University of Southern Queensland

Faculty of Health, Engineering & Sciences

Model and Analysis of a Broken Conductor (Source Isolated) Earth Fault on Radial 11kV Distribution Feeders.

A dissertation submitted by

A. Geary

in fulfilment of the requirements of

ENG4112 Research Project

towards the degree of

Bachelor of (Electrical Engineering, Power Systems)

Submitted: October, 2013

Abstract

Protection schemes of electricity distribution networks are designed to limit the damage to the network in the event of a fault, and to provide some security and safety to the network. This thesis examines the electrical characteristics of the Source Isolated Earth (SIE) Fault.

The Source Isolated Earth Fault is a type of high impedance earth fault that can occur on overhead electricity networks. SIE faults are caused by a broken overhead conductor falling to ground on the load side of the span with the source end of the span isolated from the ground.

A simplified model for calculation of the earth fault levels in SIE faults was developed by circuit reduction of the fault schematic. The SIE fault was reduced to the equivalent of a Phase to Phase to Ground fault.

Results obtained from the simplified model were compared to two peer reviewed models for SIE fault calculations in order to validate the simplified method. The comparison was undertaken in two stages, by first varying one factor at a time to determine the most significant factors and then by carrying out designed experiments on the significant factors and analysing the interactions between these factors.

The results of the one factor at a time analysis identified which of the factors had the largest effect on the earth fault current. The most significant factor in determining the earth fault level in SIE faults is the pre-fault load beyond the fault location. This knowledge can be used to identify areas where SIE fault levels may be low.

Computational efficiency of the three models was compared using MATLAB profiling. The simplified model was found to be significantly faster than the other methods.

Confidence in the theory was bolstered by the calculation of fault levels for a case study. The results were compared between all three models and data captured during an actual SIE fault event.

A process was developed that allowed existing 11 kV network feeder models to be analysed using the SIE fault models. Sections of feeder where SIE fault levels *may* be below conventional Sensitive Earth Fault (SEF) protection pickup levels were identified. Attempts to optimise the feeder analysis led to methods of reducing the number of network nodes to be tested to find the limit of the protection zone.

The extreme case analysis led to the discovery of the circuit conditions that must exist for these types of faults to be undetectable by conventional SEF protection schemes. It was discovered that the maximum possible SIE fault current can be easily estimated by applying a factor to the pre-fault load downstream of the fault location.

University of Southern Queensland

Faculty of Health, Engineering & Sciences

ENG4111/2 *Research Project*

Limitations of Use

Certification of Dissertation

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

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

A. Geary

Q9222672

Signature

Date

Acknowledgments

This thesis was produced with guidance and assistance of my supervisor Dr Tony Ah-fock. My thanks to him for the assistance provided.

My thanks to my employer Essential Energy for without their assistance I could not have found the resources to embark on such a great mission as a BENG.

I also must acknowledge the persistence and patience of my wife Katrina and my sons Nathan, David, Daniel and Stephen. Without their assistance in the matters that would otherwise distract me from my studies, none of this would be possible.

A. Geary

University of Southern Queensland

October 2013

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In a three phase network designed for the distribution of power there are many types of faults which may occur. The more common types of faults are the three phase fault, the single phase to ground fault, the phase to phase fault, and the phase to phase to ground fault. As well as these common types of faults there are some more obscure faults which *may* occur only infrequently on the system. It was one of these less frequent anomalies that was the focus of this thesis.

1.1 The Broken Conductor (Source Isolated) Earth Fault

In an overhead 11kV distribution network the conductors are strung through the air by being suspended on insulators at each pole. The poles can be of significant height and have significant separation between them. It is possible that an overhead conductor *may* break. When a conductor breaks the two parts of the broken conductor fall towards the ground. The conductor ends may or may not come into contact with the ground, depending on the heights of the poles and the location of the break.

This thesis focuses on those instances where an overhead conductor breaks and the source side of the broken conductor is suspended from the ground due to the position of the break in the conductor span and the load side of the conductor makes electrical contact with the ground.

Figure 1.1 shows a pictorial representation of the fault condition. The only path to

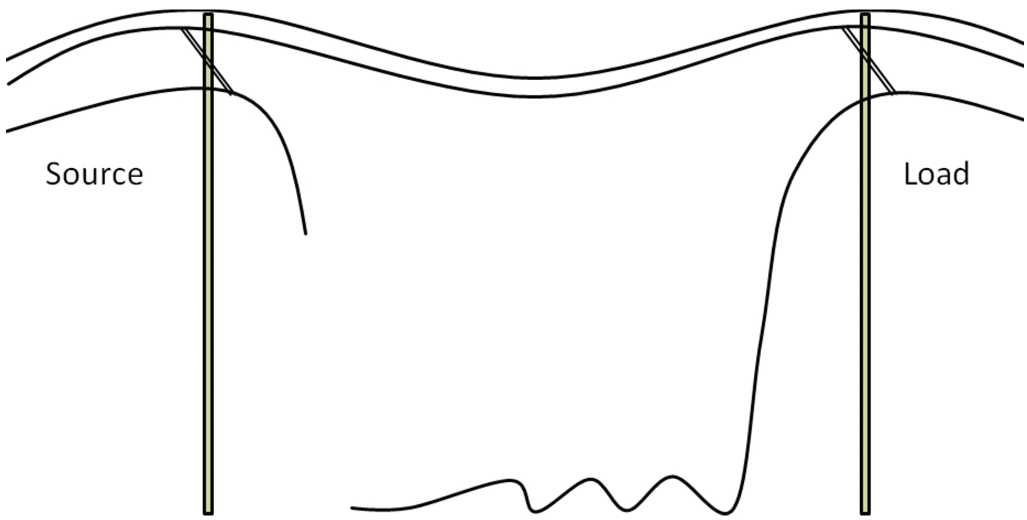


Figure 1.1: Pictorial representation of the fault condition.

earth for fault current is down the healthy two phases, through the downstream load and back along the faulted phase and to ground through the fault impedance. A schematic diagram for this fault condition is shown in Figure 3.1.

The fault current *may* be very limited in these situations, depending on the system configuration and load. As such this type of fault *may* be difficult to detect. Work has been undertaken in this thesis to develop a simplified method of estimating the fault current in these conditions. Some reports indicate that no accurate means of detecting this type of fault exist.

The aim of the thesis is to gain an understanding of the electrical nature of the Source Isolated Earth Fault by understanding the dominant factors that affect the fault levels developed by this type of fault. Methods were developed to identify where these faults may be undetectable by conventional earth fault and Sensitive Earth Fault (SEF) protection schemes.

Peer reviewed methods were discovered during literature review and these were compared to verify the derived method.

Calculations were compared to results taken from an actual case study. The case study includes actual results from sophisticated metering installed on a feeder where one of these faults has occurred.

Sensitivity analysis was undertaken to ascertain the dominant factors which controlled the level of earth fault current. This knowledge was then applied to feeder topography to illustrate where this fault may be undetectable by conventional Sensitive Earth Fault protection.

A means of identifying where SEF protection pickups are not possible was developed by further analysis of the fault condition.

Further references to this type of fault in this document will refer to it as a source isolated earth fault (SIEF).

1.2 Overview of the Thesis

This thesis is organized as follows:

Chapter 1 provides an introduction to the Source Isolated Earth Fault, and describes an overview and scope of the thesis.

Chapter 2 describes the significant findings uncovered by the literature review and discusses the modelling methods employed in analysing the Source Isolated Earth Fault.

Chapter 3 discusses Matlab functions designed according to the peer reviewed models. A new model for the solution of the Source Isolated Earth Fault is derived. Testing of the models was carried out to find the significant factors that determine the severity of this type of fault. The models were also compared to ensure that the derived model is an adequate method for estimating the fault currents.

Chapter 4 compares the model results with an actual recorded case study. This provided confidence in the models before expanding their application to testing SEF pickup on entire feeders.

Chapter 5 applies the models to test SEF pickup on example feeders and analyses the results, the analysis culminates in a derivation of an extreme case that can be used to estimate the maximum level of earth current possible in the case of a Source Isolated Earth Fault.

Chapter 6 concludes the dissertation and recommends further work in the area of understanding the mechanical factors that are required to allow the Source Isolated Earth Fault to occur.

1.3 Project Objectives

The purpose and intent of the thesis is to;

- Model the broken conductor fault in an 11 kV overhead distribution feeder.

  (broken conductor near the line side of span such that only the load side of the broken conductor hits the earth, the line side is isolated).

- Investigate the circumstances where this fault is not detectable using 'traditional' EF/SEF protection schemes.

These objectives are investigated by performing the following;

1. Research the background information relating to the Source Isolated Earth Faults on 11kV radial distribution feeders.

2. Develop MATLAB code to model the behaviour of this particular type of fault.

3. Compare the models with calculations for calibration / accuracy check of the models.

4. Investigate the factors which influence the fault levels by carrying a sensitivity analysis on the models to find the dominant factors.

5. Apply the models to a case study of an actual fault on an 11kV feeder.

6. Investigate the likelihood of this type of fault occurring.

7. Derive conclusions and recommendations from any noteworthy discoveries.

The aims and objectives are stated in the project specification, which was developed in conjunction with and approved by the project supervisor at the beginning of the project. A copy of this specification is included in Appendix A of this report.

Chapter 2

Literature Review

2.1 Literature Review

Following is a summary of the relevant discoveries made during the literature review that assisted in the understanding of this project and provided some background information that assisted in formulating the thesis.

During the literature review it was discovered that two recent works explored this fault and provided methods for the calculation of fault currents developed in source isolated earth fault conditions. The following sections of the report describe the relevant discoveries of the literature review.

2.2 Conventional Earth Fault and Sensitive Earth Fault Protection

Earth Fault (EF) and Sensitive Earth Fault (SEF) schemes are employed in earthed transmission and distribution systems. One of the main purposes of applying a reference to earth for a system is so that the system will be able to develop enough (earth fault) current when an active conductor faults to earth to allow the protection to detect the fault and operate circuit breakers to isolate the fault.

Metering and protection equipment is installed in zone substations for the monitoring and protection functions. The protection equipment is isolated from the distribution voltages by means of Current Transformers (CTs) and Voltage Transformers (VTs). The CTs and VTs sample the high voltage distribution system currents and voltages (respectively). The CTs have a transformation ratio. The CT transformation ratio is the fixed ratio of current that the CT will provide as a sample to the protection circuits.

Distribution networks are based around a three phase system. This is a system of 3 separate conductors, which are electrically isolated from each other. As the mechanical means of creating energy for a three phase electrical system involves alternators with a rotating magnetic field inducing voltages on windings that are physically 120^0 apart on the stators. The voltages that are created on the three phase output are electrically 120^0 apart.

A common arrangement for the CTs is shown in Figure 2.1 (Horowitz & Phadke 2008). On any particular feeder CTs will be installed on each phase. The CTs will produce

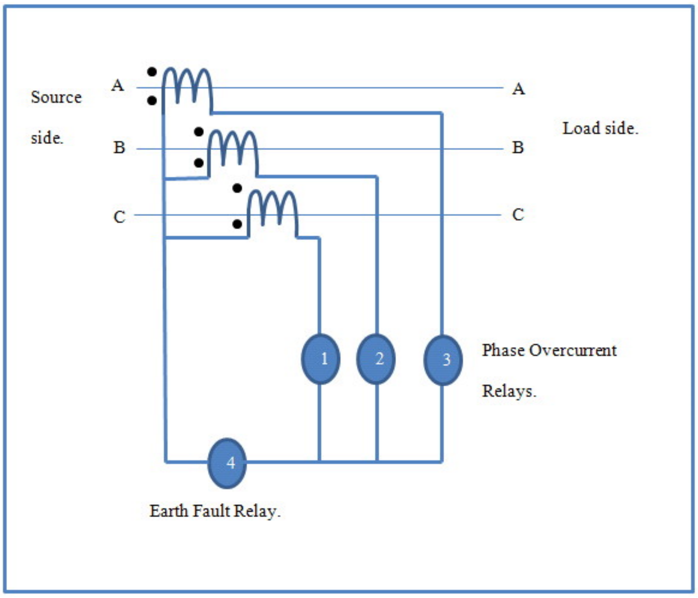


Figure 2.1: General CT arrangement for feeder CTs.

current in their secondaries to maintain the ampere-turn balance. 11kV distribution feeder CTs commonly have transformation ratios of 500:1. This means that 500 A in the primary (high voltage) circuit will be transformed into 1 A in the secondary protection circuits. The transformation is a linear response, so that protection settings can be achieved by applying the ratio directly (within specified limits of error).

Figure 2.1 shows a possible configuration of CTs to allow for conventional EF and SEF protection. The relay labelled 4 in this figure would be the position in the circuit for an EF/SEF relay. In this configuration the EF/SEF relay receives the sum of the three phase currents, providing it with a representation any earth fault current.

The SEF relay is set to lower values of pickup, than an EF relay. The pickup setting of a relay is the current that the relay will operate at. The pickup value referred to here will be in terms of the primary current. For the purposes of this thesis it was assumed that a 5A SEF pickup setting was the equivalent of 5 Amperes of primary current. As the SEF protection has the most sensitive (lowest) setting, it will be considered as the lower limit of when an earth fault will be detected by conventional protection schemes.

2.3 Non Conventional Protection

Non-conventional protection is outside the scope of this thesis. It is briefly mentioned here to highlight the fact that ongoing research us taking place in this field.

Literature was found describing alternative means for detecting high impedance faults (other than conventional EF/SEF protection schemes) (Al-Dabbagh, Daoud & Coulter 1989, Benner & Russell 1997, Sarlak & Shahrtash 2008, Sarlak & Shahrtash 2011, Torres G & Ruiz P 2011), however literature was also found that explained that the alternative methods where not suitably accurate due to a lack of discrimination, selectivity, or reliability (Li & Redfern 2001, Lukowicz, Michalik, Rebizant, Wiszniewski & Klimek 2010).

The alternate methods appear to be unreliable as they would not pick-up on known faults and they would also false-trigger sometimes. Tengdin, Baker, Burke, Russell, Jones, Wiedman & Johnson (1996) discussed various types of high impedance protection and found that they were approximately 80% effective.

Depew, Parsick, Dempsey, Benner, Russell & Adamiak (2006) carried out tests of detecting known faults by post processing the captured data and found that only 58% of downed conductors could have been detected.

Little information was given on the distances or the exact nature of the detected faults in the literature. This thesis looks to discover what are the major factors affecting the level of earth fault current in the specific case of a source isolated earth fault on 11kV distribution networks.

2.4 Sequence Components Methods

Methods have been developed to analyse networks to calculate the prospective fault currents for complicated fault situations (Mortlock 1947, Blackburn 1993, Burgess 2011). These methods build on the efforts of Fortescue (1918).

Some background information is necessary before embarking on explanations of these methods.

A method has been developed by Fortescue (1918) to use symmetrical components to assist in solving asymmetrical faults in symmetrical multi-phase systems. For the three phase power networks these components are the positive, negative, and the zero sequence components.

The sequence on a network can be determined by observing the order its phase values (voltage or current) reach their respective peaks. For example, in the power system there are three phases. The three phases are nominated A, B, and C. Any configuration whereby the phase voltages reach their maximum value in the order A, B, and then C, would be considered a positive phase sequence. Due to the cyclical nature of three phase networks a positive sequence network can equally be represented by CAB, or BCA as only the starting point changed, not the sequence. In a negative sequence the order of the phases would be reversed, ie ACB, BAC, or CBA depending on the starting point for observing the sequence. In a zero sequence the phases peak at the same time and are said to be in phase, as there is zero phase angle displacement between them.

As mentioned in section 2.2 the phase components in a three phase network are separated by an angle of 120 degrees. As the phase values have a magnitude and an angle, the phase values can be diagrammatically represented as vectors in a complex plane. For the purposes of this thesis the conventional anticlockwise rotation will be assumed for the determination of the sequence of phase values.

In a three phase network, in an unbalanced condition, the sequence components would appear as shown in the vector diagrams shown in Figure 2.2.

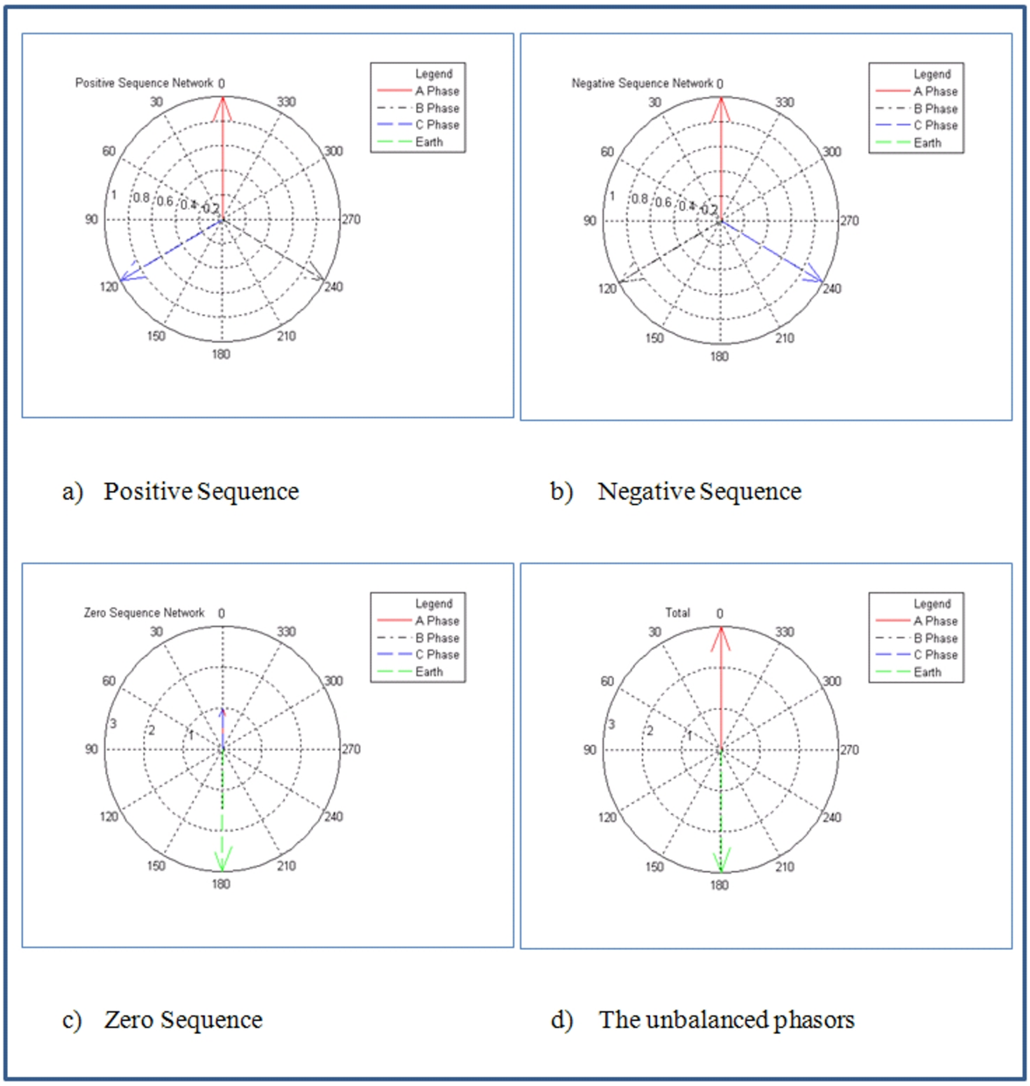


Figure 2.2: Sequence components of unbalanced phase values.

In the case of the positive sequence values, shown in Figure 2.2 a) the phase values will present in the order A, B, C as they rotate anticlockwise. The negative sequence values in Figure 2.2 b) will present in the order A, C, B. The zero sequence values appear all together in parallel as shown in Figure 2.2 c). Each of the sequences is a balanced set of three vectors (representing 3 voltages or currents). This balance refers to each vector in a sequence as having the same magnitude, the angle between phases is determined by the sequence.

Each vector within these sets is known as a phasor. Each sequence may be represented as one phase value only in calculations as the phase relationships to the other phasors are known. This allows for a simplification of the mathematics for unbalanced networks. An unbalanced situation shown in Figure 2.2 d) may be represented by three vectors, where each vector is a representation of a sequence group of 3 vectors. For consistency when sequences are represented in this way it is usual for each of the sequence components be represented by a vector of the same phase.

The sequences can be identified by using either a superscript +, -, or 0, or the numbers 1, 2, or 0 to represent the positive, negative or zero sequence current values as follows;

$$\begin{aligned} I^{+} &= I_1(positive\ sequence\ current) \\ I^{-} &= I_2(negative\ sequence\ current) \\ I^{0} &= I_0(zero\ sequence\ current) \end{aligned}$$

Likewise the superscripts/subscripts for voltages $V^{+} = V_1$, $V^{-} = V_2$, $V^{0} = V_0$ and impedance ($Z^{+} = Z_1$, $Z^{-} = Z_2$, $Z^{0} = Z_0$) follow the same pattern for the positive, negative and zero sequence values of these quantities.

For each network element, sequence impedances must be derived (Grainger & Stevenson 1994) or measured so that networks can be constructed for each of the sequences. For example, a line may have its positive sequence impedance measured by applying a three phase voltages to one end with the other ends shorted together, and measuring the currents. The negative sequence impedance may be measured using the same method, but swapping two phases. The zero sequence impedance would require all three lines to have exactly the same phase on each line, with the remote ends earthed, to carry out the test. In this way the sequence impedances reflect the behaviour of the network element with only that sequence of currents flowing through it.

The sequence impedances are then connected in various ways depending on the fault situation, so that the sequence currents can be calculated. Once the sequence currents are known, then the phase currents may be calculated by summation of each of the phase currents in each of the sequence groups. When sequence networks are connected to calculate sequence currents only the positive sequence network has a voltage source, and it is a positive sequence source. The voltage of the source is the pre-fault voltage on the network.

A total of nine sequence currents are required to fully describe an unbalanced set of three phase currents. As the phase angle relationship within each sequence group is known, only 1 of each sequence is calculated. This means that an unbalanced group of three phase currents can be described by one current from each of the sequences.

Mathematically the values can be converted between phase currents and sequence currents by the use of a couple of transformation matrices as follows:

To understand the matrix transformations it is necessary to introduce the a operator. The a operator is a mathematical representation of a rotation of 120^0 in the complex number plane (Horowitz & Phadke 2008).

$$\begin{aligned} a &= 1\angle 120^0 = -0.5 + i\frac{\sqrt{3}}{2} \\ a^2 &= 1\angle 240^0 = -0.5 - i\frac{\sqrt{3}}{2} \\ a^3 &= 1\angle 0^0 \quad = 1 \end{aligned}$$

If I_a, I_b, I_c are the A phase, B phase and C phase currents respectively, and $I^+, I^-, andI^0$ are the positive, negative and zero sequence currents then;

$$\begin{bmatrix} I^+ \\ I^- \\ I^0 \end{bmatrix} = \begin{bmatrix} 1\,, & a\,, & a^2 \\ 1\,, & a^2, & a \\ 1\,, & 1\,, & 1 \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2.1}$$

The transformation provided in equation 2.1 allows phase currents to be transformed into the sequence components. This transformation is provided in Matlab code funcPUPhase2Seq.m in Appendix B, Section B.12.

An inverse transformation is also available.

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1\,, & 1\,, & 1 \\ a^2, & a\,, & 1 \\ a\,, & a^2, & 1 \end{bmatrix} \times \begin{bmatrix} I^+ \\ I^- \\ I^0 \end{bmatrix} \tag{2.2}$$

The transformation provided in equation 2.2 allows sequence currents to be transformed into the phase currents. This transformation is provided in Matlab code funcPUSeq2Phase.m in Appendix B, Section B.13.

2.5 Burgess Model

Burgess (2011) describes a method for calculating the currents in a system where a broken conductor exists and either (or both) sides of a failed span provide an electrical circuit to ground.

Burgess (2011) included a neutral earthing impedance as this was the primary focus of that thesis, this was however easily accounted for and a modified circuit was easily derived by changing the impedance of this branch.

The Burgess model is rather complicated as it allows for the solution of a fault on either side of the broken span. This complexity results in a method involving 18 simultaneous equations to calculate the sequence currents that flow.

Burgess provided Matlab code for this method which could be used directly to solve the system and offered a means of comparison of the other methods discussed here.

2.6 Blackburn Model

Blackburn (1993) provides a method for the calculation of the currents when the Source Isolated Earth fault occurs. The mathematical method is simplified (in comparison the Burgess method) as only the Source Isolated Earth Fault is considered by this method.

One issue with this method is that the effect of fault impedance is not included. Therefore this method needs to be modified to include the effects of a fault impedance. It is necessary to develop Matlab code to model this calculation method.

2.7 Phase to Phase to Ground Fault Model

This method was discovered by circuit analysis of the fault schematic and reducing the circuit to provide a simplified circuit. The circuit simplification was ceased when the circuit resembled a phase to phase to ground fault as a method existed (Horowitz & Phadke 2008) to analyse this simplified situation.

Applying the standard arrangement of sequence components for a Phase to Phase to Ground Fault provided a simplified method of understanding the fault conditions.

The motivation for developing this model of the fault was that the phase to phase to ground fault appeared to be simplified compared to the Burgess and Blackburn models that each included transformers in the sequence circuits to represent similar current flows in different parts of the circuit. The phase to phase to ground model does not contain such contrivances, and as such is easier to understand without additional explanation.

No literature was found on the application of a phase to phase to ground method for the calculation of ground currents present in the case of a Source Isolated Earth Fault. The use of this method to solve the fault condition is considered one of the major research findings of this thesis. The steps to deriving this model are shown in the following chapter.

2.8 Consequences of Undetected Faults

In some circumstances a Source Isolated Earth Fault may result in an earth current that is too small to detect and as such the faulted conductor may remain alive on the ground (Curk & Koncnik 1999). Depew et al. (2006) reported that, in a two year period, Potomac Electric power Company (Pepco) documented 71 cases where downed conductors were not cleared by conventional protection (Depew et al. 2006).

Subsequent activity in the vicinity of the downed conductor by animals or humans could be dangerous or fatal (Toader, Blaj & Haragus 2007). Public education campaigns are run by electricity distributors to advise customers to stay away from fallen power lines (Essential Energy 2013).

Customers downstream of the downed conductor will experience quality of supply issues associated with the loss of one HV conductor. In the case of the Source Isolated Earth Fault the downed conductor *may* be close to earth potential if the fault impedance is sufficiently low. The downed conductor could also be at a voltage well above earth potential, up to a voltage approximately between the two healthy phase voltages. The resulting effect on the LV voltages will be one healthy phase to neutral voltage and two phases with significantly less than nominal voltage.

This situation is called a brown out. The low voltages *may* cause damage to some equipment if the brown out situation continues for some time. In cases where the protection fails to clear the fault customer initiated quality of supply complaints, or customer initiated reports of a wire down *may be* the only alert received by the network provider of the abnormal condition.

2.9 Frequency of Source Isolated Earth Faults

Source Isolated Earth faults are an extremely rare occurrence. A review of outage information provided by Essential Energy was undertaken to identify any HV conductor faults which *may* have been this type of fault.

Essential Energy provides energy services to over 800,000 homes and businesses in N.S.W. (Essential Energy 2013), through a network of over 200,000km of power lines. Essential Energy maintains over 1.4 million poles and 135,000 distribution substations. Essential Energy is responsible for electricity network covering approximately 95% of the state of New South Wales.

Network outage data was provided for the five year period from June 2008 to July 2013 (Gillespie & Matheson 2013). The fault information covered over 120,000 faults. Overhead conductors were reported on the ground in 3453 of these faults. Apart from the fault used for the case study in this thesis only two other faults were *possibly* source isolated earth faults, where the fault information indicated that this type of fault *may* have occurred. These two incidences were found to involve 22kV circuits, which are outside the scope of this thesis.

No reports of a Source Isolated Earth fault on 11kV circuits were found in the previous five years of data provided by Essential Energy for use in this thesis. The analysis of the outage data confirmed the rarity of this event.

Only two events where found at *any* voltage in the outage information provided. This confirms the assertion that the occurrence of this type of fault event is extremely rare.

Chapter 3

Modelling Methodologies

3.1 Building MATLAB models

Matlab was the software chosen for the creation of code to solve the mathematical calculations for the various models used in this thesis. Matlab is very versatile, powerful mathematical software. The program flow functions available in Matlab made it easy to deal with the matrix algebra required to solve some of the models.

To assist in the formulation of the function code for each of the modelling methods a common set of input arguments was required. The sensitivity analysis tested each of these system parameters in turn for a review of their significance. To facilitate this, the Matlab functions were given an input variable for each electrical element of the network. Most electrical elements required positive, negative and zero sequence components to fully describe the behaviour of the network element in each of the sequence networks.

Figure 3.1 shows a schematic representation of the fault condition. This schematic is the basic circuit for the fault and forms a common starting point for the models. The terms in this diagram are;

Zs_{PU} is the Source Impedance. The source was modelled as an infinite source feeding through the source impedance. The source impedance was a Thevinin equivalent impedance of the upstream network.

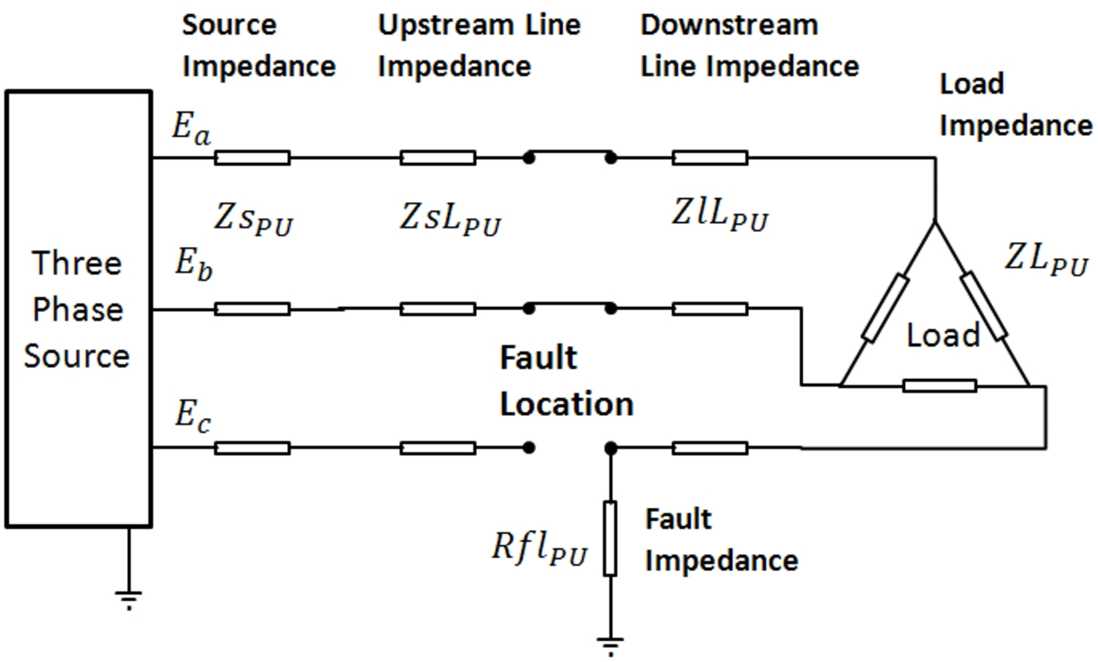


Figure 3.1: Schematic diagram of Source Isolated Earth Fault.

ZsL_{PU} is the PU impedances of the network, upstream of the fault location. ZsL_{PU} contains the positive, negative and zero sequence impedances.

ZlL_{PU} is the PU impedances of the network, downstream of the fault location. ZlL_{PU} contains the positive, negative and zero sequence impedances. The downstream network impedance used in the calculations was half of the actual network impedance. This takes into account the fact that the downstream network loads are distributed along the feeder. Halving the impedance provides a means of estimating the effects of distributed load by applying a lumped load at the end of half of the actual network impedance (Vempati, Shoults, Chen & Schwobel 1987).

ZL_{PU} is the PU impedances of the downstream load. The load impedance was assumed to be balanced across the available phases.

Rfl_{PU} is the label indicating the PU fault impedance.

Zcs_{PU} *and* Zcl_{PU} represent the upstream (Zcs_{PU}) and downstream (Zcl_{PU}) network capacitances as the equivalent PU impedances.

3.1.1 Building the Burgess Model

Burgess (2011) provided Matlab code for the solution of a broken conductor fault with a fault impedance to ground on either side of the broken conductor. The application in Burgess (2011) was related to the use of Arc Suppression Coils in the earthing circuit as an aid to detecting various high impedance faults. This detection method was interesting, and *may* show some promise, however it is outside the scope of this thesis. The provided method was adapted to the focus of this thesis very easily.

There were some inconsistencies noticed in the labelling of the original figure and the subscripts used in the math equations, however the Matlab code was correct. The inconsistencies were detected and corrected by going back to the work of Mortlock (1947) and correcting some minor typographical errors in Burgess. These corrections were also confirmed by comparison with the code provided by Burgess (2011).

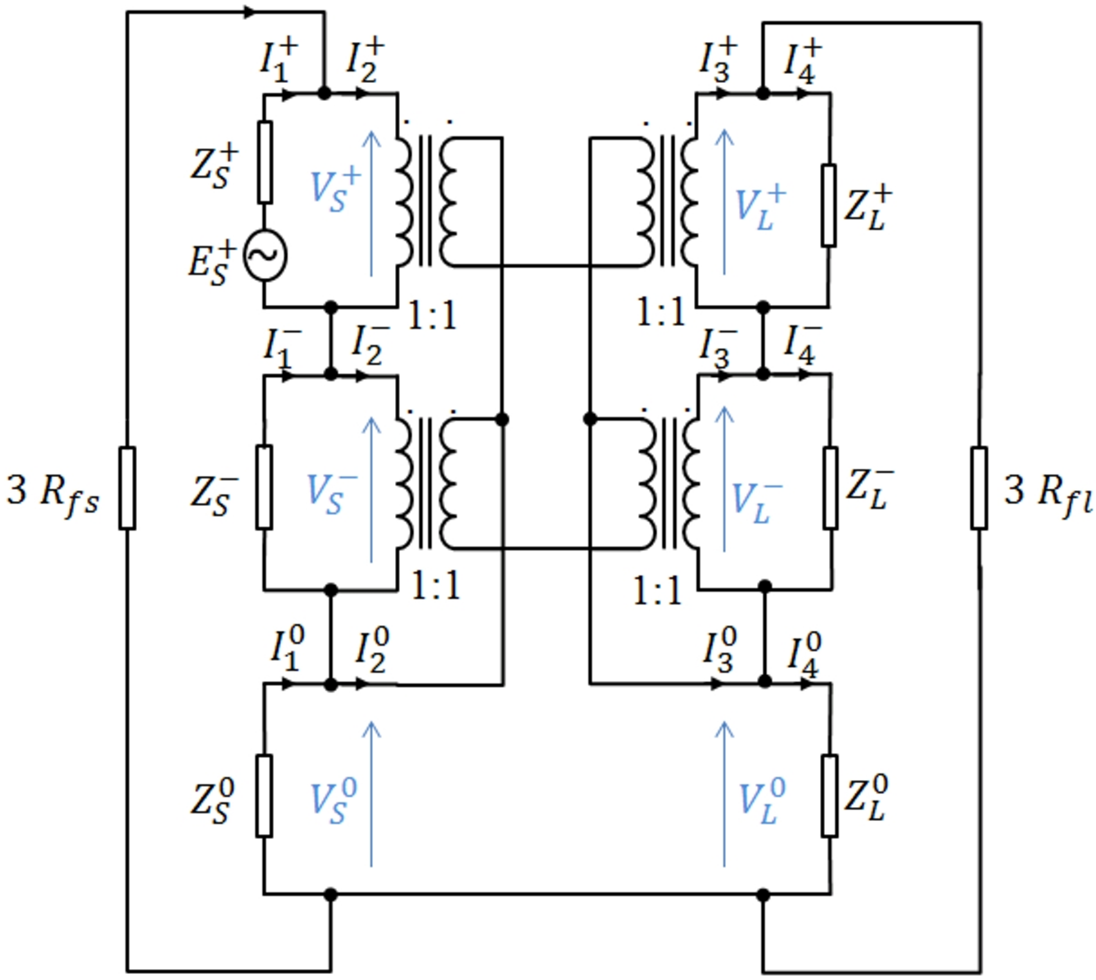


Figure 3.2: Sequence connections diagram (from the code in Burgess(2011)).

Table 3.1: Unknown quantities in Burgess model.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
I_1^+	I_1^-	I_1^0	I_2^+	I_2^-	I_2^0	I_3^+	I_3^-	I_3^0	I_4^+	I_4^-	I_4^0	V_S^+	V_S^-	V_S^0	V_L^+	V_L^-	V_L^0

Figure 3.2 shows the connections of the sequence networks as defined in the code. From Figure 3.2 it can be seen that there are 18 unknown symmetrical quantities in this representation of the sequence network connections. The unknowns are shown in Table 3.1.

The sequence currents are obtained by solving the system of 18 simultaneous equations (Burgess 2011).

The equations are as follows;

$$
\begin{aligned}
V_L^+ - I_4^+ Z_L^+ &= 0 && (3.1)\\
V_L^- - I_4^- Z_L^- &= 0 && (3.2)\\
V_L^0 - I_4^0 Z_L^0 &= 0 && (3.3)\\
V_S^+ - I_1^+ Z_S^+ &= E_S && (3.4)\\
V_S^- - I_1^- Z_S^- &= 0 && (3.5)\\
V_S^0 - I_1^0 Z_L^0 &= 0 && (3.6)\\
V_S^+ - I_4^+ Z_L^+ - V_S^- + V_L^- &= 0 && (3.7)\\
V_S^- - I_4^- Z_L^- - V_S^0 + V_L^0 &= 0 && (3.8)\\
I_1^+ - I_2^+ - \frac{V_S^+}{3R_{fS}} - \frac{V_S^-}{3R_{fS}} - \frac{V_S^0}{3R_{fS}} &= 0 && (3.9)\\
I_3^+ - I_4^+ - \frac{V_L^+}{3R_{fL}} - \frac{V_L^-}{3R_{fL}} - \frac{V_L^0}{3R_{fL}} &= 0 && (3.10)\\
I_2^0 + I_2^- + I_2^+ &= 0 && (3.11)\\
I_3^0 + I_3^+ + I_3^- &= 0 && (3.12)\\
I_1^- - I_2^- - \frac{V_S^+}{3R_{fS}} - \frac{V_S^-}{3R_{fS}} - \frac{V_S^0}{3R_{fS}} &= 0 && (3.13)\\
I_1^0 - I_2^0 - \frac{V_S^+}{3R_{fS}} - \frac{V_S^-}{3R_{fS}} - \frac{V_S^0}{3R_{fS}} &= 0 && (3.14)\\
I_3^- - I_4^- - \frac{V_L^+}{3R_{fL}} - \frac{V_L^-}{3R_{fL}} - \frac{V_L^0}{3R_{fL}} &= 0 && (3.15)\\
-I_4^0 + I_3^0 - \frac{V_L^+}{3R_{fL}} - \frac{V_L^-}{3R_{fL}} - \frac{V_L^0}{3R_{fL}} &= 0 && (3.16)\\
I_2^+ - I_3^+ &= 0 && (3.17)\\
I_2^- - I_3^- &= 0 && (3.18)
\end{aligned}
$$

The Matlab code from Burgess (2011) has been copied into a function in Matlab for calculations to be efficiently made. The Matlab function funcBurgess.m is included in Appendix B, Section B.4.

3.1.2 Building the Blackburn Model

Blackburn (1993) presented a calculation method for Source Isolated Earth Fault problems. The method offered by Blackburn (1993) is simpler than the complex model developed by Burgess (2011). This is due to the fact that Burgess allowed for a earth fault impedance on either side of the broken conductor whereas Blackburn allowed only for the downstream end of the conductor to come in contact with the earth.

The Blackburn model did not have an element to represent a fault impedance. For this thesis the fault impedance was required, if only for its significance to be tested in the sensitivity analysis. The Blackburn model was easily modified for this purpose as the fault impedance is in series with the source zero sequence impedance and therefore easily added to the sequence networks. This was almost trivial, but the method was included here for confirmation of the methods used.

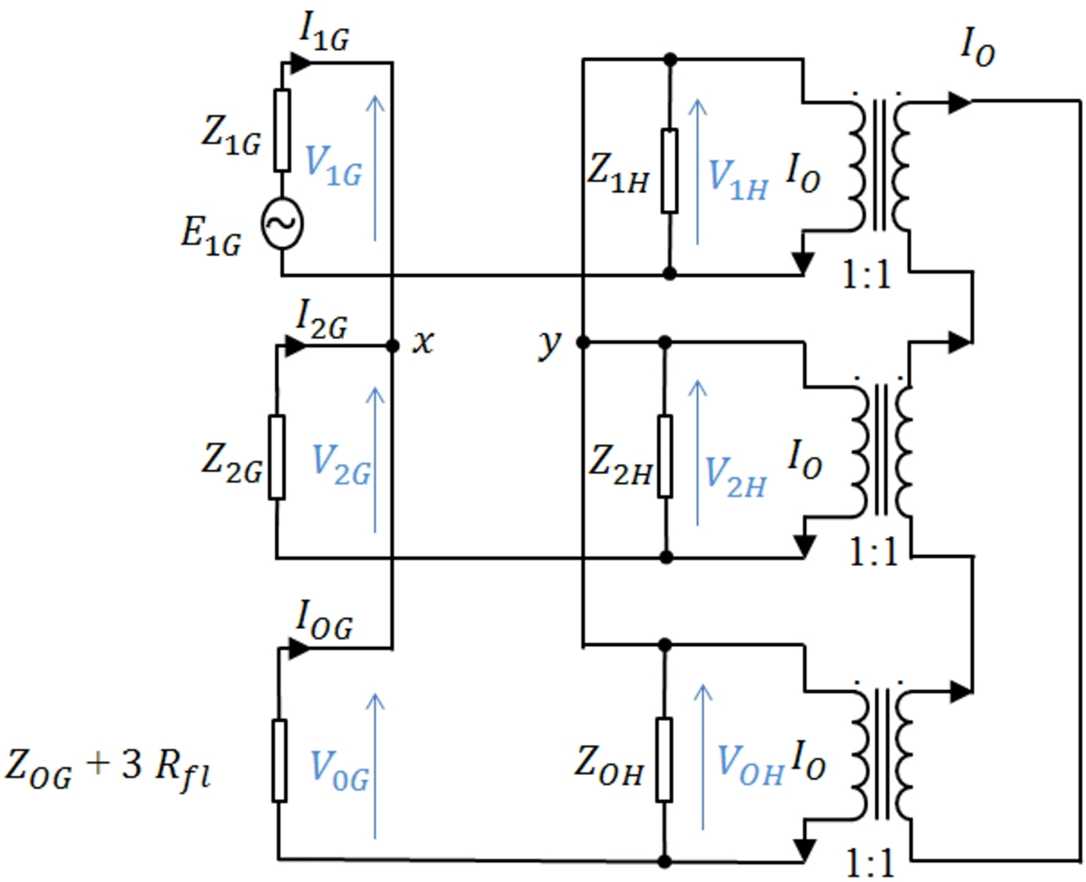


Figure 3.3: Sequence connections diagram from Blackburn(1993).

Figure 3.3 shows the sequence network connections recommended by Blackburn (1993) with the addition of three times the earth fault impedance in series with the source zero sequence impedance. The earth fault impedance was multiplied by three to allow for the fact that the sequence network is a single phase representation, however all three phases of zero sequence current flow through the earth fault impedance (Horowitz & Phadke 2008).

Blackburn used the labelling of the upstream network with a subscript G and the downstream network with a subscript H. Blackburn also used the subscripts 1, 2, and 0 to represent the positive, negative and zero sequence impedances respectively. The following equations are required in the function code to correctly assign the network impedances to the Blackburn method;

$$Z_{1G} = Zs^{+}_{PU} + ZsL^{+}_{PU} \tag{3.19}$$

$$Z_{2G} = Zs^{-}_{PU} + ZsL^{-}_{PU} \tag{3.20}$$

$$Z_{0G} = Zs^{0}_{PU} + ZsL^{0}_{PU} + 3\ Rfl_{PU} \tag{3.21}$$

$$Z_{1H} = ZlL^{+}_{PU} + ZL^{+}_{PU} \tag{3.22}$$

$$Z_{2H} = ZlL^{-}_{PU} + ZL^{-}_{PU} \tag{3.23}$$

$$Z_{0H} = ZlL^{0}_{PU} + ZL^{0}_{PU} \tag{3.24}$$

Once these assignments have been made the Blackburn equations can be implemented without modification. The Blackburn method consists of 9 equations as follows;

$$Zx = Z_{1H}(Z_{1G} + 2 * Z_{0G} + 3 * Z_{0H}) + Z_{0H}(Z_{0G} - Z_{1G}) \tag{3.25}$$

$$Zy = Z_{2H}(2 + 2Z_{0G}) + Z_{0H}(Z_{1G} + Z_{2G} + Z_{0G} + 6Z_{2H}) \tag{3.26}$$

$$I_{1H} = \frac{-Vs \times Zy}{Zx(Z_{1G} + Z_{2H}) + Zy(Z_{1G} + Z_{1H})} \tag{3.27}$$

$$I_{2H} = -I_{1H} \times \frac{Zx}{Zy} \tag{3.28}$$

$$I_{0H} = \frac{-(I_{1H} \times Z_{1H}) - (I_{2H} \times Z_{2H})}{Z_{0H}} \tag{3.29}$$

$$I_0 = -(\frac{1}{3} \times I_{1H} + \frac{1}{3} \times I_{2H} + \frac{1}{3} \times I_{0H}) \tag{3.30}$$

$$I_{1G} = -I_{1H} - I_0 \tag{3.31}$$

$$I_{2G} = -I_{2H} - I_0 \tag{3.32}$$

$$I_{0G} = -I_{0H} - I_0 \tag{3.33}$$

These equations are implemented in the Matlab function funcBBL.m to calculate the positive, negative, and zero sequence currents that flow under fault conditions. The Matlab function funcBBL.m is included in Appendix B, Section B.2.

3.1.3 Deriving the Simplified (Phase to Phase to Ground Fault) Model

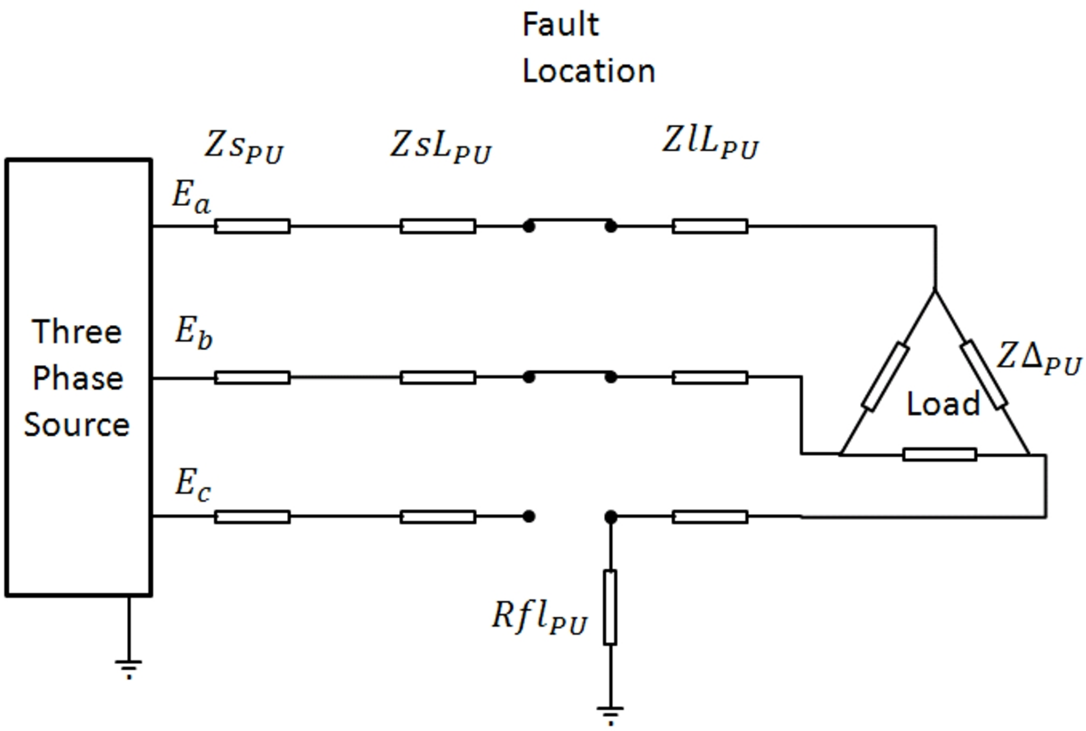


Figure 3.4: Schematic of three phase Source Isolated Earth Fault.

As mentioned in the literature review this model was derived and not found in peer reviewed literature. This method was included in this thesis so that the results from this method can be validated against the peer reviewed methods.

This method relies on the circuit reduction of the Source Isolated Earth Fault schematic diagram to a phase to phase to ground fault model. The phase to phase to ground fault is a common fault, and sequence diagrams have been established for the solution of fault currents under this fault condition (Horowitz & Phadke 2008).

Figure 3.4 shows the schematic diagram of the Source Isolated Earth Fault. Any phase can be faulted, however phase C is shown faulted here for ease of drawing.

Zs_{PU} is the source impedance (on the common base). This line may have different positive, negative and zero sequence impedances $Zs^{+}_{PU}, Zs^{-}_{PU}, Zs^{0}_{PU}$ respectively.

ZsL_{PU} is the impedance of the line on the source side of the fault (on the common base). This line may have different positive, negative and zero sequence impedances $ZsL^{+}_{PU}, ZsL^{-}_{PU}, ZsL^{0}_{PU}$ respectively.

ZlL_{PU} is the impedance of the line on the load side of the fault (on the common base). This line may have different positive, negative and zero sequence impedances $ZlL^{+}_{PU}, ZlL^{-}_{PU}, ZlL^{0}_{PU}$ respectively.

$Z\Delta_{PU}$ is the impedance of the load (on the common base). The load may have different positive, negative and zero sequence impedances $Z\Delta^{+}_{PU}, Z\Delta^{-}_{PU}, Z\Delta^{0}_{PU}$ respectively.

Rfl_{PU} is the impedance of the fault (on the common base).

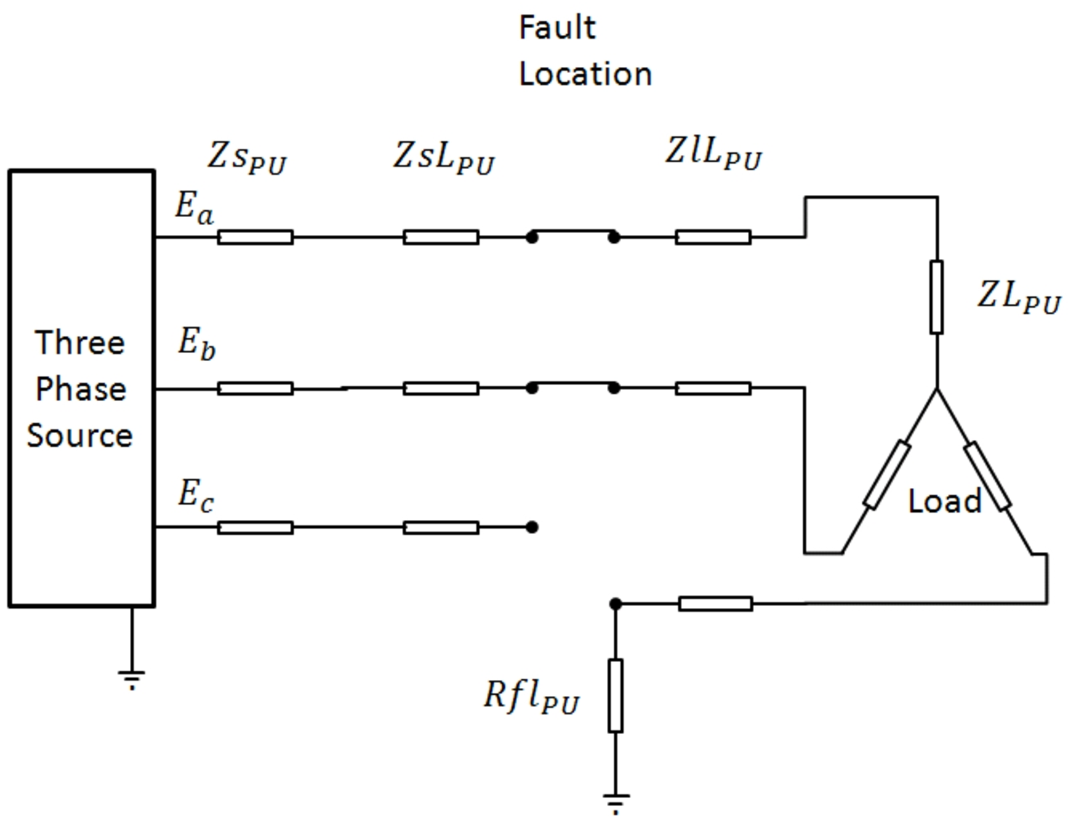


Figure 3.5: Fault schematic of Source Isolated Earth Fault with star equivalent load impedance.

The first step in simplifying the circuit shown in Figure 3.4 was to convert the delta load to a star equivalent by carrying out a delta to star conversion. Alternatively the impedance can be calculated from the load current and power factor to find an equivalent star connected impedance for the load.

The results of the delta to star conversion are shown in Figure 3.5. In this figure the star equivalent per-phase impedance of the load is labelled ZL_{PU}. Note that the star connected load does not have an earthed star point.

With the load in a star configuration, the impedances upstream of the fault location can be summed as they are in series, and the downstream impedances can be summed also as they are also in series.

The summed upstream impedances are labelled Z_{US}, and the summed downstream impedances are labelled Z_{DS}, in Figure 3.6.

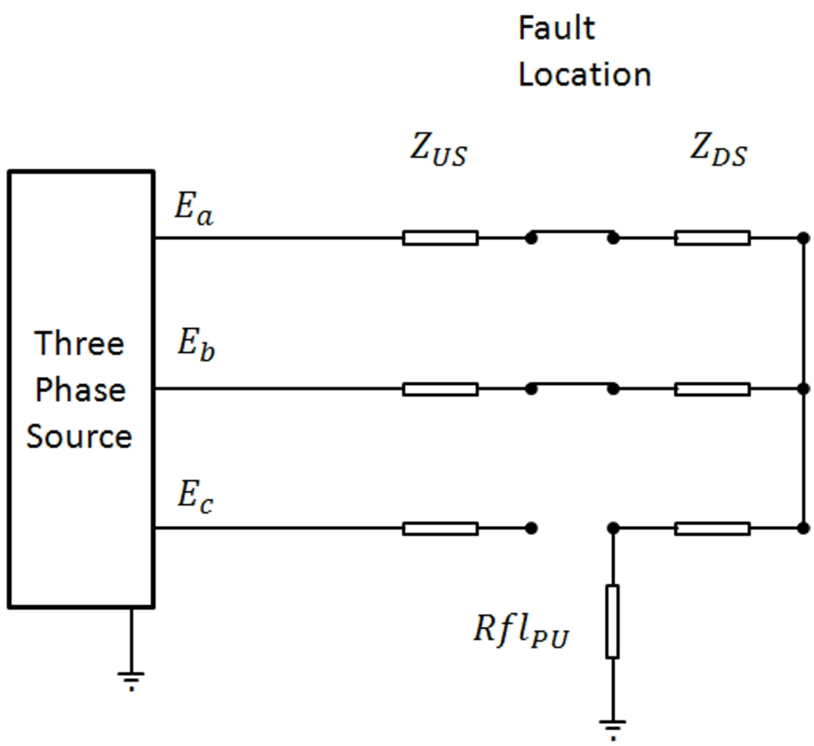


Figure 3.6: Fault schematic reduced by series addition.

Figure 3.6 shows a circuit that is similar to a phase to phase to ground fault. Figure 3.7 shows the phase to phase to ground equivalent diagram for the Source Isolated Earth Fault for comparison.

The conversion of the Source Isolated Earth Fault into the equivalent phase to phase to ground fault was a simple task. The resulting simplified circuit has a known so-

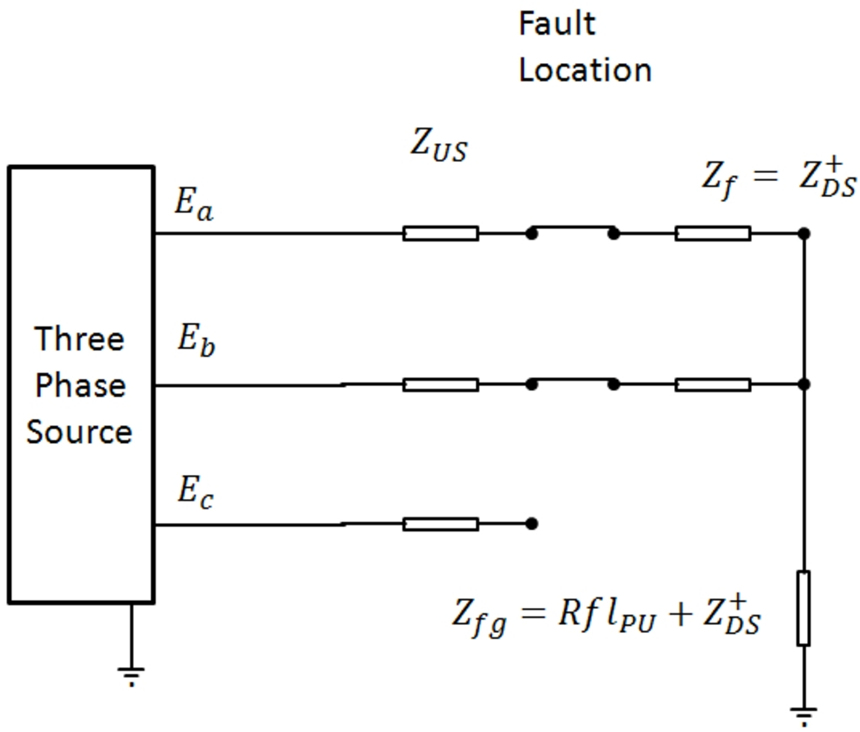


Figure 3.7: Fault schematic reduced to phase to phase to ground equivalent.

lution that is relatively simple compared with the Burgess and Blackburn solutions. The solution employed will be the phase to phase to ground method using sequence components (Horowitz & Phadke 2008).

In the Matlab script developed for this thesis, the load impedance was calculated in the star equivalent in the first instance, so the delta to star conversion is not necessary in the function used in this case.

$$Z_{US} = Zs_{PU} + ZsL_{PU} \tag{3.34}$$

$$Z_{DS} = ZlL_{PU} + ZL_{PU} \tag{3.35}$$

$$Z_f = Z_{DS}^+ \tag{3.36}$$

$$Z_{fg} = Rfl_{PU} + Z_{DS}^+ \tag{3.37}$$

Horowitz (2008) documents the sequence connections for a phase to phase to ground fault as shown in Figure 3.8. From Figure 3.8 the formulas for calculating the sequence current can be created. As the positive sequence network is the only network with an

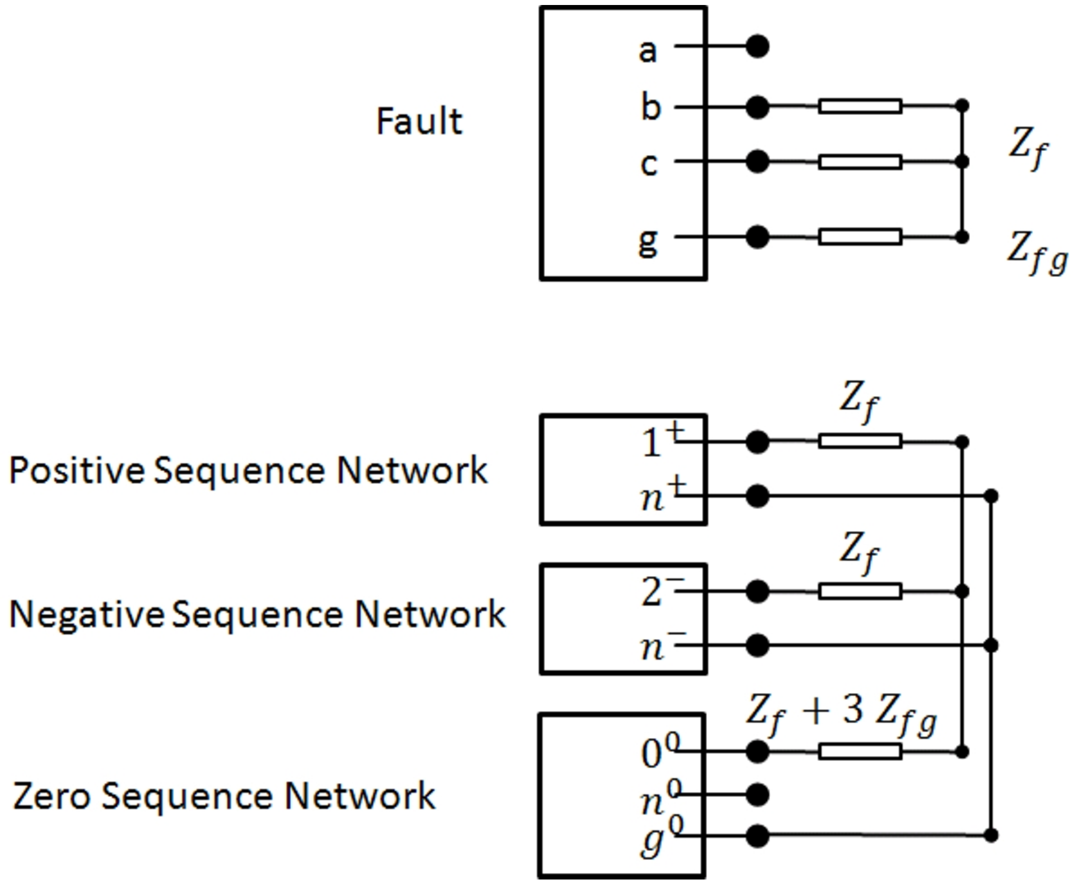


Figure 3.8: Sequence network connections diagram for phase to phase to ground faults.

active source, it must feed the other two networks in parallel.

$$Z_{Total} = ZUS^{+} + Z_f + \frac{(ZUS^{-} + Z_f)(ZUS^{0} + Z_f + 3Z_{fg})}{(ZUS^{-} + Z_f) + (ZUS^{0} + Z_f + 3Z_{fg})} \tag{3.38}$$

The positive sequence current must therefore be the supply voltage divided by the total impedance.

$$I^{+} = \frac{Vs}{Z_{Total}} \tag{3.39}$$

As the two other networks are in parallel, they share the current with the lowest impedance network drawing the most current.

$$I^{-} = -I^{+} \times \frac{(ZUS^{0} + Z_f + 3Z_{fg})}{(ZUS^{-} + Z_f) + (ZUS^{0} + Z_f + 3Z_{fg})} \tag{3.40}$$

$$I^{0} = -I^{+} \times \frac{(ZUS^{-} + Z_f)}{(ZUS^{-} + Z_f) + (ZUS^{0} + Z_f + 3Z_{fg})} \tag{3.41}$$

These equations are implemented in the Matlab function funcPPE.m to calculate the positive, negative, and zero sequence currents that will flow under fault conditions. The Matlab function funcPPE.m is included in Appendix B, Section B.10.

3.1.4 Line Capacitances Added to Models

Line capacitance can be included in the model of a line impedance in various ways. For the analysis in this thesis it was assumed that the nominal-Π method (Grainger & Stevenson 1994) is adequate. It was noted that a similar method was applied in Burgess (2011).

To ensure consistency across the models in this thesis a similar method was employed by all of the models.

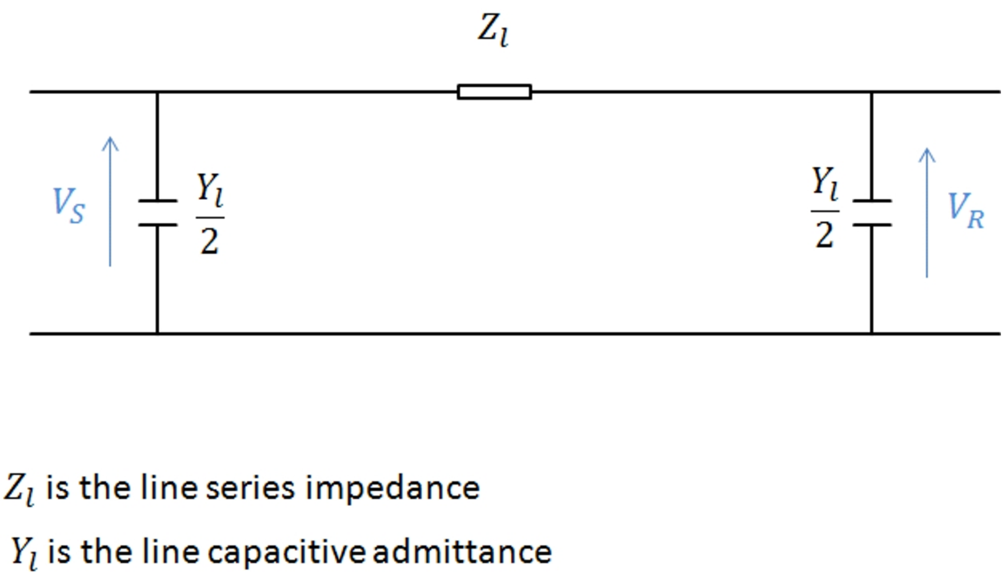
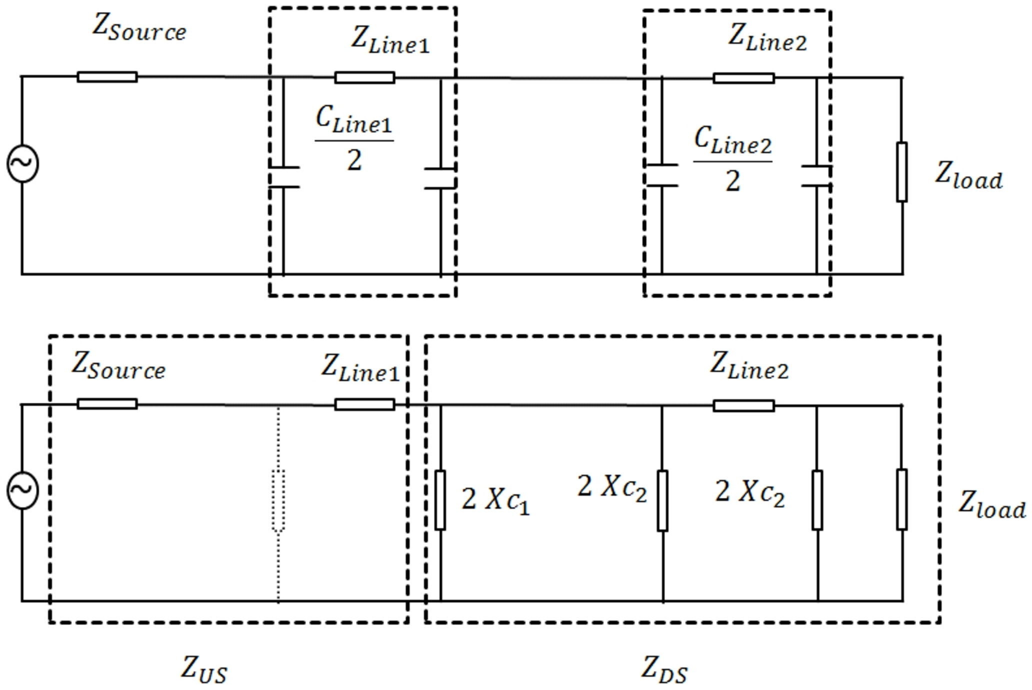


Figure 3.9: Nominal Π circuit of a medium length transmission line.

Figure 3.9 shows a method for the application of line capacitance to a model of a medium length transmission lines (Grainger & Stevenson 1994).

The schematic circuit for the Source Isolated Earth fault has two line impedances in series with the load. In this case the impedances of the capacitances can be combined. As the capacitance at the beginning of the first line was in parallel with the source in the positive sequence network and shorted in the negative and zero sequence networks, it was ignored. The remaining impedances are grouped into the upstream and downstream impedances by applying the series and parallel combinations of those impedances as appropriate.



$Z_{US} = Z_{Source} + Z_{Line1}$

$Z_{DS} = (2\,Xc_1 \backslash\backslash 2Xc2)\ \backslash\backslash(Z_{Line2} + 2\,Xc\_2 \backslash\backslash\ Z\_load)$

where \\ is the equivalent of being in parallel with.

Figure 3.10: Circuit simplification to include line capacitance.

Figure 3.10 illustrates the simplification of the line impedances to include the line capacitance of the lines. New models were created to include the effect of line capacitances in each model. The method utilised to include the effect of line capacitance was the same in each case to maintain consistency. The function name of these new models are similar to before with a suffix of WLC added to each function name to signify that they calculated the results With Line Capacitance.

These functions appear in Appendix B, funcBBLWLC.m is in Section B.3, funcBurgess-WLC.m is in Section B.5 and funcPPEWLC.m is in Section B.11.

3.1.5 Single Phase Model

Analysis carried out thus far in this thesis has been on three phase networks. Single phase network is also commonly employed, by utilising two wires only of the three phase network. Single phase is often used for spurs in lightly loaded areas. Single phase is utilised on the extremities of feeders. For complete coverage of distribution feeders, analysis of the source isolated earth fault would then also require analysis of the two wire single phase condition.

The single phase model was developed following the method developed in section 3.1.3 of this thesis. The fault schematic was reduced to the equivalent of a single phase to ground fault. The known solution (Horowitz & Phadke 2008) for a single phase to ground fault was then used to solve for the fault currents.

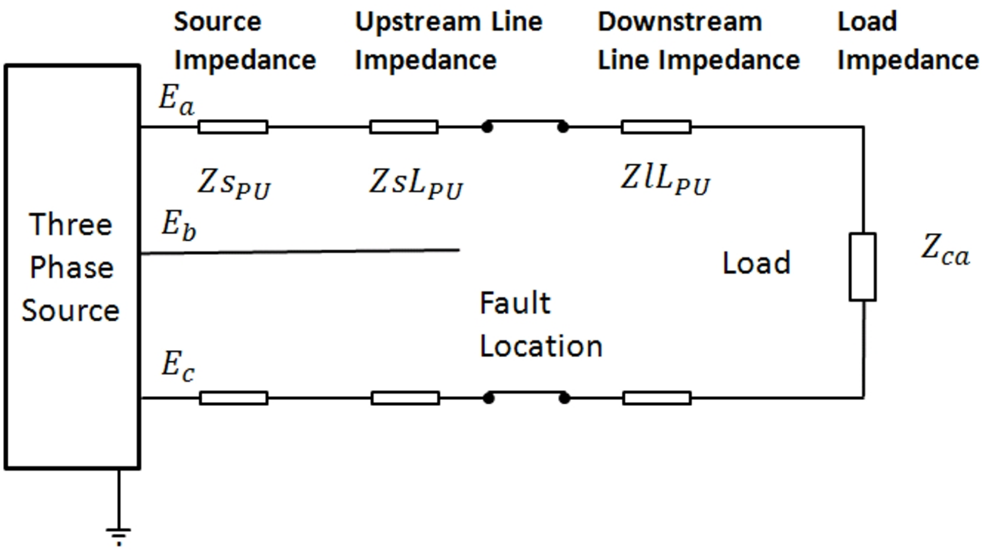


Figure 3.11: Single phase network schematic.

Figure 3.11 shows the schematic for a normal single phase network. Single phase network can be comprised of any two phases from a three phase system. Phases A and C are used in the figure for ease of drawing.

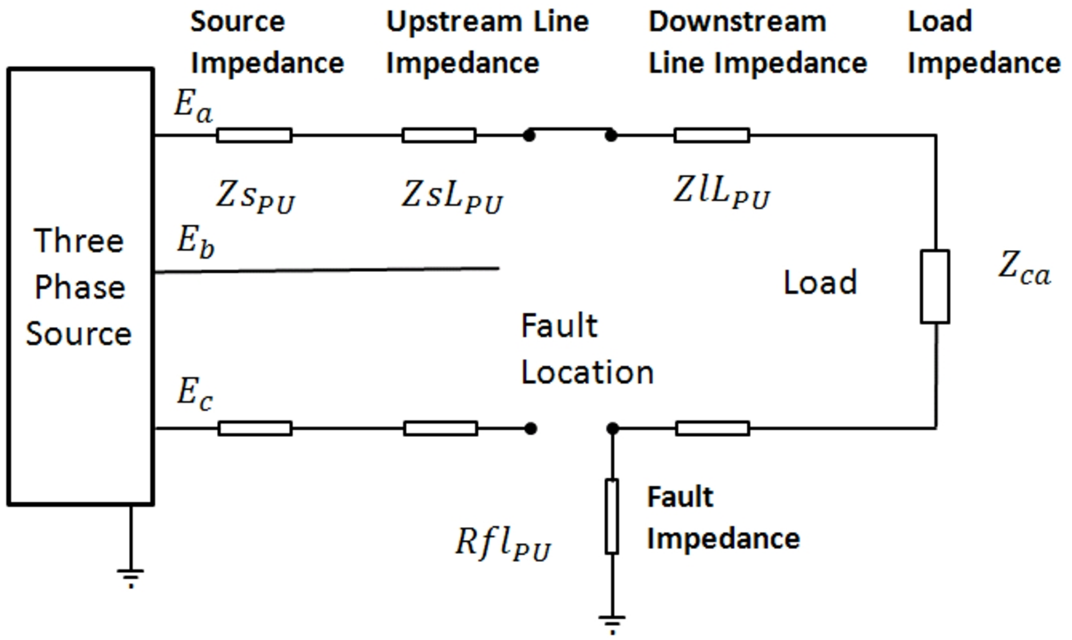


Figure 3.12: Single phase Source Isolated Earth Fault schematic.

Figure 3.12 shows the schematic diagram of the faulted system. In this case the C phase is shown faulted for ease of drawing. The single phase network is simpler to understand (than the three phase circuit) as the resulting circuit is a series circuit of all impedances as shown in Figure 3.12 . In Figure 3.13 the impedances are separated into the upstream and downstream impedances as for the three phase network for consistency across the methods. This consistency makes the function logic consistent.

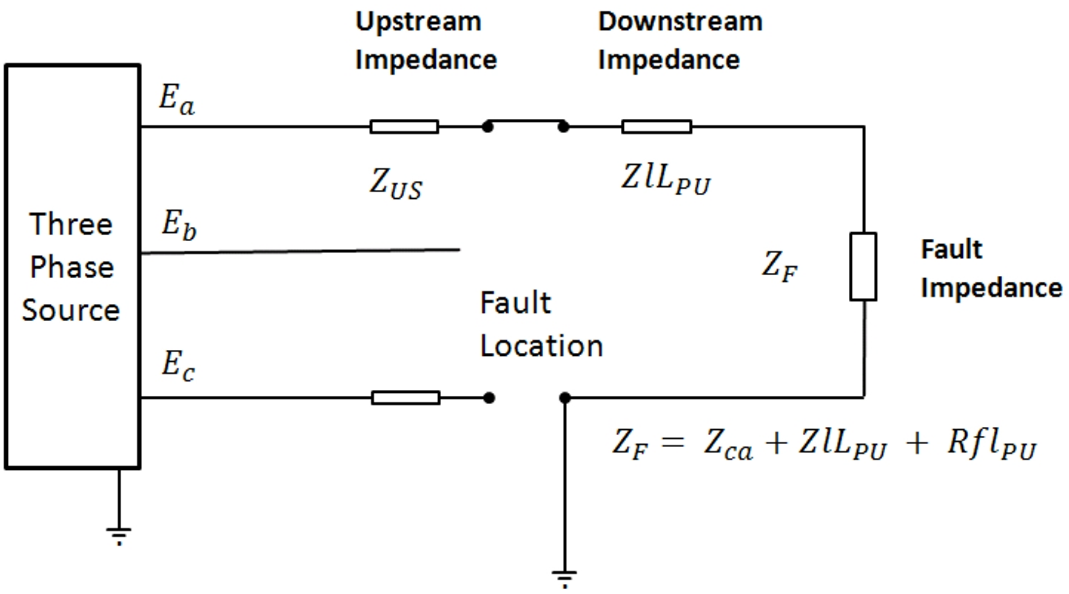


Figure 3.13: Fault schematic reduced to the equivalent of a phase to ground Fault.

Figure 3.13 shows the circuit reduction necessary for the single phase model. The impedances are collected into the upstream impedance, the downstream impedance and the fault impedance.

$$Z_{US} = Zs_{PU} + ZsL_{PU} \tag{3.42}$$

$$Z_{DS} = ZlL_{PU} \tag{3.43}$$

$$Z_F = Z_{ca}^+ + ZlL_{PU}^+ + Rfl_{PU}^+ \tag{3.44}$$

Horowitz (2008) documents the sequence connections for a phase to ground fault as shown in Figure 3.14.

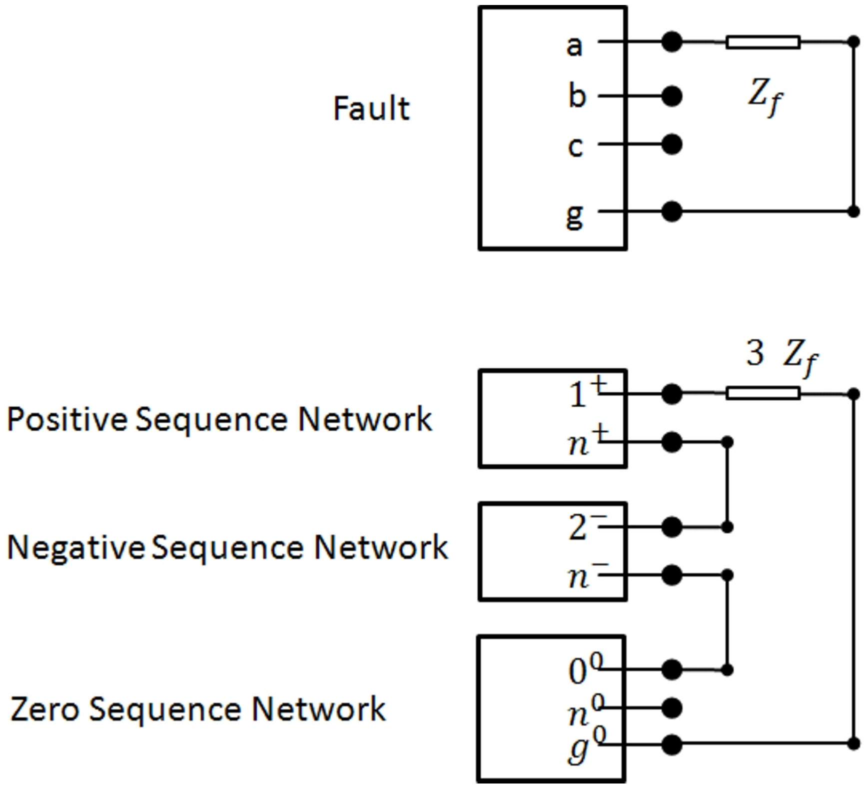


Figure 3.14: Sequence network connections diagram for phase to ground faults.

From Figure 3.14 the formulas for calculating the sequence current can be created. As the positive sequence network was the only network with an active source it must feed the other two networks in series with three times the fault impedance.

$$Z_{Total} = Z_{US}^{+} + Z_{DS}^{+} + Z_{US}^{-} + Z_{DS}^{-} + Z_{US}^{0} + Z_{DS}^{0} + 3Z_F \tag{3.45}$$

As the sequence impedances are connected in series, all sequence currents must therefore be equal to the supply voltage divided by the total impedance.

$$I^+ = I^- = I^0 = \frac{Vs}{Z_{Total}} \tag{3.46}$$

These equations are implemented in the Matlab function funcSPE.m to calculate the positive, negative, and zero sequence currents that will flow under fault conditions. The Matlab function funcSPE.m is included in Appendix B, Section B.14.

3.2 Sensitivity Analysis

The sensitivity analysis was performed to carry out two important checks;

1. To test each variable (factor) that was used in the calculation of the Source Isolated Earth Fault, to ascertain which of the factors were the most significant in determining the level of earth fault current resulting from this type of fault.
2. To ensure that the derived (phase to phase to ground) model provides a reasonable estimation of the fault in all tested situations.

The sensitivity analysis was considered more rigorous testing than the case study carried out in chapter 4 of this thesis, as the sensitivity analysis compared results across many points whereas the case study was only carried out on 1 scenario. The sensitivity analysis compared results across all three models for more than 4000 scenarios.

The procedure for the sensitivity analysis was to select a fault scenario, and vary each of the input factors to the functions from 0.2 to 10 times the chosen values and monitor the results from each of the functions. The functions will be compared with each other to check that the models give similar results in each case, and also the effect of varying each factor will be monitored to ascertain which of the factors has the most effect on the results.

The One Factor at A Time (OFAT) (Czitrom 1999) testing will be used to identify the most significant factors in the calculation methods. Further testing will be undertaken as designed experiments on the significant factors to test for any adverse effects of varying multiple factors at a time.

The Matlab script built to perform the OFAT testing is SensitivityAnalysis.m it is included in Appendix B, Section B.17.

3.2.1 OFAT Testing

The OFAT testing requires a starting point for all of the calculations. A starting point was chosen for each factor (variable) that allowed for a sensible range of likely inputs for each of the input variables. The chosen factors are listed here with an explanation of the choice of the starting point, and a graph of the results.

OFAT Results for Pre-Fault Voltage

The nominal source voltage was represented by a source voltage of 1 PU. This was the value chosen for the starting point of the OFAT testing. It was expected that the variation of voltage will create a linear characteristic curve.

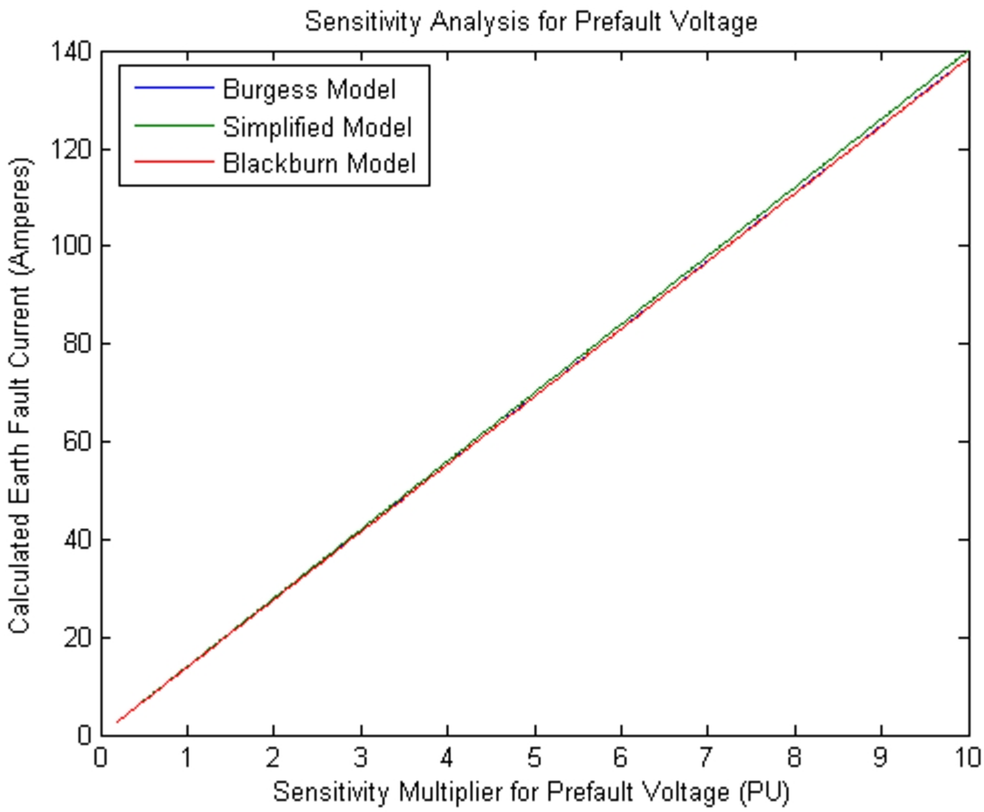


Figure 3.15: OFAT results for pre-fault voltage.

The results of varying the source voltage from 0.2PU to 10 PU are shown in Figure 3.15.

As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.58% when compared to the Burgess method.

This result was trivial, as the OFAT test in this case was testing the variation of a voltage that supplies a fixed circuit of impedances. The resultant curve approximated a straight line and indicated that the system followed Ohms law. The applied voltage of a distribution network is not likely to vary significantly as in this test. The variation of voltage was dropped from further testing.

Source Impedance

The source impedance chosen for the OFAT testing was the same source impedance as for the case study. This source impedance was supplied by the planning department of Essential Energy (Gallaher & Arnull 2013) and therefore was considered realistic. The variation of the source impedance during the OFAT testing provided insight into the effect of placing the fault models at different locations in the network.

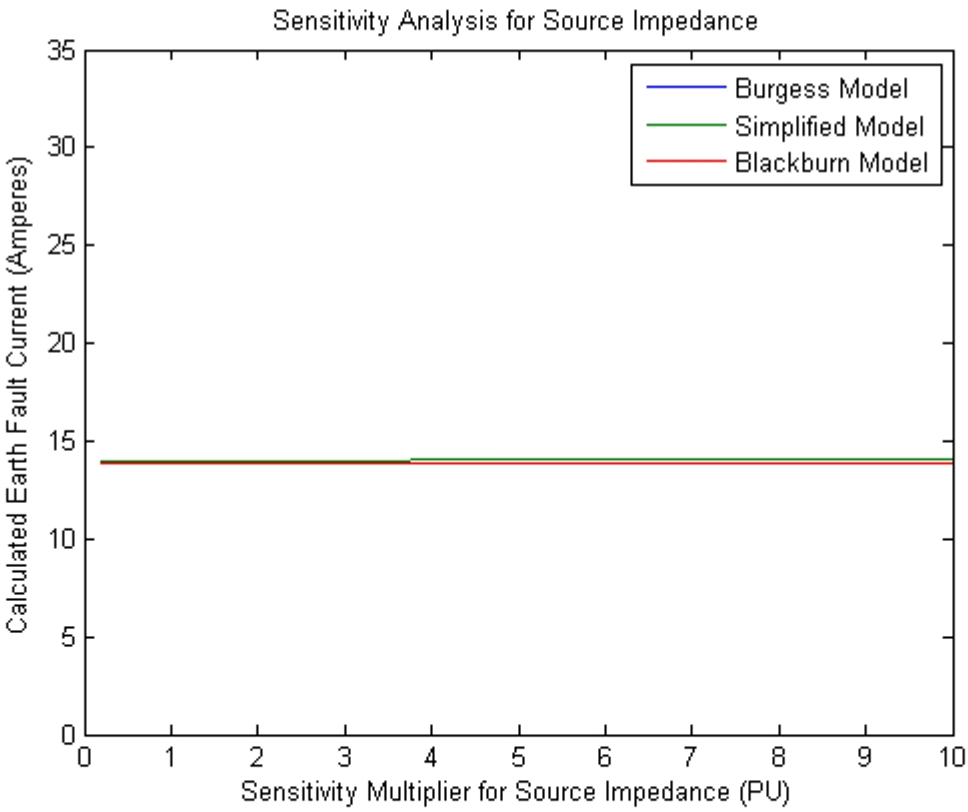


Figure 3.16: OFAT results for source impedance

The results of varying the source impedance are shown in Figure 3.16. As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.06% when compared to the Burgess method.

The results showed that varying the source impedance had very little effect on the fault current in this type of fault, with a variation of only 0.03 Amperes across the entire field of results for this testing application. This was due to the source impedance being very small in comparison to the other network impedances. The dominant factors were discovered elsewhere.

Source impedance was not considered to be an important factor in analysing this type of fault. This factor was not tested in the second stage of testing.

Network Line Impedances

The network line impedances were carefully selected to allow for a wide range of valid feeder lengths. Feeders vary in length from short CBD feeders to long rural feeders. The selection of the network impedances were based on impedances provided by the planning department of Essential Energy (Gallaher & Arnull 2013). The provided line impedances provided the positive and zero sequence impedances of the lines, negative sequence impedances were assumed to be the same as the positive sequence impedances.

The OFAT testing allowed for a maximum feeder length of 440km, and using an equal amount of the conductor impedances provided. The starting point of the feeder model for the OFAT testing used 8 km of each of the provided impedances for 7/2.50AAAC, 7/3.00AAAC, 7/3.75AAAC, 7/4.50AAAC and 19/3.75AAAC conductor. This allowed for the unaltered model to model a fault half way along an 80km (short) feeder, with an equal mix of conductors. The maximum feeder length during OFAT testing was 440km, with one of the impedances at 40km and the other at 400km. This tested the effects in long feeders, short feeders and with the fault at varied locations along the feeder.

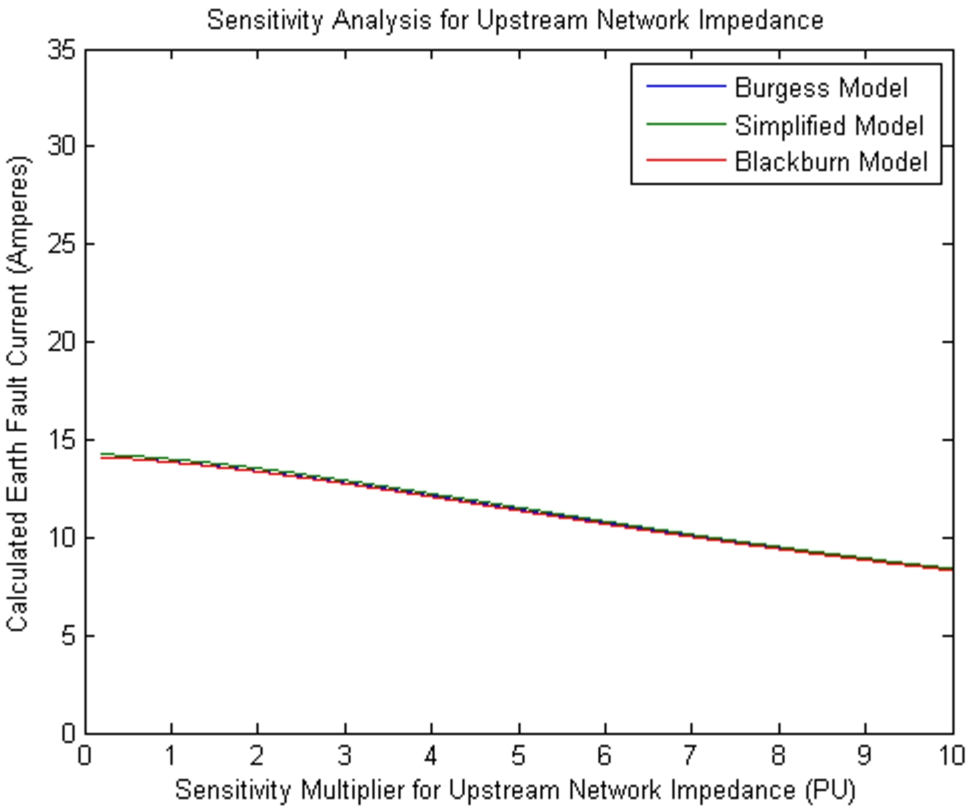


Figure 3.17: OFAT results for upstream network impedance

The results for OFAT testing of the Upstream Network impedance is summarised in Figure 3.17. As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.06% when compared to the Burgess method.

The variation of the upstream network impedance had a noticeable effect on the results, with a variation of 5.86 Amperes across the entire field of results for this testing application.

This was due to the upstream network impedance being significant, compared to the other network impedances. This was identified as one of the dominant factors in determining the level of fault current. This factor was tested further in the next stage of testing.

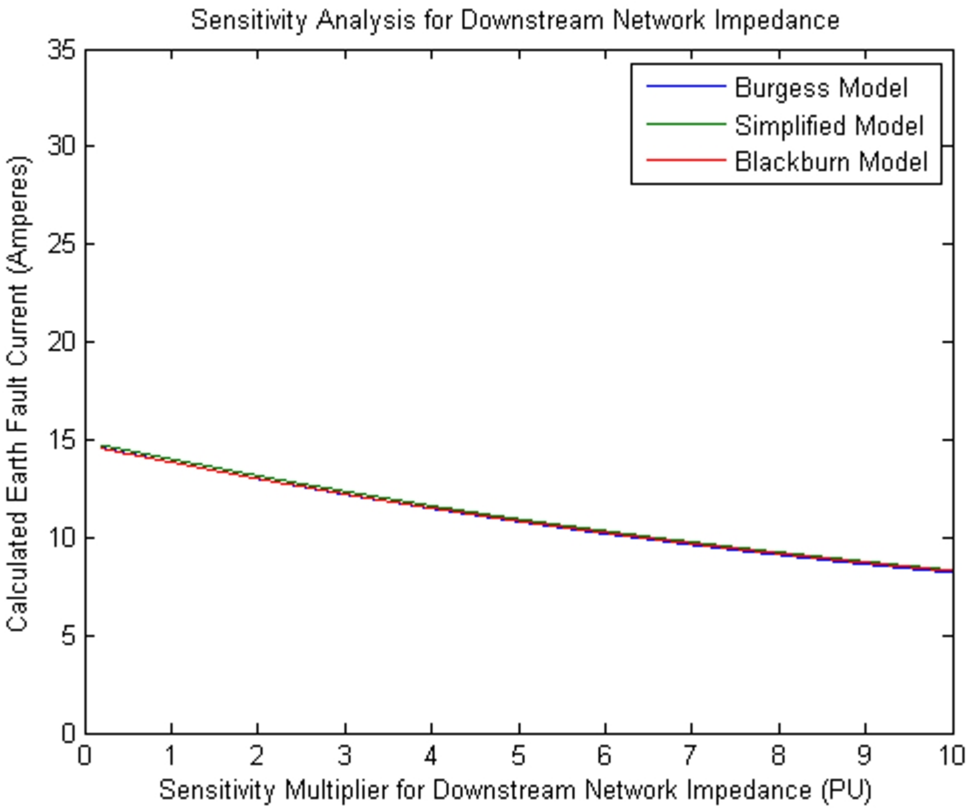


Figure 3.18: OFAT results for downstream network impedance

The results for OFAT testing of the downstream network impedance is summarised in Figure 3.18. As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.06% when compared to the Burgess method.

The variation of the downstream network impedance had a noticeable effect on the results, with a variation of 6.4 Amperes across the entire field of results for this testing application.

This was due to the downstream network impedance being significant, compared to the other network impedances. This was identified as one of the dominant factors in determining the level of fault current. This factor was tested further in the next stage of testing.

Network Line Capacitances

In a similar way to the line impedances the line capacitance was provided in a dictionary of conductors for the OFAT testing. The line capacitance used was for more than just the direct path from the source to the fault on the source side, as the capacitance of other lateral branches is also present. In a similar way the downstream network capacitance includes the capacitance of the lateral spurs as well as the direct path to the end of the feeder.

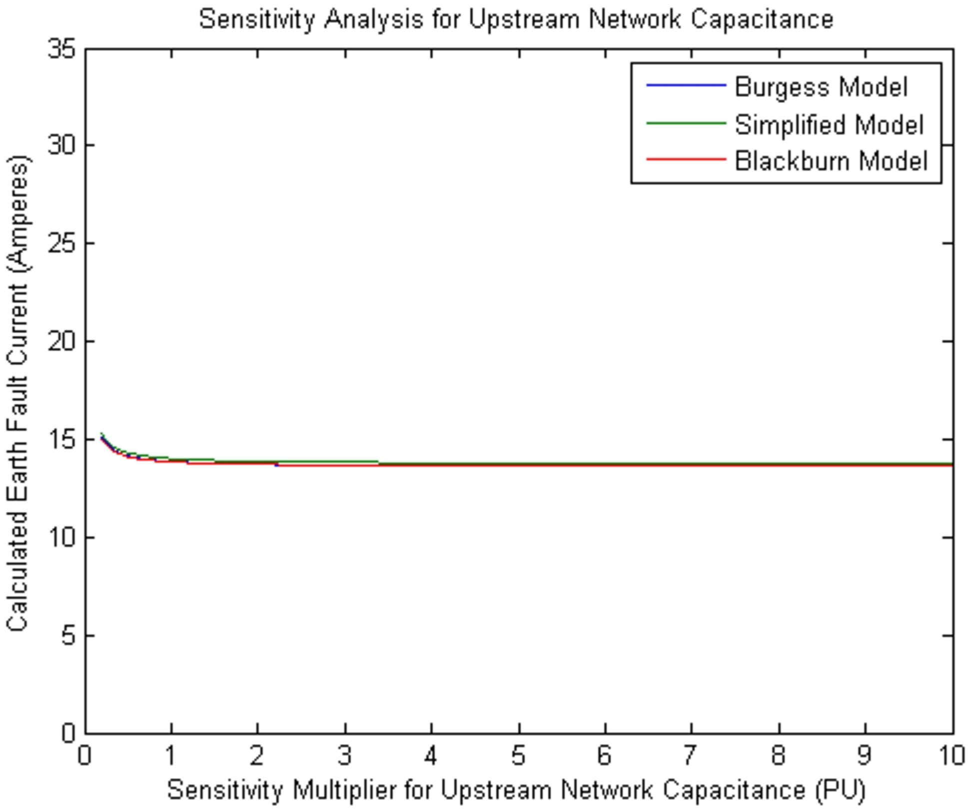


Figure 3.19: OFAT results for upstream network capacitive reactance..

The results for OFAT testing of the upstream network capacitance is summarised in Figure 3.19. As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.14% when compared to the Burgess method.

The variation of the upstream network capacitance did not have a noticeable effect on the results, with a variation of 1.55 Amperes across the entire field of results for this testing application.

This was due to the upstream network capacitance being less significant than the other network impedances. This was not identified as one of the dominant factors in determining the level of fault current. This factor was not tested further in the next stage of testing.

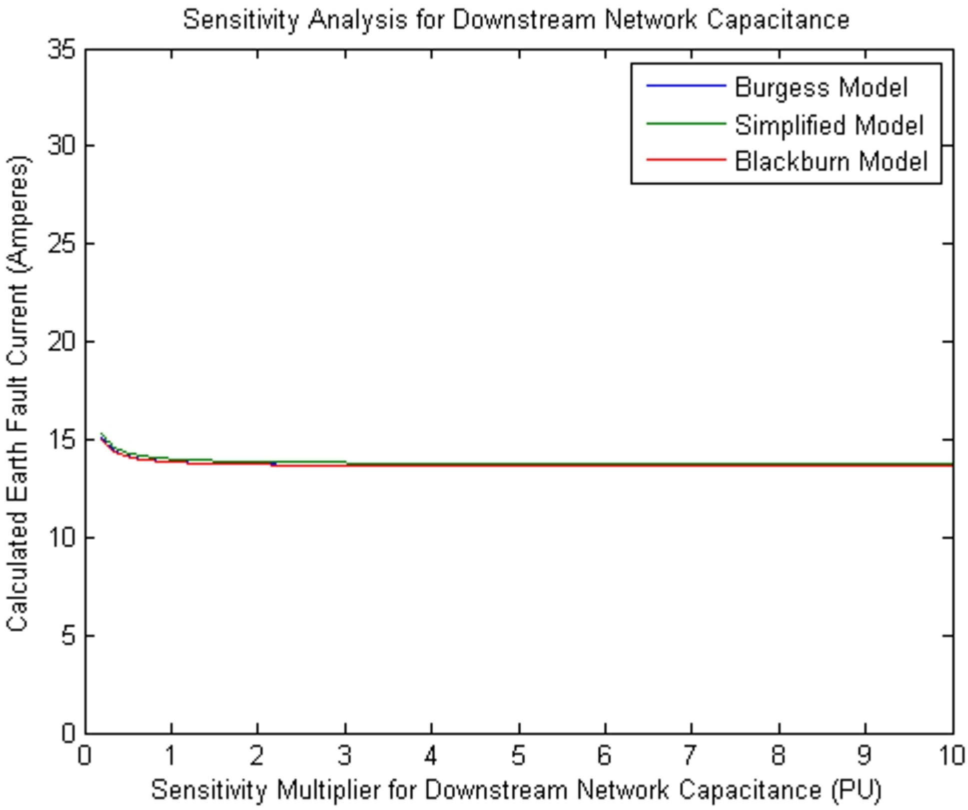


Figure 3.20: OFAT results for downstream network capacitive reactance.

The results for OFAT testing of the downstream network capacitance is summarised in Figure 3.20. As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.16% when compared to the Burgess method.

The variation of the downstream network capacitance did not have a noticeable effect on the results, with a variation of 1.59 Amperes across the entire field of results for this testing application.

This was due to the downstream network capacitance being less significant than the other network impedances. This was not identified one of the dominant factors in determining the level of fault current. This factor was not tested further in the next stage of testing.

Downstream Load Impedance

The downstream load impedance selected for OFAT testing was chosen to correspond with 50 A load current beyond the fault location. This value was chosen to allow the OFAT testing to test the range of 5 to 250A of load current beyond the fault location.

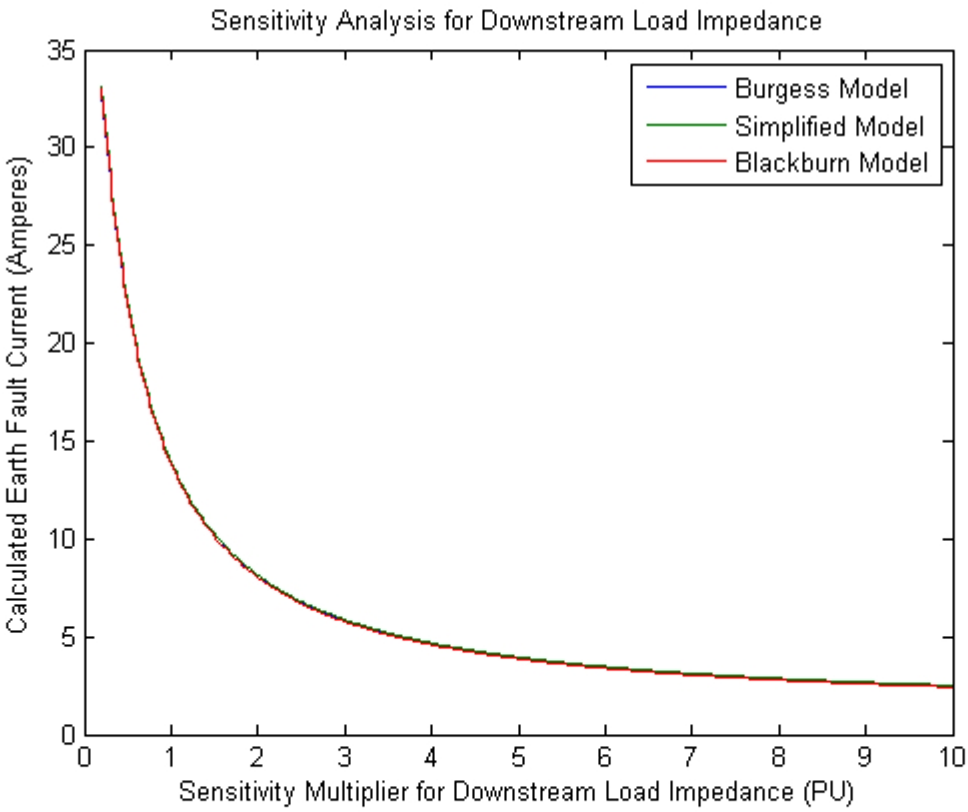


Figure 3.21: OFAT results for downstream load impedance.

The results for OFAT testing of the downstream load impedance is summarised in Figure 3.21. As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.12% when compared to the Burgess method.

The variation of the downstream load impedance had a noticeable effect on the results, with a variation of 30.6 Amperes across the entire field of results for this testing application.

This was due to the downstream load impedance being significant, compared to the other network impedances. This was identified as the dominant factor in determining the level of fault current. This factor was tested further in the next stage of testing.

Fault Impedances

As the Burgess model allowed for a source side fault as well as the load side (source isolated) fault, two fault impedances were passed to the functions. As the scope of this thesis only includes the load side (source isolated) earth fault, the source side fault impedance was assumed to be infinity. Infinity was not possible to represent directly in the code, so the source side fault impedance was set to 1 E99 which was considered sufficiently large to represent the impedance of an open circuit even at the extremes of OFAT testing. No results of the OFAT testing are provided for the source side fault impedance, as it is not within the scope of this thesis.

For the load side (source isolated) fault impedance, a value of 30 Ohm was selected in accordance with Essential Energy policy (Essential Energy 2012). The resulting OFAT range of fault impedances tested was 6 to 300 Ohms.

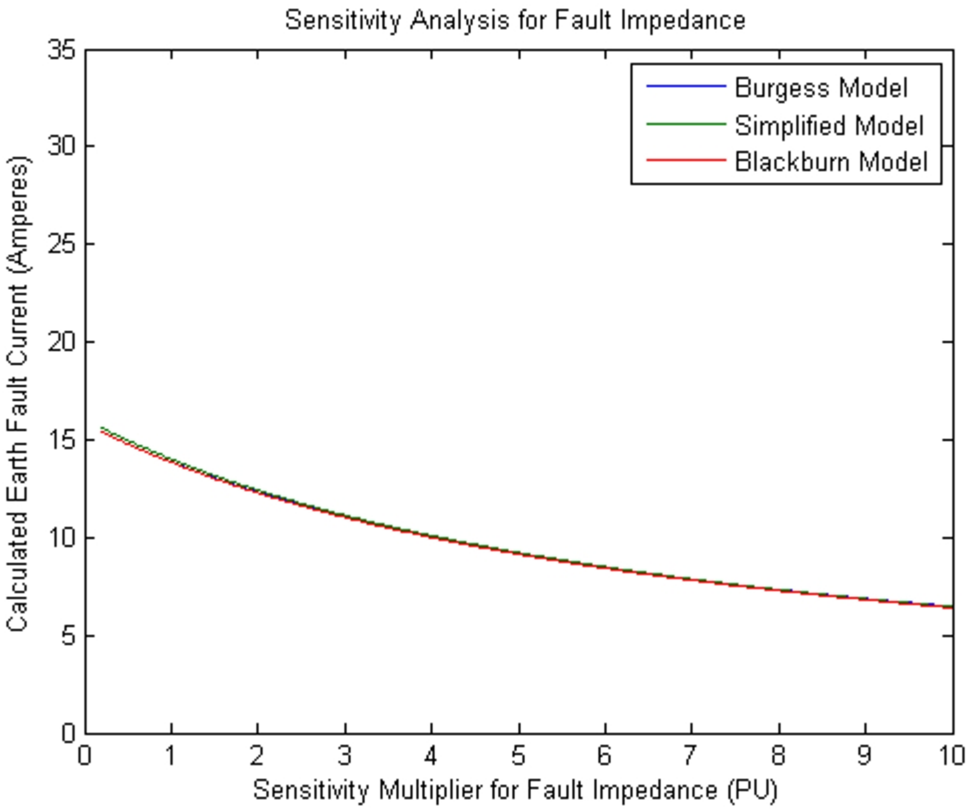


Figure 3.22: OFAT results for fault impedance.

The results for OFAT testing of the fault impedance is summarised in Figure 3.22. As expected the results of all three methods were similar. Analysis of the results found that the maximum statistical variance between the models was 0.08% when compared to the Burgess method.

The variation of the fault impedance had a noticeable effect on the results, with a variation of 9.2 Amperes across the entire field of results for this testing application.

This was due to the fault impedance being significant, compared to the other network impedances. This factor was tested further in the next stage of testing.

Summary of Results of OFAT Testing

OFAT testing was employed to identify the dominant factors in the Source Isolated Earth Fault, and to confirm the methods employed provide similar results. This confirmed both the application of the methods to the task and the coding of those methods to be suitably accurate to estimate the earth fault current developed during one of these faults.

Table 3.2: Summary of OFAT results.

	Source Voltage	Source Z	US Line Z	US Cap Z	US Fault Z	DS Line Z	DS Cap Z	DS Load Z	DS Fault Z
Variation (A)	137.3	0.03	5.86	1.55	0	6.39	1.59	30.63	9.16
Max Error (%)	0.58	0.06	0.06	0.14	0.06	0.06	0.16	0.12	0.08
Ranking	Not Ranked	7	4	5	8	3	6	1	2

Note: US = Upstream, DS = Downstream, Z = Impedance, Cap = Capacitive

The results of the OFAT testing are summarised in Table 3.2.

The maximum statistical variance between the methods was 0.58%. The simplified method was considered to be an adequate means of estimating the earth fault current under the conditions of a source isolated earth fault.

The OFAT testing allowed the factors to be ranked in order of significance. The most significant factor was found to be the load impedance beyond the fault location. The four most significant factors were concentrated on in a second stage of analysis. The second stage of analysis carried out experiments to determine any interaction between the significant factors.

3.2.2 Designed Experiments

Designed experiments (Czitrom 1999) provide a means to examine the interaction between factors in complex models. OFAT testing concentrated on varying all factors, one at a time over a large range of input possibilities to find the significant factors in the models. The designed experiments vary multiple factors at the same time to identify if there are any interactions between the input factors that produce unexpected results.

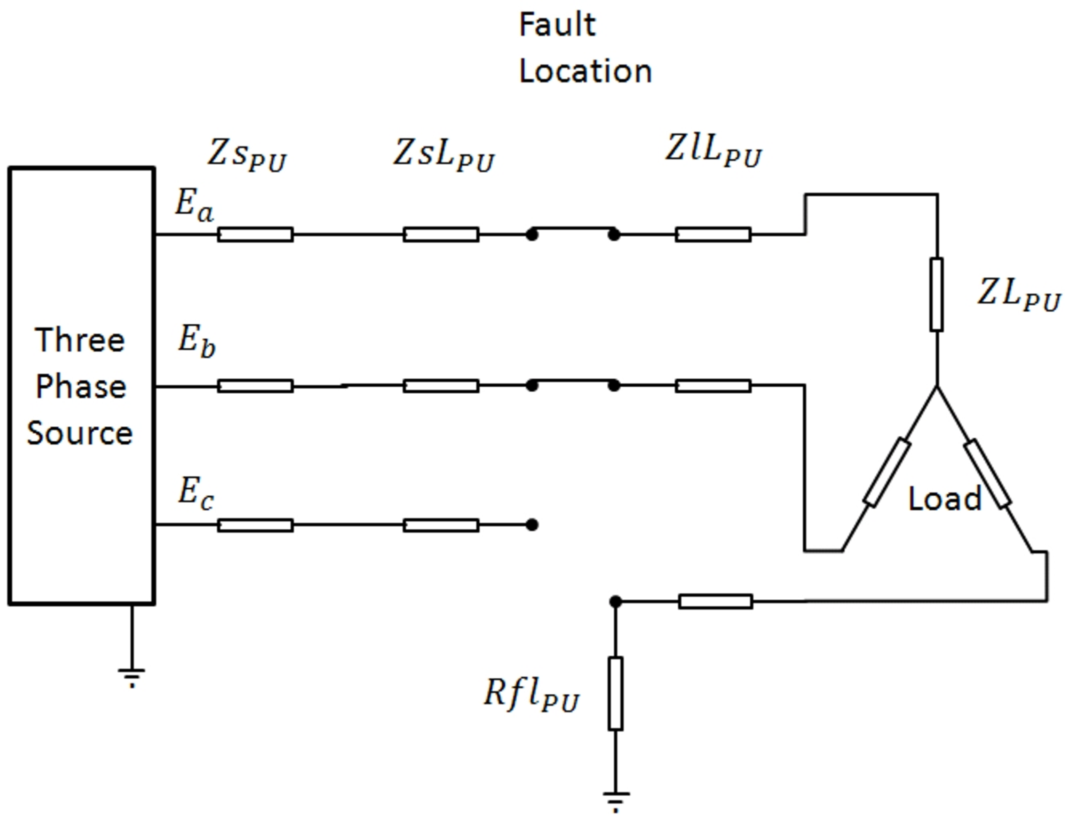


Figure 3.23: Source Isolated Earth Fault schematic.

As many factors were manipulated together a lesser variation in the input factors was allowed. This was due to the added complexity in calculating and displaying the results. The four most significant factors identified in the OFAT testing were selected for testing in the designed experiments.

Figure 3.23 shows the schematic of the source isolated earth fault. In this testing regime the focus was on the following four major factors (All in PU on the common base);

1. ZsL_{PU} was the impedance of the line on the source side of the fault.
2. ZlL_{PU} was the impedance of the line on the load side of the fault.
3. ZL_{PU} was the impedance of the load.
4. ZlL_{PU} was the impedance of the line on the load side of the fault.

For the designed experiments the multiplication factors varied from 1 to 2 in steps of 0.1 all factors were varied and the results for all possible combinations were recorded and graphed. This created a 4 dimensional array.

Displaying the 4 (mathematical) dimensions on a three dimensional graph was not easy. To build toward this three dimensional data was built on 10 separate graphs. The graphs were then combined into the output graph.

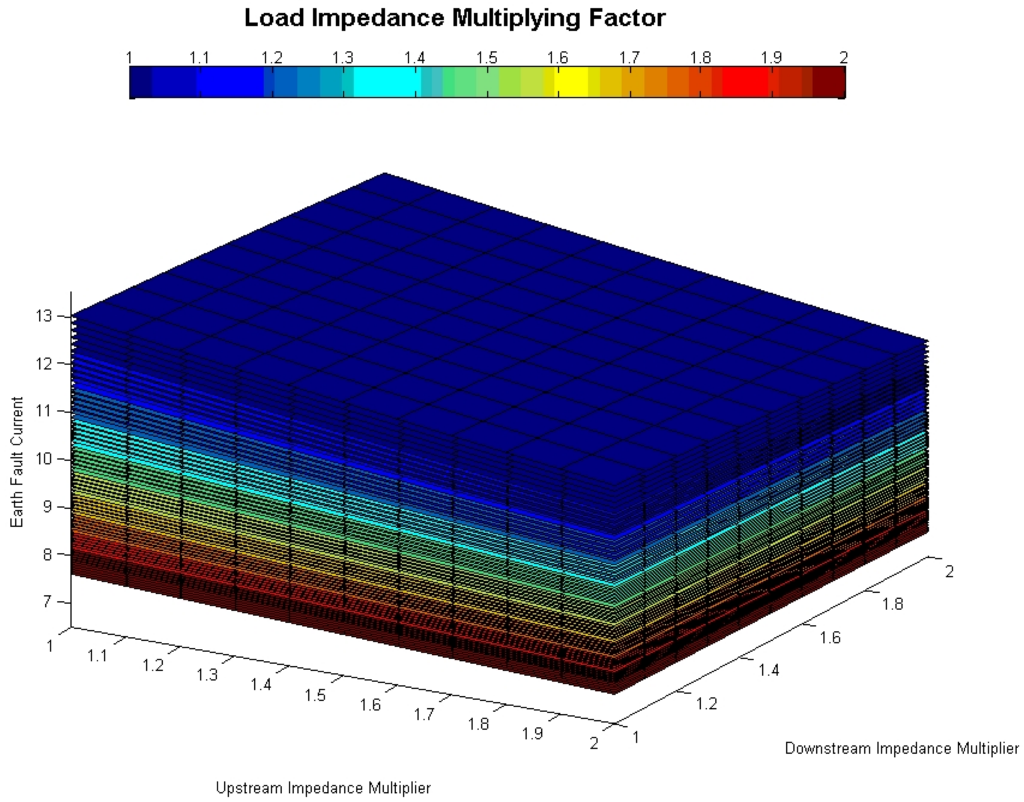


Figure 3.24: Combined graph of 10 variations in upstream, downstream, load and fault impedances.

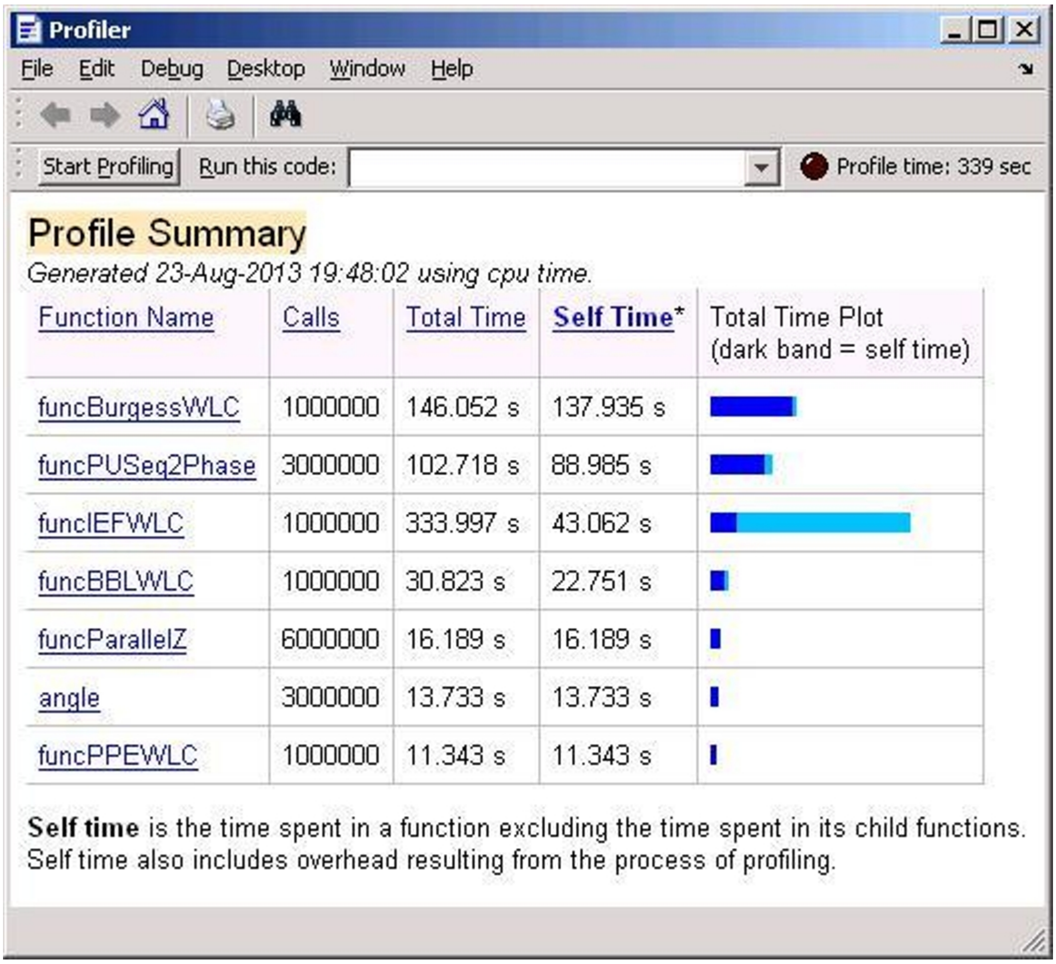
Figure 3.24 shows the combined results of the multi-variable analysis. The results were grouped by colour for the load impedance factor. In each group the fault impedance factor varied from 1 to 2 in ten steps.

The results trivially proved that higher impedance draws less current. The load impedance remained the dominant factor in the multi-variable analysis. The combined graph showed no adverse interactions between factors.

The Matlab script built to perform the designed experiments is MultiVariableAnalysis.m it is included in Appendix B, Section B.16.

3.2.3 Code Profiling

Matlab provides built in code profiling functions. Profiling allows the user to view the total time that the code spends in each function. The first attempts at profiling the code for this thesis looked at the time for the OFAT testing. It was discovered that the results were erratic due to the relative short time for the processes to occur on modern computers.



Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
funcBurgessWLC	1000000	146.052 s	137.935 s	
funcPUSeq2Phase	3000000	102.718 s	88.985 s	
funcIEFWLC	1000000	333.997 s	43.062 s	
funcBBLWLC	1000000	30.823 s	22.751 s	
funcParallelZ	6000000	16.189 s	16.189 s	
angle	3000000	13.733 s	13.733 s	
funcPPEWLC	1000000	11.343 s	11.343 s	

Self time is the time spent in a function excluding the time spent in its child functions. Self time also includes overhead resulting from the process of profiling.

Figure 3.25: Matlab profiler results.

To stabilise the profiling data The Matlab program was restricted to use only one processor (according to the method provided in MATLAB Help) and the process was run 1 million times so that adequate data could be gathered. All other non-essential software was shut down on the workstation during the profile test.

Figure 3.25 shows typical results obtained from running the source isolated earth fault functions 1 million times on the same input data. The functions of interest are funcBurgessWLC (137.935 s), funcBBLWLC (22.751 s) and funcPPEWLC (11.343 s).

The profiling results show that the simplified method was significantly faster than the other two methods.

Chapter 4

Case Study

The availability of real world data in the case of a source isolated earth fault has been elusive to Essential Energy. Only one case of confirmed source isolated earth fault was able to be provided by the protection specialists for use in this thesis (Garrett, Tree & Lever 2013). This also indicates that this fault type is extremely rare. This known fault is presented as a case study to compare the model results with a known fault condition.

4.1 Comparison of Results

A fault occurred in the Tweed Heads area where a developing fault resulted in a source isolated earth fault.

The B Phase conductor between Pole 30543 and Pole 30542 on the Fingal feeder broke. The broken conductor fell such that the load side of the span was in contact with the ground and adjacent to a fallen overhead earth wire. The source side of the span was suspended from the ground, as it was too short to reach the ground.

The fault was cleared by protection relays protecting the 11kV Fingal Feeder (BP3B3) at the Banora Point Zone substation. The protection recorded a source isolated earth fault current of 32 A.

Figure 4.1: Google Earth view of the approximate fault location.

Figure 4.1 shows an approximate location of the fault. The fault was conveniently monitored and recorded by the protection equipment installed at the zone substation. The earth fault level recorded for this source isolated earth fault event was 32A. The fault current was sufficient for the feeder earth fault protection to pickup and clear the fault, by tripping the feeder.

The fault was very close to the zone substation. The load recorded prior to the fault was estimated at 120A per phase. The network feeder was modelled using the three methods under study in this thesis to obtain the results presented in Table 4.1.

No actual readings were available for the fault impedance. It would have been difficult to replicate the fault conditions exactly, and resource limitations prevented the taking of readings. A range of fault impedances were used to calculate a range of possible fault currents. The maximum fault impedance used was the standard 30 Ω impedance for SEF fault studies (Essential Energy 2012). The minimum fault impedance calculated was 0.1 Ω as zero Ohms *may* have resulted in a divide by zero error.

Table 4.1: Summary of case study results for various values of Rfl

	Calculated Earth Fault Current			
	$Rfl = 30\Omega$	$Rfl = 20\Omega$	$Rfl = 10\Omega$	$Rfl = 0.1\Omega$
Burgess Result(A)	29.6	32.3	35.7	39.7
Blackburn Result(A)	29.8	32.6	35.9	39.9
Simplified PPE Result(A)	29.5	32.3	35.7	39.7

It was noted that a fault impedance of 20 Ohm provides results approximately equal to the measured value of 32A. Other fault impedance values tested show results of the correct order of magnitude.

The results obtained from the three models are adequate for an estimation of the earth fault current in this particular fault condition. This case study provides some confidence in the use of the methods for the estimation of earth fault currents in a source isolated earth fault situation.

The Matlab script built to perform the case study calculations is IsolatedEarthFault.m it is included in Appendix B, Section B.15.

Chapter 5

Feeder Studies

The fault modelling was used to test the SEF protection pickup across a couple of sample feeders. To achieve this, the fault modelling was extended to use the data from existing feeder models. Network planning were able to process the existing feeder models and provide Thevinin impedances and light load levels across the feeder network (Gallaher & Arnull 2013). A method was developed to use the models to calculate the prospective source isolated earth fault currents across the network.

As an enhancement to improve the computation speed the number of nodes calculated were reduced by first analysing the likely location of undetectable faults. Then by further analysis of the fault condition in the extreme case, a rule of thumb was developed to reduce the number of calculations required to a minimum.

The Matlab script built to perform the feeder studies is FeederProcess.m it is included in Appendix B, Section B.1.

5.1 Feeder Calculation Minimisation

Not every node in a feeder model needed to be calculated. The OFAT testing has indicated that the dominant factor is the downstream load level. Load levels were obviously related to the connected load on each spur of the feeders. The computational effort can be reduced if only fault levels up to the trip level are calculated. The process started at the extremities of the feeder and it worked towards the source until the trip level was reached, it only had to calculate a minimum number of results. This first pass calculation minimisation was further reduced in Section 5.3 of this thesis where the source isolated earth fault currents were found to be easily estimated.

5.2 Feeder Modelling Method

A method was devised by using an Excel spreadsheet to create a comma separated variables (.csv) file for use as an input. The spreadsheet used the Thevinin impedance to each network node and the load beyond each network node. The data was processed by the Matlab script and an output spreadsheet of results was obtained.

Network capacitances were found to have little significance to the results during the OFAT testing. Network capacitances were ignored to simplify the process.

An example of the output spreadsheet is shown in Table 5.1. The input information was identical to the first 10 columns of the output data, and so it is not necessary to present the input information separately.

Table 5.1: Selected results from feeder modelling.

	Upstream Impedances				Downstream Impedances				Input	Results	
Node Name	R1 US (PU)	X1 US (PU)	R0 US (PU)	X0 US (PU)	R1 DS (PU)	X1 DS (PU)	R0 DS (PU)	X0 DS (PU)	Load I_L (A)	Fault I_F (A)	$\frac{I_L}{I_F}$ (PU)
SUB970	2.22	2.55	3.49	9.28	0.00	0.00	0.00	0.00	1.5	0.50	3.00
SUB1568	1.36	2.26	2.52	8.12	0.87	0.28	0.97	1.16	4.7	1.56	3.01
ABS9433-2	1.29	2.18	2.42	7.73	0.93	0.36	1.07	1.55	10.7	3.52	3.04
SUB2995	1.24	2.11	2.34	7.42	0.99	0.43	1.15	1.86	15.9	5.21	3.05
SUB6672	0.58	1.24	0.88	3.21	0.00	0.00	0.00	0.00	0.1	0.03	3.00

Table 5.1 shows a sample of the results from the feeder modelling. A network node at the end of the feeder was easily identified by the downstream impedance being zero. The calculations proceeded toward the source until the 5A SEF pickup level was exceeded.

Then a new network extremity node was selected for the process to be repeated, until all of the network extremities had been examined. These results can be used to develop thematic maps showing the detail on the maps of where the predetermined level is breached.

The last column in Table 5.1 shows the ratio of pre-fault load current to the calculated source isolated earth fault current for the same network node.

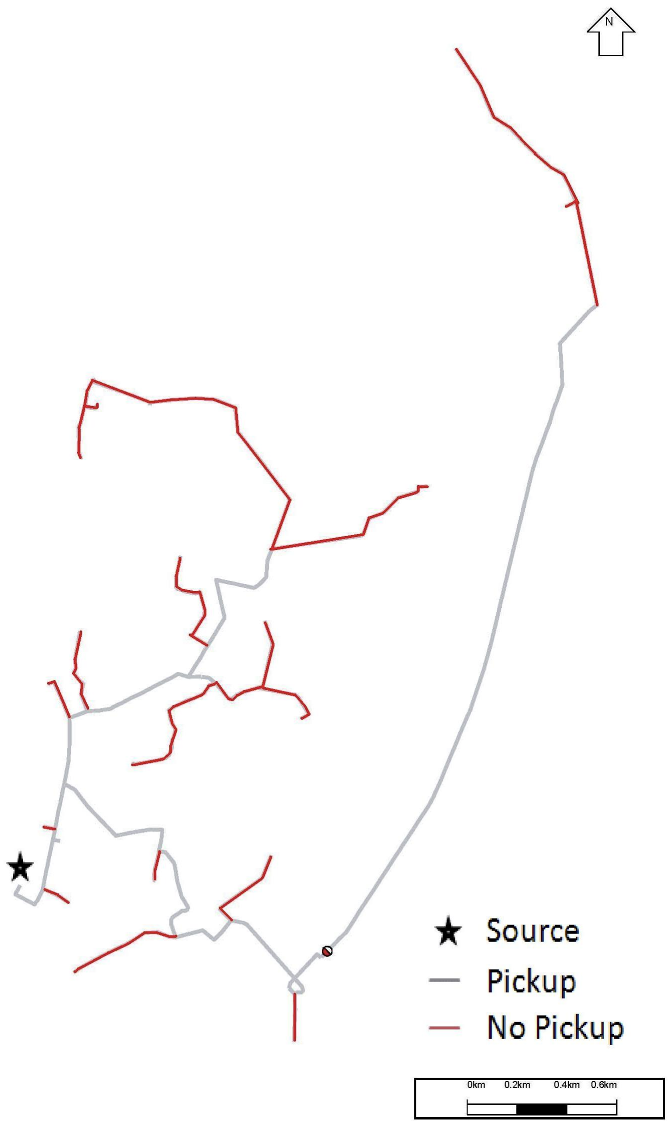


Figure 5.1: Sample CBD feeder with areas of low Source Isolated Earth Fault current highlighted in red.

Figure 5.1 shows an example CBD feeder analysis with the parts of the network highlighted in red, where the SIE fault level is less than 5 A.

The results from the feeder modelling led to a significant breakthrough in the understanding of the fault. An analysis of the results shown in Table 5.1 shows that as the extremity of the three phase network is approached, the value of the SIE fault current approaches 1/3 of the pre-fault load at the fault location. This trend was repeated throughout the output file for the sample CBD feeder.

It was considered that further analysis was warranted to understand why this situation developed. This phenomenon was explored further and that analysis is presented in section 5.3 of this thesis below.

5.3 Extreme Case Analysis

The fault circuit reduction carried out in section 3.1.3 of this thesis ceased only due to the circuit resembling the Phase to Phase to Ground Fault. This circuit was used to carry out three phase feeder analysis with a suitable amount of mathematical rigor. This led to the discovery that the SIE fault current approached 1/3 of the pre-fault load level as the extremities of the (three phase) feeder were approached. This phenomenon is investigated in this section of the thesis to gain an understanding of why this occurs. This investigation led to a further simplified method for the estimation of prospective fault currents from source isolated earth faults.

5.3.1 Three Phase Extreme Case Analysis

Analysis was carried out from the fault schematic, with the additional knowledge from the analysis that has taken place thus far in this thesis.

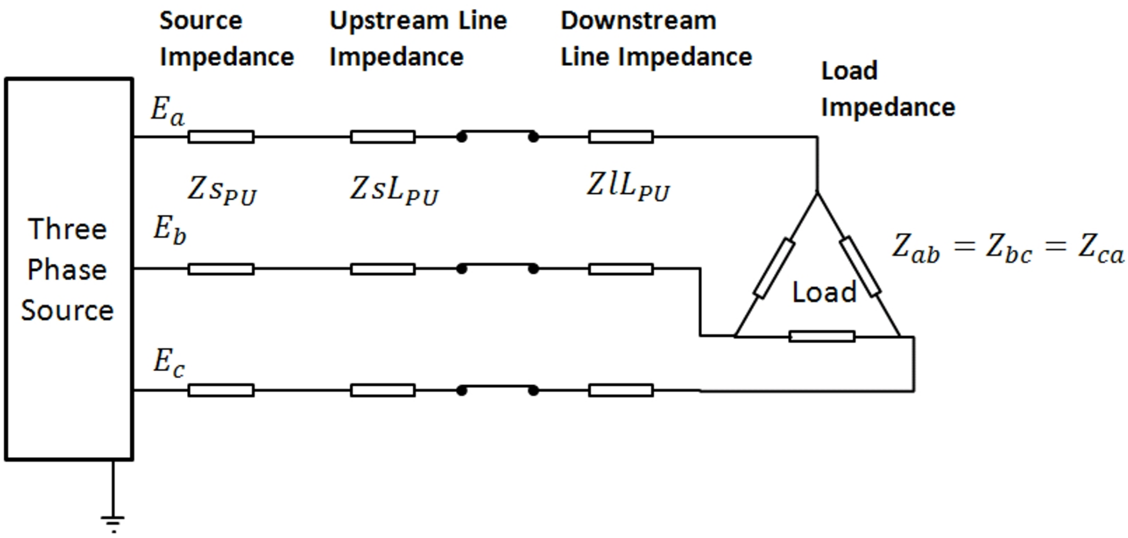


Figure 5.2: Healthy three phase network schematic.

Figure 5.2 shows the schematic circuit of the source isolated earth fault.

The circuit in Figure 5.2 was re-examined with the knowledge that the location on the network where the SIE fault becomes low is towards the extremities of the feeder. It was possible to reduce this circuit further with this knowledge.

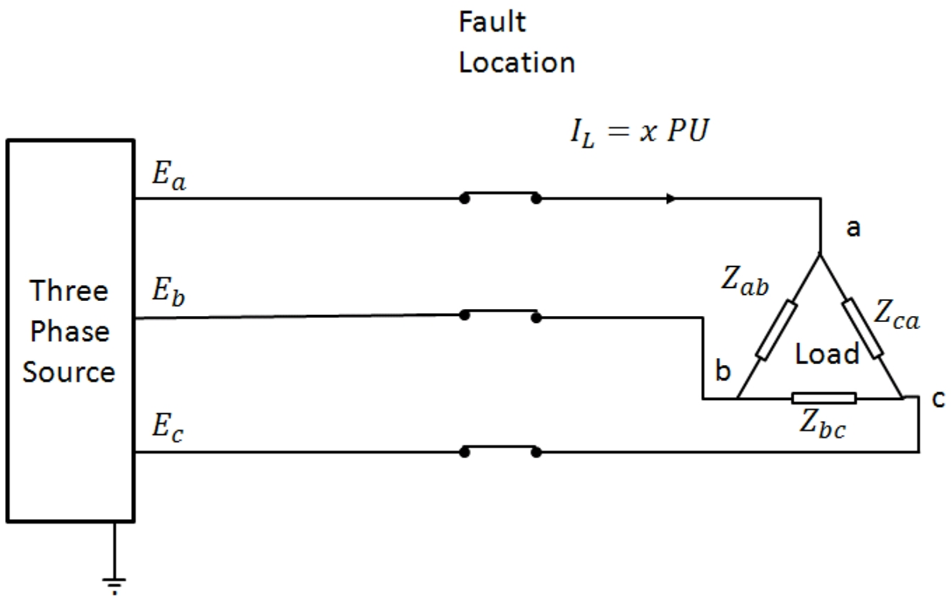


Figure 5.3: Extreme case healthy three phase network schematic.

As the end of the feeder is approached, the line impedance on the load side of the fault approaches zero. The line length reduction also causes a reduction in the line capacitance beyond the fault location. The number of transformers beyond the fault location is also reduced as the end of the feeder is approached.

The source impedance remains unchanged, however the upstream network impedance is maximised. This can be accounted for as the remainder of the load on the feeder will be flowing through the upstream network impedance, and the SIE fault causes a drop in feeder current, rather than an increase in feeder current the effect on the upstream network on voltage drop to the faulted node can possibly be ignored. Upstream network capacitance is likely to be insignificant compared to the reactance of the upstream load, so it too can be ignored. It is also noted from figure 5.1 that it is possible to have a low value for source isolated earth fault very close to the source. In this case the upstream line impedances and capacitances are minimised.

The load impedance is most likely to be the largest impedance in the circuit. In general terms for an 11kV (6351V to ground) fault to approach 5A the total impedance must exceed 1 k Ohm. Policy dictates (Essential Energy 2012) that earth fault impedances for SEF fault studies not exceed 30 Ohms. The effect of the fault impedance is therefore minimal and is ignored in the extreme case.

In the extreme case the circuit can be reduced to the circuit shown in Figure 5.3. If it is assumed that the pre-fault load current of x PU is flowing into the three phase load, the equivalent delta connected load impedance can be calculated from the following;

Assuming a three phase balanced load, where $Z_{Phase} = Z_{ab} = Z_{bc} = Z_{ca}$;

$$\begin{aligned} V_{Line} &= 1 \;\; PU \\ V_{Phase} &= V_{Line}\sqrt{3} \end{aligned} \tag{5.1}$$

$$\begin{aligned} I_{Line} &= x \;\; PU \\ I_{Phase} &= \frac{I_{Line}}{\sqrt{3}} \end{aligned} \tag{5.2}$$

It follows that the load impedance can be calculated by applying ohms law;

$$\begin{aligned} Z_{Phase} &= \frac{V_{Phase}}{I_{Phase}} \quad recalling\ equations\ 5.1\ and\ 5.2; \\ Z_{Phase} &= \frac{V_{PU}\sqrt{3}}{\frac{x}{\sqrt{3}}} \\ Z_{Phase} &= \frac{3V_{PU}}{x} \\ Z_{Phase} &= \frac{3}{x}\ (PU) \end{aligned} \tag{5.3}$$

When the fault occurs the impedance between a and b phases (Z_{ab}) will be load only and not contribute to the earth fault current.

During the fault the c phase terminal of the load will approach zero volts (neglecting fault impedance in the extreme case).

Figure 5.4 shows the schematic of the faulted condition.

The current through the impedance Z_{ca} will be;

$$\begin{aligned} I_{ca} &= \frac{V_{ca}}{Z_{ca}} \\ I_{ca} &= \frac{V_c - V_a}{Z_{ca}} \\ I_{ca} &= \frac{-1\angle 0^0}{\frac{3}{x}} \\ I_{ca} &= \frac{-x}{3}\ (PU) \end{aligned} \tag{5.4}$$

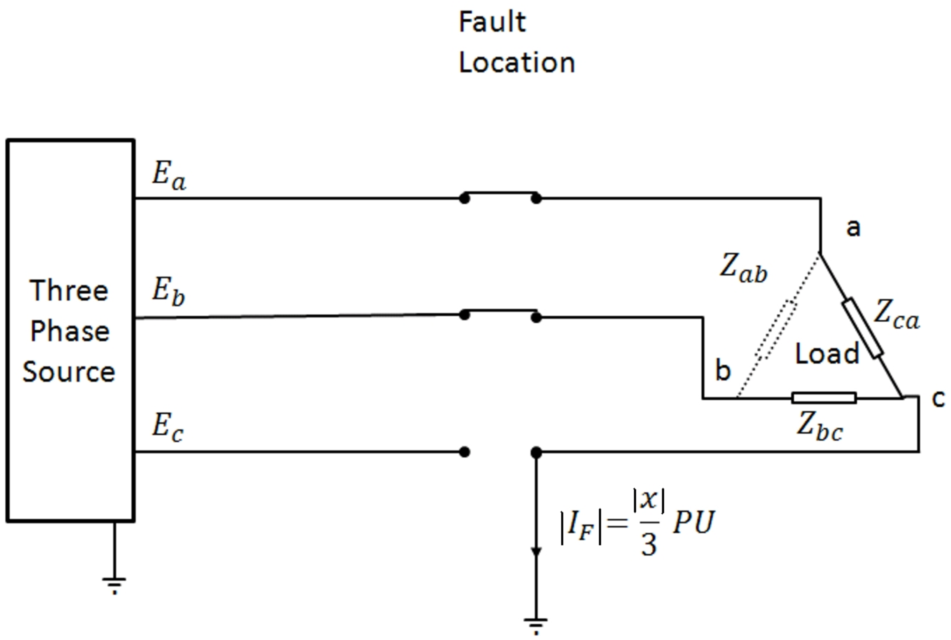


Figure 5.4: Extreme case of Source Isolated Earth Fault schematic.

The current through the impedance Z_{bc} will be;

$$
\begin{aligned}
I_{bc} &= \frac{V_{bc}}{Z_{bc}} \\
I_{bc} &= \frac{V_b - V_c}{Z_{bc}} \\
I_{bc} &= \frac{1\angle 240^0}{\frac{3}{x}} \\
I_{bc} &= \frac{1\angle 240^0 \times x}{3} \\
I_{bc} &= \frac{-0.5 - j0.866 \times x}{3} \\
I_{bc} &= \frac{-0.5 \times x}{3} - \frac{j0.866 \times x}{3} \; (PU)
\end{aligned}
\tag{5.5}
$$

$$
\begin{aligned}
I_F &= I_c \\
I_F &= I_{bc} - I_{ca} \\
I_F &= (\frac{-0.5x}{3} - \frac{j0.866x}{3}) - \frac{-x}{3} \\
I_F &= (\frac{-0.5x}{3} - \frac{j0.866x}{3}) + \frac{x}{3} \\
I_F &= \frac{0.5x}{3} - \frac{j0.866x}{3} \\
I_F &= 0.5 - j0.866 \times \frac{x}{3} \\
I_F &= 1\angle 300^0 \times \frac{x}{3} \; (PU)
\end{aligned}
\tag{5.6}
$$

Taking the absolute value of equation 5.6 gives;

$$\begin{aligned} |I_F| &= |1\angle 300^0 \times \frac{x}{3}| \\ |I_F| &= \frac{|x|}{3} \ (PU) \end{aligned} \tag{5.7}$$

Therefore, in the extreme case for three phase networks;

$$|I_F| = \frac{|I_L|}{3} \tag{5.8}$$

where I_L is the pre-fault line current feeding the load.

The maximum magnitude of earth fault current in a source isolated earth fault condition is one third of the pre-fault load current for three phase systems.

5.3.2 Single Phase Extreme Case Analysis

The extreme case analysis carried out on three phase systems is not adequate for single phase networks. Single phase network is commonly employed by constructing a spur off the main line, using only two wires of the three phase network on a spur. Single phase is often used for spurs in lightly loaded areas, because it is cheaper to build. Single phase network is utilised on the extremities of feeders.

If the same rules are applied to the extreme case for the single phase network that has been carried out for the three phase network, an equation for the extreme limit for single phase networks can also be derived.

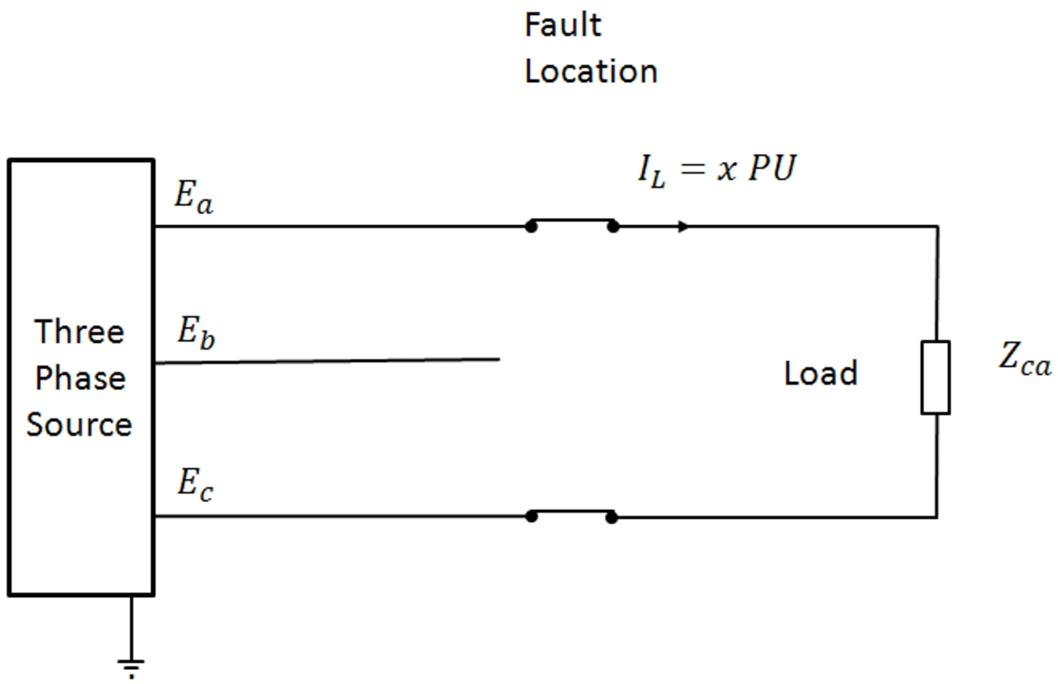


Figure 5.5: Extreme Case Single Phase Load Schematic.

Figure 5.5 shows the simplified schematic circuit of a single phase radial spur. If it is assumed that in the pre-fault condition;

$$V_{Phase} = 1 \quad PU$$
$$I_{Line} = x \quad PU$$

It follows that the load impedance can be calculated by applying ohms law;

$$\begin{aligned} Z_{ca} &= \frac{E_c - E_a}{I_L}\ (PU) \\ |Z_{ca}| &= \frac{|\sqrt{3}E_a|}{|x|}\ (PU) \end{aligned} \tag{5.9}$$

Figure 5.6 shows the case where the single phase circuit is subjected to a source isolated earth fault. The absolute value of the voltage across the load impedance has been reduced by a factor of $\frac{1}{\sqrt{3}}$.

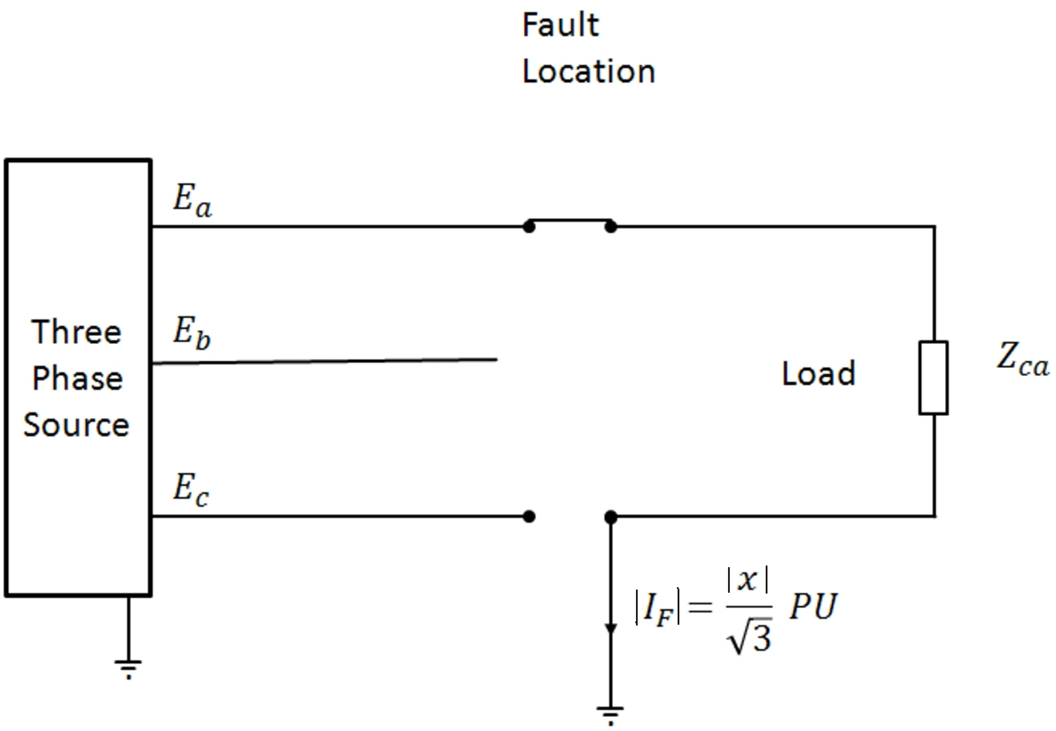


Figure 5.6: Extreme Case of Source Isolated Fault on single phase network.

$$
\begin{aligned}
I_F &= \frac{E_a}{Z_{ca}} \ (PU) \\
|I_F| &= \frac{|E_a|}{\frac{|\sqrt{3}E_a|}{|x|}} \ (PU) \\
|I_F| &= |E_a| \times \frac{|x|}{|\sqrt{3}E_a|} \ (PU) \\
|I_F| &= \frac{|E_a| \times |x|}{\sqrt{3}|E_a|} \ (PU) \\
|I_F| &= \frac{|x|}{\sqrt{3}} \ (PU) \\
|I_F| &= \frac{|I_L|}{\sqrt{3}}
\end{aligned} \tag{5.10}
$$

where I_L is the pre-fault line current feeding the load.

In single phase networks the maximum magnitude of the source isolated earth fault approaches $\frac{1}{\sqrt{3}}$ times the pre-fault load current magnitude as the fault location approaches the network extremities.

5.3.3 Summary of Extreme Case Analysis

The extreme case of fault locations approaching the end of the feeder has been analysed. It was found that there is a limit that the earth fault currents approach as the fault approaches the feeder extremities. The limit varies depending on the number of phases that exist beyond the fault, and the load level beyond the fault location.

In summary it was found that;

The maximum magnitude of the Source Isolated Earth Fault current at a location on the network will be $\frac{|I_L|}{3}$ of the pre-fault load through that location for three phase networks, and $\frac{|I_L|}{\sqrt{3}}$ for single phase networks.

When the extreme case is applied to real networks for analysis, additional impedances are added into the circuit. Additional impedance equates to a reduction in fault current. Therefore the extreme case provides the absolute maximum current that can be developed by a Source Isolated Earth fault.

This is a very important finding and can be used to assist in finding the location where Source Isolated Earth Fault currents are undetectable. As a feeder is analysed, calculations are not required for light load levels less than $\sqrt{3}$ times the pickup, these will always be undetectable by a conventional protection scheme. In three phase systems the light load limit is raised to a minimum of 3 times the pickup value.

This finding significantly reduces the number of calculations necessary for finding locations where pickup is not possible. As a feeder is analysed from the extremities toward the source, calculations are not necessary until certain load levels are exceeded.

It is concluded that the maximum Source Isolated Earth fault current can be estimated (rather than calculated) as being $\frac{I_L}{3}$ of the pre-fault load through that location for three phase networks, and $\frac{I_L}{\sqrt{3}}$ for single phase network. The estimation will always be higher than the actual fault current as there will always be some fault impedance, due to the fact that the downstream line impedance forms part of the fault impedance and the fault physically requires part of a span of conductor on the load side to be on the ground.

To gain some confidence in this theory it was applied to the case study undertaken in Section 4 of this thesis. The pre-fault load in the case study was 120A. This fault occurred on the three phase portion of the network. The extreme case estimation of the maximum fault current would be $\frac{120}{3} = 40$ Amperes. Table 4.1 shows the minimum result with negligible fault impedance as 39.7 Amperes. This represents an error between the extreme case estimation and the calculation as a maximum error of;

$$\begin{aligned}
Error\% &= \frac{Estimate - Calculated}{Calculated} \times \frac{100}{1} \\
Error\% &= \frac{40 - 39.7}{39.7} \times \frac{100}{1} \\
Error\% &= \frac{0.3}{39.7} \times \frac{100}{1} \\
Error\% &= \frac{30}{39.7} \\
Error\% &= 0.756\%
\end{aligned}$$

This confirms that the extreme case analysis is a close approximation of the maximum earth fault current possible in the case of a Source Isolated Earth Fault.

As sample feeders were analysed it was noticed that the loads along the feeder are in steps where an additional transformer is added or where an additional spur joins the main line. The load level is stepped rather than gradual as a feeder is analysed from the extremities toward the source. This means that the extreme limit location *may* be close to the location of the calculated limit.

The following two feeder examples show the locations calculated by applying the extreme limit theory and the calculated limit. It shows that the extreme limit theory is exceptionally good at estimating the location of the limit.

Figure 5.7 shows the results of a feeder analysis on a sample rural feeder. The blue dots show where the extreme limit theory estimated the fault level to exceed the trip level. The red colouring along the feeder shows where the numerical model indicated no pickup from the relay.

In Figure 5.7 the pickup level is 5 A. In this particular example the extreme limit theory lined up identically with the results from the numerical modelling. It can be inferred from the math that this will not always be the case. The location found by applying the extreme limit theory will always be close to or downstream of the calculated pickup limit. This was proven as the extreme case estimate is the maximum current that can flow and the calculated value is always less than this theoretical limit.

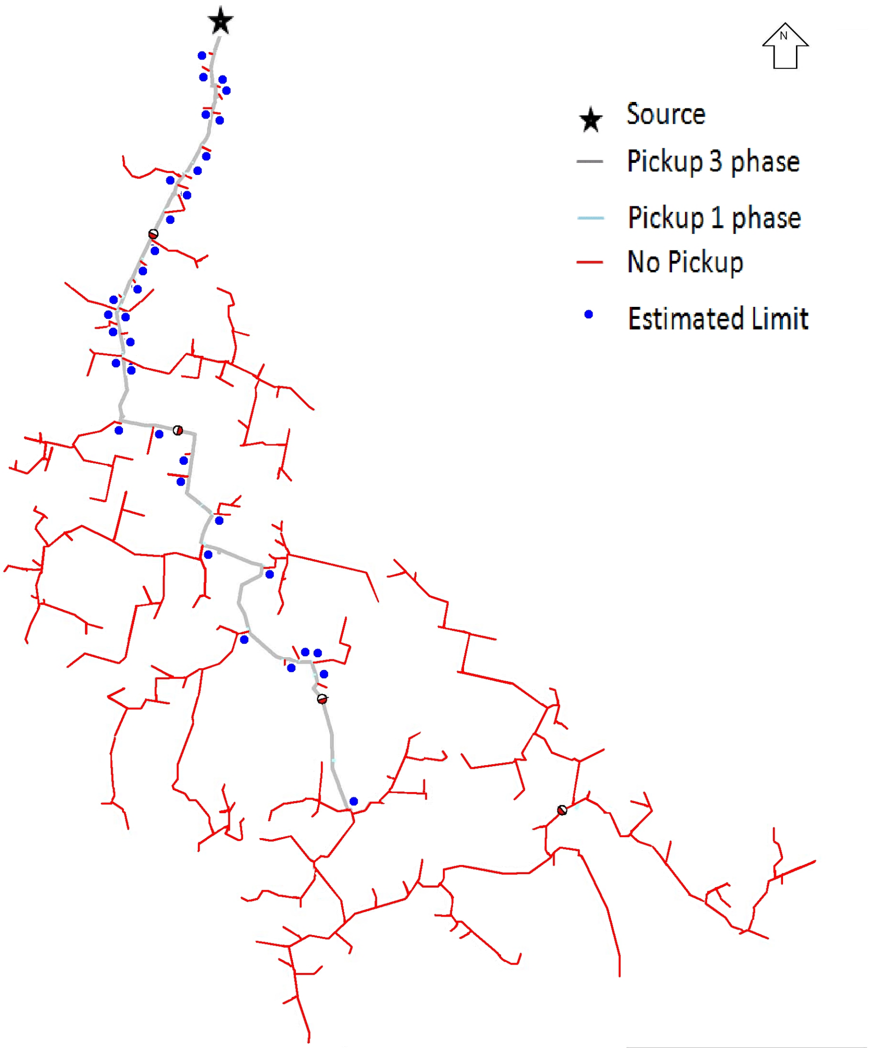


Figure 5.7: Sample 11kV rural feeder with undetectable areas shaded in red (5A SEF pickup).

5.3.4 Effect of Increasing SEF Protection Sensitivity

Conventional protection solutions to the problem of undetected high impedance earth faults include improving the sensitivity of the SEF protection to as low as 1A (Curk & Koncnik 1999, Curk & Lenardic 2005). To theoretically test this solution the sample rural feeder was retested with a SEF pickup level of 1A beyond the field reclosers. The reclosers have been chosen for the setting change as it is known that Noja reclosers have an option that allows for 1A SEF pickup.

For a SEF pickup setting of 1 Amp to be permitted on the Essential Energy network a change of policy would be required (Essential Energy 2012). The range of SEF settings

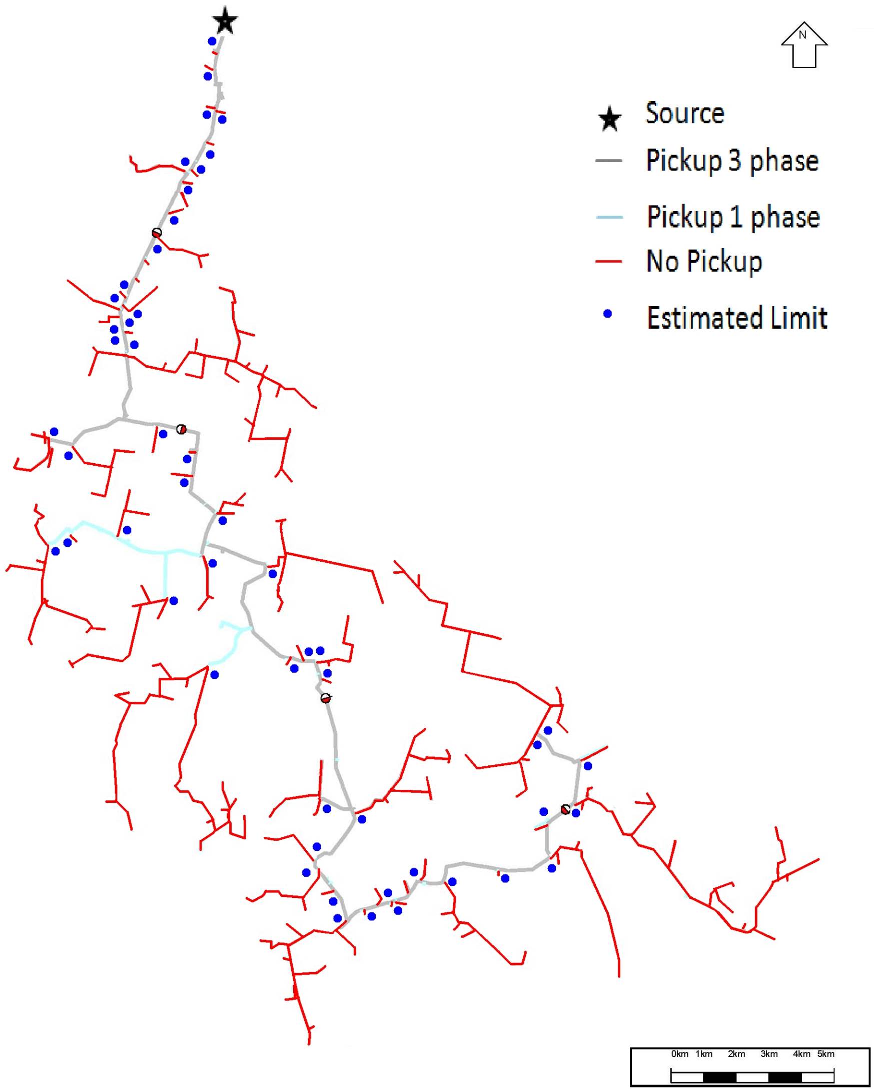


Figure 5.8: Sample 11kV rural feeder with undetectable areas shaded in red (1A SEF pickup).

permitted is presently 4-10A. This was, however, only a theoretical test to gauge the improvement of protection coverage by a setting change.

Figure 5.8 shows the results for the sample rural feeder with a SEF pickup setting of 1A. The blue dots show where the extreme limit theory estimated the fault level to exceed the trip level. The red colouring along the feeder shows where the numerical model indicated no pickup from the relay. In this particular example the extreme limit theory lined up identically with the results from the numerical modelling.

Comparing the results from Figures 5.7 and 5.8 it is observed that the decreasing of the SEF pickup level from 5 A to 1 A increased the amount of the network protected by the SEF protection scheme.

Total feeder length: 235.5 km

Feeder length protected with 5 A SEF pickup: 32.1 km

Feeder length protected with 1A SEF pickup: 60.25 km

The increased sensitivity of SEF pickup from 5A to 1 A increased the protected line from 32.1km to 60.25km, almost doubling the coverage. It is noted however that 175.25 km (74.4 %) remained unprotected from this particular type of fault, under the most sensitive pickup setting for SEF protection.

The intuition provided from the extreme condition analysis shows that the network can never be fully protected by conventional SEF protection. As the load impedance beyond the fault becomes part of the fault impedance circuit, and load impedance increases dramatically toward the extremities of feeders, the source isolated earth fault currents *may* be undetectable for a large proportion of any feeder.

5.4 Mechanical Factors

The calculation results show that major portions of feeders *may* allow for the electrical conditions to exist that allow an undetectable source isolated earth fault to develop if the fault occurred. This fault remains a rare occurrence with only one event provided by Essential Energy, and literature review struggled to find many instances reported (Depew et al. 2006, Essential Energy 2013).

Consideration must be given to the fact that, although undetectable faults *may* occur over a large area of any given feeder, in practice they very rarely occur. The overriding principle is that the occurrence of this fault requires an overhead span to fail in a specific way for the fault condition to exist. The conductor failure must occur close to the source end of the span.

The conductor must not retract toward the upstream span so much as to allow the upstream span to come in contact with the ground. An amount of retraction would be expected as the tension in the upstream sections of the broken conductor, in concert with the weight of the conductors in upstream spans, would be pulling the conductor back toward the source (Peyrot, Kluge & Lee 1980). If the conductor is allowed to move toward the source, by slipping on pin insulators, then the broken conductor *may* come in contact with the ground on the source end as well as the load end of the conductor. This would then develop into a phase to ground fault on the upstream end of the fault. A phase to ground fault would develop an earth current that would be significantly higher than for a source isolated earth fault at the same location. Slipping will not occur if the conductor is terminated by disk insulators. Pin insulators are more common than disk insulators on the Essential Energy 11kV distribution Network.

The falling conductor *may* come into contact with circuits physically constructed below the broken span. This may allow for the fault to develop into a more severe fault. The span in the case study was terminated by disk insulators and had no circuit below it.

These mechanical influences may assist in explaining why the source isolated earth fault occurs so rarely, as the event may have to occur at a rare location, thereby accounting for the event being so unusual. These mechanical aspects of the fault are outside the scope for this thesis, however in light of the apparent significance to this type of fault a recommendation is made that the mechanical effects affecting the likelihood of this fault be investigated further in a future thesis, dedicated to that outcome.

If the mechanical influences can be identified, engineering solutions *may* be able to be developed to minimise the risk of the source isolated earth fault occurring. This could be achieved by either preventing the mechanical factors from occurring, or forcing the fault to develop into a more severe type of fault to allow currents to be developed that will be detectable.

Chapter 6

Conclusions and Further Work

6.1 Achievement of Project Objectives

The following objectives have been addressed;

1. Model the broken conductor fault in an 11 kV overhead distribution feeder.

    - Chapter 2 presented a summary of two peer reviewed approaches to the fault analysis.
    - In Chapter 3 a new model for solving this type of fault was derived. The new model was compared to the peer reviewed models and was found to be suitable for solving this type of fault.
    - In Chapter 4 the models were compared to the data recorded during a case study.
    - In Chapter 5 a method was developed to apply the models to entire 11kV distribution feeders.

2. Investigate the circumstances where this fault is not detectable using 'traditional' EF/SEF protection schemes.

    - Sensitivity Analysis Section 3.2 addressed the search for dominant factors in the earth fault current developed by Source Isolated Earth Faults by doing some simulations.

- The pre-fault load impedance was found to be the dominant factor in determining the level of earth fault current able to be developed in a Source Isolated Earth Fault situation.
- In Chapter 5 a method was developed to apply the models to entire 11kV distribution feeders, and test for SEF protection pickup.
- The extreme case of this fault was analysed in Section 5.3. This led to the derivation of a simplified method for estimating the maximum possible earth fault current. The estimate of maximum earth fault current can be found by applying a simple factor to the pre-fault load in a network.

6.2 Conclusions

This thesis examined the electrical characteristics of the Source Isolated Earth Fault. This fault is characterised by a broken conductor in an overhead network falling to ground on the load end of the span and failing to make electrical contact with the ground on the source end of the span.

A simplified method for the calculation of fault currents has been developed that takes advantage of the likeness of a source isolated earth fault to a phase to phase to ground fault. The simplified method for calculation of currents during a fault was compared to the results from two peer reviewed methods and found that the simplified method is adequate in estimating the currents that flow in this fault condition. The computational efficiencies of the three methods was compared and it was found that the simplified method is significantly faster to compute.

Further simplification of the fault circuit led to the discovery that the maximum magnitude of the earth fault current developed during a source isolated earth fault was limited to a fixed ratio to the pre-fault load current flowing. The maximum magnitude of earth fault current is $\frac{1}{3}$ of the load current in three phase systems and $\frac{1}{\sqrt{3}}$ of the load in single phase networks. These absolute limits can be used reduce the number of calculations necessary to find the protection coverage. If the pickup level cannot be achieved by applying the appropriate factor to the load current then the calculations prove unnecessary. In two examples undertaken during this thesis the protected zones identified by either method were identical.

This fault occurs very infrequently in practice, with only one example able to be provided by Essential Energy for this thesis. The rareness of this fault is thought to be due to the unlikely nature of the mechanical aspects of the fault, rather than the electrical nature of the fault.

6.3 Recommendations

Further work is required into the mechanical nature of this fault so that the infrequency of the fault can be explained. The work should seek to provide insight into the reason why this fault is rare despite the common availability of the electrical factors that allow this fault to occur. Once the mechanical factors are understood, an engineering solution *may* be researched to reduce the risk of this fault occurring at all.

It is further recommended that work continue into the effective detection of the fault so that reliable alternative means of detecting this type of fault can be developed.

References

Al-Dabbagh, M., Daoud, R. & Coulter, R. (1989), Improved microprocessor based distribution feeder earth fault protection using pattern recognition, *in* 'Developments in Power Protection, 1989., Fourth International Conference on', pp. 172–176.

Benner, C. L. & Russell, B. D. (1997), 'Practical high-impedance fault detection on distribution feeders.', *IEEE Transactions on Industry Applications* **33**(3), 635–640.

Blackburn, J. L. (1993), *Symmetrical components for power systems engineering.*, M Dekker.

Burgess, R. T. (2011), 'Improving high voltage power system performance using arc suppression coils.'. PhD Thesis.

Curk, J. & Koncnik, D. (1999), Improved protection scheme for selective high resistance earth fault clearing in slovenian distribution networks, *in* 'Electric Power Engineering, 1999. PowerTech Budapest 99. International Conference on', pp. 256–.

Curk, J. & Lenardic, V. (2005), Enhanced selectivity of high resistance earth-fault clearing improves quality of electric energy supply in slovenia, *in* 'Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on', pp. 1–4.

Czitrom, V. (1999), 'One-Factor-at-a-Time versus Designed Experiments', *American Statistician* **53**, 126–131.

Depew, A., Parsick, J., Dempsey, R., Benner, C., Russell, B. & Adamiak, M. (2006), Field experience with high-impedance fault detection relays, *in* 'Transmission and Distribution Conference and Exhibition, 2005/2006 IEEE PES', pp. 868–873.

Essential Energy (2012), 'CEOP8002 Protection Guidelines.', Internal Policy.

Essential Energy (2013), 'Essential Energy website.', `http://www.essentialenergy.com.au`. [Online; accessed October-2013].

Fortescue, C. (1918), 'Method of symmetrical co-ordinates applied to the solution of polyphase networks', *American Institute of Electrical Engineers, Transactions of the* **XXXVII**(2), 1027–1140.

Gallaher, B. & Arnull, P. (2013), Sample feeder information. Unpublished.

Garrett, M., Tree, P. & Lever, D. (2013), Case study information. Unpublished.

Gillespie, D. & Matheson, E. (2013), Essential Energy outage summary 2008-2013. Unpublished.

Grainger, J. J. & Stevenson, W. D. j. (1994), *Power System Analysis.*, United States of America, McGraw-Hill.

Horowitz, S. & Phadke, A. (2008), *Power System Relaying.*, West Sussex, England, John Wiley and Sons Ltd.

Li, L. & Redfern, M. (2001), A review of techniques to detect downed conductors in overhead distribution systems, *in* 'Developments in Power System Protection, 2001, Seventh International Conference on (IEE)', pp. 169–172.

Lukowicz, M., Michalik, M., Rebizant, W., Wiszniewski, A. & Klimek, A. (2010), Detection of very high resistance faults - a new function of transmission line current differential relays, *in* 'Developments in Power System Protection (DPSP 2010). Managing the Change, 10th IET International Conference on', pp. 1–5.

Mortlock, J. (1947), 'The evaluation of simultaneous faults on three-phase systems', *Electrical Engineers - Part II: Power Engineering, Journal of the Institution of* **94**(39), 166–190.

Peyrot, A., Kluge, R. & Lee, J. (1980), 'Longitudinal loads from broken conductors and broken insulators and their effect on transmission lines', *Power Apparatus and Systems, IEEE Transactions on* **PAS-99**(1), 222–234.

Sarlak, M. & Shahrtash, S. (2008), High impedance fault detection in distribution networks using support vector machines based on wavelet transform, *in* 'Electric Power Conference, 2008. EPEC 2008. IEEE Canada', pp. 1–6.

Sarlak, M. & Shahrtash, S. (2011), 'High impedance fault detection using combination of multi-layer perceptron neural networks based on multi-resolution morphological gradient features of current waveform', *Generation, Transmission Distribution, IET* **5**(5), 588–595.

Tengdin, J., Baker, E. E., Burke, J., Russell, B., Jones, R., Wiedman, T. & Johnson, N. J. (1996), Application of high impedance fault detectors: a summary of the panel session held at the 1995 ieee pes summer meeting, *in* 'Transmission and Distribution Conference, 1996. Proceedings., 1996 IEEE', pp. 116–122.

Toader, D., Blaj, C. & Haragus, S. (2007), Electrocution danger evaluation for broken and grounded conductor, *in* 'EUROCON, 2007. The International Conference on #34;Computer as a Tool #34;', pp. 1392–1397.

Torres G, V. & Ruiz P, H. (2011), High impedance fault detection using discrete wavelet transform, *in* 'Electronics, Robotics and Automotive Mechanics Conference (CERMA), 2011 IEEE', pp. 325–329.

Vempati, N., Shoults, R., Chen, M.-S. & Schwobel, L. (1987), 'Simplified feeder modeling for loadflow calculations', *Power Systems, IEEE Transactions on* **2**(1), 168–174.

Appendix A

Project Specification

University Of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/ ENG4112 RESEARCH PROJECT SPECIFICATION.

AUTHOR: Andrew James Geary Student Q9222672

TOPIC: Model and Analysis of a Broken Conductor (Source Isolated) Earth Fault on a Radial 11kV Distribution Feeders.

SUPERVISOR: Dr Tony Ahfock.

SPONSORSHIP: Essential Energy.

PROJECT AIMS: The problem to be investigated by the project;

- Model the broken conductor fault in an 11kV overhead distribution feeder (broken conductor near line side of span such that only the load side of the broken conductor hits the earth, line side is isolated).
- Investigate the circumstances where this fault is not detectable using 'traditional' EF//SEF protection schemes.

PROGRAMME: (Issue A, 8/03/2013)

1. Research the background information relating to the broken conductor back-fed earth-faults.
2. Develop MATLAB code to model the behaviour of this type of fault.
3. Compare MATLAB model with calculations for calibration / accuracy check of the model.
4. Investigate fault behaviour as various assumptions are adjusted. For example line impedance, Source impedance, Fault impedance, Pre-fault load downstream of fault.

5. Report on the dominant factor/factors that cause this fault to be undetectable, and relate that to 11kV distribution feeders.

As Time Permits:

6. Investigate the likelihood of this type of fault occurring.
7. Develop an approach for managing this type of fault.

AGREED ______________________ (Student) ________________________ (Supervisor)

Date ____ /____ / 2013 Date ____ / ____ / 2013

Examiner/Co-Examiner________________________________

Appendix B

MATLAB Code

The Matlab code developed for the thesis is provided is this appendix. Each Matlab function or script is provided in a subsection of this appendix.

B.1 The FeederProcess.m MATLAB Script

Listing B.1: MATLAB script FeederProcess.m

```
%%file: FeederProcess.m
%*************************************************************
%% Copyright
%*************************************************************
%
% Matlab Code CopyRight (c) Andrew James Geary 2013.
%
% Author: Andrew James Geary [Student Q9222672].
%
%
% Any snippets that have been copied from elsewhere will have
% a reference to the original author in curvy brackets
% (A Geary).
%
%*************************************************************
%% Version Tracking
%*************************************************************
% Version V01 ;
% Modified from IsolatedEarthFault_V04.m
% Version V02 ;
% Includes Phases for single phase model.m
%
%*************************************************************
%% Purpose of code
%*************************************************************
% Written as part of my Thesis/Dissertation
% Subject 4111//4112, University of Southern Queensland.
% Sets up multiple simulation for The behaviour of an Isolated
% EarthFault.
% uses file input for data
%*************************************************************
%% Initialise
%*************************************************************
clear; % clear variables from Matlab
clc; % clear the (text) output from Matlab
format short

% Setting Constants
% Three Phase Fault Levels
%
a = 1 * cos(pi* 120/180) + 1i * sin(pi* 120/180);
```

```
% Base description
%
BaseV = 11000/sqrt(3); %11kV Base Voltage
BaseVA = 100000000; %100MVA Base
BaseI = (BaseVA)/(3*BaseV); % calculated Base current
BaseZ = BaseV/BaseI; % Calculated Base Impedance

% Setting Variables...
%
%

%% Impedances.
% conductor data from planning
%
%prefault Voltage
Vs_PU = 1.036;%PU

%% Source impedance
Zs_PU = [0.0+0.0i,0.0+0.0i,0.0+0.0i];
% Source Impedance (pu)
%*****************************************************
%% File input of network impedances
A = importdata('feederInput.csv')
%  ZL1_PU(:,1:2) = A.data(:,1:2);
%  ZL1_PU(:,3:4) = A.data(:,1:2);
%  ZL1_PU(:,5:6) = A.data(:,3:4);
%  ZL2_PU(:,1:2) = A.data(:,5:6);
%  ZL2_PU(:,3:4) = A.data(:,5:6);
%  ZL2_PU(:,5:6) = A.data(:,7:8);
 ZL1_PU(:,1) = A.data(:,1)+i*A.data(:,2);
 ZL1_PU(:,2) = A.data(:,1)+i*A.data(:,2);
 ZL1_PU(:,3) = A.data(:,3)+i*A.data(:,4);
 ZL2_PU(:,1) = A.data(:,5)+i*A.data(:,6);
 ZL2_PU(:,2) = A.data(:,5)+i*A.data(:,6);
 ZL2_PU(:,3) = A.data(:,7)+i*A.data(:,8);


 Phases = A.data(:,9);
 LoadI = A.data(:,10);
%  pause

%% line values from network model


%*****************************************************
%% Load calcs
% ZzLoad_PU = ZzL / BaseZ;

% Load_A = 140;
% perphase 3 phase includes all load and losses...

Load_pf = 0.9; % assume 0.9 if unknown
```

```
%Calcs;
pf = Load_pf + 1i * sin(acos(Load_pf));
Load_A_Complex = LoadI * pf;
Load_A_PU = Load_A_Complex /BaseI;

Fault_Ohm = 30;
%Fault impedance in Ohms (make this small and not zero
% for a bolted fault zero may cause a divide by zero error.
NonFault_Ohm = 1e99;%Non Fault impedance in Ohms

Fault_Zpu = Fault_Ohm/BaseZ;
NonFault_Zpu = NonFault_Ohm/BaseZ;
PreFaultVoltage_Vpu = Vs_PU;
% voltage at fault point before fault occurs.
%% For Each node point
%
%*********************************************************
%% Main
%*********************************************************

for Itter1 = 1:1:length(LoadI)

%% Build impedances

% Upstream Network Impedance (pu)
USN_Zpu = ZL1_PU(Itter1 ,:);

% Upstream Network Capacitance Impedance (pu)
USN_Zcpu =  NonFault_Zpu ;

% Upstream load Impedance (pu)
%ZL_US = [NonFault_Zpu, NonFault_Zpu, NonFault_Zpu];

% DownStream Network Impedance (pu)
DSN_Zpu = ZL2_PU(Itter1 ,:)./2;
%/2 according too (Vempati, Shoults et al. 1987)

% DownStream Network Capacitance Impedance (pu)
DSN_Zcpu = NonFault_Zpu;
PHASE=Phases(Itter1);
%*********************************************************
% Downstream load Impedance (pu)
ZL_PU = [Vs_PU / (Load_A_PU(Itter1)), Vs_PU / ...
                        (Load_A_PU(Itter1)), NonFault_Zpu ];

 [OP] = funcIEFWLCAP(Vs_PU, Zs_PU, USN_Zpu, USN_Zcpu, ...
       NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ZL_PU, ...
              Fault_Zpu, BaseI,0,PHASE);


    OutP(Itter1)=max(OP);
```

```
end
clc
OutP'
A.data=[A.data,OutP'];


xlswrite('FeederOutput.xls', A.textdata, 'Output','A1');
xlswrite('FeederOutput.xls', A.data, 'Output','B2');


%***********************************************************
%% References
%***********************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
%
%(Vempati, Shoults et al. 1987)
%Vempati, N., R. R. Shoults, M. S. Chen and L. Schwobel(1987).
% "Simplified Feeder Modeling for Loadflow Calculations."
% Power Systems, IEEE Transactions on 2(1): 168-174.
%
%% End Of Code
%
```

B.2 The funcBBL.m MATLAB Function

Listing B.2: MATLAB function funcBBL.m

```
function [ output_args ] = funcBBL( Vs, Zs_PU, Zs_L_PU, ...
                  Zcs_PU, Rfs_PU, Zl_L_PU, Zcl_PU, ZL_PU, Rfl_PU)
%***********************************************************
%
%%funcBBL function for simultaneous open circuit and
% earthfaults on the dead side in the same phase
%
% Author Andrew Geary
% Student No. Q9222672
%
% References.
%Blackburn 1993
%
%***********************************************************
%% Input arguments...
%***********************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
%
% Source side of the Open Circuit
```

```
%
% Applied fault voltage. voltage of network fault point
% pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of open circuit
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of open circuit
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of fault.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of fault.
% Rfl_PU = (resistance in PU of line side EF).
%
%**********************************************************
%% Main Code
%**********************************************************
%
%**********************************************************
%page 167 -178 of blackburn 1993 (Blackburn, 1993)
%
%
% I_0 = -( 1/3 *I_1H + 1/3 * I_2H + 1/3 * I_0H);
%    :eqn:7.16
% I_1H*Z_1H + I_2H*Z_2H + I_0H*Z_0H = 0 ;
%     :eqn:7.22
% Zx = Z_1H * (Z_1G + 2*Z_0G + 3*Z_0H) + Z_0H*(Z_0G - Z_1G)
%     ;eqn:7.26
% Zy = Z_2H * (Z_1G + 2*Z_0G) + Z_0H*(2*Z_1G + Z_0G + 6*Z_2H)
%    ;eqn:7.27
% I_2H = -I_1H * Zx/Zy
%     ;eqn:7.28
```

```
% I_1H = (-V*Zy)/(Zx*(Z_1G + Z_2H) + Zy*(Z_1G+Z_1H))
%     ;eqn:7.29
% I_0H = (-(I_1H*Z_1H) -(I_2H*Z_2H)) / Z_0H
%     :eqn:7.22
% I_1G = -I_1H -I_0
%      ;eqn:7.30
% I_2G = -I_2H -I_0
%      ;eqn:7.31
% I_0G = -I_0H -I_0
%     ;eqn:7.32
%*************************************************************
% including Line Capacitance
% map our inputs into the variables
ZsS = Zs_PU + Zs_L_PU;
Z_1G = ZsS(1);
Z_2G = ZsS(2); % book assumes Z_2G = Z_1G, so... not used
Z_0G = ZsS(3) + 3 * Rfl_PU;%fault impedance added to source
% as earth circuit is a series circuit and this is an easy
% addition here.
% 3* Rfl gets the zero seq currents correct
ZlS = Zl_L_PU + ZL_PU;
Z_1H = ZlS(1);
Z_2H = ZlS(2);
Z_0H = ZlS(3);
% (Blackburn, 1993)
%         ;eqn:7.26
Zx = Z_1H * (Z_1G + 2*Z_0G + 3*Z_0H) + Z_0H*(Z_0G - Z_1G);
%       ;eqn:7.27
%Zy = Z_2H * (Z_1G + 2*Z_0G) + Z_0H*(2*Z_1G + Z_0G + 6*Z_2H);
%probably should be...
Zy = Z_2H*(Z_2G + 2*Z_0G) + Z_0H*(Z_1G+Z_2G+Z_0G + 6*Z_2H);
% from book that assumes Z1_G = Z_2G
%however left as stated in the book
% (Blackburn, 1993)
%  ;eqn:7.29
I_1H = (-Vs*Zy)/(Zx*(Z_1G + Z_2H) + Zy*(Z_1G+Z_1H));
% ;eqn:7.28
I_2H = -I_1H * Zx/Zy;
%     :eqn:7.22
I_0H = (-(I_1H*Z_1H) -(I_2H*Z_2H)) / Z_0H;
%         :eqn:7.16
I_0 =  -(1/3 * I_1H + 1/3 * I_2H + 1/3 * I_0H);
%     ;eqn:7.30
I_1G = -I_1H -I_0  ;
%     ;eqn:7.31
 I_2G = -I_2H -I_0  ;
%     ;eqn:7.32
I_0G = -I_0H -I_0;

output_args = [I_1G; I_2G; I_0G; -3*I_0G];
%
%
```

```
end
%***********************************************************
%% References
%***********************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
% (Blackburn, 1993)
% Blackburn, J. L. (1993). Symmetrical components for
% power systems engineering. New York, M Dekker.

%% End Of Code
```

B.3 The funcBBLWLC.m MATLAB Function

Listing B.3: MATLAB function funcBBLWLC.m

```
function [ output_args ] = funcBBLWLC( Vs, Zs_PU, Zs_L_PU,...
                 Zcs_PU, Rfs_PU, Zl_L_PU, Zcl_PU, ZL_PU, Rfl_PU)
%***********************************************************

%%funcBBL function for simultaneous open circuit and
% earthfaults on the dead side in the same phase
%
% Author Andrew Geary
% Student No. Q9222672
%
% References.
% Blackburn 1993
%
%***********************************************************
%% Input arguments...
%***********************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
%
% Source side of the Open Circuit
%
% Applied fault voltage. voltage of network fault point
% pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of open circuit
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of the fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
```

```
%
% fault impedance to earth on the source side of the fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of the fault
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of the fault.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of the fault.
% Rfl_PU = (resistance in PU of line side EF).
%
%**********************************************************
%% Main Code
%**********************************************************
%
%**********************************************************
%page 167 -178 of blackburn 1993 (Blackburn, 1993)
%
%
% I_0 = -( 1/3 *I_1H + 1/3 * I_2H + 1/3 * I_0H);
%    :eqn:7.16
% I_1H*Z_1H + I_2H*Z_2H + I_0H*Z_0H = 0 ;
%     :eqn:7.22
% Zx = Z_1H * (Z_1G + 2*Z_0G + 3*Z_0H) + Z_0H*(Z_0G - Z_1G)
%     ;eqn:7.26
% Zy = Z_2H * (Z_1G + 2*Z_0G) + Z_0H*(2*Z_1G + Z_0G + 6*Z_2H)
%     ;eqn:7.27
% I_2H = -I_1H * Zx/Zy
%    ;eqn:7.28
% I_1H = (-V*Zy)/(Zx*(Z_1G + Z_2H) + Zy*(Z_1G+Z_1H))
%from 7.28)  ;eqn:7.29
% I_0H = (-(I_1H*Z_1H) -(I_2H*Z_2H)) / Z_0H
%        :eqn:7.22
% I_1G = -I_1H -I_0
%        ;eqn:7.30
% I_2G = -I_2H -I_0
%        ;eqn:7.31
% I_0G = -I_0H -I_0
%      ;eqn:7.32
%**********************************************************
% including Line Capacitance
% map our inputs into the variables
```

```
ZsS = Zs_PU + Zs_L_PU;%;
Z_1G = ZsS(1);
Z_2G = ZsS(2); % book assumes Z_2G = Z_1G, so... not used
Z_0G = ZsS(3) + 3 * Rfl_PU;%fault impedance added to source
% as earth circuit is a series circuit and this is an easy
% addition here.
% 3* Rfl gets the zero seq currents correct
ZlS = funcParallelZ(funcParallelZ(Zcl_PU*2,Zcs_PU*2),...
                    Zl_L_PU + funcParallelZ(ZL_PU,Zcl_PU*2));
Z_1H = ZlS(1);
Z_2H = ZlS(2);
Z_0H = ZlS(3);
% (Blackburn, 1993)
%          ;eqn:7.26
Zx = Z_1H * (Z_1G + 2*Z_0G + 3*Z_0H) + Z_0H*(Z_0G - Z_1G);
%        ;eqn:7.27
%Zy = Z_2H * (Z_1G + 2*Z_0G) + Z_0H*(2*Z_1G + Z_0G + 6*Z_2H);
%probably should be...
Zy = Z_2H*(Z_2G + 2*Z_0G) + Z_0H*(Z_1G+Z_2G + Z_0G + 6*Z_2H);
% from book that assumes Z1_G = Z_2G
%however left as stated in the book
%
% (from 7.28) ;eqn:7.29
I_1H = (-Vs*Zy)/(Zx*(Z_1G + Z_2H) + Zy*(Z_1G+Z_1H));
%            ;eqn:7.28
I_2H = -I_1H * Zx/Zy;
%          :eqn:7.22
I_0H = (-(I_1H*Z_1H) -(I_2H*Z_2H)) / Z_0H;
%         :eqn:7.16
I_0 =  -(1/3 * I_1H + 1/3 * I_2H + 1/3 * I_0H);
%         ;eqn:7.30
I_1G = -I_1H -I_0  ;
%         ;eqn:7.31
 I_2G = -I_2H -I_0  ;
%        ;eqn:7.32
I_0G = -I_0H -I_0;

output_args = [I_1G; I_2G; I_0G; -3*I_0G];
%
%
end
%*************************************************************
%% References
%*************************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
% (Blackburn, 1993)
% Blackburn, J. L. (1993). Symmetrical components for power
% systems engineering. New York, M Dekker.
%
%% End Of Code
```

B.4 The funcBurgess.m MATLAB Function

Listing B.4: MATLAB function funcBurgess.m

```
function [output_args] = funcBurgess( Vs, Zs_PU, Zs_L_PU, ...
                    Zcs_PU, Rfs_PU, ZL_PU, Zcl_PU, Zl_L_PU, Rfl_PU)
%**********************************************************
%%funcBurgess function for simultaneous open circuit
% and earthfaults
%
% Author Andrew Geary
% Student No. Q9222672
%
% Most of this function is based on the work of Burgess(2011).
%
%**********************************************************
% The work of burgess was specifically modelling an arc
% suppression coil in the star point of the source, however he
% developed a general sequence network connection for faults
% on either side of the open circuited line.
%
% As the suppression coil circuit relied on the network
% capacitance, the model developed included line capacitance
% on either side of the fault. For this thesis it is
% considered that this may be ignored. It is however included
% in this function so that calculations can be carried out with
% and without this capacitance to gauge it's impact on the
% complex system.
%
% Based of Figure 4.18 of Burgess, with guidance from Appendix
% 1 of Burgess and Mortlock 1947.
% (Mortlock, 1947)(Burgess, 2011)
%**********************************************************
%% Version Management
%**********************************************************
% funcBurgess
% copied from the work of Burgess and added network info
% disregarding line Capacitance

%
%**********************************************************
%% Input arguments...
%**********************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
%
% Source side of the Open Circuit
%
% Applied fault voltage.
%                   voltage of network fault point pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
```

```
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of open circuit
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of open circuit
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of open circuit.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of open circuit.
% Rfl_PU = (resistance in PU of line side EF).
%
%**********************************************************
%% Build Matrices
%**********************************************************
%
%prepare for burgess code
%pre-fault voltage
Es = Vs;

% including Line Capacitance
%source side impedances
ZsS = Zs_PU + Zs_L_PU;%;
ZposS  = ZsS(1);
ZnegS  = ZsS(2);
ZzeroS = ZsS(3);

%Load side impedances
ZlS = Zl_L_PU + ZL_PU;
ZposL = ZlS(1);
ZnegL = ZlS(2);
ZzeroL = ZlS(3);
```

```
RfS = Rfs_PU;
RfL = Rfl_PU;


% snippet from Burgess, 2011 (Burgess, 2011)
%*****************************************************
%*****************************************************

M=zeros(18,18);
S=zeros(18,1);
M(16,16)=1; M(16,10)=-ZposL; % Equation A1.1
M(17,17)=1; M(17,11)=-ZnegL; % Equation A1.2
M(18,18)=1; M(18,12)=-ZzeroL; % Equation A1.3
M(13,13)=1; M(13,1)=ZposS; S(13)=Es; % Equation A1.4
M(14,14)=1; M(14,2)=ZnegS; % Equation A1.5
M(15,15)=1; M(15,3)=ZzeroS; % Equation A1.6
M(10,13)=1;
M(10,10)=-ZposL; M(10,14)=-1; M(10,17)=1; % Equation A1.7
M(11,14)=1;
M(11,11)=-ZnegL; M(11,15)=-1; M(11,18)=1; % Equation A1.8
M(1,1)=1; M(1,4)=-1; M(1,13)=-1/(3*RfS); M(1,14)=-1/(3*RfS);
M(1,15)=-1/(3*RfS); % Equation A1.9
M(7,7)=1; M(7,10)=-1; M(7,16)=-1/(3*RfL); M(7,17)=-1/(3*RfL);
M(7,18)=-1/(3*RfL); % Equation A1.10
M(6,6)=1; M(6,5)=1; M(6,4)=1; % Equation A1.11
M(9,9)=1; M(9,7)=1; M(9,8)=1; % Equation A1.12
M(2,2)=1; M(2,5)=-1;M(2,13)=-1/(3*RfS); M(2,14)=-1/(3*RfS);
M(2,15)=-1/(3*RfS); % Equation A1.13
M(3,3)=1; M(3,6)=-1;M(3,13)=-1/(3*RfS); M(3,14)=-1/(3*RfS);
M(3,15)=-1/(3*RfS); % Equation A1.14
M(8,8)=1; M(8,11)=-1;M(8,16)=-1/(3*RfL); M(8,17)=-1/(3*RfL);
M(8,18)=-1/(3*RfL); % Equation A1.15
M(12,12)=-1;
M(12,9)=1;M(12,16)=-1/(3*RfL); M(12,17)=-1/(3*RfL);
M(12,18)=-1/(3*RfL); % Equation A1.16
M(4,4)=1; M(4,7)=-1; % Equation A1.17
M(5,5)=1; M(5,8)=-1; % Equation A1.18
U=M^-1*S;
%*****************************************************
%*****************************************************
% end snippet from Burgess
% outputs
output_args = [U(1:3,1); -3* U(3,1)];
%
%
end
%*****************************************************
%% References
%*****************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
```

```
%
% (Burgess, 2011)
% Burgess, R. T. (2011). Improving high voltage power system
% performance using arc suppression coils.
%
% (Mortlock, 1947)
% Mortlock, J. R. (1947). "The evaluation of simultaneous
% faults on three-phase systems." Electrical Engineers -
% Part II: Power Engineering,
% Journal of the Institution of 94(39): 166-190.
%
%% End Of Code
```

B.5 The funcBurgessWLC.m MATLAB Function

Listing B.5: MATLAB function funcBurgessWLC.m

```
function [output_args] = funcBurgessWLC(Vs, Zs_PU, Zs_L_PU,...
                    Zcs_PU, Rfs_PU, ZL_PU, Zcl_PU, Zl_L_PU, Rfl_PU)
%************************************************************

%%funcBurgessWLC function for simultaneous open circuit and
% earthfaults
%
% Author Andrew Geary
% Student No. Q9222672
%
% Most of this function is based on the work of Burgess.
%************************************************************
% The work of burgess was specifically modelling an arc
% suppression coil in the star point of the source, however he
% developed a general sequence network connection for faults
% on either side of the open circuited line.
%
% As the suppression coil circuit relied on the network
% capacitance, the model developed included line capacitance
% on either side of the fault. For this thesis it is
% considered that this may be ignored. It is however included
% in this function so that calculations can be carried out with
% and without this capacitance to gauge it's impact on the
% complex system.
%
% Based of Figure 4.18 of Burgess, with guidance from Appendix
% 1 of Burgess and Mortlock 1947.
% (Mortlock, 1947)(Burgess, 2011)
%************************************************************
%% Version Management
%************************************************************
% funcBurgess
% copied from the work of Burgess and added network info
% disregarding line Capacitance
```

```
% funcBurgessWLC
% included line capacitance into equations.
%
%
%************************************************************
%% Input arguments...
%************************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
%
% Source side of the Open Circuit
%
% Applied fault voltage.
%                voltage of network fault point pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of open circuit
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of open circuit
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of open circuit.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of open circuit.
% Rfl_PU = (resistance in PU of line side EF).
%
%************************************************************
%% Build Matrices
%************************************************************
%
%prepare for burgess code
%pre-fault voltage
```

```
Es = Vs;

% including Line Capacitance
%source side impedances
ZsS = Zs_PU + Zs_L_PU;%;
ZposS  = ZsS(1);
ZnegS  = ZsS(2);
ZzeroS = ZsS(3);

%Load side impedances
ZlS = funcParallelZ(funcParallelZ(Zcl_PU*2,Zcs_PU*2), ...
             Zl_L_PU + funcParallelZ(ZL_PU,Zcl_PU*2));
% ZposL = Zl_L_PU(1) + ZL_PU(1);
% ZnegL = Zl_L_PU(2) + ZL_PU(2);
% ZzeroL = (Zl_L_PU(3) + ZL_PU(3));%Zcl_PU(3));%ZL_PU(3));%
ZposL = ZlS(1);
ZnegL = ZlS(2);
ZzeroL = ZlS(3);

RfS = Rfs_PU;
RfL = Rfl_PU;


% snippet from Burgess, 2011 (Burgess, 2011)
M=zeros(18,18);
S=zeros(18,1);
M(16,16)=1; M(16,10)=-ZposL; % Equation A1.1
M(17,17)=1; M(17,11)=-ZnegL; % Equation A1.2
M(18,18)=1; M(18,12)=-ZzeroL; % Equation A1.3
M(13,13)=1; M(13,1)=ZposS; S(13)=Es; % Equation A1.4
M(14,14)=1; M(14,2)=ZnegS; % Equation A1.5
M(15,15)=1; M(15,3)=ZzeroS; % Equation A1.6
M(10,13)=1;
M(10,10)=-ZposL; M(10,14)=-1; M(10,17)=1; % Equation A1.7
M(11,14)=1;
M(11,11)=-ZnegL; M(11,15)=-1; M(11,18)=1; % Equation A1.8
M(1,1)=1; M(1,4)=-1; M(1,13)=-1/(3*RfS); M(1,14)=-1/(3*RfS);
M(1,15)=-1/(3*RfS); % Equation A1.9
M(7,7)=1; M(7,10)=-1; M(7,16)=-1/(3*RfL); M(7,17)=-1/(3*RfL);
M(7,18)=-1/(3*RfL); % Equation A1.10
M(6,6)=1; M(6,5)=1; M(6,4)=1; % Equation A1.11
M(9,9)=1; M(9,7)=1; M(9,8)=1; % Equation A1.12
M(2,2)=1; M(2,5)=-1;M(2,13)=-1/(3*RfS); M(2,14)=-1/(3*RfS);
M(2,15)=-1/(3*RfS); % Equation A1.13
M(3,3)=1; M(3,6)=-1;M(3,13)=-1/(3*RfS); M(3,14)=-1/(3*RfS);
M(3,15)=-1/(3*RfS); % Equation A1.14
M(8,8)=1; M(8,11)=-1;M(8,16)=-1/(3*RfL); M(8,17)=-1/(3*RfL);
M(8,18)=-1/(3*RfL); % Equation A1.15
M(12,12)=-1; M(12,9)=1;M(12,16)=-1/(3*RfL); M(12,17)=-1/(3*RfL);
M(12,18)=-1/(3*RfL); % Equation A1.16
M(4,4)=1; M(4,7)=-1; % Equation A1.17
M(5,5)=1; M(5,8)=-1; % Equation A1.18
```

```
U=M^-1*S;
% end snippet from Burgess
% outputs
output_args = [U(1:3,1); -3* U(3,1)];
%
%
end
%***********************************************************
%% References
%***********************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
%
%(Burgess, 2011)
% Burgess, R. T. (2011). Improving high voltage power system
% performance using arc suppression coils.
%
% (Mortlock, 1947)
% Mortlock, J. R. (1947). "The evaluation of simultaneous
% faults on % three-phase systems." Electrical Engineers -
% Part II: Power Engineering, % Journal of the Institution
% of 94(39): 166-190.
%
%% End Of Code
```

B.6 The funcGraphI.m MATLAB Function

Listing B.6: MATLAB function funcGraphI.m

```
function [ ] = funcGraphI( IInput,INumber,IName)
%***********************************************************
% funcGraphI Draws Vector Diagram of 3 phase and
% neutral/earth current.
%   %
% find the largest one
[r] = find(max(abs(IInput))==abs(IInput));
figure(INumber)
% start the graph with the largest one...
% this sets the graph with scaling big enough for the largest
% vector.
% use white as the colour for this 'dummy' run, it will be
% printed over with a colour vector.
compass(IInput(r),'-w');
view(-90,90);
hold on
% now print them in the Known Order so You know which is
% Which % use rgb as the colours as yellow is too hard to
% see on a white background.
compass(IInput(1,:),'-r');
compass(IInput(2,:),'-.k');
```

```
compass(IInput(3,:),'--b');
compass(IInput(4,:),'--g');

legend('Legend','A_Phase','B_Phase','C_Phase',...
                    'Earth','Location','BestOutside')
hold off
title(IName)
end
%***********************************************************
%References
% MatLab Help

%% End Of Code
```

B.7 The funcIEFWLC.m MATLAB Function

Listing B.7: MATLAB function funcIEFWLC.m

```
function [ output_args ] = funcIEFWLC(Vs_PU, Zs_PU, ...
          USN_Zpu, USN_Zcpu, NonFault_Zpu, DSN_Zpu, ...
                   DSN_Zcpu, ZL_PU, Fault_Zpu, BaseI,Graph)
%***********************************************************

%%file: funcIEFWLC.m
%***********************************************************
%% Version Tracking
%***********************************************************
% Version V01 ;
% First working attempt
% Version V02 ;
% added Load zero sequence capacitance to models
%***********************************************************
%% Purpose of code
%***********************************************************
% Written as part of my Thesis/Dissertation
% Subject 4111//4112, University of Southern Queensland.
% Sets up simulation for The behaviour of an Isolated
%Earth Fault.
% function for simultaneous open circuit and earth faults on
% the dead side in the same phase
%
% Author Andrew Geary
% Student No. Q9222672
%
% References.
%
%***********************************************************
%% Input arguments...
%***********************************************************
%
% All inputs are assumed to be PU On a common Base, this
```

```
% simplifies the math.
%
% Source side of the Open Circuit
%
% Applied fault voltage. voltage of network fault point
% pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of the fault
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of the fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of the fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of the fault
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of the fault.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of the fault.
% Rfl_PU = (resistance in PU of line side EF).
%
%*************************************************************
%% Main
%*************************************************************
%% Model 1: Burgess Model (Burgess, 2011)
%*************************************************************

[ O_B ] = funcBurgessWLC(Vs_PU, Zs_PU, USN_Zpu, USN_Zcpu, ...
          NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ZL_PU, Fault_Zpu);

% result includes source pos neg and zero sequence currents
% from these we can calculate the phase currents at the source
%
% first multiply by base current to get currents in amps
O_B = O_B * BaseI;
```

```
[PolarBurgessWLC, RectBurgessWLC] = ...
                          funcPUSeq2Phase(O_B(1),O_B(2),O_B(3));
if Graph == 1
    funcGraphI(RectBurgessWLC,1,...
                         ['Burgess With line Caps Method results ';
                      '                                   ']);
%PolarBurgess
%nice output should appear
end
%pause
%*********************************************************
%% Model 2:  Double Phase to earth fault (AG Derived)
%*********************************************************
[O_PPE] = funcPPEWLC(Vs_PU, Zs_PU, USN_Zpu, USN_Zcpu, ...
            NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ZL_PU, Fault_Zpu);
% first multiply by base current to get currents in amps
O_PPE = O_PPE * BaseI;

[PolarPPEWLC, RectPPEWLC] = ...
                   funcPUSeq2Phase(O_PPE(1),O_PPE(2),O_PPE(3));
if Graph == 1
   funcGraphI(RectPPEWLC,3,...
   ['Phase to Phase to Earth With Line Caps Method results';
    '                                                      ']);
%nice output should appear
end

%PolarPPE
%nice output should appear
%pause

%*********************************************************
%% Model 3: Blackburn Model (Blackburn, 1993) with load
%*********************************************************
[O_BBL] = funcBBLWLC(Vs_PU, Zs_PU, USN_Zpu, USN_Zcpu, ...
          NonFault_Zpu, DSN_Zpu, 2*DSN_Zcpu, ZL_PU, Fault_Zpu);
% first multiply by base current to get currents in amps
O_BBL = O_BBL * BaseI;

[PolarBBLWLC,RectBBLWLC] = ...
                  funcPUSeq2Phase( O_BBL(1),O_BBL(2),O_BBL(3) );
if Graph == 1
    funcGraphI(RectBBLWLC,4,...
       ['Blackburn With Line Caps Method results with load';
        '                                                 ']);
%nice output should appear
end

%*********************************************************
%% Record Results
%*********************************************************
%pause
```

```
if Graph == 1
    %verbose output
    O_B_O = O_B(1:4,1)
    O_PPE
    O_BBL

    PolarBurgessWLC
    PolarPPEWLC
    PolarBBLWLC
end
%EF magnitudes only to be output(in all cases).
output_args = [PolarBurgessWLC(4,1);
               PolarPPEWLC(4,1);
               PolarBBLWLC(4,1)];


end
%*************************************************************
%% References
%*************************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
%
%
%% End Of Code
%
```

B.8 The funcIEFWLCAP.m MATLAB Function

Listing B.8: MATLAB function funcIEFWLCAP.m

```
function [output_args] = funcIEFWLCAP(Vs_PU, Zs_PU, ...
          USN_Zpu, USN_Zcpu, NonFault_Zpu, DSN_Zpu, ...
          DSN_Zcpu, ZL_PU, Fault_Zpu, BaseI,Graph,Phases)
%*************************************************************

%%file: funcIEFWLCAP.m
%*************************************************************
%% Version Tracking
%*************************************************************
% Version V01 ;
% funcIEFWLC, added phases to account for single phase models
%*************************************************************
%% Purpose of code
%*************************************************************
% Written as part of my Thesis/Dissertation
% Subject 4111//4112, University of Southern Queensland.
% Runs the functions set up to simulate an Isolated Earth
% Fault.
% runs various functions for simultaneous open circuit and
```

```
% earth faults
% on the downstream side in the same phase
%
% Author Andrew Geary
% Student No. Q9222672
%
% References.
%
%*********************************************************
%% Input arguments...
%*********************************************************
%
%*********************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
%
% Source side of the Open Circuit
%
% Applied fault voltage. voltage of network fault point
% pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of the fault
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of the fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of the fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of the fault
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of the fault.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of the fault.
% Rfl_PU = (resistance in PU of line side EF).
%
```

```
%***************************************************************
%% Initialise Variables
%***************************************************************
    PolarBurgessWLC=[0;0;0;0];
    PolarPPEWLC=[0;0;0;0];
    PolarBBLWLC=[0;0;0;0];
    PolarSPEWLC=[0;0;0;0];

%***************************************************************
%% Main
%***************************************************************
if Phases == 3
%***************************************************************
    %% Model 1: Burgess Model (Burgess, 2011)
%***************************************************************

    [ O_B ] = funcBurgessWLC(Vs_PU, Zs_PU, USN_Zpu, ...
            USN_Zcpu, NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ...
                ZL_PU, Fault_Zpu);

    % result includes source pos neg and zero sequence
        % currents from these we can calculate the phase and
        % earth currents at the source
    %
    % first multiply by base current to get currents in amps
    O_B = O_B * BaseI;

    [ PolarBurgessWLC, RectBurgessWLC ] = ...
                        funcPUSeq2Phase( O_B(1),O_B(2),O_B(3) );
    if Graph == 1
        funcGraphI(RectBurgessWLC,1,...
                    ['Burgess With line Caps Method results ';
                     '                                      ']);
        %nice output should appear
    end

%***************************************************************
    %% Model 2:  Double Phase to earth fault (AG Derived)
%***************************************************************
    [O_PPE] = funcPPEWLC(Vs_PU, Zs_PU, USN_Zpu, USN_Zcpu, ...
           NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ZL_PU, Fault_Zpu);
    % result includes source pos neg and zero sequence
        % currents from these we can calculate the phase and
        % earth currents at the source
    %
    O_PPE = O_PPE * BaseI;

    [PolarPPEWLC, RectPPEWLC ] = ...
                  funcPUSeq2Phase(O_PPE(1),O_PPE(2),O_PPE(3));
    if Graph == 1
    funcGraphI(RectPPEWLC,2,...
    ['Phase to Phase to Earth With Line Caps Method results';
```

```
      '                                                                 ']);
        %nice output should appear
    end

%****************************************************************
    %% Model 3: Blackburn Model (Blackburn, 1993) with load
%****************************************************************
    [O_BBL] = funcBBLWLC(Vs_PU, Zs_PU, USN_Zpu, USN_Zcpu, ...
        NonFault_Zpu, DSN_Zpu, 2*DSN_Zcpu, ZL_PU, Fault_Zpu);
    % result includes source pos neg and zero sequence
    % currents from these we can calculate the phase and
        % earth currents at the source
    %
    O_BBL = O_BBL * BaseI;

    [PolarBBLWLC,RectBBLWLC ] = ...
              funcPUSeq2Phase( O_BBL(1),O_BBL(2),O_BBL(3) );
    if Graph == 1
      funcGraphI(RectBBLWLC,3 ,...
      ['Blackburn With Line Caps Method results with load';
       '                                                            ']);
      %nice output should appear
    end

else
    [O_SPE] = funcSPE(Vs_PU, Zs_PU, USN_Zpu, USN_Zcpu, ...
         NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ZL_PU, Fault_Zpu);
    % result includes source pos neg and zero sequence
    % currents from these we can calculate the phase and
        % earth currents at the source
    %
    O_SPE = O_SPE*BaseI

   [PolarSPEWLC,RectSPEWLC ] = ...
             funcPUSeq2Phase( O_SPE(1),O_SPE(2),O_SPE(3) );
    if Graph == 1
        funcGraphI(RectSPEWLC,4 ,...
        ['Single Phase Method results with load';
         '                                             ']);
      %nice output should appear
    end
end

%****************************************************************
%% Record Results
%****************************************************************
%pause
if Graph == 1
    %verbose output
    O_B_O = O_B(1:4,1)
    O_PPE
    O_BBL
```

```
    O_SPE

    PolarBurgessWLC
    PolarPPEWLC
    PolarBBLWLC
    PolarSPEWLC
end
%EF magnitudes only to be output(in all cases).
output_args = [PolarBurgessWLC(4,1);
               PolarPPEWLC(4,1);
               PolarBBLWLC(4,1);
               PolarSPEWLC(4,1)];


end
%***********************************************************
%% References
%***********************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
%
%
%% End Of Code
%
```

B.9 The funcParallelZ.m MATLAB Function

Listing B.9: MATLAB function funcParallelZ.m

```
function [ Ztot ] = funcParallelZ( Z1, Z2)
%***********************************************************
%%funcfuncParallelZ function for parallel impedance calcs
%
% Author Andrew Geary
% Student No. Q9222672
%
% References.
% Matlab Help
%***********************************************************
%% Input arguments...
%***********************************************************

%
%***********************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
%
% Z1 is a matrix full of impedances ...
%           (eg pos neg zero sequence impedances)
```

```
% Z2 is a matrix full of impedances
%
%**********************************************************
%% Output arguments...
%**********************************************************
%
%
% Ztot is the matrix full of the equivalent impedance for
% each element in Z1 in parallel with its matching element
% in Z2
%
%**********************************************************
%% Main Code
%**********************************************************
%
% (Grainger, J. J. a. S. W. D. j. 1994)
Ztot = (Z1 .* Z2)./ (Z1 + Z2);
%
%
end
%References
% (Grainger, J. J. a. S. W. D. j. 1994)
% Grainger, J. J. a. S. W. D. j. (1994). Power System Analysis.
% United States of America, McGraw-Hill.

%% End Of Code
```

B.10 The funcPPE.m MATLAB Function

Listing B.10: MATLAB function funcPPE.m

```
function [ output_args ] = funcPPE(Vs, Zs_PU, Zs_L_PU, ...
               Zcs_PU, Rfs_PU, Zl_L_PU, Zcl_PU, ZL_PU, Rfl_PU)
%**********************************************************

%%funcPPE function for simultaneous open circuit and
% earth faults on the dead side in the same phase
%
% Author Andrew Geary
% Student No. Q9222672
%
%
%**********************************************************
%% Input arguments...
%**********************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
%
% Source side of the Open Circuit
%
```

```
% Applied fault voltage. voltage of network fault point
% pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of open circuit
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of the fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of the fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of open circuit
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of open circuit.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of open circuit.
% Rfl_PU = (resistance in PU of line side EF).
%
%**********************************************************
%% Main Code
%**********************************************************

% Network upstream of open phase impedance
ZUS = Zs_PU +  Zs_L_PU;
% Network downstream of open phase impedance
%ZDS = Z_f;
 Z_f = Zl_L_PU(1) + ZL_PU(1);

%Impedance between Phases
%Z_f = ZDS;
 Z_fg = Rfl_PU + Z_f ;% earth fault impedance
% variable now setup for application to phase to phase to
% ground fault page 315 of Horowitz  Power System Relaying
% (Horowitz, 2008)

%
% all impedances in parallel including zF
```

```
% (+3Zfg in zero seq)
Zp = ZUS(1) + Z_f;
Zn = ZUS(2) + Z_f;
Zz = ZUS(3) + Z_f + 3 * Z_fg;
Zsum = Zn+Zz;
Z_Total = Zp + (Zn*Zz)/(Zsum);

I_p_PU = Vs / Z_Total ;
I_n_PU = -I_p_PU * Zz/(Zsum);
I_z_PU = -I_p_PU * Zn/(Zsum);

output_args = [I_p_PU;I_n_PU;I_z_PU; -I_z_PU-I_z_PU-I_z_PU];
%
%
end
%*********************************************************
%% References
%*********************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
% (Horowitz, 2008)
% Horowitz, S. H. P., A. G. (2008). Power System Relaying.
% West Sussex, England, John Wiley & Sons, Ltd.
%
%
%% End Of Code
%
```

B.11 The funcPPEWLC.m MATLAB Function

Listing B.11: MATLAB function funcPPEWLC.m

```
function [ output_args ] = funcPPEWLC(Vs, Zs_PU, Zs_L_PU, ...
                    Zcs_PU, Rfs_PU, Zl_L_PU, Zcl_PU, ZL_PU, Rfl_PU)
%*********************************************************

%%funcPPEWLC function for simultaneous open circuit and
% earth faults on the dead side in the same phase.
%
% Author Andrew Geary
% Student No. Q9222672
%
% References.
%
%*********************************************************
%% Input arguments...
%*********************************************************
%
% All inputs are assumed to be PU On a common Base, this
% simplifies the math.
```

```
%
% Source side of the Open Circuit
%
% Applied fault voltage. voltage of network fault point
% pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of open circuit
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of the fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of the fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of the fault
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of the fault.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of the fault.
% Rfl_PU = (resistance in PU of line side EF).
%
%**********************************************************
%% Main Code
%**********************************************************

% Network upstream of open phase impedance
ZUS = Zs_PU + Zs_L_PU;%;
% Network downstream of open phase impedance
%ZDS = Z_f;(Horowitz, 2008)
Eq1 = (Zcl_PU(1)*Zcs_PU(1)*2)/(Zcs_PU(1)+Zcl_PU(1)*2);
Eq2 =Zl_L_PU(1)+(ZL_PU(1)*Zcl_PU(1)*2)/(ZL_PU(1)+Zcl_PU(1)*2);
Z_f = (Eq1*Eq2)/(Eq1+Eq2);
%Impedance between Phases
%Z_f = ZDS;
Z_fg = Rfl_PU + Z_f ;% earth fault impedance
% variable now setup for application to phase to phase to
% ground fault page 315 of Horowitz Power System Relaying
```

```
% (Horowitz, 2008)
%
%all impedances in parallel including zF (+3Zfg in zero seq)
Zp = ZUS(1) + Z_f;
Zn = ZUS(2) + Z_f;
Zz = ZUS(3) + Z_f + 3 * Z_fg;
Zsum = Zn+Zz;
Z_Total = Zp + (Zn*Zz)/(Zsum);

I_p_PU = Vs / Z_Total ;
I_n_PU = -I_p_PU * Zz/(Zsum);
I_z_PU = -I_p_PU * Zn/(Zsum);

output_args = [I_p_PU;I_n_PU;I_z_PU; -I_z_PU-I_z_PU-I_z_PU];
%
%
end
%**************************************************************
%% References
%**************************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
% (Horowitz, 2008)
% Horowitz, S. H. P., A. G. (2008). Power System Relaying.
% West Sussex, England, John Wiley & Sons, Ltd.
%
%% End Of Code
```

B.12 The funcPUPhase2Seq.m MATLAB Function

Listing B.12: MATLAB function funcPUPhase2Seq.m.

```
function[pos,neg,zero] = funcPUPhase2Seq(aPhase,bPhase,cPhase)
%**************************************************************
    %%funcPUPhase2Seq(aPhase,bPhase,cPhase)
    % converts PU phase currents into sequence currents
    % Copyright AjGeary 2013
    %
    %usage ...
    %[pos,neg,zero] = PUPhase2seq(aPhase,bPhase,cPhase)
    % *************Example*******************
    %[aa,bb,cc] = PUPhase2seq(1,2,3+2j)
    %
    %aa =
    %    0.0774 - 0.6220i
    %
    %bb =
    %   -1.0774 - 0.0447i
    %
    %cc =
```

```
    %    2.0000 + 0.6667i
    %*************end example***************
    %
    % the a operator is a rotation of 120 degrees
    % (Horowitz, S. H. P., A. G. 2008)(USQ 2013)
    %120 degree operator
    a = cos(120*pi()/180) + sin(120*pi()/180)*i;
    %conversion matrix C
    C = [1   ,a   ,a^2;
         1   ,a^2,a   ;
         1   ,1   ,1   ];
    %
    Output = 1/3 * C * [aPhase;bPhase;cPhase] ;
    pos = Output(1,1);
    neg = Output(2,1);
    zero = Output(3,1);
end

%*********************************************************
% Reference
% ELE3804 Power system Protection Studybook (USQ 2013)
% Horowitz, S. H. P., A. G. (2008). Power System Relaying.
% West Sussex, England, John Wiley & Sons, Ltd.
%
%% End Of Code
```

B.13 The funcPUSeq2Phase.m MATLAB Function

Listing B.13: MATLAB function funcPUSeq2Phase.m.

```
function[Polar1,Rectangular1] = funcPUSeq2Phase(pos,neg,zero)
%*********************************************************
    %%funcPUSeq2Phase( pos,neg,zero )
    % converts PU sequence currents into PU phase currents
    % Copyright AjGeary 2013
    %
    %usage ...
        %[APh, BPh, CPh,N] =  PUseq2Phase(pos,neg,zero)
    % suggest that you set up figure run this function,
    %and then add the title to the graph/plot.
    % ************Example******************
    %[q r t] = PUseq2Phase( 1,2,3 )
    %q =
    %      6
    %
    %r =
    %    1.5000 + 0.8660i
    %
    %t =
    %    1.5000 - 0.8660i
    %*************end example***************
```

```
    %
    % the a operator is a rotation of 120 degrees
    %120 degree operator
    a = cos(120*pi()/180) + sin(120*pi()/180)*1i;
    %
    %conversion matrix C (Horowitz, S. H. P., A. G. (2008))
    C = [1    ,1    ,1    ;
         a^2,a    ,1    ;
         a    ,a^2,1    ];
    %
    Rectangular1 = C * [pos;neg;zero] ;
    aPhase = Rectangular1(1,1);
    bPhase = Rectangular1(2,1);
    cPhase = Rectangular1(3,1);
    Neutral = -(aPhase + bPhase + cPhase);%(USQ 2013)
    Rectangular1(4,1) = Neutral;
    %
    Polar1(:,1)=abs(Rectangular1);
    Polar1(:,2)=angle(Rectangular1)*180/pi();
    %
end
%*********************************************************
% Reference
% ELE3804 Power system Protection Studybook [USQ 2013]
% Horowitz, S. H. P., A. G. (2008). Power System Relaying.
% West Sussex, England, John Wiley & Sons, Ltd.
%
%% End Of Code
```

B.14 The funcSPE.m MATLAB Function

Listing B.14: MATLAB function funcSPE.m

```
function [ output_args ] = funcSPE(Vs, Zs_PU, Zs_L_PU, ...
                  Zcs_PU, Rfs_PU, Zl_L_PU, Zcl_PU, ZL_PU, Rfl_PU)
%*********************************************************

%%funcSPE function for simultaneous open circuit and
% earth faults on the dead side in the same phase for single
% phase circuits
%
% Author Andrew Geary
% Student No. Q9222672
%
% References.
%
%*********************************************************
%% Input arguments...
%*********************************************************
%
% All inputs are assumed to be PU On a common Base, this
```

```
% simplifies the math.
%
% Source side of the Open Circuit
%
% Applied fault voltage. voltage of network fault point
% pre-fault
% Vs = (Voltage_Source_PosSeq_PU);
%
% Impedance of Source
% Zs_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line on Source Side of the fault
% Zs_L_PU = [PosSeq, NegSeq, ZeroSeq];(PU)
%
% Impedance of line Capacitance on Source Side of the fault.
% Zcs_PU = [PosSeq, NegSeq, ZeroSeq]; (PU)
%
% fault impedance to earth on the source side of the fault.
% Rfs_PU = (resistance in PU of source side EF).
%
% Load side of the open circuit
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of line on load Side of the fault
% Zl_L_PU = [PosSeq, NegSeq, ZeroSeq] (PU);
%
% Impedance of Capacitance on load Side of the fault.
% Zcl_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% Impedance of Load.
% ZL_PU = [PosSeq, NegSeq, ZeroSeq](PU);
%
% fault impedance to earth on the load side of the fault.
% Rfl_PU = (resistance in PU of line side EF).
%
%**********************************************************
%% Main Code
%**********************************************************
% Single phase code
%**********************************************************
ZL_PU = ZL_PU*3^0.5;% single phase equivalent impedance as the
% three phase star equivalent impedance is provided

% Network upstream of open phase impedance
ZUS = Zs_PU + Zs_L_PU;%
% Network downstream of open phase impedance

ZDS = Zl_L_PU ;
%Impedance between Phases
Z_f = + ZL_PU(1) +Zl_L_PU(1) + Rfl_PU;
```

```
Z_Tot = ZUS(1)+ZDS(1)+ZUS(2)+ZDS(2)+ZUS(3)+ZDS(3)+3*Z_f;

Ip_PU = Vs /(Z_Tot);
In_PU = Ip_PU;
Iz_PU = Ip_PU;

output_args = [Ip_PU;In_PU;Iz_PU; 3*Iz_PU];
%
%
end
%**********************************************************
%% References
%**********************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
% (Horowitz, 2008)
% Horowitz, S. H. P., A. G. (2008). Power System Relaying.
% West Sussex, England, John Wiley & Sons, Ltd.
%
%
%% End Of Code
```

B.15 The IsolatedEarthFault.m MATLAB Script

Listing B.15: MATLAB script IsolatedEarthFault.m

```
%%file: IsolatedEarthFault.m
%**********************************************************
%% Copyright
%**********************************************************
%
% Matlab Code CopyRight (c) Andrew James Geary 2013.
%
% Author: Andrew James Geary [Student Q9222672].
%
%
% Any snippets that have been copied from elsewhere will have
% a reference to the original author in curvy brackets
% (A Geary).
%
%**********************************************************
%% Version Tracking
%**********************************************************
% Version V01 ;
% Modified from IsolatedEarthFault_V03.m
% Version V02 ;
% Restricted to 3 methods for comparison to focus results.
% Version V04 ;
% add phases, dns /2 to account for distributed load.
```

```
% (Vempati, Shoults et al. 1987)

%***********************************************************
%% Purpose of code
%***********************************************************
% Written as part of my Thesis/Dissertation
% Subject 4111//4112, University of Southern Queensland.
% Sets up simulation for The behaviour of an Isolated
% Earth Fault.
%
%***********************************************************
%% Initialise
%***********************************************************
clear; % clear variables from Matlab
clc; % clear the (text) output from Matlab
format short

% Setting Constants
% Three Phase Fault Levels
%
a = 1 * cos(pi* 120/180) + 1i * sin(pi* 120/180);

% Base description
%
BaseV = 11000/sqrt(3); %11kV Base Voltage
BaseVA = 100000000; %100MVA Base
BaseI = (BaseVA)/(3*BaseV); % calculated Base current
BaseZ = BaseV/BaseI; % Calculated Base Impedance

% Setting Variables...
%
%
%***********************************************************

%% Impedances.
% conductor data from planning
%
%prefault Voltage
Vs_PU = 1.036;%PU
%***********************************************************

%% Source impedance
Zs_PU = [0.07864+0.63723i,0.07864+0.63723i,0.048+0.48i];
% Source Impedance (pu)


%% line values from network model
%***********************************************************

ZL1 = [0.143133+i*0.163429, 0.143133+i*0.163429, ...
                                      0.99991+i*1.085673];
    % Source side Line Impedance (pu)
```

```
ZL2 = [2.22493+i*2.54572, 3.48879+i*9.27835, ...
                                        20.20761+i*21.03572];
    % Load side Line Impedance (pu)

CSL1 = [279.3676,279.3676,278.801];
    % Source side line capacitive susceptance (micromho).

CSL2 = [36.9011,36.9011,16.3492];
    % Load side line capacitive susceptance (micromho).

ZL1_PU = ZL1 /BaseZ;
ZL2_PU = ZL2 /BaseZ;

CcL1 = CSL1 / 1000000;% convert to Mho
CcL2 = CSL2 / 1000000;% convert to MHo

ZcL1 = (-1i) ./ CcL1;% convert to Ohm
ZcL2 = (-1i) ./ CcL2;% convert to Ohm

ZcL1_PU = (ZcL1 / BaseZ);% convert to PU
ZcL2_PU = (ZcL2 / BaseZ);% convert to PU


%% Zero Sequence Load Calcs
% unloaded model of zero sequence Capacitance
% from burgess load transformer capacitance.
% zero sequence Cap per transformer
%*************************************************************
%
% load zero sequence capacitance is important for modelling
% this fault using the Burgess and Blackburn Methods at
% extremely light load conditions.

% capacitance of each transformer is in parallel, as such
% capacitance adds.

%from burgess we can build a dictionary of capacitance based
% on transformer size.
% key [size (kVA), Capacitance(nF)]
 CDictionary = [ 25, 2.02;
                 63, 4.14;
                100, 4.63;
                200, 9.62;
                500, 5.45];
Txs = [1,5,8,8,0];% transformers of each size beyond fault

CzL = Txs * CDictionary(:,2) * 0.000000001;
% total capacitance in Farads

ZzL = (1i) * 1/(2 * pi() * 50 * CzL);
%Impedance of the Zero Sequence total capacitance
```

```
%*************************************************************
%% Load calcs
ZzLoad_PU = ZzL / BaseZ;

Load_A = 120;
% per phase 3 phase includes all load and losses.

Load_pf = 0.9;
% assume 0.9 if unknown

%Calcs;
pf = Load_pf + 1i * sin(acos(Load_pf));
Load_A_Complex = Load_A * pf;
Load_A_PU = Load_A_Complex /BaseI;

Fault_Ohm = [30,20,10,0.1];
%Fault impedance in Ohms (make this small
% for a bolted fault zero may cause a divide by zero error.
NonFault_Ohm = 1e99;%Non Fault impedance in Ohms

AjGFault_Zpu = Fault_Ohm/BaseZ;
NonFault_Zpu = NonFault_Ohm/BaseZ;
PreFaultVoltage_Vpu = Vs_PU;
% voltage at fault point before fault occurs.
%% add sensitivity loops
% sensitivity tests.


%% Build impedances

% Upstream Network Impedance (pu)
USN_Zpu = ZL1_PU;

% Upstream Network Capacitance Impedance (pu)
USN_Zcpu =  ZcL1_PU  ;

% Upstream load Impedance (pu)
ZL_US = [NonFault_Zpu, NonFault_Zpu, NonFault_Zpu];

% DownStream Network Impedance (pu)
DSN_Zpu = ZL2_PU/2;
%/2 according too (Vempati, Shoults et al. 1987)


% DownStream Network Capacitance Impedance (pu)
DSN_Zcpu = ZcL2_PU;

% Downstream load Impedance (pu)
ZL_PU = [Vs_PU / (Load_A_PU), Vs_PU / (Load_A_PU), ZzLoad_PU ];

%*************************************************************
```

```
%% Main
%*****************************************************************
for IterAjG = 1:1:4
    Fault_Zpu = AjGFault_Zpu(IterAjG)
[ OP(:,IterAjG) ] = funcIEFWLC(  Vs_PU,  Zs_PU, USN_Zpu, ...
                         USN_Zcpu, NonFault_Zpu, DSN_Zpu,      ...
                         DSN_Zcpu, ZL_PU, Fault_Zpu, BaseI,1);
end
clc
fprintf('For \n')
Fault_Ohm
fprintf('Results are; \n')

OP
%*****************************************************************
%% References
%*****************************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
%
%(Vempati, Shoults et al. 1987)
% Vempati, N., R. R. Shoults, M. S. Chen and L. Schwobel(1987).
% "Simplified Feeder Modeling for Loadflow Calculations."
% Power Systems, IEEE Transactions on 2(1): 168-174.
%
%% End Of Code
%
```

B.16 The MultiVariableAnalysis.m MATLAB Script

Listing B.16: MATLAB script MultiVariableAnalysis.m

```
%%file: MultiVariableAnalysis.m
%*****************************************************************
%% Copyright
%*****************************************************************
%
% Matlab Code CopyRight (c) Andrew James Geary 2013.
%
% Author: Andrew James Geary [Student Q9222672].
%
%
% Any snippets that have been copied from elsewhere will have
% a reference to the original author in curvy brackets
% (A Geary).
%
%*****************************************************************
%% Version Tracking
%*****************************************************************
% Version V01 ;
```

```
% Modified from SensitivityAnalysis_V02.m
%*********************************************************
%% Purpose of code
%*********************************************************
% Written as part of my Thesis/Dissertation
% Subject 4111//4112, University of Southern Queensland.
% Sets up simulation for The behaviour of an Isolated
% Earth Fault.
%
% Designed experiments vary multiple factors at a time in an
% endeavour to discover interactions between factors in
% complex formula/functions (Czitrom, 1999)
%
%*********************************************************
%% Initialise Variables
%*********************************************************
clear; % clear variables from Matlab
clc; % clear the (text) output from Matlab
format short

% Setting Constants
%********************
% Three Phase Fault Levels
%
a = 1 * cos(pi* 120/180) + 1i * sin(pi* 120/180);
MatrixA = [1 a a^2; 1 a^2 a; 1 1 1];

% Base description
%********************
%
BaseV = 11000/sqrt(3); %11kV Base Voltage
BaseVA = 100000000; %100MVA Base
BaseI = (BaseVA)/(3*BaseV); % calculated Base current
BaseZ = BaseV/BaseI; % Calculated Base Impedance

% Setting Variables...
%********************
%
%
% Impedances.
%*********************************************************
% conductor data from planning
% format
% ConductorName, Code, R1, X1, R2, X2, R0, X0, CS1(2), CS0.
% 1 = pos seq
% 2 = neg seq
% 0 = zero seq
% CS = capacitive susceptance (micro mho)
% ohms and umho ...
ZDictionary = [1,1.065+.4023i,1.213+1.735i,2.920,1.321;
               2,.7408+.3911i,.8890+1.723i,3.012,1.339;
               3,.4721+.3771i,.6203+1.709i,3.135,1.363;
```

```
                4,.3279+.3655i,.4761+1.698i,3.238,1.383;
                5,.1750+.3383i,.3232+1.671i,3.450,1.420];
% conductor list
%*********************************************************
%'7/2.50AAAC','1'
%'7/3.00AAAC','2'
%'7/3.75AAAC','3'
%'7/4.50AAAC','4'
%'19/3.75AAAC','5'
%
%prefault Voltage
%*********************************************************
Vs_PU = 1.00;%PU

% Source impedance
%*********************************************************
Zs_PU = [0.07864+0.63723i,0.07864+0.63723i,0.048+0.48i];
% Source Impedance (pu)

% Line impedances, direct path to fault/beyond fault to
% (longest)end of feeder
%*********************************************************
SourceLine = [8,8,8,8,8]; %km of line in Z Dictionary.
LoadLine = [8,8,8,8,8]; %km of line in Z Dictionary.
% Capacitance impedance, tree length of line
%*********************************************************
SourceCap = [20,20,20,20,20];
LoadCap = [20,20,20,20,20];

% Calculation of line values
%*********************************************************

ZL1 = [SourceLine * ZDictionary(:,2),...
    SourceLine * ZDictionary(:,2),...
    SourceLine * ZDictionary(:,3)];
    % Source side Line Impedance (pu)

ZL2 = [LoadLine * ZDictionary(:,2),...
    LoadLine * ZDictionary(:,2),...
    LoadLine * ZDictionary(:,3)];
    % Load side Line Impedance (pu)

CSL1 = [SourceCap * ZDictionary(:,4),...
    SourceCap * ZDictionary(:,4),...
    SourceCap * ZDictionary(:,5)];
    % Source side line capacitive susceptance (micromho).

CSL2 = [LoadCap * ZDictionary(:,4),...
    LoadCap * ZDictionary(:,4),...
    LoadCap * ZDictionary(:,5)];
    % Load side line capacitive susceptance (micromho).
```

```
ZL1_PU = ZL1 /BaseZ;
ZL2_PU = ZL2 /BaseZ;

CcL1 = CSL1 / 1000000;% convert to Mho
CcL2 = CSL2 / 1000000;% convert to Mho

ZcL1 = (-1i) ./ CcL1;% convert to Ohm
ZcL2 = (-1i) ./ CcL2;% convert to Ohm

ZcL1_PU = (ZcL1 / BaseZ);% convert to PU
ZcL2_PU = (ZcL2 / BaseZ);% convert to PU


% Zero Sequency Load Calcs
%*************************************************************
% unloaded model of zero sequence Capacitance
% from burgess load transformer capacitance.
% zero sequence Cap per transformer
%*************************************************************
%
% load zero sequence capacitance is important for modelling
% this fault using the Burgess and Blackburn Methods at
% extremely light load conditions.
% capacitance of each transformer is in parallel, as such
% capacitance adds.
% from burgess we can build a dictionary of capacitance based
% on transformer size.
% key [size (kVA), Capacitance(nF)]
CDictionary = [ 25, 2.02;
                63, 4.14;
               100, 4.63;
               200, 9.62;
               500, 5.45];
Txs = [10,10,10,10,0];% transformers of each size beyond fault

CzL = Txs * CDictionary(:,2) * 0.000000001;
% total capacitance in Farads

ZzL = (1i) * 1/(2 * pi() * 50 * CzL);
%Impedance of the Zero Sequence total capacitance

%*************************************************************
% Load calcs
%*************************************************************
ZzLoad_PU = ZzL / BaseZ;

Load_A = 50; % perphase 3 phase includes all load and losses

Load_pf = 0.9; % assume 0.9 if unknown

%Calcs;
%*************************************************************
```

```
pf = Load_pf + 1i * sin(acos(Load_pf));
Load_A_Complex = Load_A * pf;
Load_A_PU = Load_A_Complex /BaseI;

Fault_Ohm = 30;
%Fault impedance in Ohms (make this small and not zero
% for a bolted fault zero makes a divide by zero error.
NonFault_Ohm = 1e99;%Non Fault impedance in Ohms

Fault_Zpu = Fault_Ohm/BaseZ;
NonFault_Zpu = NonFault_Ohm/BaseZ;
PreFaultVoltage_Vpu = Vs_PU;
% voltage at fault point before fault occurs.


% Build impedances
%***********************************************************

% Upstream Network Impedance (pu)
USN_Zpu = ZL1_PU;

% Upstream Network Capacitance Impedance (pu)
USN_Zcpu =  ZcL1_PU  ;

% Upstream load Impedance (pu)
ZL_US = [NonFault_Zpu, NonFault_Zpu, NonFault_Zpu];

% DownStream Network Impedance (pu)
DSN_Zpu = ZL2_PU;

% DownStream Network Capacitance Impedance (pu)
DSN_Zcpu = ZcL2_PU;

% Downstream load Impedance (pu)
ZL_PU = [Vs_PU / (Load_A_PU), Vs_PU / (Load_A_PU), ZzLoad_PU ];

%***********************************************************
%% Main
%***********************************************************
NumberOfPoints=11;
%OriginalArguments = [ Vs_PU ,  Zs_PU, USN_Zpu, USN_Zcpu, ...
%                      NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ...
%                      ZL_PU, Fault_Zpu, BaseI, 0];
M=[1,1,1,1,1,1,1,1,1];% once only
Multiplier = 1:0.1:2;

for S1 = 1:1:NumberOfPoints;%Sensitivity1
    M1= Multiplier(S1);
    for S2 = 1:1:NumberOfPoints;%Sensitivity2
        M2= Multiplier(S2);
        for S3 = 1:1:NumberOfPoints;%Sensitivity3
            M3= Multiplier(S3);
```

```
            for S4 = 1:1:NumberOfPoints;%Sensitivity4
                M4= Multiplier(S4);
    OP(S1,S2,S3,S4,:) = ...
     funcIEFWLC(Vs_PU,  Zs_PU, USN_Zpu * M1, USN_Zcpu, ...
     NonFault_Zpu, DSN_Zpu * M2, DSN_Zcpu, ZL_PU * M3, ...
     Fault_Zpu * M4, BaseI, 0);
            end
        end
    end


end
%*************************************************************

% %
for Loop0 = 1:1:NumberOfPoints
    for Loop1 = 1:1:NumberOfPoints
        A(:,:)=OP(:,:,Loop0,Loop1,1);
        B((Loop0-1)*10+Loop1,:,:) = A(:,:);
        figure(10+Loop0)
        axis([1,2,1,2,6.5,13.5])
        view(30,30)
        hold on
        surf(1:0.1:2,1:0.1:2,A,ceil(Loop1*ones(10,10)))
        %this makes the colours correct for the output
        % was...
        %surf(1:0.1:2,1:0.1:2,A,ceil(Loop0*ones(10,10)))
        title(...
            ['Graph Where Load Impedance Multiplier is ', ...
                                    num2str(Loop0*.1+ 0.9)])
        xlabel('Upstream Impedance Multiplier')
        ylabel('Downstream Impedance Multiplier')
        zlabel('Earth Fault Current' )
        hold off

    end
    pause
end

for Loop5 = 1:1:100

    figure(5)
    axis([1,2,1,2,6.5,13.5])
    view(30,30)
    hold on
    Data(:,:) = B(Loop5,:,:);
    surf(1:0.1:2,1:0.1:2,Data, ceil(Loop5/10)*ones(10,10))
end
        title(['';'Combined Graph';''])
        xlabel('Upstream Impedance Multiplier')
        ylabel('Downstream Impedance Multiplier')
        zlabel('Earth Fault Current' )
```

```
hold off
%
%************************************************************
%% References
%************************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
% (Czitrom, 1999)
%Czitrom, V. (1999). "One-Factor-at-a-Time versus Designed
% Experiments. The American Statistician 53(2): 126-131.
%
%% End Of Code
```

B.17 The SensitivityAnalysis.m MATLAB Script

Listing B.17: MATLAB script SensitivityAnalysis.m

```
%%file: SensitivityAnalysis.m
%************************************************************
%% Copyright
%************************************************************
%
% Matlab Code CopyRight (c) Andrew James Geary 2013.
%
% Author: Andrew James Geary [Student Q9222672].
%
%
% Any snippets that have been copied from elsewhere will have
% a reference to the original author in curvy brackets
% (A Geary).
%
%************************************************************
%% Version Tracking
%************************************************************
% Version V01 ;
% Modified from IsolatedEarthFault_V03.m
% Version V02 ;
% Restricted to 3 methods for comparison to focus results.
% Version V03 ;
% Downstream impedance halved to account for distributed load.
%************************************************************
%% Purpose of code
%************************************************************
% Written as part of my Thesis/Dissertation
% Subject 4111//4112, University of Southern Queensland.
% Sets up simulation for The behaviour of an Isolated
% Earth Fault.
%
%************************************************************
%% Initialise Variables
```

```
%*************************************************************
clear; % clear variables from Matlab
clc; % clear the (text) output from Matlab
format short
% Setting Constants
% Three Phase Fault Levels
%
a = 1 * cos(pi* 120/180) + 1i * sin(pi* 120/180);
MatrixA = [1 a a^2; 1 a^2 a; 1 1 1];

% Base description
%*************************************************************
%
BaseV = 11000/sqrt(3); %11kV Base Voltage
BaseVA = 100000000; %100MVA Base
BaseI = (BaseVA)/(3*BaseV); % calculated Base current
BaseZ = BaseV/BaseI; % Calculated Base Impedance
%
% Impedances.
%*************************************************************
% conductor data from planning
% format
%ConductorName, Code, R1, X1, R2, X2, R0, X0, CS1(2), CS0.
% 1 = pos seq
% 2 = neg seq
% 0 = zero seq
% CS = capacitive susceptance (micro mho)
% ohms and umho ...
ZDictionary = [1,1.065+.4023i,1.213+1.735i,2.920,1.321;
               2,.7408+.3911i,.8890+1.723i,3.012,1.339;
               3,.4721+.3771i,.6203+1.709i,3.135,1.363;
               4,.3279+.3655i,.4761+1.698i,3.238,1.383;
               5,.1750+.3383i,.3232+1.671i,3.450,1.420];
% conductor list
%*************************************************************
%'7/2.50AAAC','1'
%'7/3.00AAAC','2'
%'7/3.75AAAC','3'
%'7/4.50AAAC','4'
%'19/3.75AAAC','5'
%*************************************************************
%prefault Voltage
%*************************************************************
Vs_PU = 1.00;%PU
%*************************************************************
% Source impedance
%*************************************************************
Zs_PU = [0.07864+0.63723i,0.07864+0.63723i,0.048+0.48i];
% Source Impedance (pu)

% Line impedances, direct path to fault/beyond fault to
% (longest)end of feeder
```

```
%*********************************************************
SourceLine = [8,8,8,8,8]; %km of line in Z Dictionary.
LoadLine = [8,8,8,8,8]; %km of line in Z Dictionary.
% Capacitance impedance, tree length of line
SourceCap = [20,20,20,20,20];
LoadCap = [20,20,20,20,20];
% Calculation of line values
%*********************************************************

ZL1 = [SourceLine * ZDictionary(:,2),...
    SourceLine * ZDictionary(:,2),...
    SourceLine * ZDictionary(:,3)];
    % Source side Line Impedance (pu)

ZL2 = [LoadLine * ZDictionary(:,2),...
    LoadLine * ZDictionary(:,2),...
    LoadLine * ZDictionary(:,3)];
    % Load side Line Impedance (pu)

CSL1 = [SourceCap * ZDictionary(:,4),...
    SourceCap * ZDictionary(:,4),...
    SourceCap * ZDictionary(:,5)];
    % Source side line capacitive susceptance (micromho).

CSL2 = [LoadCap * ZDictionary(:,4),...
    LoadCap * ZDictionary(:,4),...
    LoadCap * ZDictionary(:,5)];
    % Load side line capacitive susceptance (micromho).

ZL1_PU = ZL1 /BaseZ;
ZL2_PU = ZL2 /BaseZ;

CcL1 = CSL1 / 1000000;% convert to Mho
CcL2 = CSL2 / 1000000;% convert to Mho

ZcL1 = (-1i) ./ CcL1;% convert to Ohm
ZcL2 = (-1i) ./ CcL2;% convert to Ohm

ZcL1_PU = (ZcL1 / BaseZ);% convert to PU
ZcL2_PU = (ZcL2 / BaseZ);% convert to PU

% Zero Sequence Load Calcs
%*********************************************************
% unloaded model of zero sequence Capacitance
% from burgess load transformer capacitance.
% zero sequence Cap per transformer
%*********************************************************
%
% load zero sequence capacitance is important for modelling
% this fault using the Burgess and Blackburn Methods at
% extremely light load conditions.
% capacitance of each transformer is in parallel, as such
```

```
% capacitance adds.

%from burgess we can build a dictionary of capacitance based
% on transformer size.
% key [size (kVA), Capacitance(nF)]
CDictionary = [ 25, 2.02;
                63, 4.14;
               100, 4.63;
               200, 9.62;
               500, 5.45];
Txs = [10,10,10,10,0];
% transformers of each size beyond fault

CzL = Txs * CDictionary(:,2) * 0.000000001;
% total capacitance in Farads

ZzL = (1i) * 1/(2 * pi() * 50 * CzL);
%Impedance of the Zero Sequence total capacitance

% Load calcs
%*************************************************************
ZzLoad_PU = ZzL / BaseZ;

Load_A = 50;
% perphase 3 phase includes all load and losses...

Load_pf = 0.9;
% assume 0.9 if unknown

%Calcs;
%*************************************************************
pf = Load_pf + 1i * sin(acos(Load_pf));
Load_A_Complex = Load_A * pf;
Load_A_PU = Load_A_Complex /BaseI;

Fault_Ohm = 30;
% Fault impedance in Ohms (make this small and not zero for a
% bolted fault zero makes a divide by zero error in the math).
NonFault_Ohm = 1e99;%Non Fault impedance in Ohms

Fault_Zpu = Fault_Ohm/BaseZ;
NonFault_Zpu = NonFault_Ohm/BaseZ;
PreFaultVoltage_Vpu = Vs_PU;
% voltage at fault point before fault occurs.

% Build impedances
%*************************************************************

% Upstream Network Impedance (pu)
USN_Zpu = ZL1_PU;

% Upstream Network Capacitance Impedance (pu)
```

```
USN_Zcpu =  ZcL1_PU  ;

% Upstream load Impedance (pu)
ZL_US = [NonFault_Zpu, NonFault_Zpu, NonFault_Zpu];

% DownStream Network Impedance (pu)
DSN_Zpu = ZL2_PU/2;
%/2 according too (Vempati, Shoults et al. 1987)

% DownStream Network Capacitance Impedance (pu)
DSN_Zcpu = ZcL2_PU;

% Downstream load Impedance (pu)
ZL_PU = [Vs_PU / (Load_A_PU), Vs_PU / (Load_A_PU), ZzLoad_PU ];

%**********************************************************
%% Main
%**********************************************************
% add sensitivity loops

NumberOfPoints=((10-0.2)/0.02)+1;
%OriginalArguments = [ Vs_PU ,  Zs_PU, USN_Zpu, USN_Zcpu, ...
%NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ZL_PU, Fault_Zpu, BaseI, 0];
M=[1,1,1,1,1,1,1,1,1];% once only
 Multiplier = (0.2:0.02:10) ;
 for f = 1:9 %factors to test
     for Sensitivity = 1:1:NumberOfPoints

          M(f)= Multiplier(Sensitivity);
          OP(Sensitivity,:) = funcIEFWLC(Vs_PU*M(1), ...
             Zs_PU*M(2), USN_Zpu*M(3), USN_Zcpu*M(4), ...
                        NonFault_Zpu, DSN_Zpu*M(6), DSN_Zcpu*M(7), ...
                        ZL_PU*M(8), Fault_Zpu*M(9), BaseI, 0);
end
M(f)= 1;%set it back to the original
xmin = 0 ;
xmax = max(Multiplier);
ymin=0;
ymax=35;
figure(f)
plot (Multiplier,OP)
axis([xmin xmax ymin ymax])
legend('Burgess Model','Simplified Model','Blackburn Model')
hold off
switch f
     case 1
          Gname = 'Prefault Voltage';
          axis([0 10 0 max(abs(OP(:)))]);
     case 2
          Gname = 'Source Impedance';
     case 3
          Gname = 'Upstream Network Impedance';
```

```
    case 4
        Gname = 'Upstream Network Capacitance';
    case 5
        Gname = 'Source Side Fault Impedance';
    case 6
        Gname = 'Downstream Network Impedance';
    case 7
        Gname = 'Downstream Network Capacitance';
    case 8
        Gname = 'Downstream Load Impedance';
    case 9
        Gname = 'Fault Impedance';

end
%*****************************************************************

        OPSave(f,:,:) = OP(:,:);
        OPVariation(:,f) = max(OP(:,:)) - min(OP(:,:));
        OPVariationBetweenMethods(:,f) = ...
                  max(abs([OP(:,2)-OP(:,1), OP(:,2)-OP(:,3)])')';
        OPVariationBetweenMethodsPercent(:,f) = ...
                   (OPVariationBetweenMethods(:,f))*100./OP(:,2);
        OPVariance(:,f) = var(OP,0,1);
        OPStd(:,f) = std(OP,0,1);
        OPmaxVarianceBetweenMethods(:,f) = max(var(OP,0,2));
        OPmaxStdevBetweenMethods(:,f) = max(std(OP,0,2));
        OPmaxVarBMPercent(:,f) = ...
                                 max(100*(var(OP,0,2)./OP(:,2)));
        OPmaxStdevMPercent(:,f) = ...
                                 max(100*(std(OP,0,2)./OP(:,2)));

        MaxOPR(f) = max(OPVariance(:,f));
        MaxOPRStd(f) = max(OPStd(:,f));

title(['Sensitivity Analysis for ', Gname]);
xlabel(['Sensitivity Multiplier for ',Gname,' (PU)']);
ylabel('Calculated Earth Fault Current (Amperes)');
end
%*****************************************************************
%% Results Summary
%*****************************************************************

fprintf('OPVariance= \n\n')

fprintf('%f4  ',(OPVariance(1,:)))
fprintf('\n',max(OPVariance))
fprintf('%f4  ',(OPVariance(2,:)))
fprintf('\n',max(OPVariance))
fprintf('%f4  ',(OPVariance(3,:)))
fprintf('\n',max(OPVariance))

OPmaxVarianceBetweenMethods
```

```
OPmaxStdevBetweenMethods
OPmaxVarBMPercent
OPmaxStdevMPercent

[~,VarRanking] = sort(MaxOPR,2,'descend') ;
[~,StdRanking] = sort(MaxOPRStd,2,'descend') ;
VarRanking
StdRanking

fprintf('Variation')
max(OPVariation)
fprintf('Variation between Methods as a percentage')
max(OPVariationBetweenMethodsPercent)
fprintf('Variation between methods ')
max(OPVariationBetweenMethods)
xlswrite('sensitivity.xls', OPSave(:,:,1)', 'BurgessWLC');
xlswrite('sensitivity.xls', OPSave(:,:,2)', 'PPEWLC');
xlswrite('sensitivity.xls', OPSave(:,:,3)', 'BlackburnWLC');

%*************************************************************
%% Performance Profiling
%*************************************************************
profile on
for testprofile=1:1:10000;
    %set to 1000000 for a profile test.
    %clc; testprofile

OP(Sensitivity,:) = funcIEFWLC(Vs_PU ,Zs_PU, USN_Zpu, ...
          USN_Zcpu, NonFault_Zpu, DSN_Zpu, DSN_Zcpu, ...
          ZL_PU, Fault_Zpu, BaseI, 0);
end
profile off

profile viewer

%*************************************************************
%% References
%*************************************************************
%
%Ref (MATLAB HELP)
% help from within the MATLAB Program, Version 2010a.
%(Vempati, Shoults et al. 1987)
%Vempati, N., R. R. Shoults, M. S. Chen and L. Schwobel(1987).
%"Simplified Feeder Modeling for Loadflow Calculations."
%Power Systems, IEEE Transactions on 2(1): 168-174.
%
%
%% End Of Code
%
```