated as V_{ws} minus $I_3(R_{pb} + R_{polefooting})$.

Finally the current that would flow the the line worker is equal to loop current $I_3 - I_4$.

A script to perform the analysis was prepared in Matlab. A representative Matlab script is included in Appendix B. A summary of the work site values used for the calculations is provided in Table 4.6. Figure 4.3 illustrates dimensions of the pole which are important in the calculations.

Input	Value	Notes
Pole length	12.5m	Obtained from pole button
Embedment	2.05m	$Estimated - Polelength \times 0.1 + 0.8m$
H_{11kV}	10.05m	11kV conductor height
H_{LW}	2.2m	Line worker height including reach above head
BP_{attach}	2.4m	Bonding point - Minimum 2.4m required by ESR
$Pole_{topsection}$	5.85m	$H_{11kV} - H_{LW} - BP_{attach}$
$Pole_{bottomsection}$	4.45m	$BP_{attach} + Embedment$
$R_{lineworker}$	900Ω	Estimate from AS60479
R_{timber}	24.5$M\Omega/m$	Creosote treated timber at 20% moisture level
$R_{poletop}$	143.3$M\Omega/m$	$R_{timber} \times Pole_{topsection}$
$R_{polebottom}$	109$M\Omega$	$R_{timber} \times Pole_{bottomsection}$
$R_{polefooting}$	37Ω	Calculated with Equation 3.15
R_{PPB}	0.0023Ω	5m x 50mm sq Cu cable
$R_{A.Pcable}$	0.00705Ω	50mm sq Cu cable
$R_{A.Pelectrode}$	1930Ω	Calculated with Equation 3.15
$R_{W.Ecable}$	0.0071Ω	$15m \times 35mmsqCucable$
$R_{W.Eelectrode}$	1930Ω	Calculated with Equation 3.15

Table 4.6: Values used to in calculation of equivalent resistance of worksite

A summary of the critical work site currents and voltages determined in Matlab are in Table 4.7.

I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{TOUCH} (V)	I_{LW} (A)
6.57	3.29	0.00006	6342.8	0.000	0.00000

Table 4.7: Voltage and current values for energisation of work site at pole CE19321

Conclusion

The results in Table 4.7 show that there was zero current flowing through the PPB. This is due to the high timber resistance of the pole in series with the lineworker and earth. The lineworker would most probably have been safe even if the PPB had not been applied. However, with PPB in place, there would be no doubt that equipotential conditions would be maintained across the line workers work area.

Due to the high resistance values of the APE and WE electrodes, the fault current flowing as a result of the energisation, was relatively small at 6.57A. An interesting situation would arise if pole CE69899 was a steel pole instead of timber. The conductive property of steel, and its relatively low footing resistance when compared with the APE and WE electrodes, would provide low impedance path for the fault current to flow. A much higher fault current would flow as a result. With the line worker in series with the pole, the performance of the PPB would become much more important.

In the analysis for the worksite at pole CE19317 (Section 4.1.2), the APE's either side of the pole diverted the fault current away from the worksite. The APE's in that case provided useful protection. However, at pole CE69899, the APE and WE do not offer the same protection for a SLG fault due to the high resistance of their electrodes. The majority of fault current arising through an unexpected single phase energisation will flow through the pole the worker is standing on.

Further analysis on the performance of the PPB on steel poles is provided in Section 4.2.5.

4.2 Personal Protective Bonding and Earthing Technique Analysis

The site analysis in Section 4.1 demonstrated the effectiveness of the current PPB practices, as shown in Figures 2.4 to 2.8 of Section 2.4, when applied in real situations. However, it was decided that the analysis did not test against a broad enough range of possible site conditions. Therefore, further analysis of the practices is needed.

This analysis is a test each of each technique against a varying range of theoretical site conditions. Many of the factors which determine the level of fault current, touch voltage, and the degree of hazard, will vary from pole to pole, and network to network. The aim of the analysis is to identify whether conditions can occur where the PPB will not adequately protect the lineworker.

4.2.1 Bonding application shown in CEOP2377 Figure 1

Analysis

This analysis is of the bonding technique shown in Figure 2.4. The technique is used on timber poles when APE are applied at the upstream isolation position, and are in view of the work site. The technique is the attachment of a PPB between the conductor being worked on, and the pole, at a position below the line worker's feet. When the line worker needs to work on the other conductors, they must relocate the PPB to that conductor before making contact with any part of their body.

The analysis is of a hypothetical work site located immediately outside the zone substation. In this situation the performance of the PPB is analysed under maximum fault, or, worst case conditions. The only line impedance is from the isolation point to the work site. The analysis includes variance of this line impedance to examine the effect of this on the performance of the PPB technique.

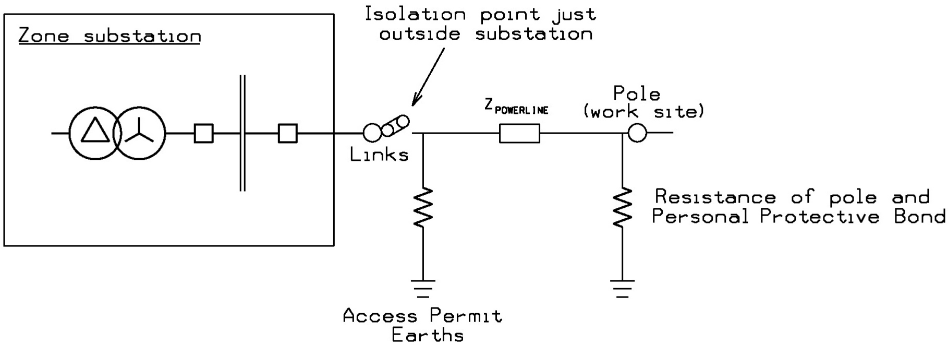


Figure 4.23: Worksite set up immediately downstream of zone substation

Figure 4.24 shows a simple connection diagram of the network situation under test. Figure 4.25 shows a sequence diagram representing of a SLG fault energised at the isolation point just outside the substation. The diagram is further simplified in Figure 4.26.

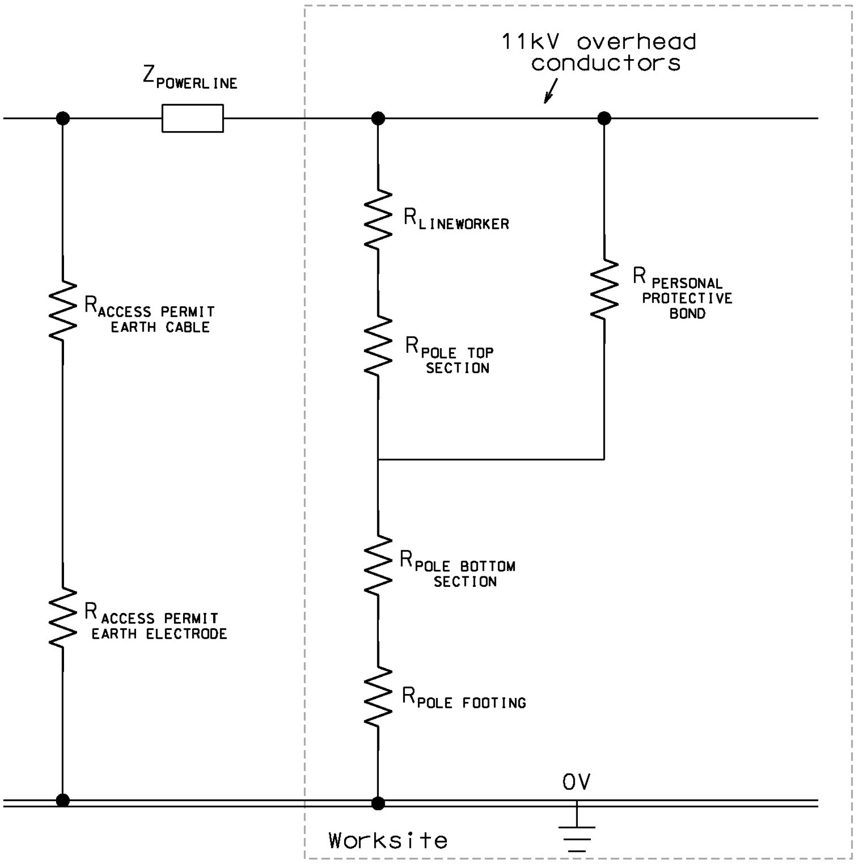


Figure 4.24: Schematic diagram of personal protective bonding technique shown in Figure 2.4

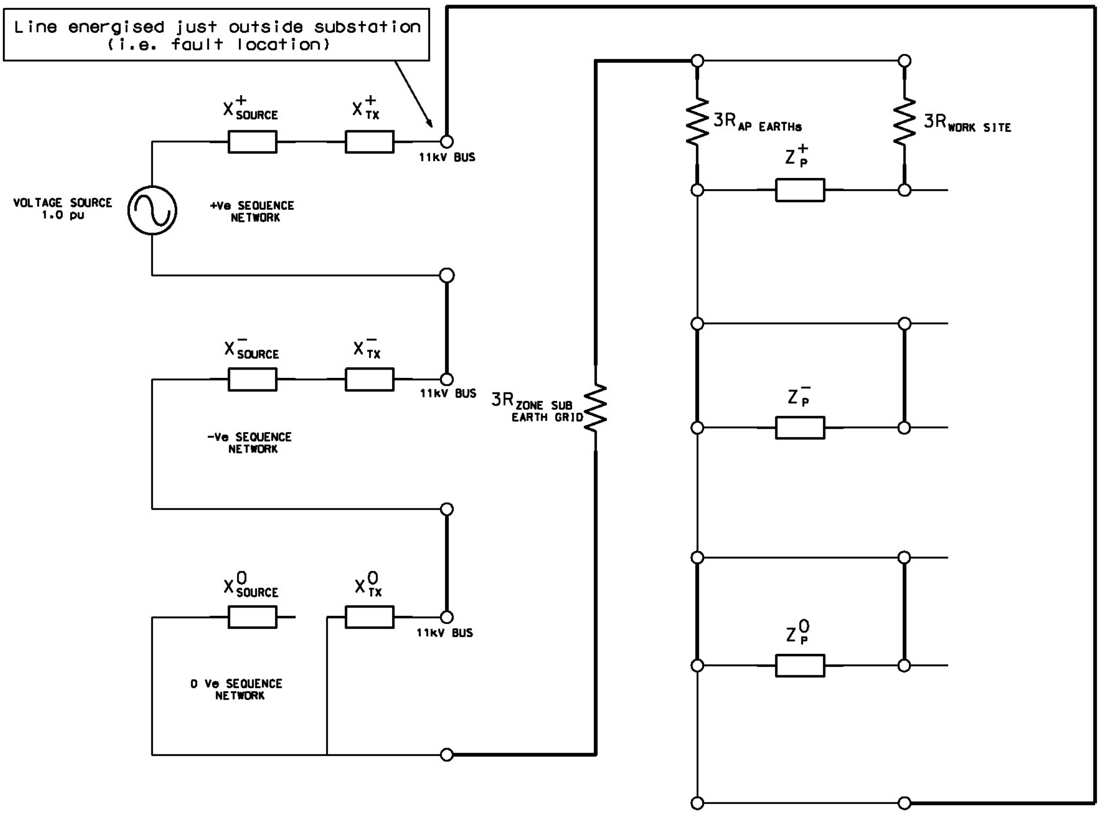


Figure 4.25: Sequence diagram used to determine fault current flow

The maximum fault current, the worksite current, and touch voltage experienced by the line worker is now determined. Loop analysis is used to calculate the fault current through the APE and worksite. Figure 4.26 is circuit diagram to be used for the loop analysis.

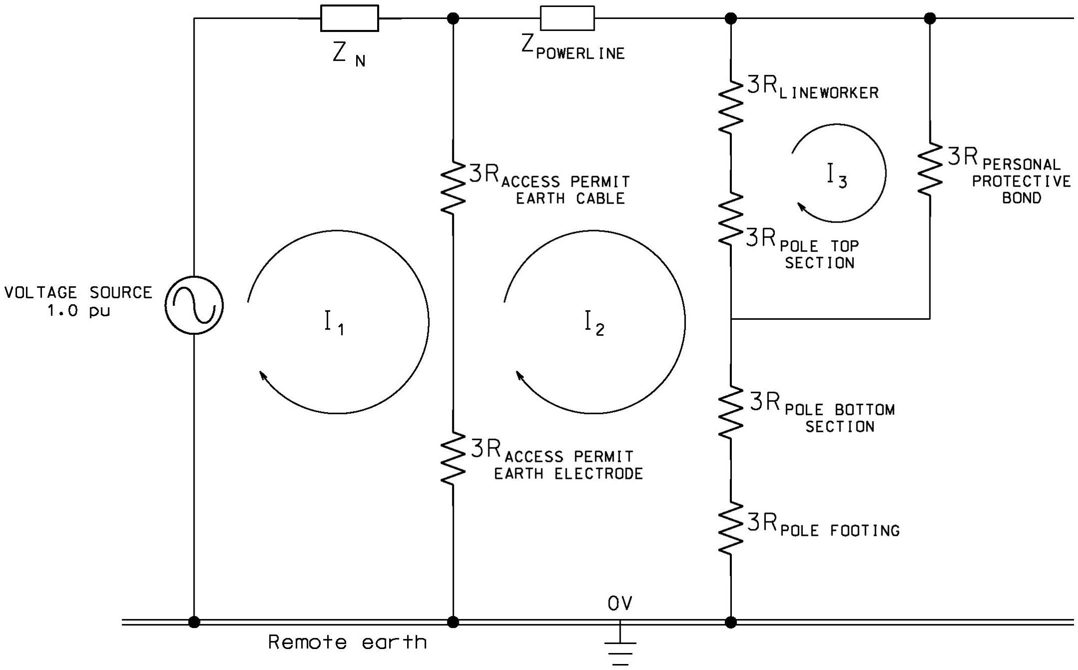


Figure 4.26: Simplified circuit for loop analysis

To determine the current I_1, I_2, and I_3, a system of equations is developed as follows.

Let

$$Z_N = X_S^+ + X_T^+ + X_S^- + X_T^- + X_T^0 + 3R_{ZS} + 3R_f \tag{4.56}$$

and

$$3R_{AP} = 3R_{APC} + 3R_{APE} \tag{4.57}$$

then

$$(Z_N + 3R_{AP})I_1 - 3R_{AP}I_2 = V_S \tag{4.58}$$

and

$$-3R_{AP}I_1+(3R_{AP}+Z_P+3R_{LW}+3R_{PA}+3R_{PB}+3R_{Polefooting})I_2-(3R_{LW}+3R_{PA})I_3 = 0 \tag{4.59}$$

$$-(3R_{LW} + 3R_{PA})I_2 + (3R_{LW} + 3R_{PA} + 3R_{PPB})I_3 = 0 \tag{4.60}$$

The Equations 4.58 to 4.60 are now represented in matrix form. This facilitates easy implementation into Matlab which was used to solve the equations.

$$\begin{bmatrix} (Z_N + 3R_{AP}) & -3R_{AP} & 0 \\ -3R_{AP} & \begin{matrix}(3R_{AP} + Z_P + 3R_{LW} + 3R_{PA} \\ +3R_{PB} + 3R_{Polefooting})\end{matrix} & -(3R_{LW} + 3R_{PA}) \\ 0 & -(3R_{LW} + 3R_{PA}) & (3R_{LW} + 3R_{PA} + 3R_{PPB}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \end{bmatrix}$$

The zero sequence current is found by Equation 4.61:

$$I_0 = Z^{-1} \times V \tag{4.61}$$

The actual fault current is equal to $3I_0$

The 'touch voltage' V_{touch} is the voltage appearing across the body of the line worker. V_{touch} is equal to the difference in voltage between the overhead conductors (the 'work site' voltage V_{ws}) and the bonding point V_{bp}.

The worksite voltage is found by equation 4.62:

$$V_{ws} = I_3 R_{ppb} + I_2(R_{ppb} + R_{polefooting}) \tag{4.62}$$

The bonding point voltage is found by equation 4.63:

$$V_{bp} = I_2(R_{ppb} + R_{polefooting}) \tag{4.63}$$

The touch voltage is determined by equation 4.64:

$$V_{touch} = V_{ws} - V_{bp} \tag{4.64}$$

In reality many of the input values used in the calculations would vary depending upon the worksite location, the substation size and configuration, and other factors such as soil resistivity. To test the performance of this PPB technique, input values which could realistically change in practice have been varied. The resulting critical voltage and currents have then been recorded. The initial input values for the calculations are summarised in Table 4.8. The calculated results are displayed in Tables 4.9 to **??**

Input variable	Value	Unit	Notes
Powerline distance	40	m	Distance between APE and worksite
Z_P	0.000167 +j0.000228	Ω/m	Lemon (30/7/3.00 ACSR)
R_{AP} cable	0.00498	Ω	70mm^2 sq Cu - rated 16kAs
Soil resistivity	100	Ω.m	
R_{AP} electrode	50	Ω	Nominal value
R_{LW}	900	Ω	Resistance of lineworker
Pole length	11.0	m	Total length
Line worker height	2.2	m	Includes reach
Bonding Point Attachment	2.4	m	Height above ground
R_{timber}	2.45×10^7	Ω/m	CCA pole at 20% moisture
R_{PA}	110.25	MΩ	Pole section between LW and BP
R_{PB}	105.35	MΩ	Pole section below BP
$R_{polefooting}$	37	Ω	Estimated
R_{PPB}	0.00337	Ω	5m length

Table 4.8: Initial input values for analysis of PPB bonding method of Figure 2.4

Powerline length (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{TOUCH} (V)	I_{LW} (A)
Initial - 40m	126.2	0.0000	0.0001	6312.8	0.0000	0.0000
100	126.2	0.0000	0.0001	6312.8	0.0000	0.0000
250	126.2	0.0000	0.0001	6312.8	0.0000	0.0000
500	126.2	0.0000	0.0001	6312.8	0.0000	0.0000

Table 4.9: Critical voltage and current values with changes in powerline length (Z_P)

R_{AP} elecrode (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{TOUCH} (V)	I_{LW} (A)
Initial - 50	126.2	0.0001	0.0001	6312.8	0.000	0.0000
10	615.4	0.0001	0.0001	6161.3	0.000	0.0000
500	12.7	0.0001	0.0001	6347	0.000	0.0000
1000	6.3	0.0001	0.0001	6348.9	0.000	0.0000

Table 4.10: Critical voltage and current values with changes in APE electrode resistance (R_{AP})

R_{PPB} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
50mm^2 Cu	126.2	0.0001	0.0001	6312.6	0.000	0.0000
95mm^2 Cu	126.2	0.0001	0.0001	6312.6	0.000	0.0000

Table 4.11: Critical voltage and current values with changes PPB cable size (R_{PPB})

Attachment height (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
2.4m	126.2	0.00006	0.00006	6312.6	0.000	0.0000
6.9m	126.2	0.00003	0.00003	6312.6	0.000	0.0000

Table 4.12: Critical voltage and current values with change in Bonding Point attachment height

R_{timber} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
2.45×10^7 (20% moisture)	126.2	0.00006	0.00006	6312.58	0.0000	0.0000
6.03×10^3 (saturated)	126.2	0.2431	0.2431	6312.47	0.0008	0.0000

Table 4.13: Critical voltage and current values with change in timber resistance (R_{timber})

Results

The performance of the application technique shown in Figure 2.5 was tested by varying a number of site parameters. The results in Tables 4.9 to 4.13 demonstrate how this technique provides excellent protection to the lineworker. The touch voltage V_{touch} was kept to less than 1mV under all test conditions.

The resistance of the timber pole provided a very high impedance to the flow of current through the worksite. As such, the sizing of the PPB or its attachment height made no impact upon the outcome. The fault current that flowed as a result of the energisation flowed almost exclusively through the APE. Equipotential conditions were maintained for the lineworker aloft on the pole.

4.2.2 Bonding application shown in CEOP2377 Figure 2

Analysis

The following analysis is of the bonding technique shown in Figure 2.5. The technique is similar to that of Figure 2.4 in that a PPB is used, APE are applied at the upstream isolation point, and the APE must be in view of the worksite. The key difference is that the PPB is connected to a Permanent Earth (PE) at the pole being worked on. This technique only applies to timber poles.

A permanent earth is an earthing conductor connected to an electrode below ground and attached to the pole above ground. Permanent earths often exist at substation poles, or at 'operational' poles. Operational poles are those which have network switch gear, such as an Air Break Switch, at the pole top. Permanent earths are also found on poles where lightning arresters are installed on the pole.

The analysis is of the bonding method performance under maximum fault conditions. In a practical situation, these conditions would exist just outside the zone substation where line impedance is minimised and fault levels are highest. The APE are assumed to be one span away but as part of the analysis, the line distance is varied to examine this effect on the performance of the PPBE.

Figure 4.27 is the connection diagram representing the upstream APEs, the line impedance, and the worksite PPB and permanent earth. A resistance R_{ptpe} is shown between the bonding point and between pole resistance values R_{pa} and R_{pb}. In the past, many permanent earths were installed using bare copper cable. This resistance represents the contact between a bare earth cable and the pole. The modern practice is the use of an insulated earth cable where a cable loop is provided above ground and a test point. Essential Energy's CEOP2377 does not stipulate whether the PPB must be in contact with the pole when connected to the permanent earth. Therefore, in some cases, the pole and permanent earth cable may be electrically disconnected. The inclusion of resistance R_{ptpe} allows both scenarios to analysed to see if this has an effect on the performance of this bonding technique.

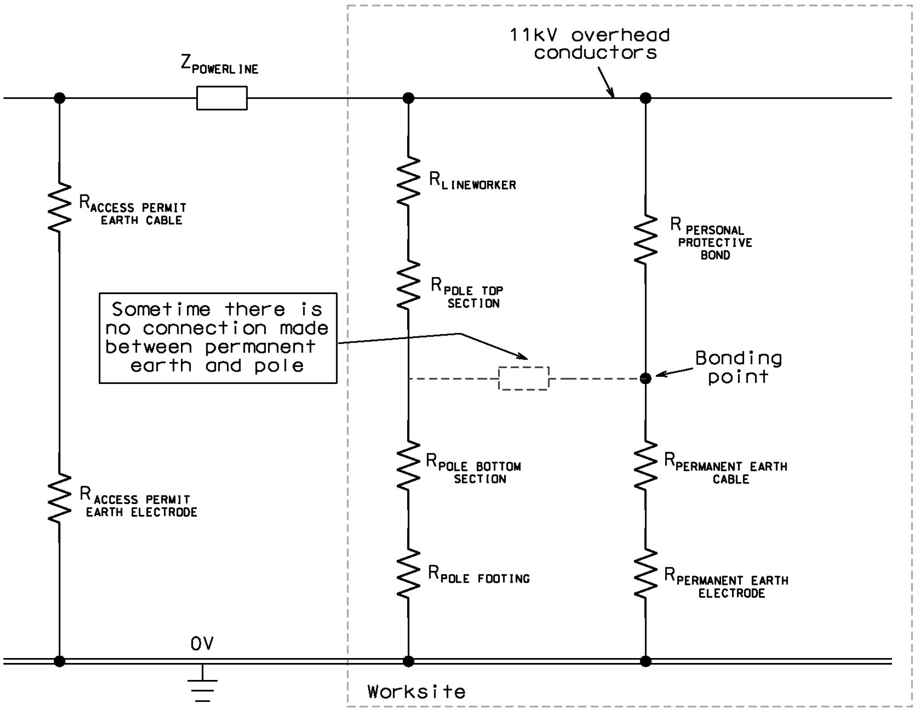


Figure 4.27: Schematic diagram of personal protective bonding technique shown in Figure 2.5

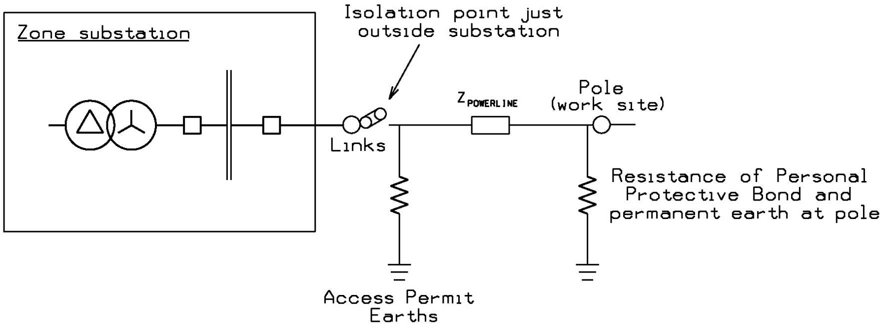


Figure 4.28: Worksite set up immediately downstream of zone substation

Figure 4.29 is a sequence diagram representing a single line to ground fault which would occur at the substation. This type of fault would cause the maximum fault current to flow through earth, and therefore, test the performance of this bonding technique in a worst case scenario. The sequence diagram shows the energised 'normally operating' system source and transformer impedances, as well as the section of line earthed by the APE and PPB and PE.

The value Z_n is the sum of the upstream system impedances which will limit the size of fault current available at the work site. Z_n has been determined to simplify the following calculations.

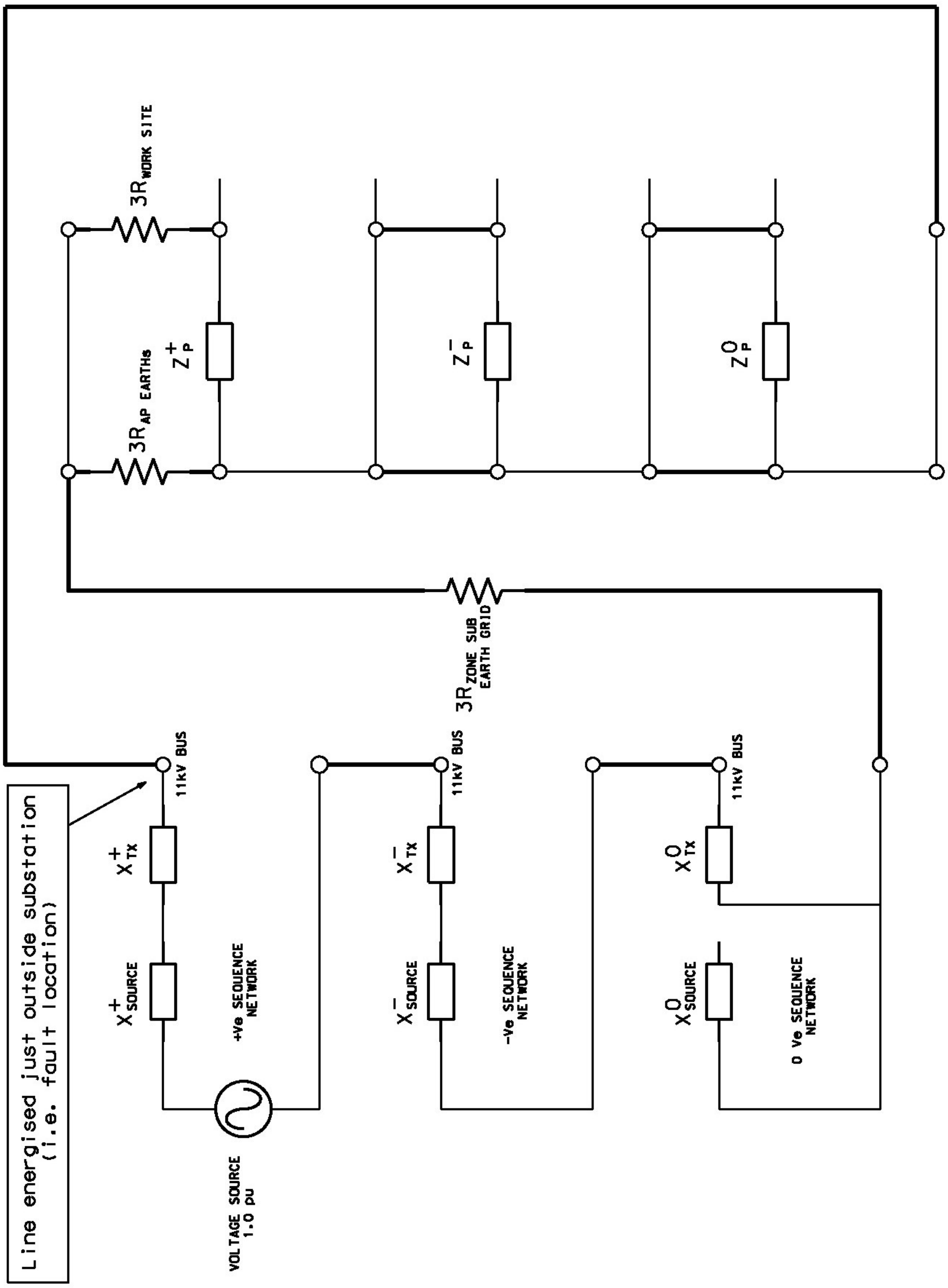


Figure 4.29: Sequence diagram used to determine fault current flow

Figure 4.30 is a simplified circuit used for loop analysis. When the values of current, I_1

to I_4, are determined, it is possible to determine the maximum work site current, and the prospective touch voltage a line worker may be exposed to. The degree of safety this bonding technique provides can then be critically assessed.

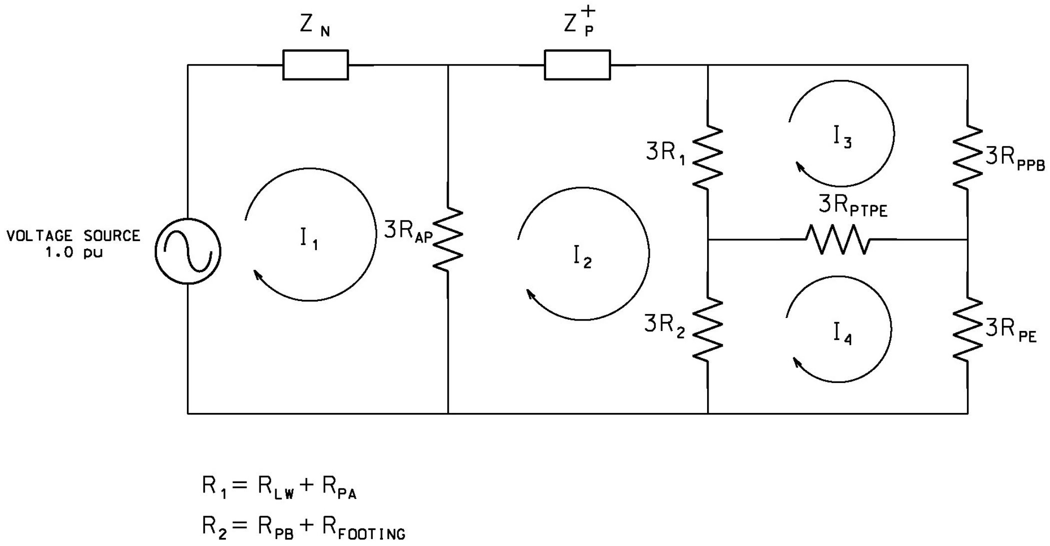


Figure 4.30: Simplified circuit for loop analysis

To determine the currents I_1, I_2, I_3 and I_4, a system of equations is developed as follows.

Let

$$Z_n = X_S^+ + X_T^+ + X_S^- + X_T^- + X_T^0 + 3R_{ZS} + 3R_f \tag{4.65}$$

then

$$(Z_n + 3R_{ap})I_1 - 3R_{ap}I_2 = V_s \tag{4.66}$$

then

$$-3R_{ap}I_1 + (3R_{ap} + Z_p + 3R_1 + 3R_2)I_2 - 3R_1I_3 - 3R_2I_4 = 0 \tag{4.67}$$

$$-3R_1I_2 + (3R_1 + 3R_{ptpe} + 3R_{ppb})I_3 - 3R_{ptpe}I_4 = 0 \tag{4.68}$$

$$-3R_2I_2 - 3R_{ptpe}I_3 + (3R_2 + 3R_{ptpe} + 3R_{pe})I_4 = 0 \tag{4.69}$$

Equations 4.66 to 4.69 can now be represented in Matrix form to allow Matlab to be used for easy solution. As can be seen in Figure 4.30, current I_1 equals the total fault current flowing as a result of the single line to ground fault occurring. The current through the APE is the difference between currents I_1 and I_2. The total worksite current is equal to I_2. The touch current experienced by a line worker is the difference between I_2 and I_3. The current carried by the PPB is the difference between I_3 and I_4.

$$\begin{bmatrix} (Z_n + 3R_{ap}) & -3R_{ap} & 0 & 0 \\ -3R_{ap} & (3R_{ap} + 3R_1 + 3R_2 + Z_p) & -3R_1 & -3R_2 \\ 0 & -3R_1 & (3R_1 + 3R_{ptpe} + 3R_{ppb}) & -3R_{ptpe} \\ 0 & -3R_2 & -3R_{ptpe} & (3R_2 + 3R_{ptpe} + 3R_{pe} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

A Matlab script has been developed to perform the required calculations and allow experimentation with the input values. A representative Matlab script is included in Appendix B. The initial input values used in the calculations are listed in Table 4.14.

Input values which could realistically change in practice have been varied and the resulting critical voltage and currents recorded. The calculated results are displayed in Tables 4.15 to 4.21

Input variable	Value	Unit	Notes
Powerline distance	40	m	Distance between APE and worksite
Z_P	0.000167 +j0.000228	Ω/m	Lemon (30/7/3.00 ACSR)
R_{AP} cable	0.00498	Ω	70mm^2 sq Cu - rated 16kAs
Soil resistivity	100	Ω.m	
R_{AP} electrode	50	Ω	Nominal value
R_{PE} cable	0.0027	Ω	35mm^2 sq Cu cable
R_{PE} electrode	30	Ω	Estimated value
R_{LW}	900	Ω	Resistance of lineworker
Pole length	11.0	m	Total length
Line worker height	2.2	m	Includes reach
Bonding Point Attachment	2.4	m	Height above ground
R_{timber}	2.45×10^7	Ω/m	CCA pole at 20% moisture
R_{PA}	110.25	MΩ	Pole section between LW and BP
R_{PB}	105.35	MΩ	Pole section below BP
$R_{polefooting}$	37	Ω	Estimated
R_{PPB}	0.00337	Ω	5m length
R_{PTPE}	1	Ω	(If present)

Table 4.14: Initial input values for analysis of PPB bonding method of Figure 2.5

Variance of Z_P:

Powerline length (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
Initial - 40m	333.16	208.2	208.2	6249.0	0.702	0.0000
100	333.13	208.18	208.18	6248.3	0.702	0.0000
250	333.08	208.12	208.12	6246.5	0.702	0.0000
500	332.97	208.02	208.02	6243.6	0.701	0.0000

Table 4.15: Critical voltage and current values with changes in powerline length (Z_P)

R_{AP} elecrode (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
Initial - 50	333.16	208.2	208.2	6249.0	0.702	0.0000
10	811.7	202.96	202.96	6098.1	0.685	0.0000
500	221.9	209.37	209.37	6283.1	0.706	0.0000
1000	215.7	209.44	209.44	6285.1	0.705	0.0000

Table 4.16: Critical voltage and current values with changes in APE electrode resistance (R_{AP})

R_{PE} electrode (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
1	4485.7	4396.9	4396.9	4637.2	15.53	0.0000
10	733.5	611.2	611.2	6122.3	2.062	0.0000
50	333.16	208.2	208.2	6249.0	0.702	0.0000
500	138.8	12.62	12.61	6308.9	0.043	0.0000
1000	132.5	6.31	6.31	6310.9	0.021	0.0000

Table 4.17: Critical voltage and current values with changes in permanent earth electrode resistance (R_{AP})

R_{PPB} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
35mm^2 Cu	333.16	208.2	208.2	6249	0.701	0.0000
95mm^2 Cu	333.17	208.2	208.2	6248.9	0.262	0.0000

Table 4.18: Critical voltage and current values with changes PPB cable size (R_{PPB})

Attachment height (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
2.4m	333.16	208.2	208.2	6249	0.701	0.0000
6.9m	333.16	208.2	208.2	6249	0.701	0.00078

Table 4.19: Critical voltage and current values with change in Bonding Point attachment height

R_{timber} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
2.45×10^7 (20% moisture)	333.16	208.2	208.2	6249.0	0.701	0.0000
6.03×10^3 (saturated)	333.39	208.45	208.45	6248.9	0.943	0.00003

Table 4.20: Critical voltage and current values with change in timber resistance (R_{timber})

R_{PTPE} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
1	333.16	208.2	208.2	6249	0.701	0.0000
10	333.16	208.2	208.2	6249	0.701	0.0000
1000	333.16	208.2	208.2	6249.0	0.701	0.0000
1 x 10^9	333.16	208.2	208.2	6249	3032	0.00003

Table 4.21: Critical voltage and current values with changes in resistance between pole and permanent earth (R_{PTPE})

Results

The following results were observed from the analysis:

- Increasing the line impedance Z_p from 40m to 500m had negligible impact on results. From the results it can be seen that the touch voltage V_{touch} decreases slightly as Z_p increases.
- Varying the resistance of the access permit earth electrode R_{ap} made no impact upon the voltages and currents at the worksite.
- Using a larger PPB reduces the size of V_{touch}. However, V_{touch} was so small under worst case conditions that no practical benefit would be achieved from an oversized PPB cable.
- The results indicate that a lower bonding point attachment height is preferable. This ensures a larger length of timber pole, and therefore larger series impedance, between the line worker's feet and the bonding point for the PPB. The value of I_{LW} is reduced with a lower bonding point attachment.
- Varying the resistance of the timber pole did not significantly affect the results.

- Varying the connection resistance R_{ptpe} between the pole surface and permanent earth did not influence the results. Provided that a solid connection is made between the PPB and permanent earth cable, the majority of fault current will flow through this path.

The performance of the application technique shown in Figure 2.5 was tested by varying a number of site parameters. Under all test conditions, the resulting values of V_{touch} and I_{LW} were at very safe levels. Therefore, the bonding technique of Figure 2.5 can be considered safe and effective.

4.2.3 Bonding application shown in CEOP2377 Figure 3

Analysis

The following analysis is of the bonding technique shown in Figure 2.6. This technique is used when earthing and shorting is required at the pole being worked on. Earthing and short circuiting will be required at the work site under two conditions. Firstly, the APE at the isolation point is out of view and a set of 'working earths' are required in accordance with the Electrical Safety Rules. Secondly, the work site is located close to the isolation point, and the earthing and short circuiting at the pole is the APE. When earthing and short circuiting is provided at the pole, and a permanent earth exists also, the permanent earth and temporary earths must be bonded together with a personal protective bond.

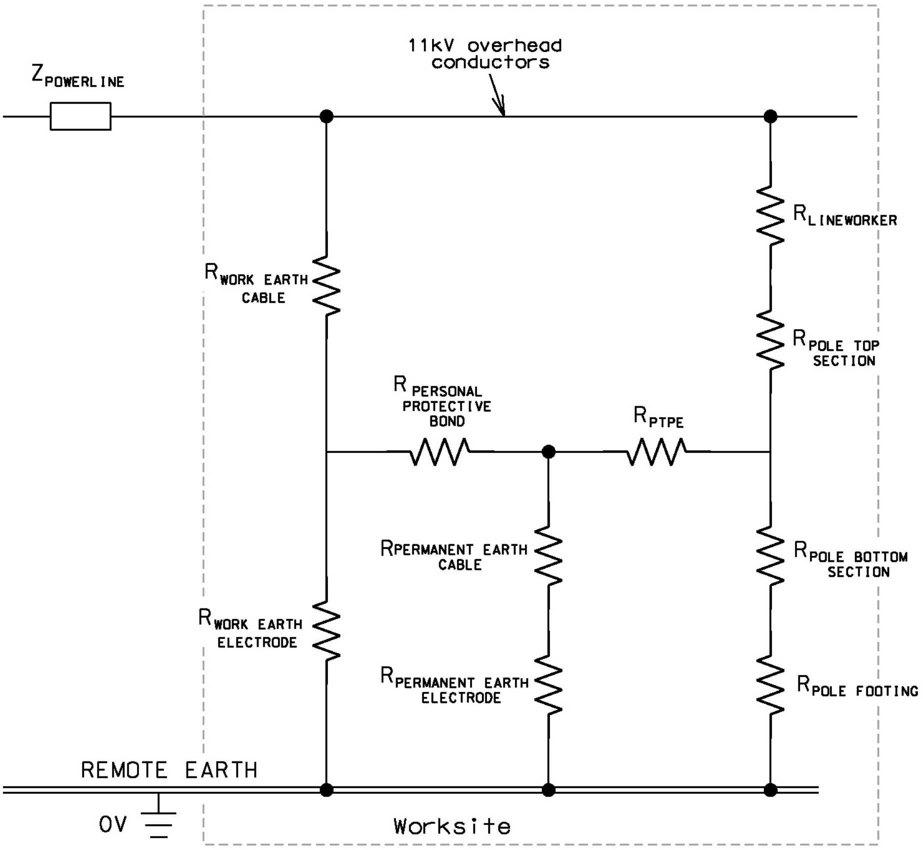


Figure 4.31: Schematic diagram of personal protective bonding technique shown in Figure 2.4

The purpose of this analysis is to verify the effectiveness of this bonding method under maximum fault conditions. In a practical situation, the worst case conditions will occur close to the zone substation where line impedance is negligible and the prospective fault level at a maximum. The analysis is based on just one set of temporary earths being applied. However, in many practical situations (but not all), distribution feeders leaving a substation have ties to alternative feeders. Therefore, additional sets of temporary earths and short circuits will be installed, and the level of risk to the lineworker reduced.

Figure 4.31 is the connection diagram detailing the worksite resistive components. The value R_{ptpe} is included to represent the electrical contact that may or may not exist between the permanent earth and the pole, or the PPB and the pole. Figure 4.32 illustrates the fault situation located just outside the substation. The worksite (including APE) are shown to be one span away. This allows the effect of line distance on the results to be analysed as well.

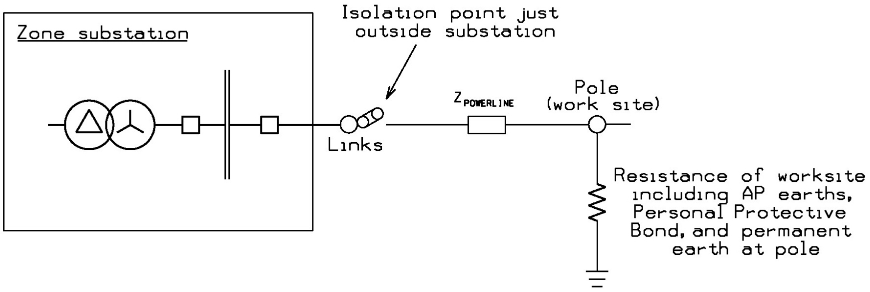


Figure 4.32: Worksite set up immediately downstream of zone substation

Figure 4.33 shows the sequence diagram used to determine the maximum fault current that can flow. The sequence diagram is representative of a single line to ground fault. As such, the positive, negative and zero sequence networks are connected in series. The SLG fault would be be the most serious as it would cause the largest flow of current through the work site and to earth.

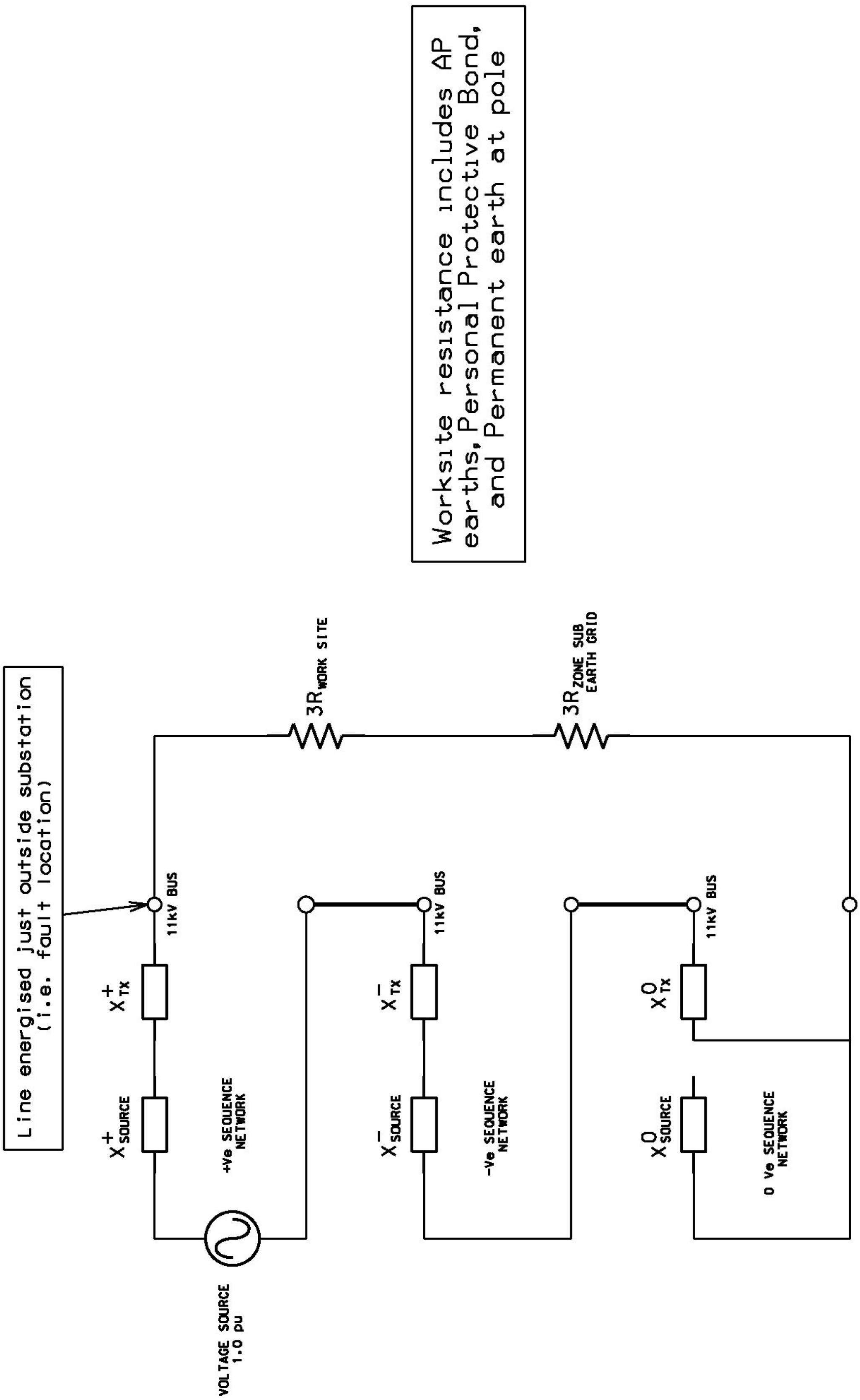


Figure 4.33: Sequence diagram used to determine fault current flow

Figure 4.34 is a simplified circuit used for loop analysis. When the values of current, I_1 to I_4, are determined, it is possible to determine the maximum work site current, as well as the prospective touch voltage a line worker may be subjected to. The degree of safety this bonding technique provides may then be critically assessed.

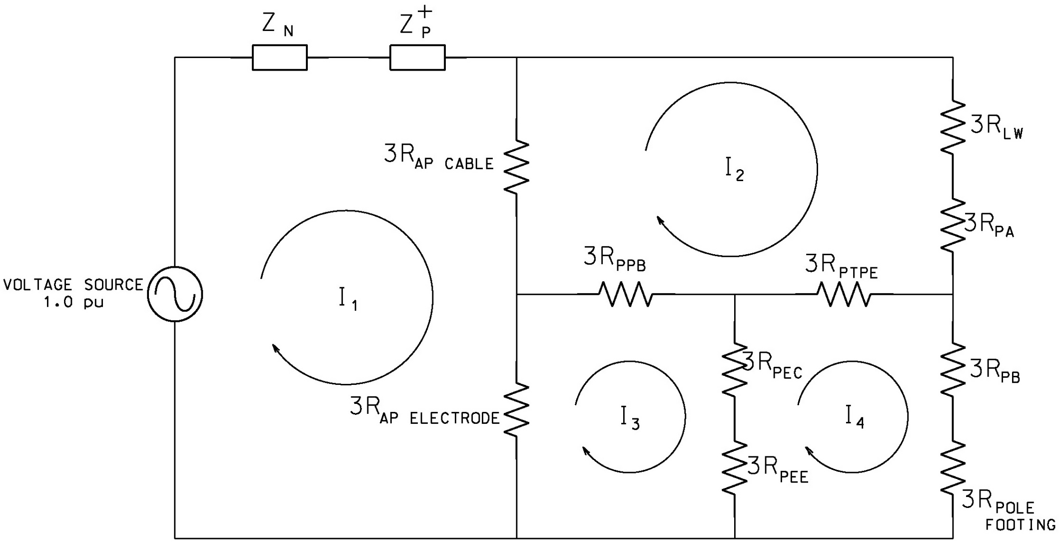


Figure 4.34: Simplified circuit for loop analysis

To determine the currents I_1, I_2, I_3 and I_4, a system of equations has been developed as follows.

$$(Z_n + Z_p + 3R_{apc} + 3R_{ape})I_1 - 3R_{apc}I_2 - 3R_{ape}I_3 = V_S \tag{4.70}$$

$$-3R_{apc}I_1 + (3R_{apc} + 3R_{lw} + 3R_{pa} + 3R_{ppb} + 3R_{ptpe})I_2 - 3R_{ppb}I_3 - 3R_{ptpe}I_4 = 0 \tag{4.71}$$

$$-3R_{ape}I_1 - 3R_{ppb}I_2 + (3R_{ape} + 3R_{ppb} + 3R_{pec} + 3R_{pee})I_3 - (3R_{pec}I_3 + 3R_{pee})I_4 = 0 \tag{4.72}$$

$$-3R_{ptpe}I_2 - (3R_{pec} + 3R_{pee})I_3 + (3R_{pee} + 3R_{pec} + 3R_{ptpe} + 3R_{pb} + 3R_{polefooting})I_4 = 0 \tag{4.73}$$

Equations 4.70 to 4.73 can now be represented in Matrix form to allow Matlab to be used for easy solution. As can be seen in Figure 4.34, current I_1 equals the total fault current flowing as a result of the single line to ground fault occurring. The current through the APE is the difference between currents I_1 and I_2. The total worksite current is equal to I_2. The touch current experienced by a line worker is the difference between I_2 and I_3. The current carried by the PPB is the difference between I_3 and I_4.

$$\begin{bmatrix} \begin{array}{c}(Z_n + Z_p \\ 3R_{apc} + 3R_{ape})\end{array} & -3R_{apc} & -3R_{ape} & 0 \\ -3R_{apc} & \begin{array}{c}(3R_{apc} + 3R_{lw} + 3R_{pa} \\ +3R_{ppb} + 3R_{ptpe})\end{array} & -3R_{ppb} & -3R_{ptpe} \\ -3R_{ape} & -3R_{ppb} & \begin{array}{c}(3R_{ape} + 3R_{ppb} \\ +3R_{pec} + 3R_{pee})\end{array} & -(3R_{pec}I_3 + 3R_{pee}) \\ 0 & -3R_{ptpe} & -(3R_{pec} + 3R_{pee}) & \begin{array}{c}(3R_{pee} + 3R_{pec} + 3R_{ptpe} \\ +3R_{pb} + 3R_{polefooting})\end{array} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The ‘touch voltage’ V_{touch} is the voltage appearing across the body of the line worker. V_{touch} is equal to the difference in voltage between the overhead conductors (the ‘work site’ voltage V_{ws}) and the bonding point V_{bp}.

The worksite voltage is found by equation 4.74:

$$V_{ws} = (I_1 - I_2)R_{ap-cable} + (I_1 - I_e)R_{ap-electrode} \tag{4.74}$$

The bonding point voltage is found by equation 4.75:

$$V_{bp} = I_4(R_{pb} - R_{polefooting}) \tag{4.75}$$

The touch voltage is determined by equation 4.76:

$$V_{touch} = V_{ws} - V_{bp} \tag{4.76}$$

V_{touch} and its duration are significant factors affecting the amount of current experienced by the line worker. The actual current will depend upon other factors including the body current path, size of the line worker, and the contact surface area. A nominal line worker resistance value of 900Ω has been selected for these calculations. Although in practice the real resistance will vary, this value provides a reasonable indication of line worker current, and therefore, how well the PPB technique has worked.

A Matlab script has been developed to perform the required calculations and allow experimentation with the input values. A representative Matlab script is included in Appendix B. The initial input values used in the calculations are listed in Table 4.22.

Input values which could realistically change in practice have been varied and the resulting critical voltage and currents recorded. The results are provided in Tables 4.26 to 4.28.

Input variable	Value	Unit	Notes
Powerline distance	40	m	Distance between APE and worksite
Z_P	0.000167 +j0.000228	Ω/m	Lemon (30/7/3.00 ACSR)
R_{AP} cable	0.00498	Ω	70mm^2 sq Cu - rated 16kAs
Soil resistivity	100	Ω.m	
R_{AP} electrode	206.9	Ω	Calculated value at 0.5m depth
R_{PE} cable	0.002656	Ω	35mm^2 cable
R_{PE} electrode	88	Ω	Estimated value
R_{LW}	900	Ω	Resistance of lineworker
Pole length	11.0	m	Total length
Line worker height	2.2	m	Includes reach
Bonding Point Attachment	2.4	m	Height above ground
R_{timber}	2.45×10^7	Ω/m	CCA pole at 20% moisture
R_{PA}	110.25	MΩ	Pole section between LW and BP
R_{PB}	105.35	MΩ	Pole section below BP
$R_{polefooting}$	37	Ω	Estimated
R_{PPB}	0.00337	Ω	5m length
R_{PTPE}	0.1	Ω	(If present)

Table 4.22: Initial input values for analysis of PPB bonding method of Figure 2.6

Variance of Z_P:

Powerline length (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
Initial - 40m	102.3	102.3	71.8	6319.8	2.708	0.0000
100	102.3	102.3	71.79	6319.5	2.708	0.0000
250	102.3	102.29	71.76	6318.6	2.707	0.0000
500	102.3	102.27	71.75	6317.2	2.707	0.0000

Table 4.23: Critical voltage and current values with changes in powerline length (Z_P)

R_{AP} elecrode (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
10	681.8	681.8	69.57	6138.8	16.67	0.0000
Initial - 206.9	102.3	102.3	71.8	6319.8	2.708	0.0000
500	84.5	84.5	71.85	6325.2	2.279	0.0000
1000	78.2	78.2	71.87	6327.1	2.127	0.0000

Table 4.24: Critical voltage and current values with changes in APE electrode resistance (R_{AP})

R_{PE} elecrode (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
1	4575.5	4575.5	4553.4	4691.1	125.63	0.0000
Initial - 30	102.3	102.3	71.8	6319.8	2.708	0.0000
10	642.9	642.9	613.2	6151.2	17.561	0.0000
500	43.3	12.673	12.673	6337.7	1.086	0.0000
1000	37.0	37.0	6339	6339.7	0.913	0.0000

Table 4.25: Critical voltage and current values with changes in permanent earth electrode resistance (R_{PE})

R_{PPB} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} μA
35mm^2 Cu	4575	4575	4553	4691	125.63	1.14
95mm^2 Cu	4582	4582	4560	4683	116.19	1.06

Table 4.26: Critical voltage and current values with changes PPB cable size (R_{PPB})

Attachment height (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
2.4m	102.3	102.3	71.8	6319.8	2.708	0.0000
6.9m	102.3	102.3	71.8	6319.8	2.705	0.0030

Table 4.27: Critical voltage and current values with change in Bonding Point attachment height

R_{timber} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (A)
2.45×10^7 (20% moisture)	4575.5	4575.5	4553.4	4691.1	125.63	0.0000
6.03×10^3 (saturated)	4575.7	4575.7	4553	4691	125.805	0.00449

Table 4.28: Critical voltage and current values with change in timber resistance (R_{timber})

Results

The following results were observed from the analysis:

- Increasing the line impedance Z_p from 40m to 500m had very little impact. As would be expected, the increased impedance reduced the fault current and magnitude slightly.
- When the resistance of the access permit earths R_{ap} was set at 10Ω, the fault current was much higher and V_{touch} rose to almost 17V. As R_{ap} increased, V_{touch} decreased.
- When the resistance of the permanent earth at the worksite pole R_{PE} was set at 1Ω, V_{touch} rose to a significant level of 125.6V. This is due to a large fault current of 4575A. Even with this occurring, the calculated current through the line worker was still at safe levels.
- Varying the bonding point attachment height affected the magnitude of current through the line worker I_{LW}. Attaching at 6.9m caused 3mA to flow which would be below the 'threshold of let-go'. Attaching at 2.4m above ground caused a much smaller I_{LW}. This is due to the additional timber series impedance between the line worker and bonding point.

- At moisture levels of 20%, the lineworker current was negligible. If the pole was 'saturated' (see Section 3.2.4 the value of R_{timber} reduces significantly. The line worker current I_{LW} reached 4.5mA which would be below the ‘threshold of let-go’. As explained in Section 3.2.4, a pole exposed to normal climatic conditions would not reach the saturated state.

The performance of the application technique shown in Figure 2.6 was tested by varying a number of site parameters. Even with the worst case fault currents and touch voltages, the result indicate the line worker would have been kept safe. The maximum value of I_{LW} recorded would have been below the ‘threshold of let-go’ and unlikely to cause any injury to the worker.

4.2.4 Bonding application shown in CEOP2377 Figure 4

Analysis

The following analysis is of the bonding technique shown in Figure 2.7. The technique is similar to that of Figure 2.6 except it applies to conductive poles made of steel or concrete. On a steel pole, there is no permanent earth cable installed as the pole itself, being a large conductor, acts as a connection to earth. When earthing and short circuiting is applied at the pole, a bridge must be made between the pole and temporary earths in the form of a PPB. CEOP2377 specifies that the bonding point on a steel or concrete pole be attached at a height of 2.4m

Similar analysis to that used in Section 4.2.3 has been performed on this technique. The situation under analysis is the same as shown in Figure 4.32. That is, a work site located just outside the zone substation. Figure 4.35 is the connection diagram showing the worksite resistive components. This varies slightly to Figure 4.31 with the absence of a permanent earth cable, permanent earth electrode, and resistive value R_{ptpe}. Figure 4.36 shows the sequence diagram to determine the maximum fault current level at the worksite. Only steel poles have been analysed as all surfaces of the pole are conductive, and more so compared to concrete.

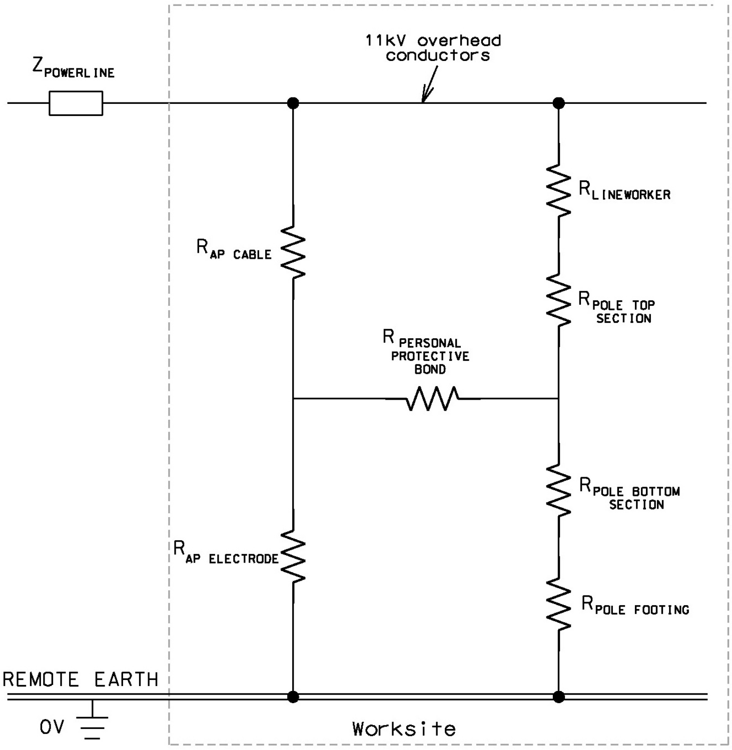


Figure 4.35: Schematic diagram of personal protective bonding technique shown in Figure 2.7

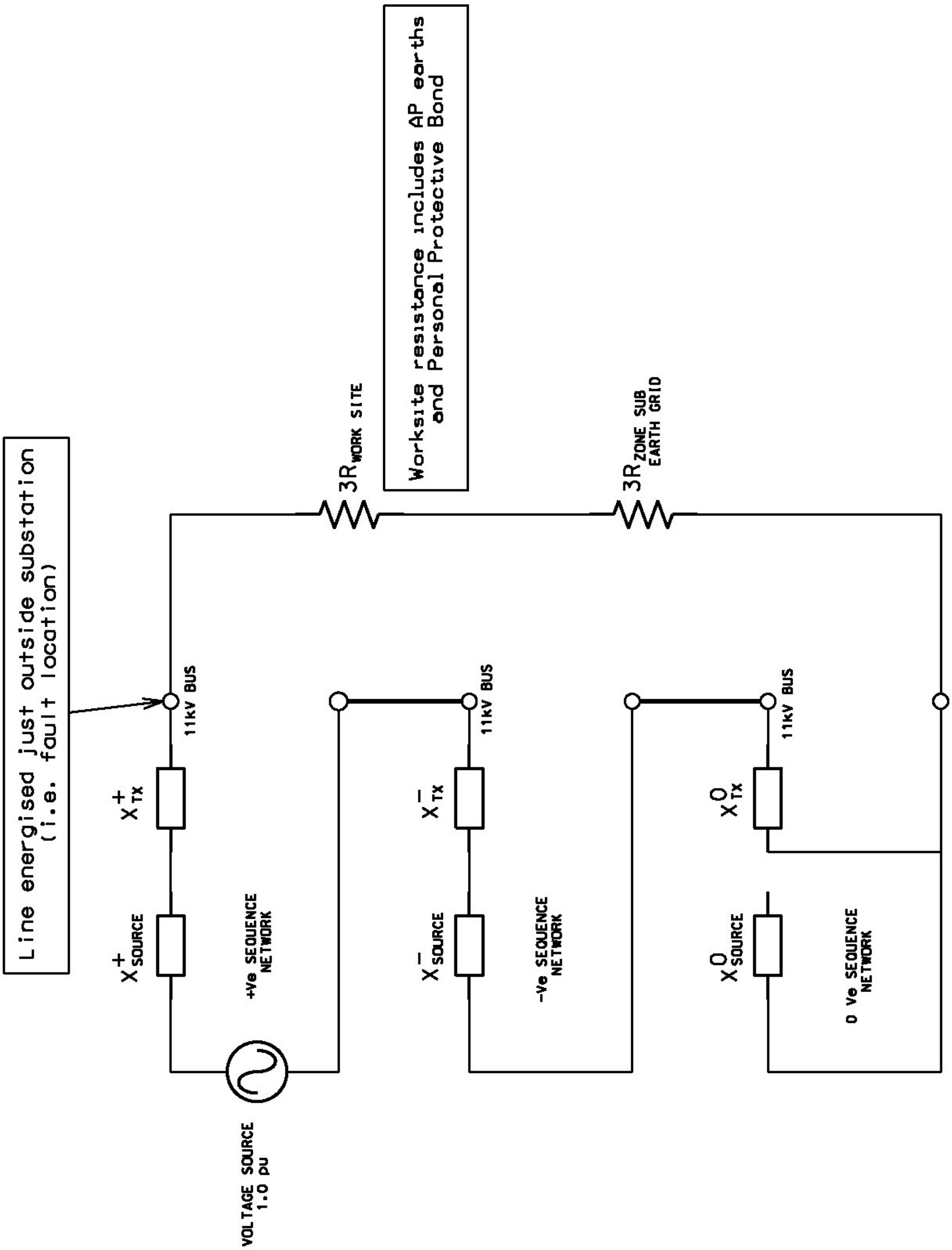


Figure 4.36: Sequence diagram used to determine fault current flow

The resistance of a steel pole is an important consideration. Given the much larger cross section area a steel pole has compared to the earthing cables used, and even allowing for the difference in conductivity of steel and copper, it is reasonable to expect that the resistance of the pole will be less than that of the earth cable. Therefore, a greater portion of fault current may be drawn through the pole compared to a timber pole.

The resistance value used for the steel pole analysis has been determined two ways. Information obtained from Ingal Poles quote the resistivity of steel as being 190 microOhm.mm (Gillespie 2013). The equivalent cross sectional area of 12.5m 12kN pole has been calculated using diameter information obtained from Essential Energy's standard constructions. A 12.5m 12kN pole is a typical size for a distribution application. The calculated resistance value was also compared to a resistance measurement taken from an actual pole located at the Essential Energy Queanbeyan depot. The measured resistance successfully verified the results calculated below.

The resistance of a steel pole is calculated as follows:

$$\rho = 190 \times 10^{-6} \Omega.mm$$

$$l = 1m$$

$$Pole_{Outside\,Diameter} = 0.273m$$

$$Pole_{CSA1} = \pi r_{OD}^2$$

$$Pole_{CSA1} = 0.05853m^2$$

$$Pole_{Inside\,Diameter} = 0.2634m$$

$$Pole_{CSA2} = \pi r_{ID}^2$$

$$Pole_{CSA2} = 0.054490m^2$$

$$Pole_{CSA} = Pole_{CSA1} - Pole_{CSA1}$$

$$Pole_{CSA} = 0.00404436m^2$$

The formula for resistance is:

$$R_{pole} = \frac{\rho l}{a} \tag{4.77}$$

The resistance per metre is calculated as follows:

$$R_{pole} = \frac{190 \times 10^{-6}\Omega.m \times 1m}{0.00404436m^2}$$
$$R_{pole} = 46.9 \times 10^{-6}\Omega m$$

Figure 4.37 is the simplified circuit used for loop analysis. When the values of current, I_1 to I_3, are determined, it is possible to determine the maximum work site current, and then the prospective touch voltage a line worker may be subjected to. The degree of safety this bonding technique provides can then be critically assessed.

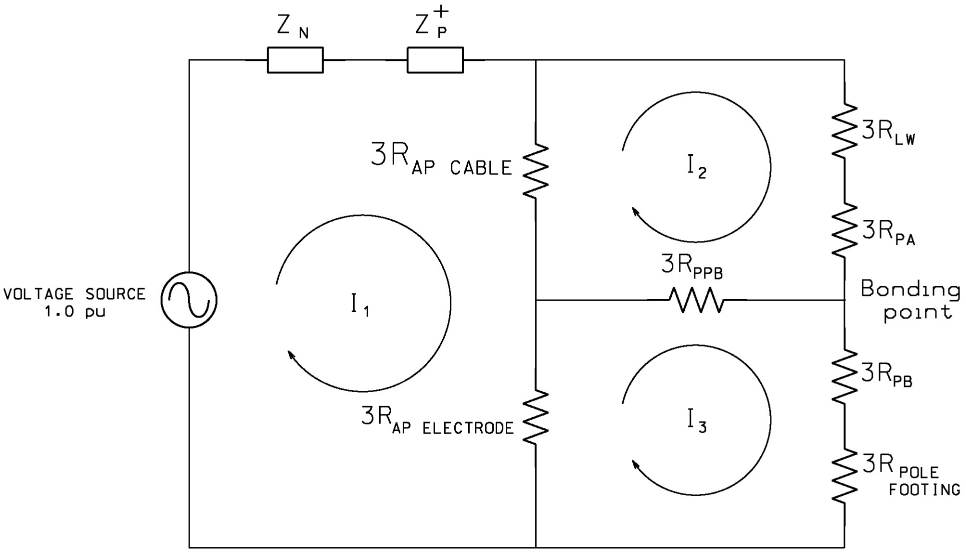


Figure 4.37: Simplified circuit for loop analysis

To determine the current I_1, I_2 and I_3, a system of equations has been developed as follows.

$$(Z_n + Z_p + 3R_{apc} + 3R_{ape})I_1 - 3R_{apc}I_2 - 3R_{ape}I_3 = V_S \tag{4.78}$$

$$-3R_{apc}I_1 + (3R_{apc} + 3R_{lw} + 3R_{pa} + 3R_{ppb})I_2 - 3R_{ppb}I_3 = 0 \tag{4.79}$$

$$-3R_{ape}I_1 - 3R_{ppb}I_2 + (3R_{ape} + 3R_{ppb} + 3R_{pb} + 3R_{polefooting})I_3 = 0 \tag{4.80}$$

Equations 4.78 to 4.80 can now be represented in Matrix form to allow Matlab to be used for easy solution. As can be seen in Figure 4.37, current I_1 equals the total fault current flowing as a result of the single line to ground fault occurring. All this current flows via the worksite. The touch current experienced by a line worker is equal to I_2. The current carried by the PPB is the difference between I_2 and I_3.

$$\begin{bmatrix} (Z_n + Z_P & -3R_{apc} & -3R_{ape} \\ +3R_{apc} + 3R_{ape}) & & \\ & & \\ -3R_{apc} & (3R_{apc} + 3R_{lw} + 3R_{pa} + 3R_{ppb}) & -3R_{ppb} \\ & & \\ -3R_{ape} & -3R_{ppb} & (3R_{ape} + 3R_{ppb} \\ -3R_{ape} & -3R_{ppb} & +3R_{pb} + 3R_{polefooting}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

A Matlab script has been developed to perform the required calculations and allow experimentation with the input values. A representative Matlab script is included in Appendix B.

Input values which could realistically change in practice have been varied and the resulting critical voltage and currents recorded. The results are provided in Tables 4.30 to 4.33. The input values for the calculations are summarised in Table 4.29.

Input variable	Value	Unit	Notes
Powerline distance	40	m	Distance between APE and worksite
Z_P	0.000167 +j0.000228	Ω/m	Lemon (30/7/3.00 ACSR)
R_{AP} cable	0.00498	Ω	70mm^2 sq Cu - rated 16kAs
Soil resistivity	100	Ω.m	
R_{AP} electrode	206.93	Ω	Calculated value
R_{LW}	900	Ω	Resistance of lineworker
Pole length	12.5	m	Total length
Line worker height	2.2	m	Includes reach
Bonding Point Attachment	2.4	m	Height above ground
R_{steel}	0.0469	mΩ/m	CCA pole at 20% moisture
R_{PA}	0.21141	mΩ	Pole section between LW and BP
R_{PB}	0.20201	mΩ	Pole section below BP
$R_{polefooting}$	46.39	Ω	Calculated
R_{PPB}	0.00337	Ω	5m length

Table 4.29: Initial input values for analysis of PPB bonding method of Figure 2.7

Variance of Z_P:

Powerline length (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (mA)
Initial - 40m	166.1	166.1	135.7	6300.3	4.462	4.96
100	166.1	166.1	135.7	6299.7	4.461	4.96
250	166.1	166.1	135.7	6298.3	4.460	4.96
500	166.0	166.0	135.6	6296.0	4.459	4.95

Table 4.30: Critical voltage and current values with changes in powerline length (Z_P)

Rho @0.5m	R_{AP} electrode (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (mA)
216	446	149.9	149.9	135.8	6305.3	4.071	4.52
300	620	146	146.0	135.8	6306.4	3.977	4.42
468	968	142.4	142.4	135.9	6307.6	3.89	4.32
750	1551	140.0	140.0	135.9	6308.3	3.831	4.26
933	1930	139.2	139.2	135.9	6308.5	3.812	4.24

Table 4.31: Critical voltage and current values with changes in APE electrode resistance (R_{AP})

Rho @2.0m	$R_{polefooting}$ (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (mA)
10	3.71	1589.2	1589.2	1561.1	5837.8	43.56	48.40
25	9.27	688.9	688.9	659.3	6136.5	18.826	20.92
50	18.86	365.8	365.8	335.6	6238.6	9.947	11.05
125	46.39	166.1	166.1	135.7	6300.3	4.462	4.96
200	74.23	115.6	115.6	85.0	6324.4	3.072	3.41
300	111.3	87.3	87.3	56.8	6308.5	2.296	2.55

Table 4.32: Critical voltage and current values with changes in pole footing resistance ($R_{polefooting}$)

R_{PPB} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{BP} (V)	V_{TOUCH} (V)	I_{LW} (mA)
50mm^2 Cu	166.1	166.1	135.7	6300.3	4.462	4.96
95mm^2 Cu	166.1	166.1	135.7	6300.3	4.175	4.64

Table 4.33: Critical voltage and current values with changes PPB cable size (R_{PPB})

Results

The following results were observed from the analysis:

- Increasing the line impedance Z_p from 40m to 500m mde very little impact.

As would be expected, the increased impedance reduced the fault current and magnitude only slightly. With the initial values of Table 4.29, the line worker experienced nearly 5mA of body current.

- Varying the resistance of the access permit earth electrode R_{ap} had minimal impact upon the performance of the PPB system. The resistance values used in testing were calculated from soil resistivity measured in the field. As the temporary earthing electrode is only installed at a shallow depth, the resistance is generally high. Consequently, this high resistance impedes the fault current and limits the risk to the line worker.
- Different values of pole footing resistance $R_{polefooting}$ were calculated over a range of soil resistivity values. Low $R_{polefooting}$ values allowed a higher level of fault current to flow through the worksite. Under the worst case conditions, $R_{polefooting}$ equalled 3.71Ω, the fault level rose to 1589A, V_{touch} was 43.56V and the line worker current 48.4mA. The lineworker current would be close to the 'threshold of ventricular fibrillation' for some people. However, at this relatively low level, the current would need to be sustained for several seconds according to Figure 20 of AS60479. The fault current level of 1589A should result in the upstream protection device isolating the fault in well under 1 second. Thus, even though I_{LW} is of a concerning magnitude, it would be unlikely to cause serious harm to the line worker.
- Varying the size of the PPB cable had negligible impact upon the results.

Results

The performance of the application technique shown in Figure 2.7 was tested by varying a number of site parameters. The conductive property of the steel pole resulted in higher levels of I_{LW} compared with the insulating property of timber. However, even with the worst case fault currents and touch voltages, the value of I_{LW} was still low enough to expect line worker would have been safe given the quick operation of the upstream protection.

4.2.5 Bonding application shown in CEOP2377 Figure 5

Analysis

This analysis is of the bonding technique shown in Figure 2.8. The technique is used on steel and concrete poles when APE are applied at the upstream isolation point, and are in view of the work site. A PPB is applied from the conductor being worked on to the pole below the workers feet. This application is similar to both Figures 2.4 and 2.5. The conductive properties of the steel pole replicate the existence of a permanent earth on a timber pole.

This technique was analysed using a similar approach to the techniques of Figures 2.4 to 2.7. The safety of the lineworker was assessed with the worksite subjected to a worst case network situation. In practice this would occur with a single phase energisation and, the worksite located as close as possible to the zone substation. In this circumstance the prospective fault current will be at a maximum. This situation is shown in Figure 4.38.

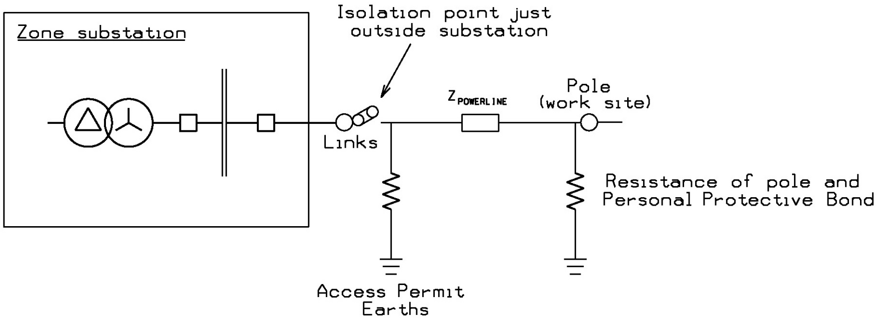


Figure 4.38: Worksite set up immediately downstream of zone substation

A connection diagram representing this technique is shown in Figure 4.39. The determination of maximum fault current caused by a single phase energisation of the worksite, can be determined using the sequence diagram shown in Figure 4.40.

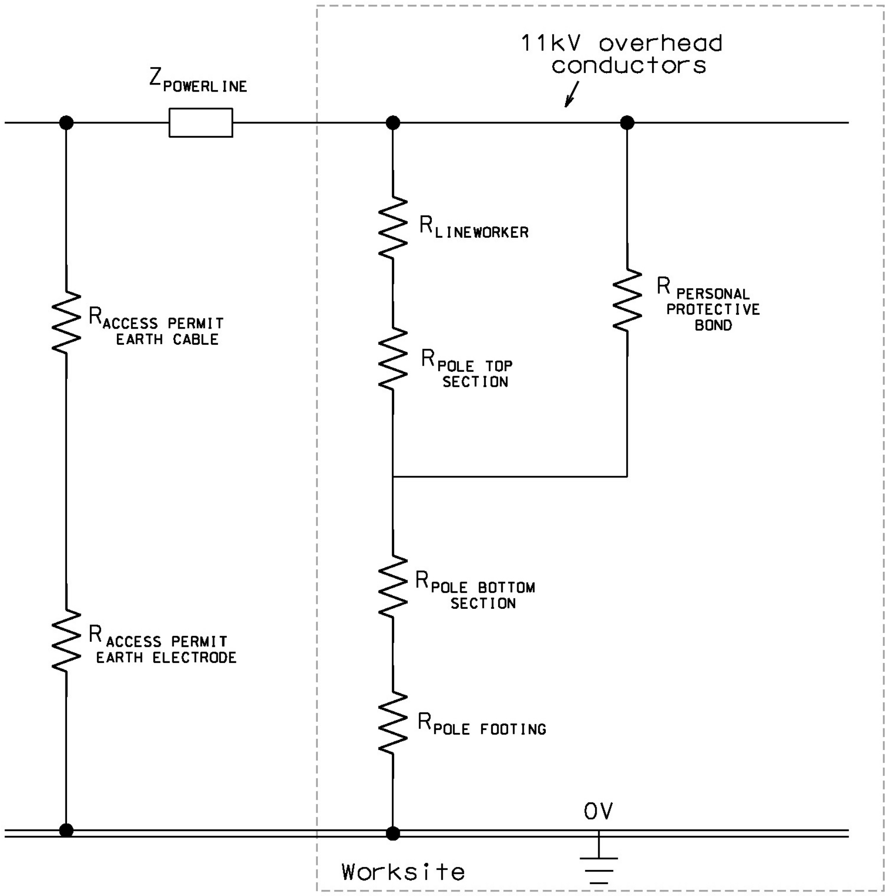


Figure 4.39: Schematic diagram of personal protective bonding technique shown in Figure 2.8

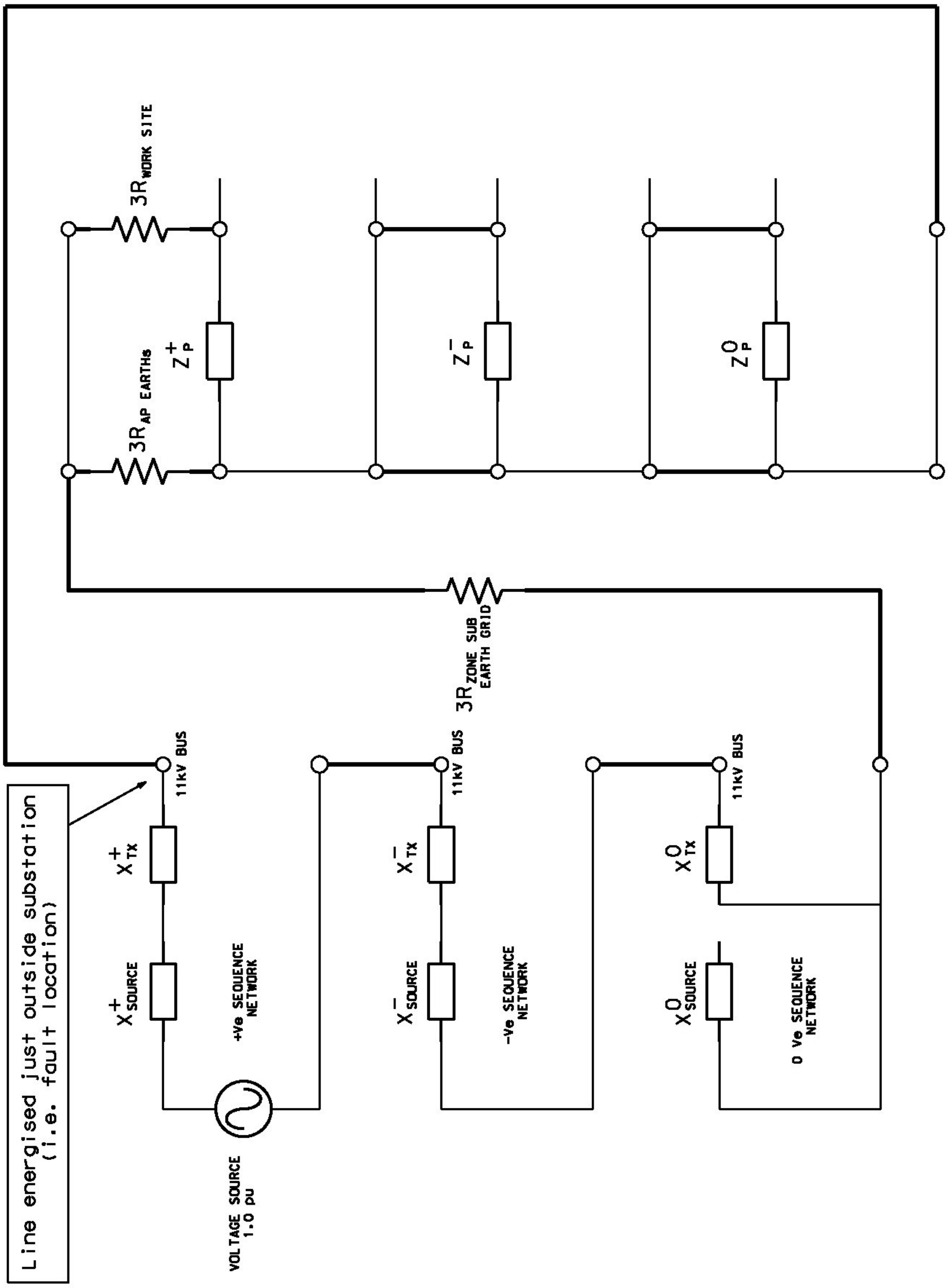


Figure 4.40: Sequence diagram used to determine fault current flow

Figure 4.41 the simplified circuit used for loop analysis. When the values of current, I_1 to I_3, are determined, it is possible to determine the maximum work site current, as well as the prospective touch voltage a line worker would be subjected to. From the figure, it can be seen that the total fault current I_f equals I_1, and the touch voltage V_{touch} equals I_3 times R_{ppb}. When the current values are determined, the degree of safety this bonding technique affords the line worker can then be critically assessed.

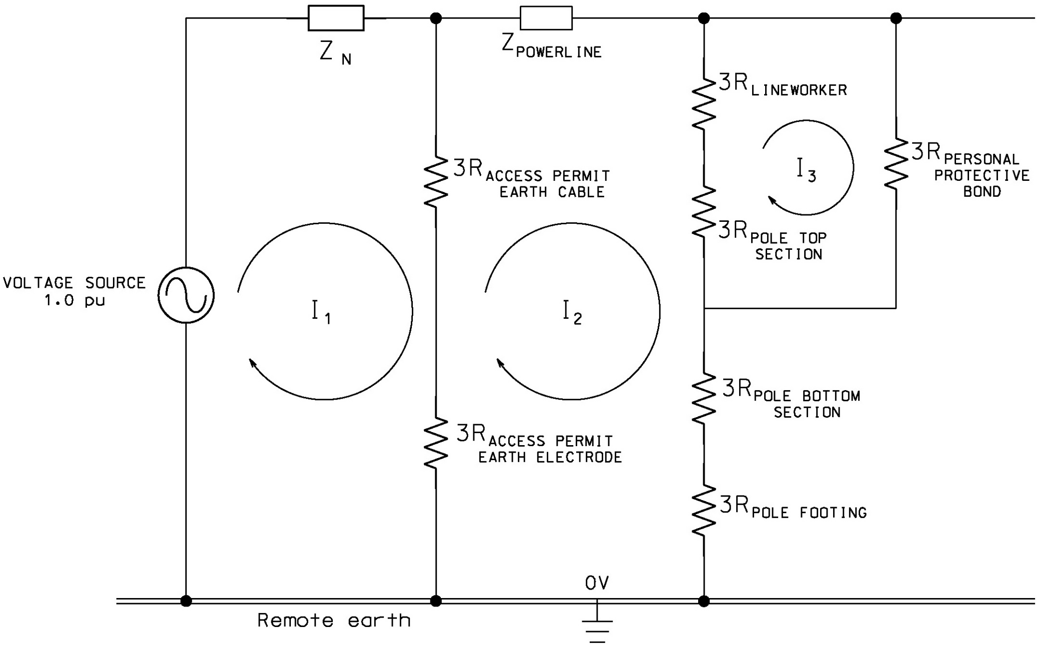


Figure 4.41: Simplified circuit for loop analysis

To determine the current I_1, I_2, and I_3, a system of equations has been developed as follows.

Let

$$Z_N = X_S^+ + X_T^+ + X_S^- + X_T^- + X_T^0 + 3R_{ZS} + 3R_f \tag{4.81}$$

and

$$R_{AP} = R_{APC} + R_{APE} \tag{4.82}$$

then

$$(Z_N + 3R_{ap})I_1 - 3R_{ap}I_2 = V_S \tag{4.83}$$

and

$$-3R_{ap}I_1 + (3R_{ap} + Z_P + 3R_{lw} + 3R_{pa} + 3R_{pb} + 3R_{polefooting})I_2 - (3R_{lw} + 3R_{pa})I_3 = 0 \tag{4.84}$$

$$-(3R_{lw} + 3R_{pa})I_2 + (3R_{lw} + 3R_{pa} + 3R_{ppb})I_3 = 0 \tag{4.85}$$

The Equations 4.83 to 4.85 have been converted to the matrix form. This facilitates the use of Matlab to solve the equations.

$$\begin{bmatrix} (Z_n+3R_{ap}) & -3R_{ap} & 0 \\ -3R_{ap} & \begin{array}{c}(3R_{ap}+Z_p+3R_{lw}+3R_{pa} \\ +3R_{pb}+3R_{polefooting})\end{array} & -(3R_{lw}+3R_{pa}) \\ & -(3R_{lw}+3R_{pa}) & (3R_{lw}+3R_{pa}+3R_{ppb}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ 0 \end{bmatrix}$$

A Matlab script has been developed to perform the required calculations and allow experimentation with the input values. A representative Matlab script is included in Appendix B. The initial input values used in the calculations are listed in Table 4.34.

Input values which could realistically change in practice have been varied and the resulting critical voltage and currents recorded. The calculated results are displayed in Tables 4.35 to 4.38

Input variable	Value	Unit	Notes
Powerline distance	40	m	Distance between APE and worksite
Z_P	0.0067 +j0.0091	Ω/m	Lemon (30/7/3.00 ACSR)
R_{AP} cable	0.00498	Ω	70mm^2 sq Cu - rated 16kAs
Soil resistivity	100	Ω.m	Nominal ‘good soil’ value
R_{AP} electrode	206.9	Ω	Calculated on soil resistivity
R_{LW}	900	Ω	Resistance of lineworker
Pole length	12.5	m	Total length
Line worker height	2.2	m	Includes reach
Bonding Point Attachment	2.4	m	Height above ground
R_{steel}	0.0469	Ω/m	CCA pole at 20% moisture
R_{PA}	0.000211	Ω	Pole section between LW and BP
R_{PB}	0.000202	Ω	Pole section below BP
$R_{polefooting}$	46.4	Ω	Estimated
R_{PPB}	0.000696	Ω	5m length

Table 4.34: Initial input values for analysis of PPB bonding method of Figure 2.8

Variance of Z_P:

Powerline length (m)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{Touch} (V)	I_{LW} (A)
Initial - 40m	166.2	135.8	135.8	6300.3	0.319	0.00035
100	166.2	135.8	135.8	6299.8	0.319	0.00035
250	166.2	135.8	135.8	6298.7	0.319	0.00035
500	166.2	135.7	135.7	6296.8	0.3189	0.00035

Table 4.35: Critical voltage and current values with changes in powerline length (Z_P)

Rho @2.0m	R_{AP} elecrode (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{Touch} (V)	I_{LW} (A)
216	446.9	150	135.90	135.90	6305.3	0.3193	0.00035
300	620.8	146.1	135.92	135.92	6306.5	0.3194	0.00035
468	968.4	142.5	135.95	135.95	6307.5	0.3195	0.00035
750	1551	140.0	135.96	135.96	6308.3	0.3195	0.00036
933	1930	139.2	135.97	135.97	6307.9	0.3195	0.00036

Table 4.36: Critical voltage and current values with changes in APE electrode resistance (R_{AP})

R_{PPB} (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{Touch} (V)	I_{LW} (A)
35mm^2 Cu	166.2	135.8	135.8	6300.3	0.4576	0.00051
95mm^2 Cu	166.2	135.8	135.8	6300.3	0.1711	0.00019

Table 4.37: Critical voltage and current values with changes PPB cable size (R_{PPB})

Rho @2.0m	$R_{polefooting}$ (Ω)	I_F (A)	I_{WS} (A)	I_{PPB} (A)	V_{ws} (V)	V_{Touch} (V)	I_{LW} (A)
10	3.71	1591	1562	1562	5834	5.29	0.00585
25	9.3	690	660	660	6135.9	2.22	0.00247
50	18.9	366	336	336	6238.4	1.13	0.00126
125	46.4	166	135.8	135.8	6300.3	0.46	0.00051
200	74.3	116	85.1	85.1	6315.8	0.29	0.00032
300	111.3	87	56.8	56.8	6324.4	0.19	0.00021

Table 4.38: Critical voltage and current values with changes in pole footing resistance (R_{AP})

Results

The following results were observed from the analysis:

- Increasing the line impedance Z_p from 40m to 500m made a negligible impact.
- The resistance of the access permit earth electrode R_{ap} was relatively very high compared to the pole footing value $R_{polefooting}$. As such, varying R_{ap} did not significantly affect the touch voltage V_{touch} or line worker current I_{LW}.
- Using a larger cable for the PPB caused a reduction in V_{touch} and I_{LW}. However, both these values were at very low safe levels so there would be no practical benefit in using a larger cable.
- The value of pole footing resistance $R_{polefooting}$ had the greatest influence on V_{touch} and I_{LW}. When $R_{polefooting}$ is low, the total fault current flowing is relatively high. This increased fault current resulted in greater voltage drop across the PPB, and therefore, a higher V_{touch}. However, under a worst case condition where I_{ws} was 1562A, V_{touch} had a maximum value 5.3V which is safely below harmful levels.

The performance of the application technique shown in Figure 2.8 was tested by varying a number of site parameters. Even with the worst case fault currents and touch voltages, the result indicate the line worker would be safe. The maximum value of I_{LW}

recorded would only have been approaching the ‘threshold of let-go’, and therefore, most probably be at a safe level.

Chapter 5

Conclusions

5.1 Achievements

My research has demonstrated that current practices in protective bonding and earthing work well on distribution overhead lines. The combination of ESR requirements and PPB application techniques ensure potentially lethal currents are diverted around the line worker. The use of personal protective bonding at the pole where workers are aloft ensure that equipotential conditions are practically achieved. In the worst case situations, the touch potentials which a line worker is exposed to are confined below safe limits.

The placement of short circuits and earths (APE) at each network isolation point provide an additional layer of protection. Often the APE's are connected to permanent earthing installations which provide a lower resistance to the general mass of earth. This increases the fault current magnitude which in turn causes a faster operation of the network protection device. Therefore, the duration of an unexpected line energisation is minimised, and the likelihood of injury to the line worker greatly reduced.

As my research was based upon a specific distribution network in Queanbeyan, the results do not guarantee that the PPB techniques examined will work in every other network or geographical location. However, the results do provide useful guidance and indicate these PPB techniques will be adequate in larger systems with much higher fault levels. Overall, my research provides reassurance that line workers will be adequately protected in the event of an unforseen energisation of the power line.

It was anticipated that the analysis may uncover deficiencies in the current practices. The challenge then would have been to devise practical solutions or improvements. Depending on the cost of the recommendations, a cost benefit analysis would have been required to justify the cost of implementation versus the cost of a serious accident. The research did not uncover any serious problems with current practices. Therefore, the completion of this project objective was not required.

5.2 Further work

Due to time constraints, not all possible hazards or work situations were analysed. Further research and analysis would be beneficial to enhance these findings and to provide even greater certainty to the effectiveness of current PPB practices.

The techniques and equipment used for underground cable work are unique compared to those for overhead powerlines. However, underground cable work is subject to many of the same hazards including accidental energisation and transferred potentials. For underground work these hazards are just as lethal.

Lightning discharge is potentially the most lethal hazard a line worker may be exposed to depending upon the magnitude and proximity of the lightning strike. The average lightning strike is in the order of 30kA (National Weather Service Office of Climate & Services n.d.). With much larger strikes possible, the safest approach is for workers to be clear of the powerlines when lightning activity is nearby. Many ENO's, including Essential Energy, have a policy of prudent avoidance where lightning activity is monitored and work stops when lightning is detected within 10km of the worksite.

The findings from the case study in Section 2.6 demonstrated how PPB was credited for protecting the line workers when a distant lightning strike occurred. Further analysis of PPB performance in the event of a 'direct' lightning strike close to the work site would be beneficial. This analysis would determine whether current PPB techniques, and the equipment in use, will be adequate in the event of a direct strike.

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Appendix A

Project Specification

ENG 4111/2 Research Project

Project Specification

For:	**Andrew James PRATT**
Topic:	Prevention of electrical accidents with safe personal protection bonding and earthing
Supervisors:	Dr Bob Burgess
Enrolment:	ENG4111 - Semester 1, 2014 ENG4112 - Semester 2, 2014 ENG4903 - Semester 2, 2014
Project Aim:	This project seeks to examine the adequacy, and improve the safety, of personal protective bonding and earthing techniques for the protection of workers on de-energised overhead and underground powerlines.

Program: Issue A, 4 March 2014

1. Research current practices regarding the use of Personal Protective Bonds and Earths (PPB and E) for worker safety on de-energized overhead and underground powerlines.
2. Use case studies of past accidents to highlight problems that exist with current practices. Demonstrate how it is still possible for accidents to occur in the future.
3. Devise technical solutions and make recommendations to ensure the use of PPB and E provides a safe environment for powerline workers, and that future accidents are prevented.
4. Determine the economic cost for implementing my proposed solutions and recommendations. Provide a cost benefit analysis of the implementation cost versus the cost of a serious accident.
5. Submit an academic dissertation on my research.

Agreed:

Student Name: Andrew Pratt
Date: 19 March 2014

Supervisor Name: Dr Bob Burgess
Date:

Examiner: AA Kist
Date: 11 April 2014

Appendix B

Matlab files

```
% CE19317_TP.m - October, 2014
% Written by Andrew Pratt - Student number 0050088032
% Contact details: andrewpratt99@bigpond.com or 0478 075 836
% For ENG4111 & ENG4112 - Research Project

% Description: This script calculates the voltages and currents at the
% worksite caused by an Earth Potential Rise on the zone substation earth
% grid. The network information (zone substation details, line impedance
% etc.) contained in the script is common for most of the network analysis
% in the project. Thus, the script can be adjusted to analyse other
% scenarios discussed in the project.

% Note: The Excel file OHfaultlevels.xlsx needs to be saved and added to
% the Matlab directory for the script to work. The Excel file contains the
% conductor data used in the calculations.

clear;clc;
format shortg

% INPUTS *****************************************************************

% NETWORK INFORMATION - SOURCE AND ZONE SUB********************************
% *************************************************************************

% 66kV bus data
TP_66=4.51;     % 3 phase fault level (normal configuration)in kA
SLG_66=4.1;     % Single line to ground fault level (normal config)in kA

% Transformer data
MVA=25;         % Transformer MVA rating
Zt=10.11i;      % Transformer impedance as %
Vprim=66000;    % Transformer primary voltage (V)
Vsec=11000;     % Tranformer secondary voltage (V)
Rzs=0.3;        % Resistance of earthing grid at Zone Substation (Ohms)
Rzs2=0.1;       % Resistance of earth grid at Transgrid 132kV substation
                % (Ohms) - estimated value only

% Determine 66kV source and Zone transformer impedance (in per unit)

% Base values with 25MVA base.
Ib_66=MVA*1e6/(sqrt(3)*Vprim);  % Base current in 66kV system (Amps)
Zb_66=Vprim/(sqrt(3)*Ib_66);    % Base impedance in 66kV system (Ohms)
Ib_11=MVA*1e6/(sqrt(3)*Vsec);   % Base current in 11KV system (Amps)
Z11base=Vsec/(sqrt(3)*Ib_11);   % Base impedance in 11kV system (Ohms)
Van=Vprim/sqrt(3);              % Primary phase to neutral voltage (Volts)

% 66kV source impedance values in per unit
XSpos=(Van/(TP_66*1000));       % Positive sequence source impedance (Ohms)
XSneg=XSpos;                    % Negative sequence source impedance (Ohms)
XSzero=(3*Van/(SLG_66*1000-XSpos-XSneg));  % Zero sequence impedance (Ohms)
XSpos=(XSpos/Zb_66)*1i;
XSneg=XSpos;
XSzero=(XSzero/Zb_66)*1i;

% Zone power transformer impedance values in per unit
```

```
XTpos=Zt/100; % Transformer impedance (pu)
XTneg=XTpos; % Transformer impedance (pu)
XTzero=XTpos; % Transformer impedance (pu)

% 11kV bus impedance values in per unit
Z11pos=XSpos+XTpos;         % 11kV bus positive sequence impedance (pu)
Z11neg=XSneg+XTneg;         % 11kV bus negative sequence impedance (pu)
Z11zero=XSzero+XTzero;      % 11kV bus zero sequence impedance (pu)

% South Queanbeyan Zone substation earth grid in per unit
Rzs=Rzs/Z11base;           % Zone substation earth grid in per unit

% Single ground to line fault level at 11kV bus (Amps)
If_SLG_bus=1/(Z11pos+Z11neg+XTzero)*Ib_11*3;
If_BUS=abs(If_SLG_bus);
fprintf('The single line to ground fault level at the 11kV bus is %2.1f Amps.\n\n',...
     If_BUS(1,1))

% NETWORK INFORMATION - OH AND UG POWERLINE DETAILS************************
% *************************************************************************

% Cable and conductor details
n= xlsread('OHfaultlevels.xlsx',2,'J4:O9'); % Import line data from Excel
n(:,2)=n(:,2)*j;    % Convert column 2 numbers to j numbers
n(:,4)=n(:,4)*j;   % Convert column 4 numbers to j numbers
n(:,6)=n(:,6)*j;   % Convert column 6 numbers to j numbers

% Powerline section distances
Sect1=35;       % Distance of section 1 of feeder (m)
Sect2=612;      % Distance of section 2 of feeder (m)
Sect2A=20;      % Distance of section 2A of feeder (m)
Sect3=15;       % Distance of section 3 of feeder (m)
Sect3A=29;      % Distance of section 3A of feeder (m)
Sect4=112;      % Distance of section 4 of feeder (m)
Sect5=260;      % Distance of section 4 of feeder (m)
Sect6=346;      % Distance of section 5 of feeder (m)
Sect7=72;       % Distance of section 6 of feeder (m)
Sect8=348;      % Distance of section 7 of feeder (m)
Sect9=122;      % Distance of section 8 of feeder (m)
Sect10=660;     % Distance of section 9 of feeder (m)
Sect11=162;     % Distance of section 10 of feeder (m)
Sect12=511;     % Distance of section 10 of feeder (m)
Sect13=1174;    % Distance of section 10 of feeder (m)
Sect14=1837;    % Distance of section 10 of feeder (m)
Sect15=211;     % Distance of section 10 of feeder (m)
Sect16=3936;    % Distance of section 10 of feeder (m)
Sect17=2146;    % Distance of section 10 of feeder (m)
Sect18=1534;    % Distance of section 10 of feeder (m)

% PART 2 - Calculate line impedance value
num=n/Z11base;      % Convert values to per unit
PASS=num(1,:);      % Create individual conductor/cable data (pu/m)
Lemon=num(2,:);     % Create individual conductor/cable data (pu/m)
Mercury=num(3,:);   % Create individual conductor/cable data (pu/m)
UG240=num(4,:);     % Create individual conductor/cable data (pu/m)
```

```
Neon=num(5,:);      % Create individual conductor/cable data (pu/m)
Hydrogen=num(6,:);  % Create individual conductor/cable data (pu/m)

s1=Sect1*PASS;          % Create actual section impedance in pu
s2=Sect2*Lemon;         % Create actual section impedance in pu
s2A=Sect2A*Mercury;     % Create actual section impedance in pu
s3=Sect3A*Lemon;        % Create actual section impedance in pu
s3A=Sect3A*Mercury;     % Create actual section impedance in pu
s4=Sect4*Lemon;         % Create actual section impedance in pu
s5=Sect5*Mercury;       % Create actual section impedance in pu
s6=Sect6*Mercury;       % Create actual section impedance in pu
s7=Sect7*UG240;         % Create actual section impedance in pu
s8=Sect8*UG240;         % Create actual section impedance in pu
s9=Sect9*Mercury;       % Create actual section impedance in pu
s10=Sect10*Mercury;     % Create actual section impedance in pu
s11=Sect11*Mercury;     % Create actual section impedance in pu
s12=Sect12*Lemon;       % Create actual section impedance in pu
s13=Sect13*Lemon;       % Create actual section impedance in pu
s14=Sect14*Neon;        % Create actual section impedance in pu
s15=Sect15*Neon;        % Create actual section impedance in pu
s16=Sect16*Neon;        % Create actual section impedance in pu
s17=Sect17*Hydrogen;    % Create actual section impedance in pu
s18=Sect16*Neon;        % Create actual section impedance in pu
% Note - Pole CE19317 is at the end of Section 5

% TOTAL FEEDER line impedance details (per unit) - Can be uncommented for
% use in other analysis.

% Positive sequence line impedance in per unit
% LinePI=s1(1)+s1(2)+s2(1)+s2(2)+s2A(1)+s2A(2)+s3(1)+s3(2)+s3A(1)+s3A(2)+s4(1)+s4(2)+s5↙
(1)+s5(2)+s6(1)+s6(2)+s7(1)+s7(2)+s8(1)+s8(2)+s9(1)+s9(2)+s10(1)+s10(2)+s11(1)+s11(2)↙
+s12(1)+s12(2)+s13(1)+s13(2)+s14(1)+s14(2)+s15(1)+s15(2)+s16(1)+s16(2)+s17(1)+s17(2)↙
+s18(1)+s18(2);

% Negative sequence line impedance in per unit
% LineNI=s1(3)+s1(4)+s2(3)+s2(4)+s2A(3)+s2A(4)+s3(3)+s3(4)+s3A(3)+s3A(4)+s4(3)+s4(4)+s5↙
(3)+s5(4)+s6(3)+s6(4)+s7(3)+s7(4)+s8(3)+s8(4)+s9(3)+s9(4)+s10(3)+s10(4)+s11(3)+s11(4)↙
+s12(3)+s12(4)+s13(3)+s13(4)+s14(3)+s14(4)+s15(3)+s15(4)+s16(3)+s16(4)+s17(3)+s17(4)↙
+s18(3)+s18(4);

% Zero sequence line impedance in per unit
% LineZI=s1(5)+s1(6)+s2(5)+s2(6)+s2A(5)+s2A(6)+s3(5)+s3(6)+s3A(5)+s3A(6)+s4(5)+s4(6)+s5↙
(5)+s5(6)+s6(5)+s6(6)+s7(5)+s7(6)+s8(5)+s8(6)+s9(5)+s9(6)+s10(5)+s10(6)+s11(5)+s11(6)↙
+s12(5)+s12(6)+s13(5)+s13(6)+s14(5)+s14(6)+s15(5)+s15(6)+s16(5)+s16(6)+s17(5)+s17(6)↙
+s18(5)+s18(6);

% POWERLINE SEQUENCE VALUES TO POLE CE19317 AND SWITCHING STATION (per unit).

% Positive sequence values
Z1p=s1(1)+s1(2)+s2(1)+s2(2); %Positve sequence impedance of overhead powerline in per↙
unit
Z2p=s3(1)+s3(2); %Positve sequence impedance of overhead powerline in per unit
Z3p=s4(1)+s4(2)+s5(1)+s5(2); %Positve sequence impedance of overhead powerline in per↙
unit
Z4p=s6(1)+s6(2)+s7(1)+s7(2); %Positve sequence impedance of overhead powerline in per↙
```

```
unit
Z5p=s2A(1)+s2A(2); %Positve sequence impedance of overhead powerline to G16540 in per↙
unit
Z6p=s3A(1)+s3A(2); %Positve sequence impedance of overhead powerline to ABS 2337 in per↙
unit

% Negative sequence values
Z1n=s1(3)+s1(4)+s2(3)+s2(4); %Negative sequence impedance of overhead powerline in per↙
unit
Z2n=s3(3)+s3(4); %Negative sequence impedance of overhead powerline in per unit
Z3n=s4(3)+s4(4)+s5(3)+s5(4); %Negative sequence impedance of overhead powerline in per↙
unit
Z4n=s6(3)+s6(4)+s7(3)+s7(4); %Negative sequence impedance of overhead powerline in per↙
unit
Z5n=s2A(3)+s2A(4); %Negative sequence impedance of overhead powerline to G16540 in per↙
unit
Z6n=s3A(3)+s3A(4); %Negative sequence impedance of overhead powerline to ABS 2337 in↙
per unit

% Zero sequence values
Z1z=s1(5)+s1(6)+s2(5)+s2(6); %Zero sequence impedance of overhead powerline in per unit
Z2z=s3(5)+s3(6); %Zero sequence impedance of overhead powerline in per unit
Z3z=s4(5)+s4(6)+s5(5)+s5(6); %Zero sequence impedance of overhead powerline in per unit
Z4z=s6(5)+s6(6)+s7(5)+s7(6); %Zero sequence impedance of overhead powerline in per unit
Z5z=s2A(5)+s2A(6); %Zero sequence impedance of overhead powerline to G16540 in per unit
Z6z=s3A(5)+s3A(6); %Zero sequence impedance of overhead powerline to ABS 2337 in per↙
unit

% ACCESS PERMIT EARTHS AT ISOLATION POINTS ******************************
% **********************************************************************

% ISOLATION 1 - Connected to zone substation earth grid
Rc1=(15*0.470/1000)/Z11base;    % Access permit earth cables resistance (pu)

% ISOLATION 2 - At gas switch G16540
% Import soil resistivity information
G16540_ER=xlsread('OHfaultlevels.xlsx',3,'B42:C43'); % Import earth resistance reading↙
data from Excel
a2=G16540_ER(1,1);              % horizontal spacing of electrode (m)
R2=G16540_ER(1,2);              % Resistance reading obtained (Ohms)
l=0.5;                          % buried depth of electrode (m)
r=0.012;                        % rod diameter (m)
% Calculate electrode resistance
%Re2=((2*pi*a2*R2)/(2*pi*l))*log(8*l/r-1)
Re2=25;                         % From EE records of permanent earth
% Calculate portable earth cable
Rc2=(15*0.470/1000);            % Access permit earth cable resistance (Ohms)
Rap2=(Re2+Rc2)/Z11base;

% ISOLATION 3 - At Air Break Switch ABS2337
% Import soil resistivity information
A2337_ER=xlsread('OHfaultlevels.xlsx',3,'B45:C46'); % Import earth resistance reading↙
data from Excel
a3=A2337_ER(1,1);               % horizontal spacing of electrode (m)
R3=A2337_ER(1,2);               % Resistance reading obtained (Ohms)
```

```
l=0.5;                          % buried depth of electrode (m)
r=0.012;                        % rod diameter (m)
% Re3=((2*pi*a3*R3)/(2*pi*l))*log(8*l/r-1);
Re3=25;                         % From EE records of permanent earth
Rc3=(15*0.470/1000);            %Access permit earth cables resistance (Ohms)
Rap3=(Re3+Rc3)/Z11base;

% WORKSITE at pole CE19317
% Working earth cable and electrode resistances (pu)
CE19317_ER=xlsread('OHfaultlevels.xlsx',3,'B2:C8'); % Import earth resistance reading↙
data from Excel
a4=CE19317_ER(1,1);             % horizontal spacing of electrode (m)
R4=CE19317_ER(1,2);             % Resistance reading obtained (Ohms)
l=0.5;                          % buried depth of electrode (m)
r=0.012;                        % rod diameter (m)
Rwe_electrode=((2*pi*a4*R4)/(2*pi*l))*log(8*l/r-1); % Working earth electrode↙
resistance
Rc4=(15*0.470/1000);            % Access permit earth cables resistance (Ohms)
Rap4=(Rwe_electrode+Rc4)/Z11base;

% POLE CE19317 - Dimensions and resistance values.
% Pole and line worker resistance (including permanent earth)

% Input values
PoleR=3.14e7;       % Resistance of timber pole treated with creosote at 20% moisture↙
(Ohms/m)
Rpolefooting=37;    % Nominal resistance of pole footing to remote earth (Ohms)
Polelength=16.8;    % Length of pole (m)
Pole66sect=5.22;    % Adjustment for length of pole above 11kV conductors to support↙
66kV circuit (m)
LWh=2.2;            % Line worker height including reach above head (m)
BPattach=2.4;       % Attachment height above ground of Bonding Point (m)
Rlw=900;            % Resistance of line worker (Ohms)
Rpermee=88;         % Resistance of permanent earth electrode (measured Ohms)
Rptpe=10;           % Resistance between permanent earth and pole (Ohms)
% Calculated values
Rppb=5*0.674/1000;  % Resistance of personal protective bond (35mm sq Cu)(Ohms)
Rwe_cable=15*0.674/1000;    % Resistance of working earth cable (35mm sq Cu)(Ohms)
Embed=Polelength*0.1+0.8;   % Footing depth (m)
Poleabove=Polelength-Embed; % Height of pole section above ground (m)
Rpa=(Poleabove-LWh-BPattach-Pole66sect)*PoleR; % Pole top section distance (m)
Rpb=BPattach*PoleR;         % Pole to section distance (m)
Rpermec=(BPattach+0.5)*0.593/1000; %Resistance of permanent 35mm sq Cu earth cable↙
(Ohms)

% Equivalent resistance of worksite (if required to know) *****************
% System of equations developed in Loop analysis to determine the equivalent
% resistance of the worksite
Z=zeros(4,4);
Z(1,1)=Rwe_cable+Rwe_electrode;
Z(1,3)=-Rwe_electrode;
Z(2,1)=-Rwe_cable;
Z(2,2)=Rlw+Rpa+Rptpe+Rppb+Rwe_cable;
Z(2,3)=-Rppb;
Z(2,4)=-Rptpe;
```

```
Z(3,1)=-Rwe_electrode;
Z(3,2)=-Rppb;
Z(3,3)=Rwe_electrode+Rppb+Rpermec+Rpermee;
Z(3,4)=Rpermee+Rpermec;
Z(4,2)=-Rptpe;
Z(4,3)=-(Rpermee+Rpermec);
Z(4,4)=Rpermee+Rpermec+Rpb+Rpolefooting+Rptpe;

% Determine loop currents
V=[11000/sqrt(3);0;0;0];
I=inv(Z)*V; % Loop currents I1, I2, I3, I4 - Total current flowing from source is I1

% Determine total worksite resistance
Rws=(V(1)/I(1))/Z11base;
fprintf('The total equivalent worksite resistance is %2.1f pu.\n\n',...
     Rws)

% ISOLATION 4 - 11kV cable earthed at Switching Station P12553.
Rss=15/Z11base; % Switching station earth value obtained from System Data

% WORKSITE VOLTAGE AND CURRENT CALCULATIONS CAUSED BY GROUND FAULT ON ADJACENT FEEDER
% ****************************************************************************

% Simplify upstream energised network to one equivalent value
Rf=0;    % Fault resistance (for the purposes of this evaluation - nominally 0)
Zn=XSpos+XTpos+XSneg+XTneg+XTzero+3*Rf; % Equivalent impedance which can be attributed↙
to the 11kV bus.

% Set up impedance matrix to represent the de-energised and earthed section
% (which includes the worksite).

Z=zeros(5,5);
Z(1,1)=Zn+3*Rzs;
Z(1,2)=-3*Rzs;
Z(2,1)=-3*Rzs;
Z(2,2)=3*Rzs+3*Rap2+Z1p+3*Rc1;
Z(2,3)=-3*Rap2;
Z(3,2)=-3*Rap2;
Z(3,3)=3*Rap2+3*Rap3+Z5p+Z2p;
Z(3,4)=-3*Rap3-Z5p;
Z(4,3)=-3*Rap3-Z5p;
Z(4,4)=Z5p+3*Rap3+3*Rws+Z6p;
Z(4,5)=-3*Rws-Z6p;
Z(5,4)=-3*Rws-Z6p;
Z(5,5)=Z6p+3*Rws+3*Rss+Z4p;

% Determine the fault current flowing in the network and through the
% worksite as a result of the EPR.

V=[1;0;0;0;0];
I=inv(Z)*V*3;        % Calculates the fault currents (i.e. 3 x zero sequence current)
I_mag=abs(I)*Ib_11;  % Magnitude of loop currents in Amps
If=abs(I(1))*Ib_11;  % Total fault current in Amps
Iws=abs(I(4)-I(5))*Ib_11; % Amount of fault current flowing through worksite
```

```
% Determine voltage rise due to returning earth current from fault on
% neighbouring feeder ****************************************************

% Zone sub earth grid voltage rise
Vepr=(I(1)-I(2))*Rzs*Vsec/sqrt(3);
Vepr=abs(Vepr);
fprintf('The voltage rise of the substation earth grid is %2.1f Volts.\n\n',...
    Vepr)
% Voltage rise at worksite
Vws=(I(4)-I(5))*Rws*Vsec/sqrt(3);
Vws=abs(Vws);
fprintf('The voltage appearing across the worksite is %2.1f Volts.\n\n',...
    Vws)

% Determine touch voltage for line worker on pole at worksite.
% The worksite is set up as per Figure 3 of CEOP2377
% System of equations developed from Loop analysis

Z=zeros(4,4);
Z(1,1)=Rwe_cable+Rwe_electrode;
Z(1,3)=-Rwe_electrode;
Z(2,1)=-Rwe_cable;
Z(2,2)=Rlw+Rpa+Rptpe+Rppb+Rwe_cable;
Z(2,3)=-Rppb;
Z(2,4)=-Rptpe;
Z(3,1)=-Rwe_electrode;
Z(3,2)=-Rppb;
Z(3,3)=Rwe_electrode+Rppb+Rpermec+Rpermee;
Z(3,4)=Rpermee+Rpermec;
Z(4,2)=-Rptpe;
Z(4,3)=-(Rpermee+Rpermec);
Z(4,4)=Rpermee+Rpermec+Rpb+Rpolefooting+Rptpe;

% Determine loop currents at the worksite
V1=[Vws;0;0;0];
I=inv(Z)*V1; % Loop currents I1, I2, I3, I4 - Total current flowing from source is I1

% Determine the lineworker TOUCH VOLTAGE.

Vtouch=Vws-(I(4)*(Rpb+Rpolefooting)+I(2)*Rpa);
fprintf('The touch voltage experienced by the line worker is %2.3f Volts.\n\n',...
    Vtouch)
```

```
% ceop2377fig3.m - October 2014
% Written by Andrew Pratt - Student number 0050088032
% Contact details: andrewpratt99@bigpond.com or 0478 075 836
% For ENG4111 & ENG4112 - Research Project

% This script models the performance of PPB and E setup as per Figure 3 of
% CEOP2377. The script can be adapted to the analysis of other bonding
% configurations discussed in the project.

% Note: The Excel file OHfaultlevels.xlsx needs to be saved and added to
% the Matlab directory for the script to work. The Excel file contains the
% conductor data used in the calculations.

clear;clc;
format shortg

% INPUTS *******************************************************************

% NETWORK INFORMATION - SOURCE AND ZONE SUB********************************

% 66kV bus data
TP_66=4.51;     % 3 phase fault level (normal configuration)in kA
SLG_66=4.1;     % Single line to ground fault level (normal config)in kA

% Transformer data
MVA=25;         % Transformer MVA rating
Zt1=10.11i;     % Transformer No.1 impedance as %
Zt2=10.21i;     % Transformer No.2 impedance as %
Vprim=66000;    % Transformer primary voltage (V)
Vsec=11000;     % Tranformer secondary voltage (V)
Rzs=0.3;        % Resistance of earthing grid at Zone Substation (Ohms)
Rzs2=0.1;       % Resistance of earth grid at Transgrid 132kV substation (Ohms) -↙
estimated value only

% Determine 66kV source and Zone transformer impedance (in per unit)

% Base values with 25MVA base.
Ib_66=MVA*1e6/(sqrt(3)*Vprim);  % Base current in 66kV system (Amps)
Zb_66=Vprim/(sqrt(3)*Ib_66);    % Base impedance in 66kV system (Ohms)
Ib_11=MVA*1e6/(sqrt(3)*Vsec);   % Base current in 11KV system (Amps)
Z11base=Vsec/(sqrt(3)*Ib_11);   % Base impedance in 11kV system (Ohms)
Van=Vprim/sqrt(3);              % Primary phase to neutral voltage

% 66kV source impedance values in per unit
XSpos=(Van/(TP_66*1000));       % Positive sequence source impedance (Ohms)
XSneg=XSpos;                    % Negative sequence source impedance (Ohms)
XSzero=(3*Van/(SLG_66*1000-XSpos-XSneg));% Zero sequence impedance (Ohms)
XSpos=(XSpos/Zb_66)*1i;
XSneg=XSpos;
XSzero=(XSzero/Zb_66)*1i;

% Zone power transformer impedance values in per unit
Zt_parallel=(Zt1*Zt2)/(Zt1+Zt2);
XTpos=Zt_parallel/100;          % Transformer impedance (pu)
XTneg=XTpos;                    % Transformer impedance (pu)
```

```
XTzero=XTpos;                   % Transformer impedance (pu)

% 11kV bus impedance values in per unit
Z11pos=XSpos+XTpos;             % 11kV bus positive sequence impedance (pu)
Z11neg=XSneg+XTneg;             % 11kV bus negative sequence impedance (pu)
Z11zero=XSzero+XTzero;          % 11kV bus zero sequence impedance (pu)

% South Queanbeyan Zone substation earth grid in per unit
Rzs=Rzs/Z11base;                % Zone substation earth grid in per unit

% Cable and conductor details
n= xlsread('OHfaultlevels.xlsx',2,'J4:O9'); % Import line data from Excel
n(:,2)=n(:,2)*j;                            % Convert column 2 numbers to j numbers
n(:,4)=n(:,4)*j;                            % Convert column 4 numbers to j numbers
n(:,6)=n(:,6)*j;                            % Convert column 6 numbers to j numbers
Lemon=n(2,:);                               % Create individual conductor/cable data↙
(pu/m)
Neon=n(5,:);                                % Create individual conductor/cable data↙
(pu/m)

% Powerline
dist_ape=40;                             % Distance from worksite to Access Permit↙
earths (m)
Zp=Lemon(1)+Lemon(2);                    % Conductor impedance per metre
Zp=Zp*dist_ape;                          % Impedance of overhead powerline (ohms)

% Portable earth cables
cable=[3.5 16 0.00147;6.0 25 0.000949;8.0 35 0.000674;12.0 50 0.000470;16.0 70↙
0.000332;20 95 0.000252];
length=15;                                   % length of portable earth cable
Rap_cable=cable(5,3)*length;                 % Resistance of access permit earth cable↙
(16kA set with 70mm Cu)
Rwe_cable=cable(3,3)*length;                 % Resistance of working earth cable (8kA↙
set with 35mm Cu)

% Personal protective bond
length_ppb=5;                               % length of personal protective bond
Rppb=cable(3,3)*length_ppb/Z11base;         % Resistance of personal protective bond↙
(8kA set with 35mm Cu)

% Portable earth electrodes
rho=100;                                     % Soil resistivity at electrode depth↙
(ohm.m)
d=0.5;                                       % depth of working earth electrode (m)
r=0.006;                                     % radius or working earth electrode (m)
Rap_electrode=(rho/(2*pi*d))*log(8*d/r-1)/Z11base; % Resistance of working earth↙
electrode (ohms)
% Rap_electrode= 1000/Z11base;                           % Resistance of access permit↙
earth electrode (ohms)

% Steel pole resistance
rho_st=190e-9;  % Resistivity of steel from manufacturer (Ohm.m)
l=1;             % section length (m)
pole_OD=0.273;   % Outside diameter of pole
pole_ID=0.2634; % inside diameter of pole
```

```
csa_outside=pi*(pole_OD/2)^2;
csa_inside=pi*(pole_ID/2)^2;
csa=csa_outside-csa_inside; % Area of steel csa
R_st=rho_st*l/csa; % Resistance of steel pole (Ohms/m)

% Pole length and resistance
Polelength=11;                              % Length of pole (m)
Embed=Polelength*0.1+0.8;                   % Footing depth (m)
PoleR=2.45e7;                               % Resistance of timber pole (Ohms/m)-↙
Creosote 3.14e7, CCA 2.45e7, NR 2.31e7, Steel
LWh=2.2;                                    % Line worker height including reach above↙
head (m)
BPattach=2.4;                               % Attachment height above ground of Bonding↙
Point (m)
Poleabove=Polelength-Embed;                 % Height of pole section above ground (m)
Poletop=Poleabove-LWh-BPattach;             % Pole section between lineworker feet and↙
BP (m)
Polebottom=BPattach+Embed;                  % Pole section below bonding point (m)
Rlw=900;                                    % Resistance of line worker (Ohms)
Rpa=Poletop*PoleR;                          % Pole top section resistance (m)
Rpb=Polebottom*PoleR;                       % Pole to section resistance (m)
Rpolefooting=37;                            % Nominal resistance of pole footing to↙
remote earth (Ohms)

% Permanent earth details
Rpe_cable=8*0.000332/Z11base;
Rpermee=30/Z11base;                          % Resistance of permanent earth electrode↙
( Ohms)
Rptpe=1/Z11base;                            % Resistance between permanent earth and↙
pole (Ohms)

% Fault resistance
Rf=0;                                       % Resistance between permanent earth and↙
pole (Ohms)

% CALCULATED OUTPUTS *******************************************************

fprintf('The Bonding Point (BP) height is %2.1f m.\n\n',...
    BPattach)
fprintf('The length of pole between the line worker and the BP is %2.1f m.\n\n',...
    Poletop)
fprintf('The length of pole (including footing) below the BP %2.1f m.\n\n',...
    Polebottom)

% 1. Calculate upstream (of isolation point) source impedance
Zn=XSpos+XTpos+XSneg+XTneg+XTzero+3*Rf+3*Rzs;
If_bus=1/Zn*3*Ib_11;
fprintf('The maximum current supplied from the 11kV bus %2.1f Amps.\n\n\n\n',...
    abs(If_bus))

Zp=Zp/Z11base;                          % Convert to per unit
Rlw=Rlw/Z11base;                        % Convert to per unit
Rpa=Rpa/Z11base;                        % Convert to per unit
Rpb=Rpb/Z11base;                        % Convert to per unit
Rpolefooting=Rpolefooting/Z11base;      % Convert to per unit
```

```
% System of equations developed in Loop analysis (Matrix form)
Z=zeros(4,4);
Z(1,1)=Zn+Zp+3*Rap_cable+3*Rap_electrode;
Z(1,2)=-3*Rap_cable;
Z(1,3)=-3*Rap_electrode;
Z(2,1)=-3*Rap_cable;
Z(2,2)=(3*Rap_cable+3*Rlw+3*Rpa+3*Rppb+3*Rptpe);
Z(2,3)=-3*Rppb;
Z(2,4)=-3*Rptpe;
Z(3,1)=-3*Rap_electrode;
Z(3,2)=-3*Rppb;
Z(3,3)=3*Rap_electrode+3*Rppb+3*Rpermee+3*Rpe_cable;
Z(3,4)=-(3*Rpermee+3*Rpe_cable);
Z(4,2)=-3*Rptpe;
Z(4,3)=-(3*Rpermee+3*Rpe_cable);
Z(4,4)=(3*Rpermee+3*Rpe_cable+3*Rptpe+3*Rpb+3*Rpolefooting);

% Determine network currents
V=[1;0;0;0];
I=inv(Z)*V*3; % Loop currents I1, I2, I3, I4 - Total current flowing from source is I1
abs(I)*Ib_11;

If=I(1)*Ib_11;
Iapc=(I(1)-I(2))*Ib_11;
Ilw=I(2)*Ib_11;
Ippb=(I(2)-I(3))*Ib_11;
Iwe_electrode=(I(1)-I(3))*Ib_11;
Ipe_electrode=(I(3)-I(4))*Ib_11;
Vbp=I(4)*(Rpb+Rpolefooting)*Vsec/sqrt(3);
fprintf('The total fault current (also work site current) is %2.1f Amps.\n\n',...
    abs(If))
fprintf('The current in the lineworker is %2.8f Amps.\n\n',...
    abs(Ilw))
fprintf('The current in the AP earth cable is %2.3f Amps.\n\n',...
    abs(Iapc))
fprintf('The current in the PPB cable is %2.3f Amps.\n\n',...
    abs(Ippb))
fprintf('The AP earth electrode current is %2.3f Amps.\n\n',...
    abs(Iwe_electrode))
fprintf('The PE earth electrode current is %2.3f Amps.\n\n',...
    abs(Ipe_electrode))

% Worksite voltage and lineworker touch voltage

Vws=((I(1)-I(2))*Rap_cable+(I(1)-I(3))*Rap_electrode)*Vsec/sqrt(3);
fprintf('The voltage across the worksite is %2.1f Volts.\n\n\n',...
    abs(Vws))

Vbp=I(4)*(Rpb+Rpolefooting)*Vsec/sqrt(3);
Vtouch=abs(Vws-Vbp);
fprintf('The touch voltage experienced by the line worker is %2.3f Volts.\n\n\n',...
    abs(Vtouch))
```