University of Southern Queensland

Faculty of Engineering and Surveying

High Voltage Earthing System Testing :–
An Investigation into The Effects of Test Lead Coupling on Test Results

A dissertation submitted by

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Abstract

High Voltage Earthing System testing is the focus of this research project, in particular the effects of test lead coupling when conducting soil resitivity tests. Many of the tests conducted to verify the correct and efficient design of an Earthing system, are carried out using and AC signal of specified frequency, with very low level readings of voltage and current recorded by a test set or technician. With measured signals being very low amplitude (often in the milli-volt and milli-ampere range, for example) the effects of test lead coupling, can reasonably be expected to have a significant effect on the results obtained.

The intent of this research project is to attempt to quantify such effects and to deduce a mathematical relationship to predict or quantify coupling effects. The aim is to allow for improved test accuracy and hence improve the quality of the results, of such testing.

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Background

1.1 Introduction

Modern electricity supply systems are complex integrated systems which allow the transmittal of large quantities of electrical energy over great distances. From the point of generation, electricity is transmitted through an interconnected network of lines and substations, to a multitude of different locations, eventually arriving at the point of final usage, by the customer. Such a large and complex network can be thought of as many smaller sub systems operating in unison to deliver a safe, economic and reliable supply of electricity to the consumer.

One such system that forms an integral part of the safe and efficient operation of any electricity system, is the High Voltage Earthing System, specifically the earthing systems associated with high voltage substations. Earthing systems are generally applicable, to all stages of electrical power systems including generation, transmission, distribution and utilisation. This dissertation is primarily concerned with high voltage earthing systems, as would be found in any high voltage substation, and in particular the testing and design verification of such earthing systems.

High Voltage Substation earthing systems, form one component within a high voltage electrical system, and perform several functions. Typical functions of a High Voltage Earthing System include the safety of plant and personnel, equipment protection and correct electrical system operation. With such functions as these, it becomes immediately evident that an Earthing system must be adequately designed and tested, prior to being placed in service, to ensure fulfilment of such requirements.

In a General sense, any installation must undergo some form of testing during each of the stages of the system's intended life, to ensure correct and proper operation. Substation earthing is no different, and testing is required in several stages of the design, installation and operation phases of an earthing system. In the context of this research project, the stages of importance may be considered as the conceptual (design) phase, the post construction-pre-commissioning phase, and the maintenance phases of an installed system.

During the design phase, accurate data is required of the soil resistivity, which is a term used to describe the conductive properties of the soil. The soil resistivity is required to determine the Earthing system design, including the spacing, size and number of conductors installed to form the earthing system. Using modelling techniques, the soil resistivity also can be used to determine how the theoretical earthing system may operate when a fault is present on the electrical network to which it is connected.

In the post construction, pre-commissioning phase, tests are completed to assess the performance of the earthing system, prior to it being placed in service. Tests conducted at this stage will be used to verify the theoretical calculations used in the design of the earthing system, and also to identify any areas in need of improvement, prior to commissioning of the system.

Maintenance testing can be considered as a verification of the integrity and correct operation of the earthing system, once it has been in service for a given period of time. Deterioration of the earthing system due to corrosion, for example, can lead to significant problems associated with safety and a reduction in the performance of the earthing system, in the case of a fault on the electrical network.

Earthing testing is the focus of this research project, in particular the effects of test lead “self coupling” when conducting soil resistivity tests. Self coupling in this context, refers to the electrical test signals, creating interference between the test leads used to conduct the test. This interference creates an error in the results obtained, and therefore reduces the quality of the results obtained.

Many earth resistivity tests conducted for an earthing system are carried out using an alternating current (AC) or alternating direct current (DC) signal of specified frequency, with very low level readings of voltage and/or current measured by the test set or technician. With measured signals being very low amplitude (in many cases in the millivolt or milliamp range) the effects of test lead coupling, can reasonably be expected to have a significant effect on the results obtained. The intent of this research project is to investigate and attempt to quantify such effects and to deduce a mathematical relationship to predict or quantify self coupling effects. The aim is to allow for improved test accuracy and hence improve the quality of the results, of such testing.

2. Literature Review

2.1 Literature Selection

The range of literature and information available relevant to substation earthing testing and the effects of coupling have been classified into three areas.

- Standards and codes relevant to electrical earthing
- Text books and literature relevant to Electro Magnetics and Inductive and Capacitive Coupling
- Technical references relevant to test equipment used.

2.1.1 Relevant Standards and Codes

There are several standards relevant to earthing of electrical apparatus, and low frequency induction. The known standards, which will be utilised for this research project are:

- IEEE 80: 2006 Guide for Safety in AC Substation Grounding
- ENA EG1: 2006 Substation Earthing Guide
- SAA HB 102: 1997 **-** Coordination of Power and Telecommunications – Low Frequency Induction
- The Australian and New Zealand standard AS/NZS 4360:1999 together with Downer EDI Engineering’s Risk Assessment procedures will be used as a reference to establish and implement the risk management process.

Several notable excerpts from the above documents have been included due to their relevance to this research project, as follows.

Chapter 5, ENA EG1: When conducting resistivity tests, measurements at larger spacings often present considerable problems such as inductive coupling, insufficient resolution on test set and physical barriers.

Chapter 5, ENA EG1: States practical testing recommendations, for soil resistivity tests. Of relevance to this discussion, is the first point in the list on page 29:

- Eliminate mutual coupling or interference due to leads parallel to power lines. Cable reels with parallel axes for current injection and voltage measurements, and small cable separation for large spacings (>100m) can result in errors.

Chapter 11, ENA EG1: Mention is made of the need to exercise caution to ensure that conductive and inductive interference components are taken into account when conducting Impedance and Step, Touch and Transfer voltage measurements.

Chapter 11, ENA EG1: Calculation of system impedance is made using the given equation (Eqn 11-1) and the assumption that measurements are not influenced by mutual coupling or other interference. There appears to be no means by which to calculate or account for such interference, other than the testing guidelines to minimise coupling effects as stated in section 11.1

Perhaps the most notable reference is made in section 11.2.3 of the ESAA EG1. It states:
"For a complex electrode, such as an earthing system of a substation, the earth resistance is very low. Many instruments cannot measure low resistances and the great majority of them do not account for the reactive part. In addition to the required instrument capabilities, testing configuration and analytical calculations are required to handle errors due to power frequency standing voltages and injection current induced voltage errors."

All of these quotes outlined above, add further weight to the need and hence purpose of this project to investigate the effects of test lead coupling. It should be noted that while general recommendations exist to avoid test lead coupling, there appears to be little or no specific information on the required separation of test leads, lead layout patterns, or the means of calculating interference.

2.1.2 Text Books and Literature Relevant to Electro Magnetics

There is a large amount of literature and text books available relevant to electromagnetics, however for the sake of simplicity and ease of reference, several sources have been selected, each of which is detailed below.

- Elements of electromagnetics - Matthew NO Sadiku, 4th ed. 2007, Oxford University Press.
- Power Systems Analysis - Grainger and Stevenson, 1994, McGraw Hill Press
- Various Internet resources as required.
- SAA HB 102 1997 - Coordination of Power and Telecommunications - Low Frequency Induction.

Again, several notable excerpts have been taken from these sources, as relevant to this research project.

Grainger and Stevenson: Chapter 4 details the means to calculate flux linkages between transmission lines of varying configuration. The portion of greatest interest is likely to be section 4.6, I.e. The inductance of a single phase two wire line (as is the case during earthing testing).

SAA HB 102: Section 2 details the method of calculating induced voltages in parallel lines, which is again of relevance to the interference we expect to encounter.

2.1.3 Technical References Relevant to Test Equipment Used

The test equipment selected for use in this project was originally intended to be limited to two pieces of test equipment, each of different purpose and function. These items of were initially proposed as 1) an earth resistivity test set, and 2) a current injection test set. During the completion of this research project, the equipment selection was revised, based on the realisation that the scope of research required for two different test functions, was unachievable in the time allocated, and resource availability for completion of the project. The equipment selection hence became limited to two items of similar function, capable of testing Earth Resistivity, which has become the main test function under analysis in this project. The equipment selection and relevant documentation has thus been limited to:

- Fluke 1625 GEO Earth Ground Tester, User Manual, Fluke Corporation, 2006
- Megger DET2/2 Digital Earth Tester, User Guide, Megger Inc, 2007

Relevant sections of these instruction manuals have not been included, as there are a large number relevant sections, too numerous to be adequately included here. These documents primarily deal with the carrying out of tests and the recording of results, and hence contain large amounts of information on the specific processes used, when conducting earthing testing.

2.2 Project Justification

Substation earthing testing is by no means a new field as there is a large amount of relevant literature available, however, to date there appears to be little, or no analysis undertaken on the effect of errors introduced, through electromagnetic interference due to self coupling effects. Currently tests are conducted and the results obtained are assumed to be correct, with little consideration given to possible errors introduced by the test leads themselves. Errors introduced can have significant effects on the overall earthing system in the design, installation and operational stages of the substation in question. Such errors, duly identified and allowed for, yield following consequences.

2.2.1 Improvement in Design and Verification

The allowance for, or correction of, errors introduced will inherently mean a more accurate and effective earthing system is able to be designed and installed, to perform all of the required functions of such an earthing system.

2.2.2 Cost Savings

The implementation of an improved earthing system by design, may lead to reduced equipment and installation costs. An accurately designed earthing system may require considerably less earthing conductors and electrodes to be installed, leading to considerable savings in material, labour and installation costs. Correct initial design also alleviates the need for alteration or re-work of poorly designed earthing installations.

2.2.3 Improved Safety and Stability

Although somewhat already accounted for by the improvement in design and verification, the improvements in safety and security warrant a separate mention.

The implications of a safer and more effective substation earthing system are of obvious benefit when considering the safety of the general public and personnel working within or in proximity to a substation. Improvements in safety, also extends to the safety of plant and equipment located within or adjacent to the substation, which becomes less likely to suffer damage in the event of a system disturbance such as a fault or lightning strike.

Stability in this context refers to the stability of a power system and acts as a measure of the response of a power system to an unplanned disturbance (a fault). Ideally, the load on the electrical system must be fed at constant voltage and frequency at all times. In practical terms this means that both voltage and frequency must be held within close tolerances so that the consumer's equipment may operate satisfactorily. For example, a drop in voltage of 10-15% or a reduction of the system frequency of as little as 5-10 % may lead to stalling of some motor loads on the system. Effective earthing systems allow for improved fault clearing times and as such, reduce the effect of a disturbance on system voltages and system frequency.

3. Methodology

3.1 Project Methodology

To effectively investigate the effects of test lead coupling, the methodology to employed, can be broken into three broad categories, Technical research, conducting of the tests and analysis of the results.

3.1.1 Technical Research

Before analysing the effects of test lead coupling, the process of carrying out earthing testing had to be understood. Information was gathered on the complete range of tests as well as the processes involved and the reasons for conducting such tests. Information on the signals injected and measured, the calculations applicable and the analysis required are all relevant to help determine the signals and tests which may be affected by coupling effects. From this research, one particular test was selected to be researched further, based on the test characteristics and the likelihood to suffer from interference and coupling. Based on the technical research completed, the test process to be analysed further is:

- Soil Resistivity Testing

Soil Resistivity has been selected based on the criteria that the signals to be injected and measured are of low level and are likely to be significantly altered by the effects of inductive coupling. Expected values of injected current are in the milliamp range, and measured voltages, are similarly in the millivolt range.

Relevant sources of information for the methods used to carry out soil resistivity testing have been listed in the "Literature Review" section. The specifics of the test instruments and test process is outlined further in section 4.

3.1.2 Conducting of Tests

Based on the results and findings obtained in the technical research, a schedule of tests was created to provide a well structured and logical "plan" of tests to be conducted. The schedule of tests has been created to try and take into account all logical configurations and therefore reduce the likelihood of bias or operator error. The schedule of tests acted as a "live" document and was added during the course of testing, dependant on the results obtained. The final schedule of tests, including all additional tests completed is included in Appendix C.

3.1.3 Analysis of the Results

Once the schedule of tests was complete, analysis of the results was conducted to try and determine the effects and situations where coupling is present. This analysis had the broad aims of:

- Determining the level of interference due to coupling, based on data obtained
- Determining situations and configurations where coupling is likely to be present
- Determining alternative configurations and or test lead layouts to conduct the same tests.

4. High Voltage Earthing Systems

4.1 The High Voltage Substation Earthing System

4.1.1 Function and Design of an Earthing system

A high voltage earthing system is generally comprised of two functions, namely the provision of a low impedance connection to the general mass of earth, and the connection of the electrical system, to this low impedance connection to earth.

With regard to the provision of a low impedance connection to the general mass of earth, this may be achieved by a number of means, generally involving the burial of a number of conductors and/or electrodes, in some form of predetermined arrangement, at a specified depth and spacing. This series of conductors and electrodes is commonly referred to as an “earth grid”. The earth grid design including the number of conductors, electrodes, spacing and depth of burial, is determined by the site properties and the intended use for the site.

Examples of the factors to be taken into consideration, when designing an earth grid, include:

- The required conductor spacing and depth - determined by a number of factors such as the prospective fault current level of the site, conductive properties of the soil, soil profile levels, etc
- The conductor size, and conductor material – determined by factors such as required fault current carrying capacity, required mechanical strength, corrosive properties of the soil, etc.

There are many different materials suitable for use as a conductor or electrode in an earth grid. Examples of widely used and commercially available materials include Copper (either in strip or cable form), Copper clad steel, Stainless Steel, Zinc Coated Steel, and Aluminium.

As indicated previously, the physical arrangement of the chosen conductor is determined by a combination of the physical properties of the site together with the anticipated electrical properties. The properties of the soil are of particular interest, including the resistivity (a measure of the resistance) of the soil and the different strata levels present within the soil profile. Different soil types exhibit different electrical and physical properties and hence need to be considered when determining the layout of the earth grid.

Examples of typical earth grid arrangements include:

- Strips of conductor or bare cables laid in mesh pattern to form a Horizontal mesh.
- A series of rods connected with suitable cabling
- A series of rods drilled deep into the earth and connected via cabling back to a central connection point

Figure 1 shows an example of a schematic of a typical earthing grid, designed for a High Voltage substation

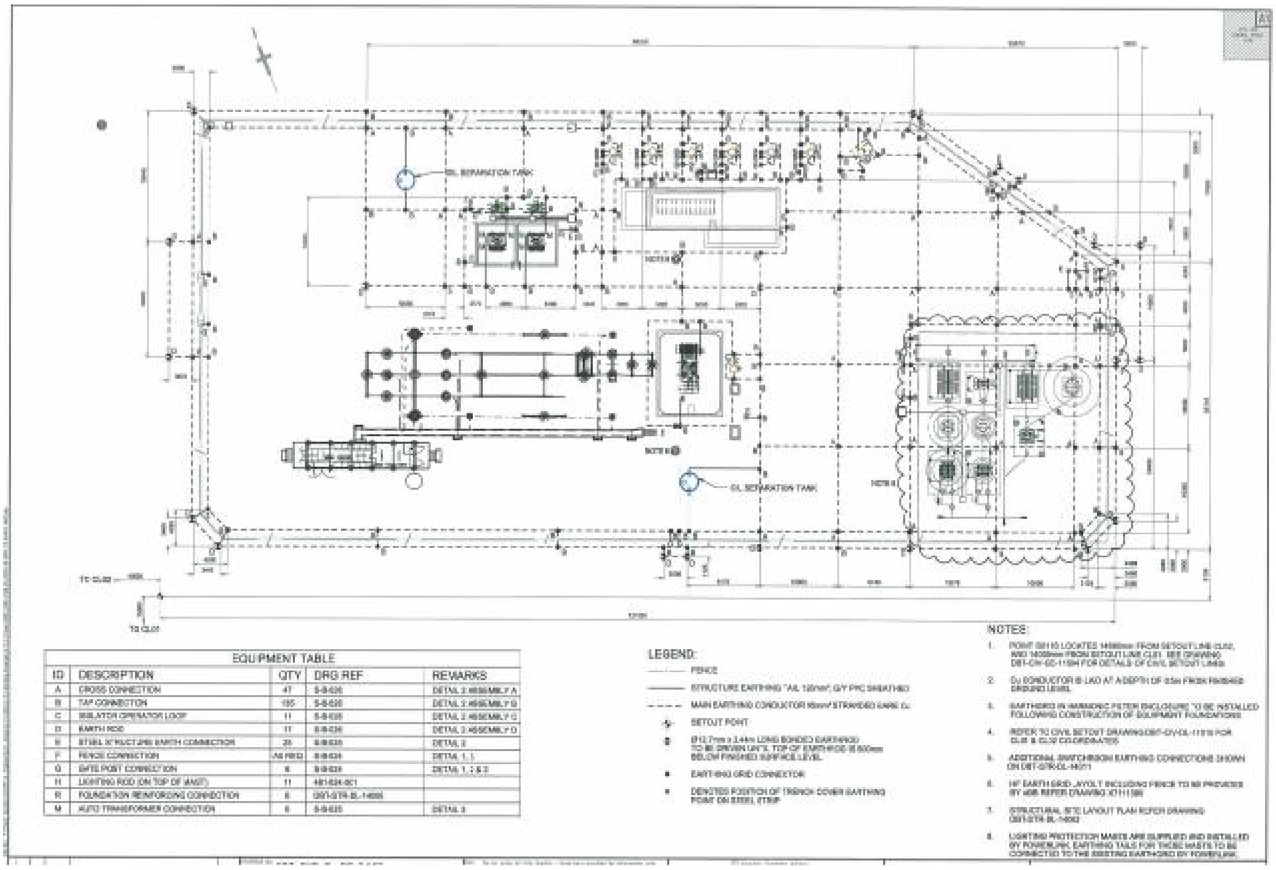

Figure 1: Example of a High Voltage Substation Earthing Grid (Reproduced with permission of Downer EDI Engineering)

As detailed in section 2, The Electricity Supply Association of Australia (ESAA) and Institute for Electrical and Electronic Engineers have each released standards applicable to High Voltage Substation Earthing systems. These documents are the Substation earthing Guide (ENA EG1 (2006)) and The IEEE Guide for Safety in AC Substation Grounding (IEEE 80 (2000)). These documents detail the following, as typical functions of a high voltage earthing system.

Safety:

- To ensure that metallic structures and equipment within a substation are maintained at the same potential.
- To discharge any induced potentials or static build up that may be present.
- To ensure that hazardous step and touch potentials do not exist during a fault event, either at system frequency or due to transient disturbance
- The design criteria are maintained over the design life of the installation despite additions or modifications.

Equipment Protection:

- To limit the level of transient voltages present on equipment by safely providing a low impedance path for lightning discharges, switching surges, fault currents and other system disturbances. Without adequate earthing system protection, equipment damage may become extensive and can include insulation breakdown, thermal or mechanical damage, fire or electrically generated explosions.
- To limit the level of interference and or damage caused to sensitive electronic protection and control devices as a result of such transient voltages being present on the power system.

Correct Electrical System Operation:

- To ensure the correct and timely operation of protective devices in the case of abnormal system conditions.
- To limit the overall disturbance to the power system as a result of a fault event

As can be clearly seen by these reasons, any high voltage electrical substation must therefore have an adequately designed and installed earthing system associated with it. Poor earthing system design or implementation can lead to serious consequences, particularly when considering the safety of plant and personnel. The accuracy of any results of testing, therefore becomes extremely important in the overall effectivness of an earthing system.

4.1.2 Earthing System Types

As discussed previously, earthing systems consist predominantly of two components, the earth grid, and the connection arrangement between the electrical system and the earth grid. The connection arrangement refers to the means of providing the earth reference for the electrical system, and allows classification of earthing connections based on the connection arrangement in use. There exists several different means of connection of electrical equipment to an Earth Grid, and for a typical system, IEC 60364:2001 defines the types of earthing systems by a lettering system, as follows:

First Letter – The relationship of the power system to earth

T: Direct connection of one point to earth

I: All live parts isolated form earth, one part connected through an impedance

Second Letter – The relationship of the exposed conductive parts of the installation to earth

T: Direct electrical connection of exposed conductive parts to earth, independently of the earthing of any part of the power system

N: Direct electrical connection of exposed conductive parts to the earthed point of the power system (the neutral in AC systems)

Subsequent Letters (if any) – Arrangement of neutral and protective conductors

S: Protective function provided by a conductor separate from the neutral or the earthed line (phase) conductor

C: Neutral and protective functions provided in a single conductor

Several examples of commonly used earthing systems within Australia include:

Direct Earthing: Protective earths are connected by an electrode or series of electrodes, to the general mass of earth. Using the letter designations detailed above, this system is called the TT earthing system and relies on a low impedance connection to the mass of earth to provide a low impedance path through which any earth fault current will flow. If the connection to the general mass of earth is of high impedance, then the resulting earth fault current will become limited, and may lead to a fault remaining undetected or uncleared as well as damage to equipment and dangerous voltage potentials. This system is widely used in High voltage electrical substations, where transmission voltages are used (33kV and above)

Multiple Earthed Neutral (MEN) System: Protective earths are connected to the system neutral conductor at the source and at multiple points along the system. This system is designated the TN system of earthing and operates on the presence of multiple connections of the neutral conductor to the general mass of earth. By connecting the neutral at many locations the overall impedance of the connection to earth becomes very low, hence promoting large earth fault currents, which are easily detected. Because this system uses a 4 wire system, it is not readily adaptable to High Voltage situations, which predominantly use a three wire method of connection (i.e no neutral conductor). Figure 3 depicts a typical MEN system. The MEN system is the predominant method in use for low voltage electrical systems (230/400VAC) within Australia.

Impedance Earthed System: The installation is either isolated from earth, or connected to Earth through an impedance to limit the fault current. This system is designated the IT system, where the magnitude of earth fault current is limited by the impedance of the return path. This system is frequently used in High voltage substations using distribution voltages (11kV and 22kV), to limit the flow of earth fault current to a reasonable (and less damaging level). A diagram of an Impedance earthed system is shown in figure 4.

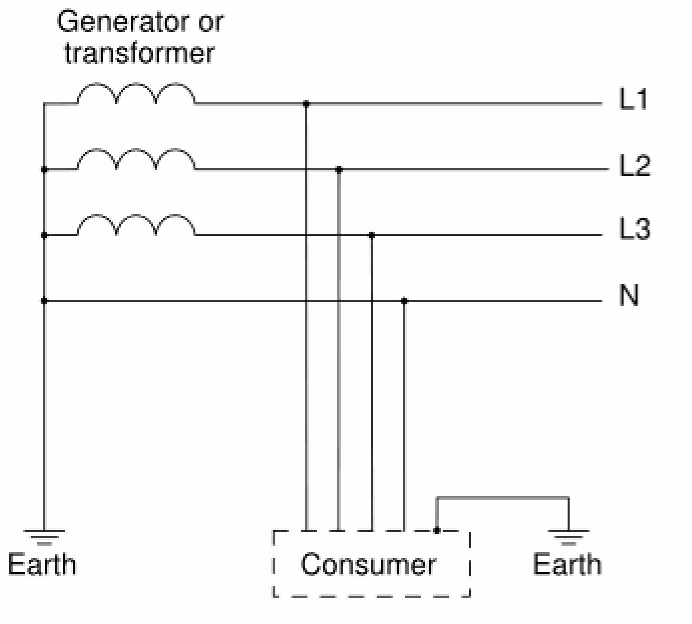

Figure 2: TT Earthing System. Note direct connection of supply source to Earth, as well as consumer equipment, but no connection between N-E at consumer terminals

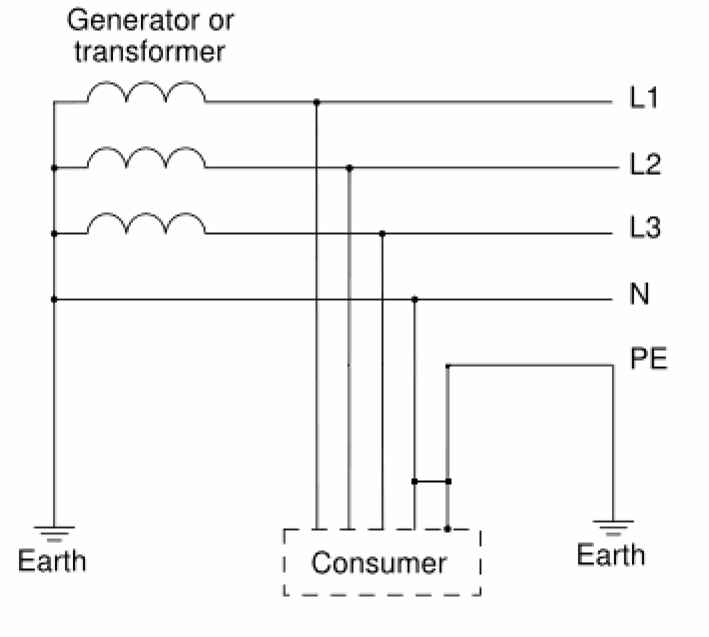

Figure 3: TN Earthing System. Note direct connection of supply source to Earth, as well as neutral conductor connection to earth at source and consumer terminals.

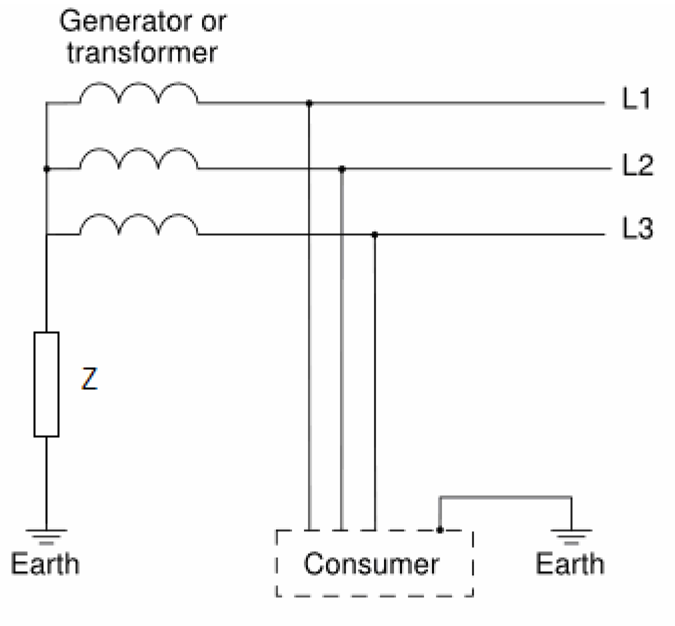

Figure 4: IT Earthing System. Note connection of supply source to Earth via an impedance, Z.

From the systems discussed, a High Voltage substation earthing system can thus be considered as either a TT or IT system, where the high voltage system is earthed directly (TT System) or via an impedance (IT system)

The TT system, is widely used in transmission type substations (i.e EHV substations with voltages of 66kV and above). This system ensures that for a fault on the high voltage system, any equipment that may become part of the fault circuit will be directly connected to earth and hence ensure rapid isolation of the faulted plant or equipment. Rapid isolation of faults in the EHV network is critical to the stability of a power system, as these lines form the main points of connection between power stations and distribution networks. (**source**: Network Protection and Automation Guide, Alstom, 2002)

The IT system is more widely used in major substations operating at a lower voltage level, such as would be found in distribution type zone substations (11kV or 33kV for example). Reduced voltage levels inherently lead to increased current levels, in order to deliver the same amount of power to the required load or system. For a fault close to the substation, destructive earth fault currents may hence occur, or high earth potential rise on the main earth grid. To limit the fault current an impedance (commonly a resistance or reactance) is chosen and installed in the earth return path to the main transformer at the substation. (**source**: Network Protection and Automation Guide, Alstom, 2002)

5. Earthing System Testing

High Voltage Earthing system testing is divided into two stages, namely, tests to be completed prior to installation, and tests to be completed after installation and prior to commissioning. Maintenance testing can be argued to be a third stage, however the tests conducted as part of routine maintenance are a replication of some or all of the tests completed in the post installation – pre commissioning phase.

The tests conducted prior to installation are primarily concerned with obtaining information about the site geology and soil properties, in order to accurately design the earthing system for the proposed site. Tests conducted in this phase are primarily concerned with the soil Resistivity. Tests conducted in the post installation – pre commissioning phase include, Earthing system impedance, Earth grid Potential rise, Current Distribution tests, and Step and Touch Voltage tests. As this research project is based primarily around the effects of coupling during Resistivity tests, the following discussion will focus around Resistivity testing only.

5.1 Earth Resistivity Testing

The Resistivity of a material is defined as

$$r = \frac{RA}{L}$$

where

R = resistance of the material,
A = cross-sectional area through which current flows and
L = length of the material.

Resistivity is therefore a measure of the electrical resistance of a conductor (in this case the soil) of 1 unit cross-sectional area and 1 unit length. Think of a 1m x 1m x 1m cube of soil with a metallic plate fixed to each end. The resistivity in this case is the resistance between the two plates, and hence is measured in ohm metres (Ωm). Resistivity is a characteristic property of the soil, and is useful in comparing various soil types, based on their ability to conduct electrical current. High soil Resistivity designates a poor conducting soil, and likewise a low Resistivity indicates a high conducting soil.

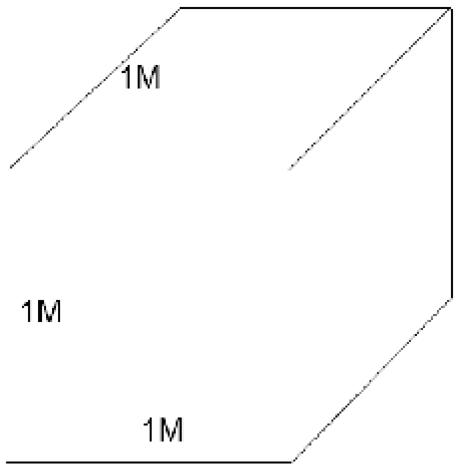

Figure 5: Resistivity. Conductor of 1m cross sectional area, and 1m length

ENA EG1, 2006 states there are three common test methods, for conducting soil resistivity tests. These three methods are:

- Wenner Array Method
- Schlumberger Array Method
- Driven Rod Method

5.1.1 The Wenner Array Method

The Wenner array is one of the most commonly used methods of soil Resistivity testing and uses 4 electrodes as shown in figure 6. Four test spikes are inserted into the ground in a straight line at equal distances ‘a’ and to a depth ‘b’ of less than 1/20 of ‘a’. A current signal, (AC, DC or complex) is injected via the two outermost electrodes (C1 and C2), and then measurement of the resulting voltage signal is taken across the two inner probes (P1 and P2). The instrument then returns a Resistance measurement, from which the Resistivity can be calculated, using the formula (source: ENA EG1-2006):

$$r_{aw} = 2paR$$

or

$$r_{aw} = 2pa\frac{\Delta v}{I}$$

Where

$r_{aw} = Apparent\ \text{Re}sistivity\ (\Omega m)$

$a \quad = \text{Pr}obe\ \ Spacing$

$\Delta v\ =\ Measured\ Voltage\ (V)$

$I \quad =\ Injected\ Current\ (A)$

$R \quad = Measured\ \ \text{Re}\,sis\,\text{tan}\,ce$

To obtain the Resistivity of the soil at various depths, this test is repeatedly conducted as part of a traverse of the site, I.e. at several probe spacings, as denoted by "a" in figure 6. The spacing of the probes, is altered from close spacings (1m +), up to spacings of at least the radius or longest diagonal of the proposed earth grid. An example of a range of probe spacings for a resistivity traverse is shown below in Table 1.

Resistivity Traverse – Site 123 – Wenner Array								
Probe Spacing 'a'	1	2	4	8	16	32	64	128
Resistance Measured Ω	34.2	16.22	1.344	0.832	0.453	0.321	0.256	0.222

Table 1: Resistivity Traverse. Traverse of site indicating probe spacings of up to 128m

This method is the most effective, when the test equipment has limited power output or limited ability to detect low voltage signals. This effectiveness is due to the ratio of received voltage per unit of transmitted current. (source ENA EG1, 2006). As a drawback, the Wenner array requires the longest cable layout and can also be time consuming due to each of the electrodes having to be moved, for each electrode spacing test.

Portable test equipment often specifies the use of the Wenner array, due to the limited power output available from a Battery power supply within the test instrument. The user manuals for the Fluke 1625 and the Megger DET/2, as specified in section 2.1.3, both specify the use of the Wenner array for Resistivity testing. As this equipment was selected for use in this research project, the Wenner array has been used for all of the investigation experiments into test lead coupling for this project.

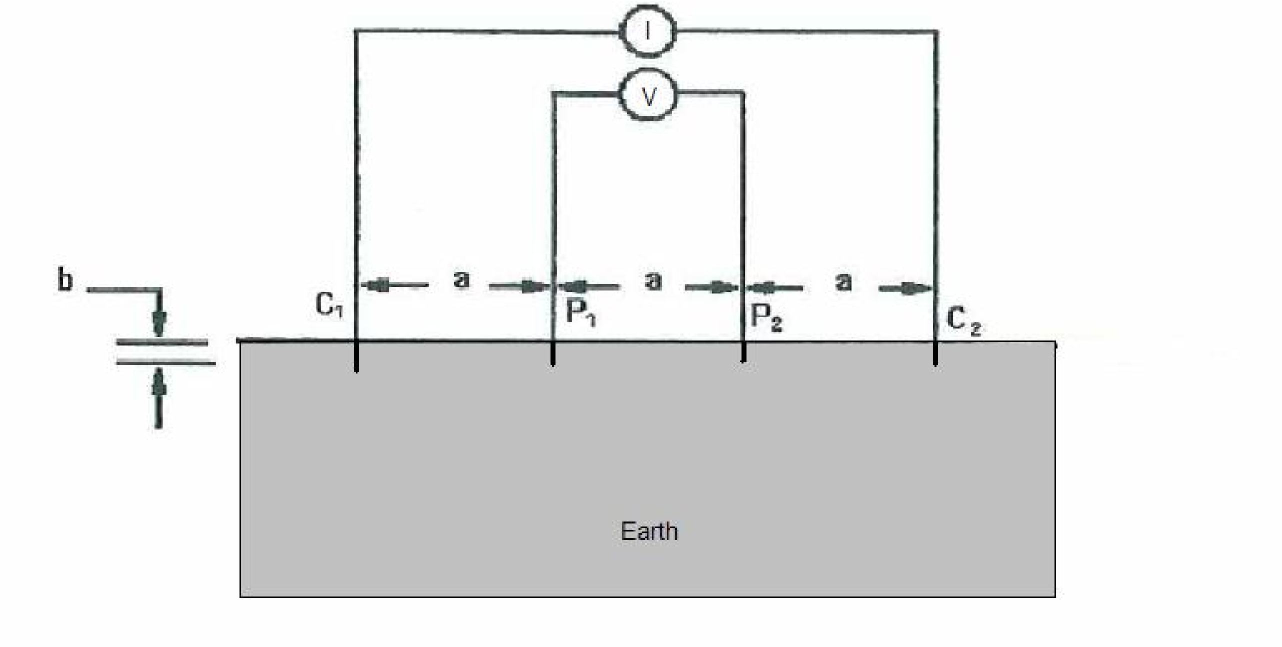

Figure 6: Wenner Array. Probe layout and injected and measured signals.

5.1.2 The Schlumberger Array Method

The Schlumberger array is similar to the Wenner array, as it also uses 4 electrodes and operates on the injected current and measured voltage principle of the Wenner array. There are, of course, several major differences with the Schlumberger array, namely the probe spacing requirements, the magnitude of injected current and the magnitude of the voltage measured.

The Schlumberger array is an electrode configuration in which the spacing of the two potential electrodes (P1 and P2) is less than one-fifth of the distance between the centre of the array and one current electrode (L). The use of the Schlumberger array allows for reduced testing time, since the current electrodes are moved four or five times for each move of the Voltage electrodes. The Schlumberger array is also considered more accurate than the Wenner or Driven rod methods, provided a current source of sufficient power is used. (source ENA EG1, 2006). Lower voltage readings are obtained when using Schlumberger arrays, which may present problems where the voltage measured is too small to be accurately measured, or the depth to be tested is beyond the power capabilities of the test equipment.

As with the Wenner array, a traverse of the site is used to obtain the resistivity of the soil at various depths. The test equipment returns a reading of resistance, which can be converted to resistivity using:

$$r_{as} = \frac{pL^2 R}{2l}$$

Where

$$r_{as} = Apparent\ Resistivity\ (\Omega m)$$
$$L = Spacing\ from\ centre\ to\ current\ probes\ (m)$$
$$l = Spacing\ from\ centre\ to\ voltage\ probes\ (m)$$
$$R = Measured\ resistance$$

(source: ENA EG1, 2006).

An example of a Schlumberger array is shown in figure 7.

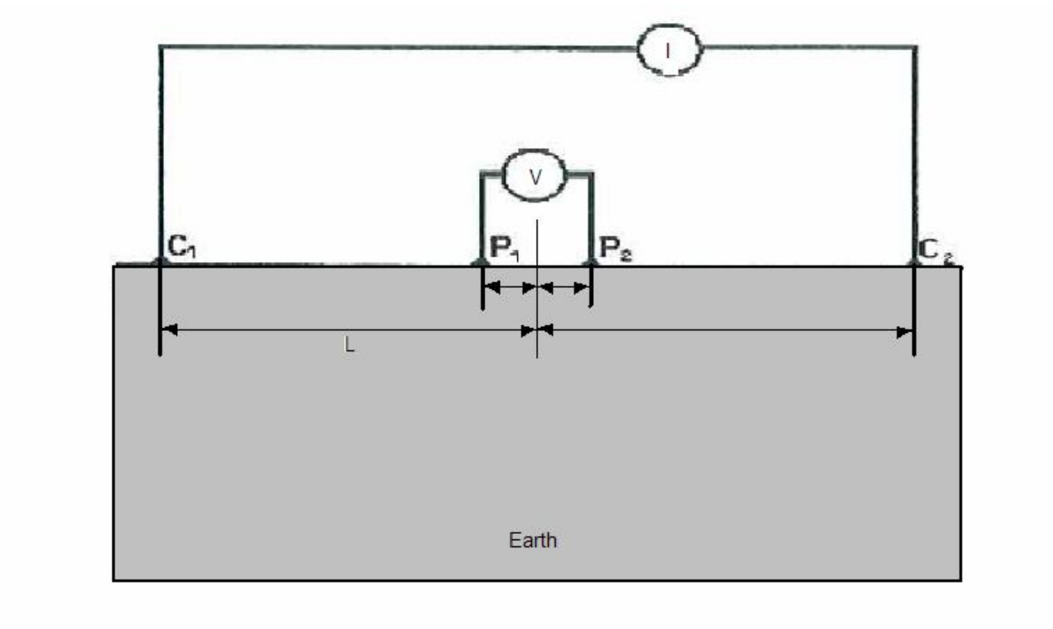

Figure 7: Schlumberger Array. Probe layout and injected and measured signals

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5.1.3 The Driven Rod (3 Pin) Method

The Driven rod method is sometimes referred to as the three pin, or fall of potential method. This method, as the name implies, uses only three electrodes in a configuration as shown in figure 8. The driven rod method is suitable for use in areas of difficult terrain, or for proposed simple earthing arrays (i.e. Transmission line structures). Similar to both the Wenner and Schlumberger arrays, a traverse is completed of the site, and the resistance of the soil taken at varying distances.

From the resistance readings obtained, the resistivity of the soil can be calculated using:

$$r_{ad} = \frac{2plR}{\ln\left(\frac{8l}{d}\right)}$$

Where

r_{as} = *Apparent Resistivity* (Ωm)
l = *Length of driven rod in contact with soil* (m)
d = *Driven rod diameter* (m)
R = *Measured resistance*

(source: ENA EG1, 2006).

A diagram of the Driven rod array is shown in figure 8.

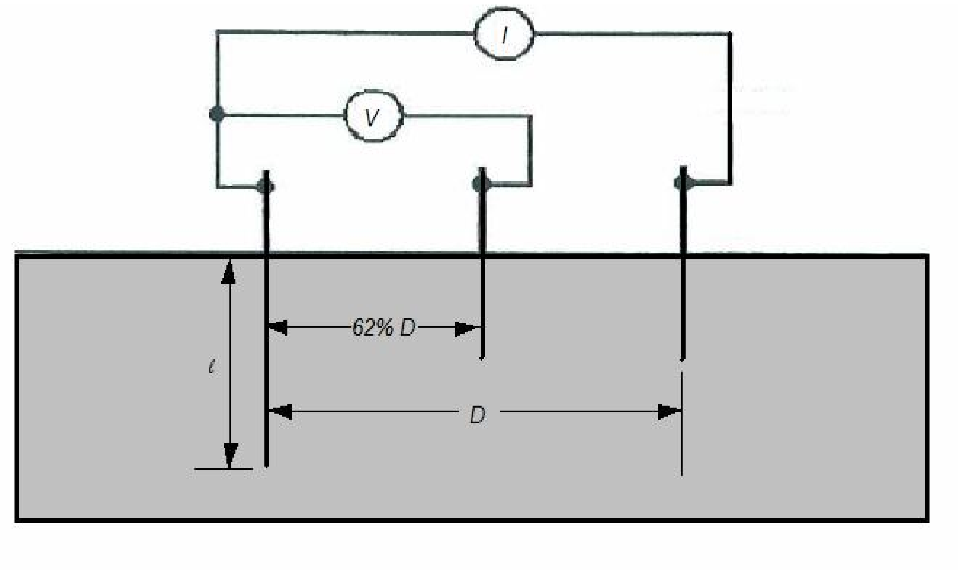


Figure 8: 3 Pin Array. Probe layout and injected and measured signals

6. Tests Conducted and Results Obtained

6.1 Introduction

As indicated in section 3.2, a schedule of tests was created to provide a logical, well though out plan of tests to be conducted, in order to try and obtain as accurate and repeatable data as possible. The schedule of tests was created as a “live” document as the findings of the initial tests, provided the reasoning for additional tests to be completed. The full schedule of tests is attached to this document in appendix C, with an outline of the creation process of the schedule of tests, as follows.

6.2 Initial Tests (Stage 1)

6.2.1 Site and Test Instrument Selection

Initially, the schedule of tests was created based on conducting a Resistivity Traverse at two different locations, using the Wenner Array. These locations were selected as vacant parcels of land, well clear of any fences, pipelines, power lines or other sources of potential interference. Numerous sources of information relative to earth resistivity including ENA EG1: 2006 and IEEE:80 mention the need for careful selection of sites clear of powerlines, pipelines, fences, etc which may influence test results.

Site 1 was selected in an area west of Caboolture, approx 1 Hr north of Brisbane, and site 2, selected just outside of Pittsworth, approximately ½ Hr South West of Toowoomba. These sites were selected based on their natural terrain, ease of access, and affiliation with the relevant property owners. Both sites were carefully examined for evidence of buried pipelines, communications cables or other services, as well as proximity to powerlines and other potential sources of interference. Due to each site being farmland which has not undergone any type of development other than clearing for grazing and cropping, both sites were assessed as suitable for the testing.

The initial tests were conducted using the Megger DET2/2 and the Fluke 1625 with the respective test leads in a number of different layouts and at several electrode spacings. The use of two instruments were selected, in order to compare readings between the selected instruments and highlight any inaccuracy that may be due to coupling effects, or shortfalls of the test instruments themselves. For each resistivity traverse (series of tests), the test probe spacing was selected in 1 metre increments up to 4m, then in 4m increments up to 16m, then 8m increments up to the largest probe spacing of 32m. 32m was the largest possible spacing to be used in this instance, due to the physical length of the test leads being 50 metres. Using a probe spacing of 32 metres, the distance from the centre of the array to each potential electrode (P1 and P2) is 16 metres, and then a further 32 metres, to each current electrode, hence the maximum lead length required in this situation is the current leads, of length 48m.

6.2.2 Test Lead Layout

The selected test lead layouts were based on the orientation of the injected current signal leads with respect to the measured voltage leads. Recall from the discussion in section 4.1.1 that the Wenner array uses four electrodes, with the outermost two carrying the injected current signal, and the innermost two electrodes, the measured voltage signal. As magnetic and capacitive coupling affects conductors in parallel, three logical test lead orientations were derived. These layouts were: Leads at 90 degrees, Leads in parallel at 0 Degrees and Leads in parallel at 180 Degrees. An aerial view diagram of these lead layouts are as shown below in figures 9, 10 and 11.

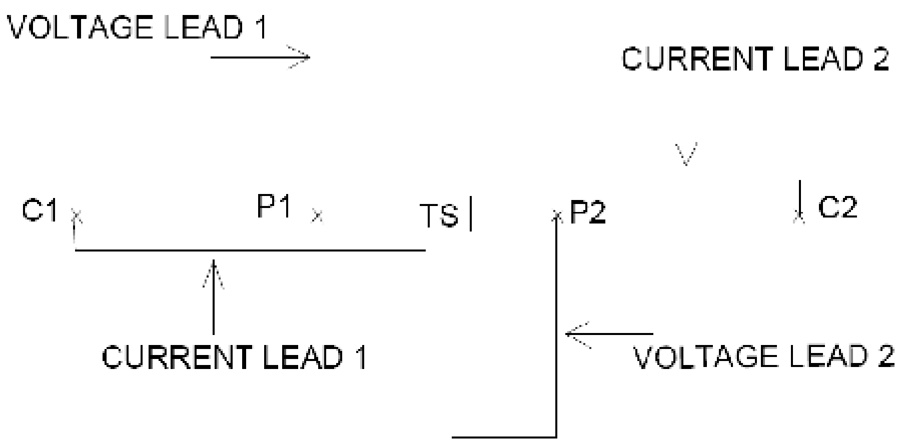


Figure 9: Test Leads at 90°. Wenner array with current and voltage leads separated by 90 degrees.

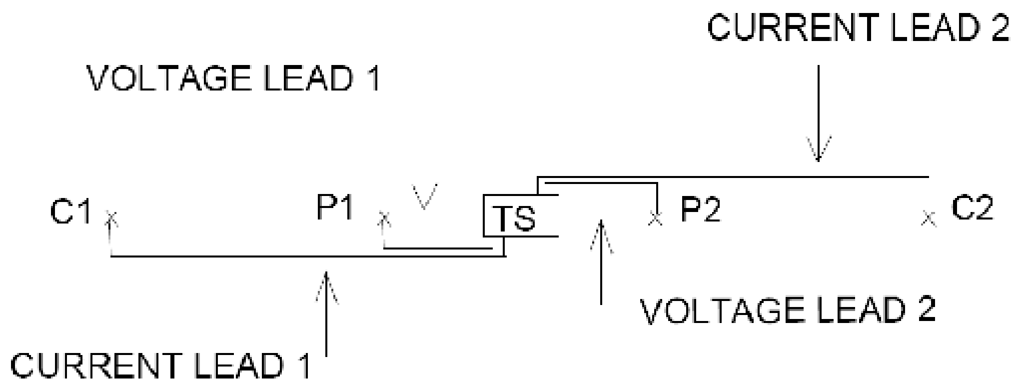


Figure 10: Test Leads in Parallel (0°). Wenner array with current and voltage leads in parallel (0 degrees).

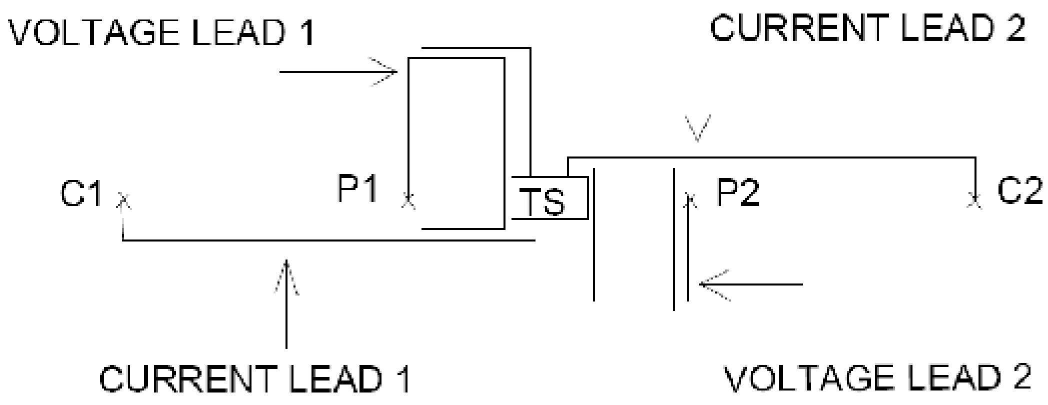


Figure 11: Test Leads in Parallel (180°). Wenner array with current and voltage leads in parallel (180 degrees).

For both lead configuration 2 and 3 (conductors in parallel at 0° and 180°) the parallel sections of cable were very carefully "strung" between the centre of the array and the potential electrodes, taking care to avoid any twists in the cables. This was achieved by using wooden support structures at the relevant locations, to which the current and voltage leads were fixed. Proximity of the leads was further ensured, by using a simple clothes peg to ensure the conductor orientation was correct.. Figure 12 shows an example of the array configuration for a test with leads in parallel. Note that this configuration did not require a wooden support in the centre of the array due to the short parallel section of cable.

Figure 12: Parallel Test Lead Configuration : Wenner array with current and voltage leads in parallel.

6.2.3 The Effects of Electrode Contact Resistance

Using these test lead configurations, the very early stages of testing, revealed a substantial variation in the resistance readings displayed by each test instrument instrument, depending on the lead configuration. These results were initially recorded, however the results obtained were highly inconsistent and largely non-repeatable. Through further investigation, the test equipment manuals indicated the probable cause of the variation in the results was due to a high contact resistance between the electrodes and the soil. The soil under test was reasonably dry and hence the contact resistance between the electrode and the general mass of earth was changing as the electrode was disturbed (even slightly) during alteration of the lead layout.

To overcome this variation due to the electrode contact resistance, a salt water solution was prepared, and a small amount applied to each electrode, to negate these contact resistance effects. Repeat testing with the salt water solution applied to all electrodes, obtained much more stable and repeatable results, and hence this method was then adopted for all future testing to be conducted. The quantity of the salt water solution applied to each electrode was kept to an absolute minimum, as the conductive properties of the soil would be affected considerably, if large amounts of solution were applied, particularly at close probe spacings.

6.2.4 Information Recorded During Each Test

For each of the tests conducted, readings of the Injected Current, Measured Voltage, Displayed Resistance and Signal Frequency, were recorded. In order to accurately record the variation in these parameters, the careful selection of additional test instruments was required.

The instruction Manuals for the Megger DET2/2 and the Fluke 1625 indicate the injected current signal is alternating DC, at various frequency ranges (as set by user). Based on an alternating DC current signal being injected, the measured voltage signal will also be an alternating DC voltage, and hence, the theoretical injected and measured signals will each be a square wave, similar to the waveform shown in Figure 13.

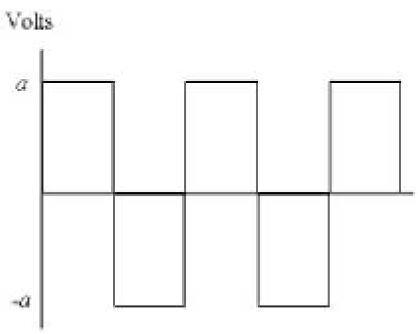


Figure 13: Example Square Wave: Example of a typical square wave, as is the injected current and measured voltage signal of the Fluke 1625 and Megger DET2/2.

In order to measure what is therefore effectively a square wave, a True RMS multimeter and Current clamp meter were selected. True RMS is stated as a specific method of measuring the RMS, or "DC Equivalent" value of a signal. This method results in the most accurate RMS value regardless of the shape of the waveform. Other methods of measuring RMS values exist, such as the rectifier or mean absolute deviation method; however, these methods are accurate only for sine wave signals. **Source:** National Instruments, 2009

Consideration was also given to the accuracy of the Multimeter and Clamp Meter for measurement of higher frequency signals. The injected signals were, as previously stated, alternating DC signals between 100-150Hz (depending on desired setting). The accuracy specifications for the Multimeter and Clamp Meter are attached in appendix D, and show an accuracy of +/- 1% for sinusoidal signals up to 1kHz for the multimeter and +/- 2% for signals up to 2kHz, for the clamp meter. On initial inspection, these specifications, indicate good accuracy for signals in the expected frequency range (100-150Hz) , however if the injected signal were considered as series of sinusoidal components, I.e. a Fourier series, the issue of accuracy with respect to frequency, soon became evident.

Fourier's theorem states that any periodic signal can be decomposed into an infinite series of sine and cosine functions. For a square wave as shown in Figure 13, the Fourier series can be described as:

$$a + \sum_{n=1}^{N} \frac{1}{n} \sin(n w_0 t)$$
$$for\ n = 1,3,5,7 \ldots$$

Where ω_0 is the fundamental frequency, and a is the DC component, or average DC offset.

Source: Facstaff, 2009.

For the Earth test signals of interest, it was assumed that the offset DC component was zero, (hence a=0) and the waveform was symmetrical about the x axis. The stated default frequency for the Fluke 1625 is 111 Hz, so the Fourier components of this signal can be calculated using the above equation. The resulting theoretical frequency components are as shown in table 2.

Multiple Of Fundamental Frequency (111Hz)	1 (111Hz)	3 (333Hz)	5 (555Hz)	7 (777Hz)	9 (999Hz)	11 (1221Hz)
Magnitude Present In Signal (multiple of fundamental amplitude)	1	1/3	1/5	1/7	1/9	1/11

Table 2: Fourier components of a square wave signal

From table 2 it can be seen, for example that the 11th harmonic component of the Fourier series (1221 Hz component), the magnitude will be 1/11 of the peak value of the fundamental component. If the peak of the fundamental measured signal is 50mV for example, the peak value of the 11th harmonic component will be approximately 4.54mV, or ≈9% of the original signal. Attenuation of these higher frequency components would therefore lead to considerable inaccuracy in the results obtained.

The Manufacturers data for the Fluke 179 indicates that while accuracy of signals >1kHz is not specified, the relative accuracy of a non-sinusoidal waveform is accounted for in a footnote to the table of specifications. This states that: For non-sinusoidal waveforms accuracy, add -(2% reading + 2% full scale) typical. Therefore the overall accuracy of the Fluke 179 can be considered as 3%, comprised of 1% accuracy for AC signals up to 500Hz, plus the additional 2% for non sinusoidal waveforms.

Similarly, the Hioki 3283 states an accuracy of 2% for signals up to 2kHz, and the meter is stated as a True RMS instrument, therefore the accuracy should be sufficient for this purpose.

Based on the requirements for the use of True RMS equipment and the frequency accuracy considerations above, the instruments for measurement of the required parameters of the test signals, were selected as:

- Injected Current: Hioki 3283 High accuracy clamp meter. Resolution: 0.1mA True RMS meter
- Measured Voltage. Fluke 179 III Multimeter. Resolution 0.1mV, True RMS Multimeter
- Resistance– Taken directly from the readout of the Earth testing device.
- Frequency of the injected signal. Fluke 179 III Multimeter. Resolution 0.1 Hz, True RMS Multimeter

6.2.5 Calculation of Resistivity from Results Obtained

As defined in section 4.1.1, Soil Resistivity from a Wenner array test layout, can be calculated by using the formulae:

$$r_{aw} = 2paR$$

or

$$r_{aw} = 2pa\frac{\Delta v}{I}$$

Since the tests to be conducted record the paramenters *R*, as displayed by the test instrument, *Δv* as measured by the Fluke 179, and *I* as measured by the Hioki 3283, two separate calculations of the Soil Resistivity were carried out. These results were then compared and have been presented in section 5.3.

6.3 Considerations of Test Current Waveform Vs Power System Waveform

From section 6.2.4, the injected current waveform has been found as an alternating DC signal, which then raises the question of accuracy in terms of AC current propagation through the same soil under test. Soil Resistivity tests are conducted to establish the resistive properties of the soil, and therefore the use of a DC signal is appropriate for such a purpose, however, it seems little or no consideration has been given to the propagation of AC sinusoidal current through the same soil. The soil resistivity results obtained by using an alternating DC test signal may not accurately represent the flow of current through the same soil, for a 50Hz current signal.

If we consider the soil under test in a similar manner to a simple conductor, or group of conductors, the soil may exhibit different electrical properties such as inductive or capacitive effects, under different circumstances. It appears that significant research has been conducted into the dielectric properties of soil, and the findings of others (see references) appear to indicate the presence of frequency dependent characteristics within the soil.

An example of such a finding is outlined by Van Dam et al in the paper entitled "Methods for prediction of soil dielectric properties: a review". The paper outlines the electrical and magnetic properties of soils, based on the nature and dielectric properties of the soil, and how these properties are dependant on frequency. One notable quote from this paper is the statement "The interaction of electromagnetic energy with matter is affected by the characteristics of the material and by the frequency of the electromagnetic energy". Boydell et al, indicate a similar discussion, detailing that the "Soil Elelctrical Conductivity properties are dependant on the electrolyte concentration and its connectivity or continuity within the profile".

The research into the electrical properties of soils is outside the scope of this research paper, however the intent of the above citations are to raise awareness to the reader, of such frequency dependant effects. Further investigation into the propagation of DC and AC current through the same soil strata is a possible area of future research.

6.3.1 Results Obtained From Initial (Stage 1) Testing

Using the specifications above the initial tests and required calculations were carried out. The results of these tests have been presented in the following sections in graphical form, for ease of perusal, and comparison of results. The presentation of results has been based on the following Characteristics:

- Comparison of the Resistivity curves as calculated from the measured resistance (instrument reading), for each of the test lead layout patterns.

- Comparison of the Resistivity curves as calculated from the resistance readings and as calculated from the measured V and I signals for each test lead layout

The full table of Soil Resistivity results from which these graphs have been produced, have been included in appendix E.

6.3.2 Resistivity Curves Calculated From Measured Resistance – Caboolture Site

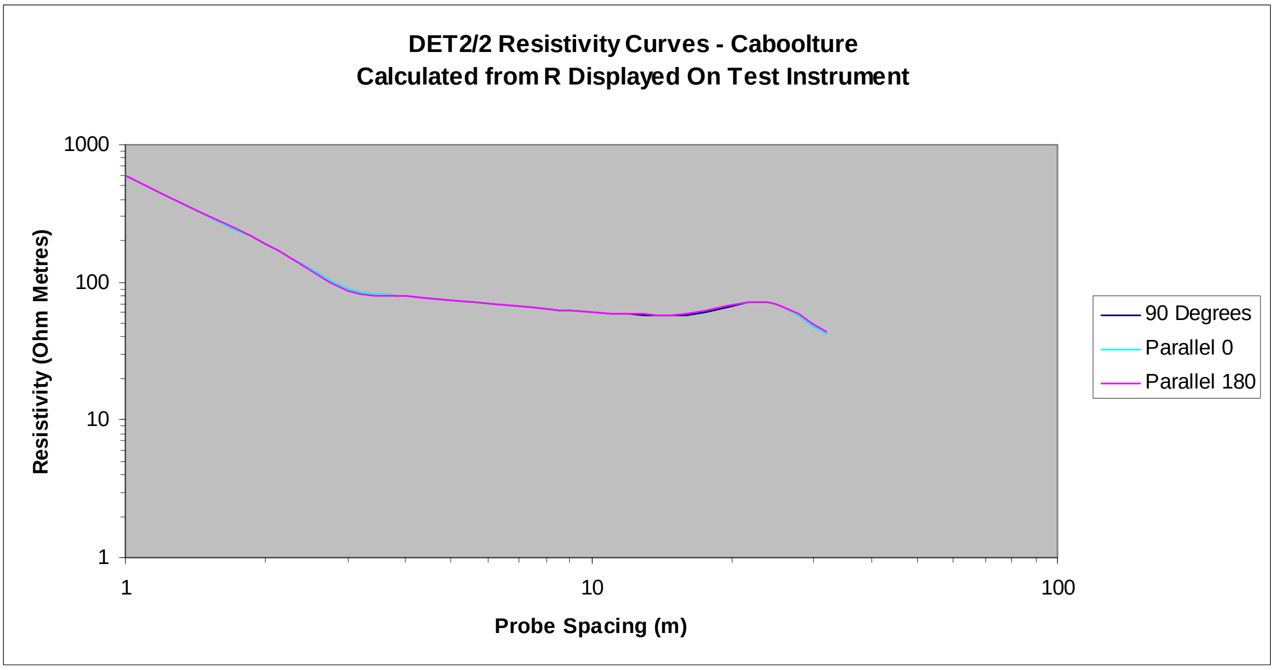


Figure 14: Resistivity Curves. DET2/2 - Caboolture Site: Resistivity curves as calculated from resistance readings- Megger DET2/2 instrument at Caboolture site.

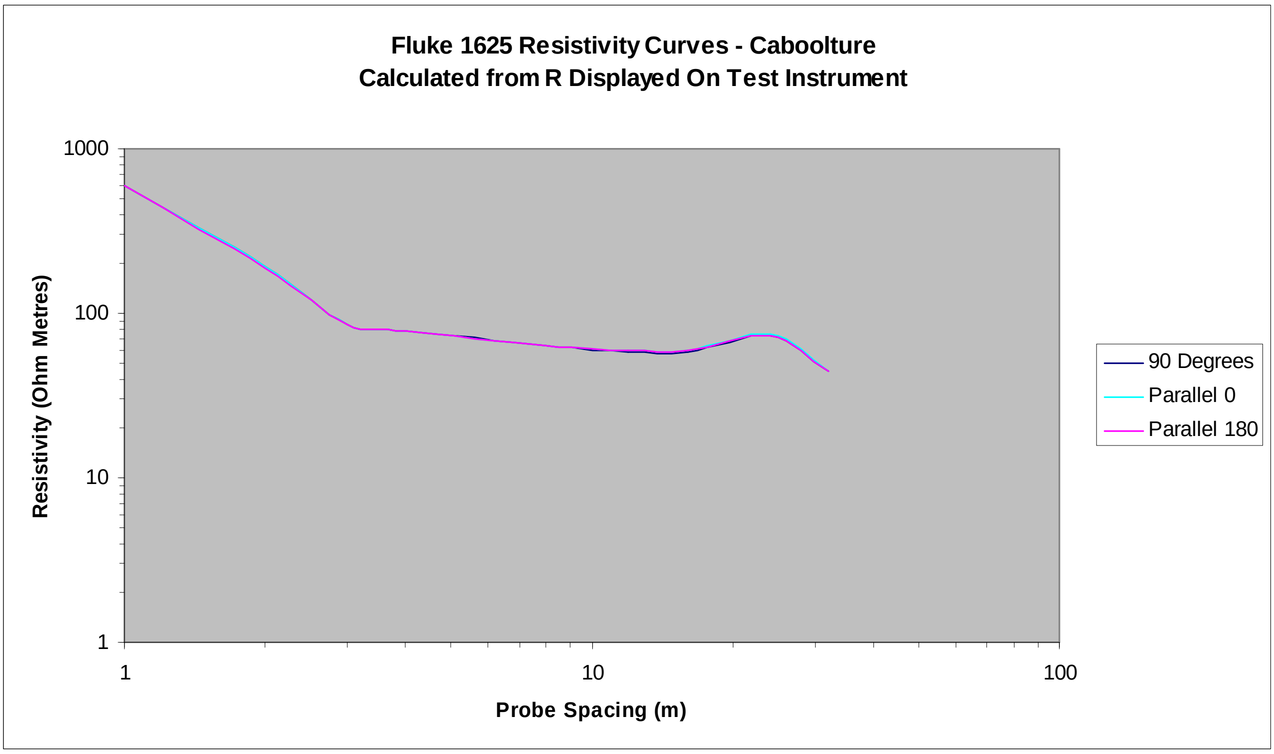


Figure 15: Resistivity Curves. Fluke 1625 - Caboolture Site: Resistivity curves as calculated from resistance readings- Fluke 1625 instrument at Caboolture site.

6.3.3 Resistivity Curves Calculated From Measured Resistance – Pittsworth Site

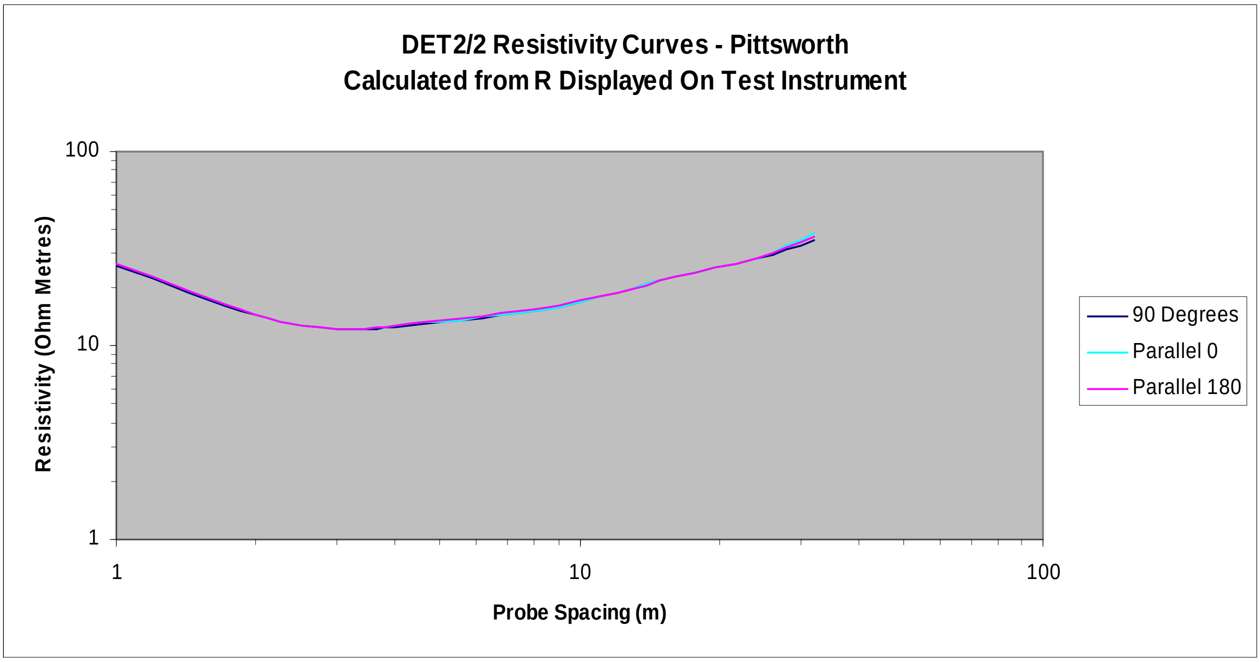


Figure 16: Resistivity Curves. DET2/2 - Pittsworth Site: Resistivity curves as calculated from resistance readings- Megger DET2/2 instrument at Pittsworth site.

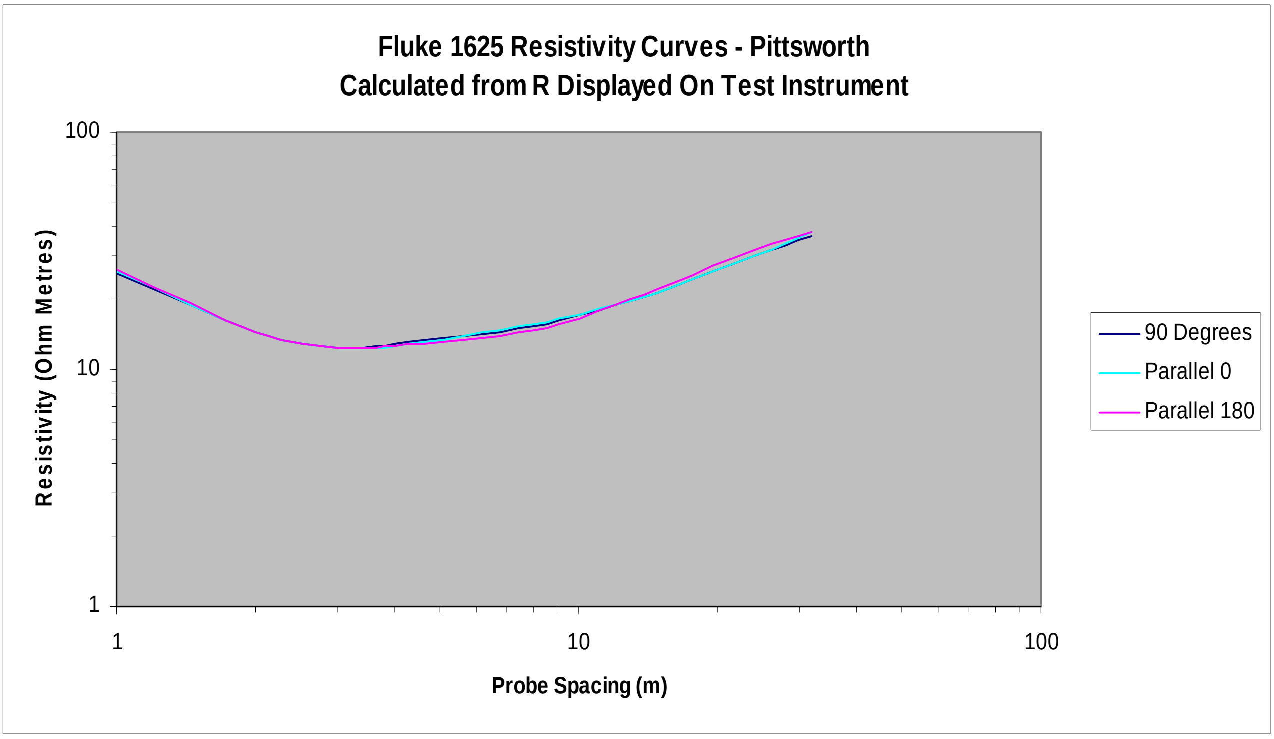


Figure 17: Resistivity Curves. Fluke 1625 - Pittsworth Site: Resistivity curves as calculated from resistance readings- Fluke 1625 instrument at Pittsworth site.

6.3.4 Resistivity Curves as Calculated From Measured Resistance Vs Measured Voltage and Current: Megger DET2/2 Instrument – Caboolture Site.

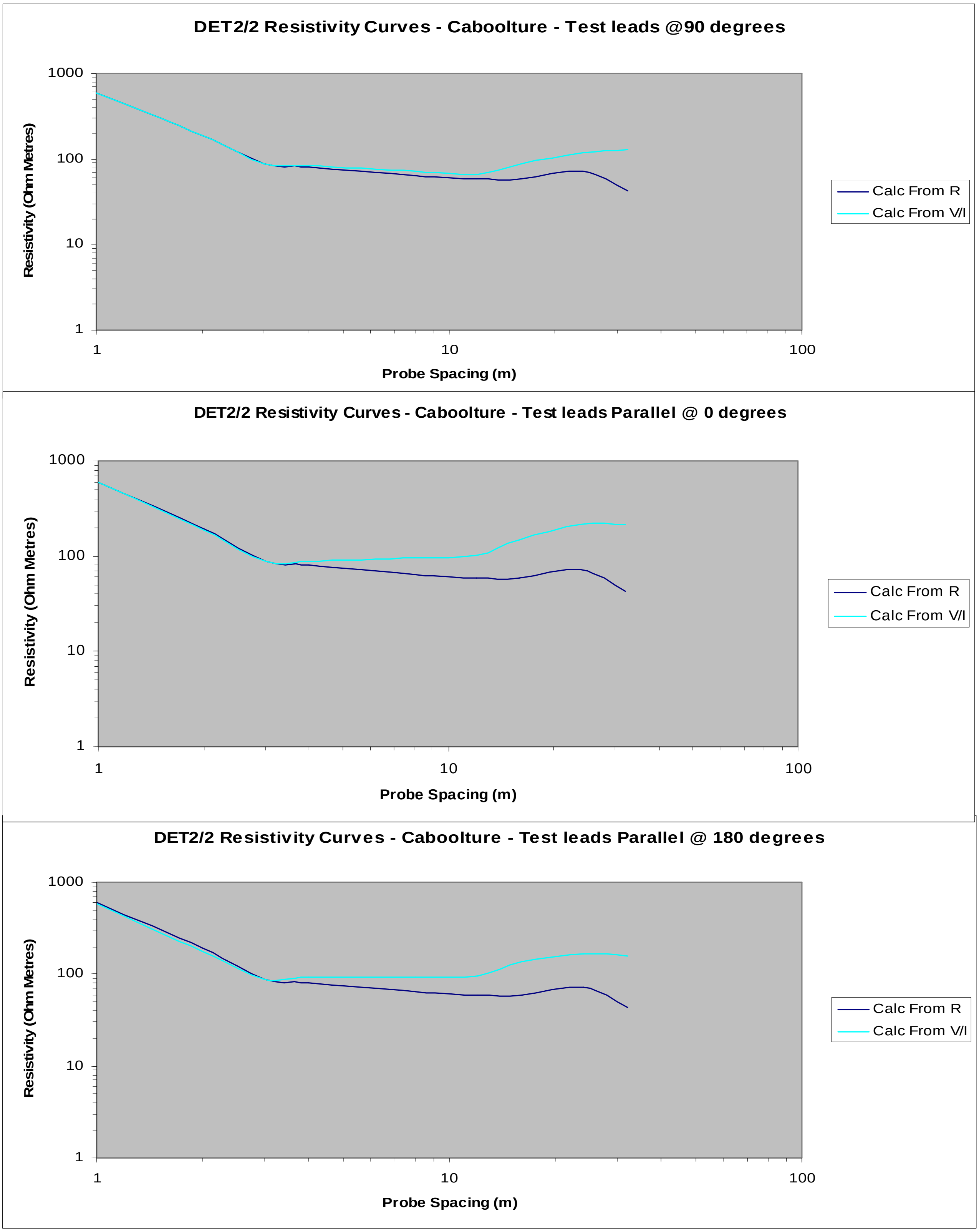


Figure 18: Resistivity Curves. Megger DET2/2 - Caboolture Site: Resistivity curves as calculated from Resistance readings Vs measured Current and Voltage.

6.3.5 Resistivity Curves as Calculated From Measured Resistance Vs Measured Voltage and Current: Fluke 1625 Instrument – Caboolture Site.

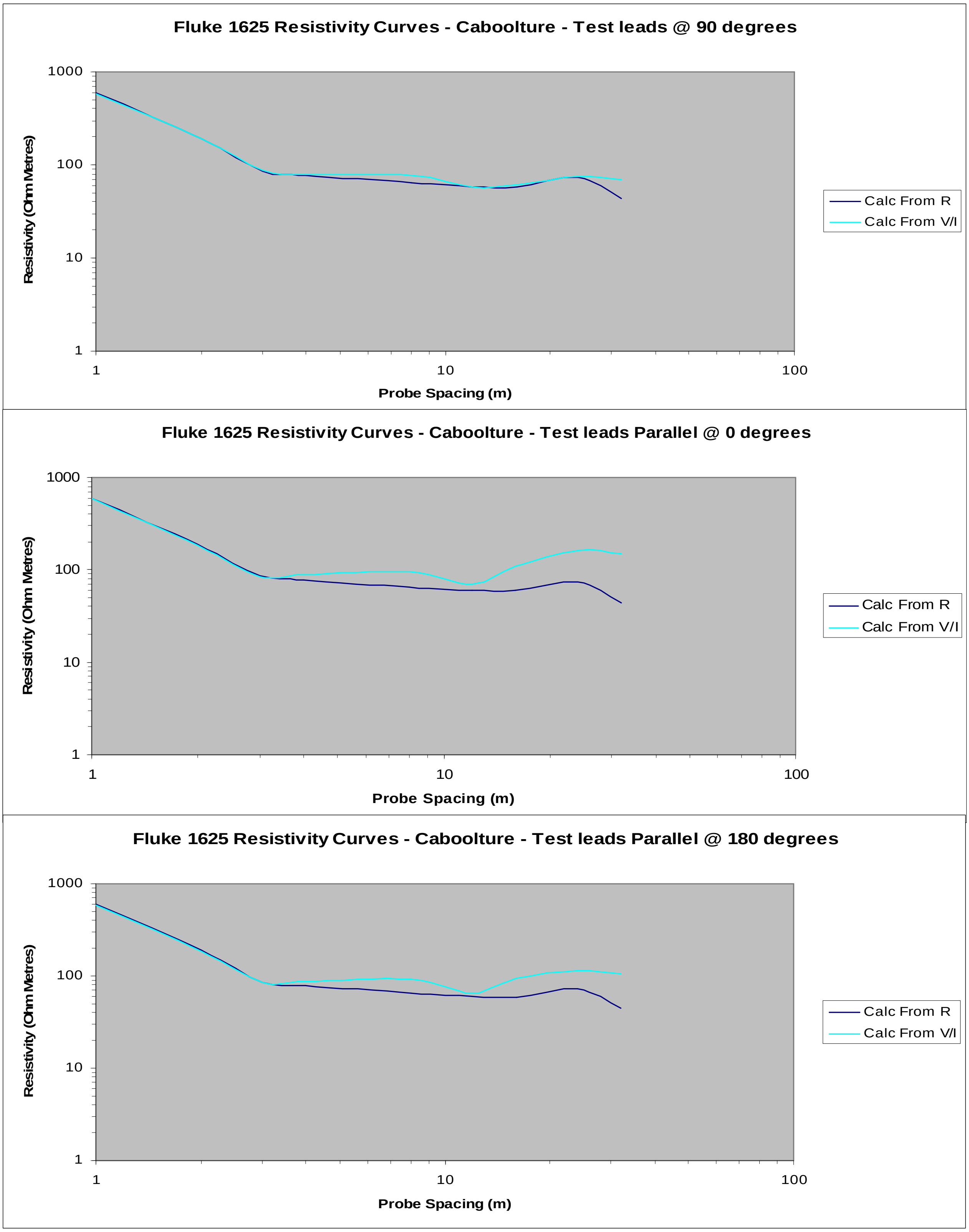
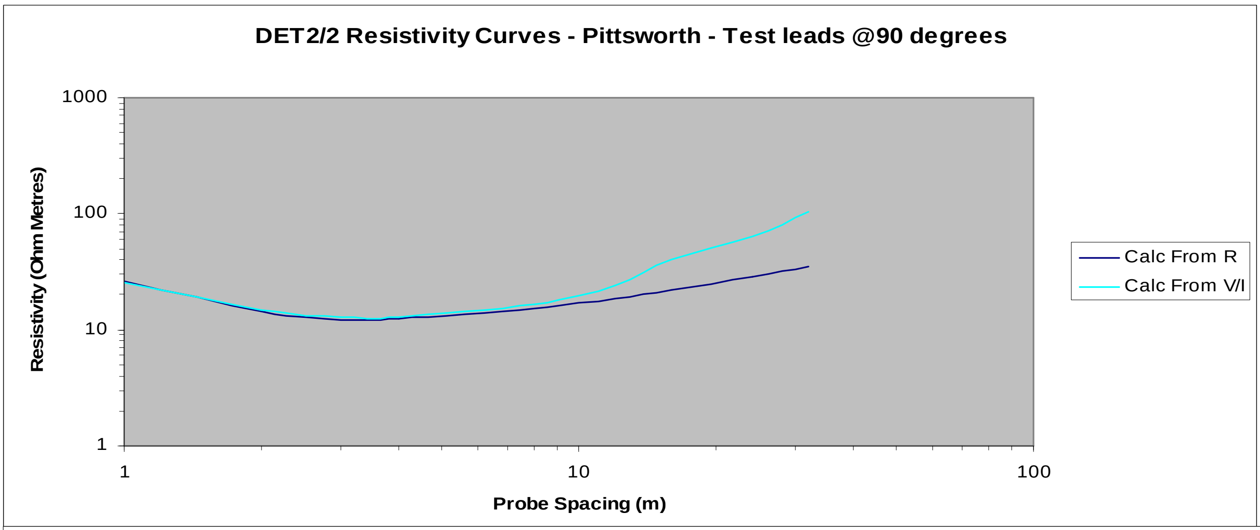
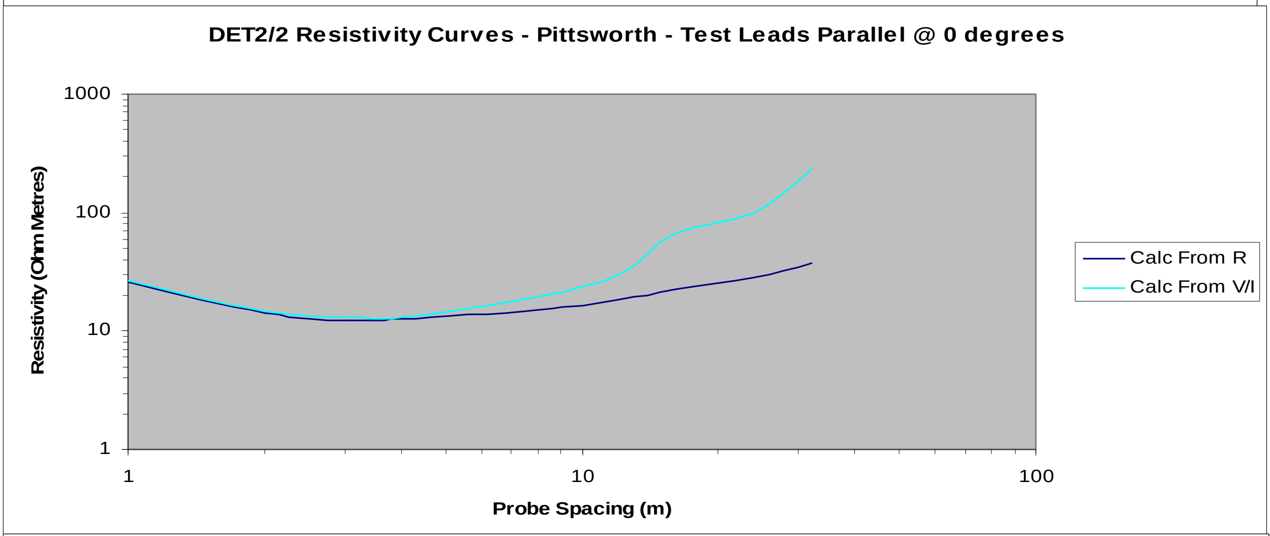


Figure 19: Resistivity Curves. Fluke 1625 - Caboolture Site: Resistivity curves as calculated from Resistance readings Vs measured Current and Voltage.

6.3.6 Resistivity Curves as Calculated From Measured Resistance Vs Measured Voltage and Current: Megger DET2/2 Instrument – Pittsworth Site





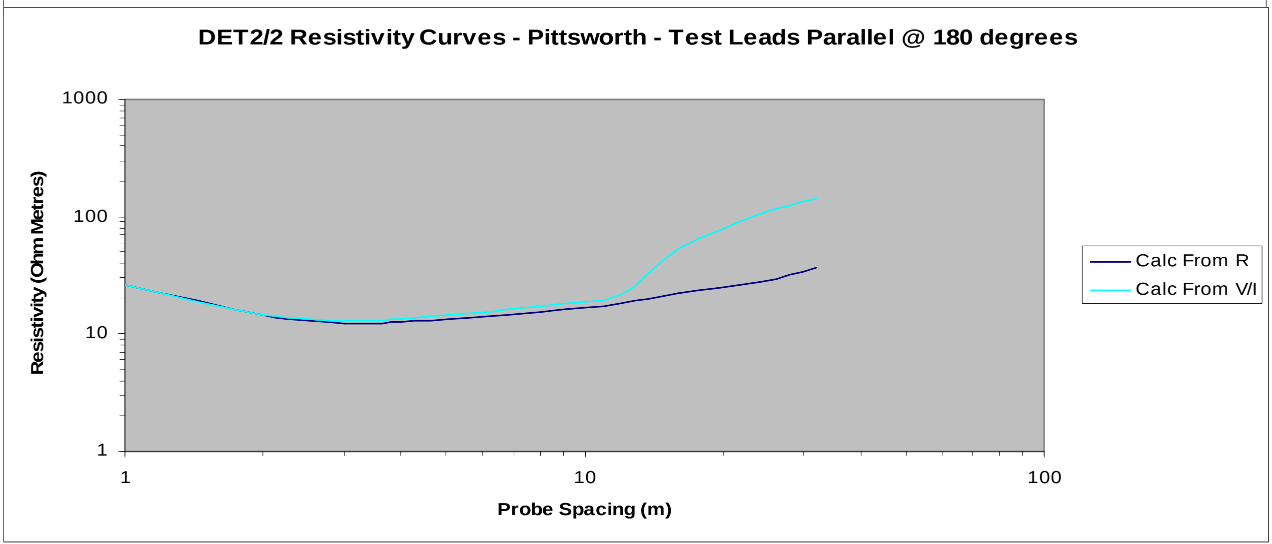


Figure 20: Resistivity Curves. Megger DET2/2 - Pittsworth Site: Resistivity curves as calculated from Resistance readings Vs measured Current and Voltage.

6.3.7 Resistivity Curves as Calculated From Measured Resistance Vs Measured Voltage and Current: Fluke 1625 Instrument – Pittsworth Site

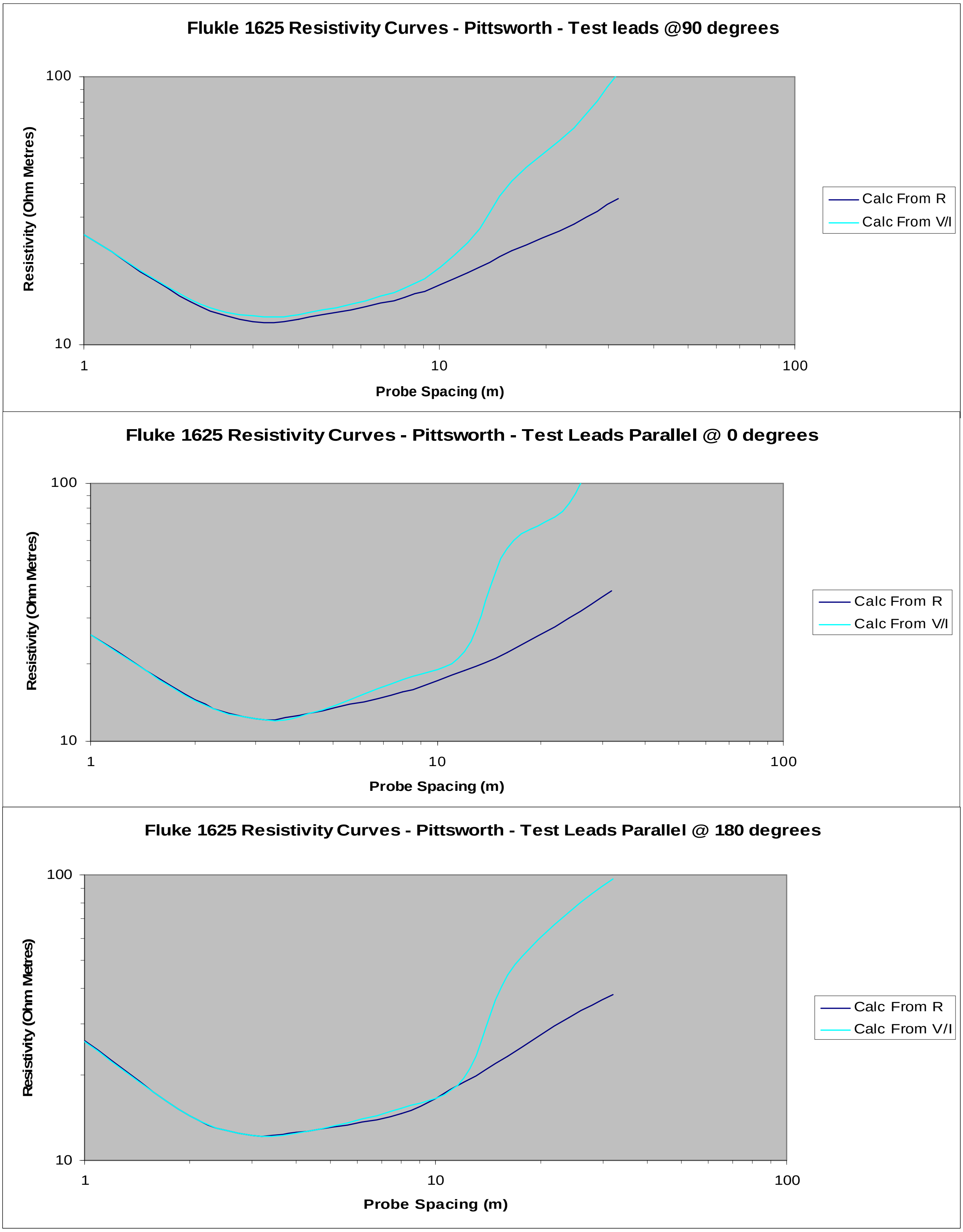


Figure 21: Resistivity Curves. Fluke 1625 - Pittsworth Site: Resistivity curves as calculated from Resistance readings Vs measured Current and Voltage.

6.4 Discussion of Initial (Stage 1) Test Results

6.4.1 Test Lead Coupling and the Resistance Indicated by the Test Instrument

With respect to the Resistivity traverses conducted as per section 5.3, the effect of test lead coupling does not appear to have significant effect on the Resistance displayed by the test instruments. Based on the information displayed in figures 14 to 17, the effects of test lead coupling, does not appear to be significant, for tests conducted at spacing up to and including 32 metres. These Resistivity curves show slight variation, and inspection of the results obtained, (Refer Appendix E) reveals the relatively small magnitude of this variation. The cause of the variation could be attributed to coupling effects only, however consideration must be given to other external influences that may have been present. Several external factors which may have been present and therefore require consideration are:

- Disturbance of the test electrodes during alteration of the test lead Layouts. Slight movement of the electrodes is unavoidable when changing the layout of the test leads to the 3 predefined configurations. As previously discussed, a salt water solution was used to overcome the effects of electrode contact resistance, however this does not guarantee the properties of the contact area will remain identical for each test, particularly when the electrode is disturbed between tests.

- Transferral of leads between instruments for each lead configuration. With the test leads set up for each lead configuration, each test was completed using both instruments, before alteration of the leads or electrodes to the next required configuration. By transferring the leads between instruments, the connections between the test leads and the instrument are altered, and therefore may lead to slight variation in the test results.

Taking into account the inaccuracies that may have been introduced by the above factors, variation in the results recorded, still appears to be present. The variation in the Resistance readings obtained, while small in nature, does appear to increase, as probe spacing is increased. A summary of the results obtained from both sites, for probe spacing of 1 and 32 metres has been included below in table 3, to outline the variation present between the different tests. The results obtained for 1 metre spacing show a very small percentage variation in resistance reading between the 90 degree test lead configuration and the parallel test lead configurations of zero and 180 degrees. Comparison of these results with the results of tests conducted at 32 metre probe spacing, clearly reveals the larger percentage variation in resistance readings obtained. As coupling effects would reasonably be expected to increase, with an increase in the parallel section of test lead, tests conducted with very large probe spacing may therefore become increasingly inaccurate.

Further investigation into the effect of coupling on the resistance displayed, appears warranted as the test probe spacing is increased above 32 metres. As previously indicated, the equipment available for these tests had a test lead length of approximately 50 metres, hence testing with probe spacing greater than 32 Metres was unachievable using the equipment available at the time of the initial tests.

Caboolture Site					
Lead Orientation	**Instrument**	**R Measured 1m**	**Variation From 90° Reading**	**R Measured 32m**	**Variation From 90° Reading**
90 Degrees	DET2/2	95	N/A	0.211	N/A
Parallel 0	DET2/2	95.1	0.105%	0.213	0.947%
Parallel 180	DET2/2	95.1	0.105%	0.216	2.37%
90 Degrees	Fluke 1625	95	N/A	0.21	N/A
Parallel 0	Fluke 1625	95	0 %	0.22	4.7%
Parallel 180	Fluke 1625	95.1	0.105%	0.22	4.7%
Pittsworth Site					
Lead Orientation	**Instrument**	**R Measured 1m**	**Variation From 90° Reading**	**R Measured 32m**	**Variation From 90° Reading**
90 Degrees	DET2/2	4.12	N/A	0.175	N/A
Parallel 0	DET2/2	4.17	1.21%	0.187	6.86%
Parallel 180	DET2/2	4.21	2.18%	0.182	4%
90 Degrees	Fluke 1625	4.08	N/A	0.18	N/A
Parallel 0	Fluke 1625	4.13	1.23%	0.19	5.55%
Parallel 180	Fluke 1625	4.17	2.21%	0.19	5.55%

Table 3: Variation in Resistance readings for probe spacing of 1metre and 32 metres

6.4.2 Test Lead Coupling and the Measured Voltage and Current Signals

On inspection of Figures 18 to 21, the effects of test lead coupling appears to become more evident when considering the True RMS Voltage and Current signals measured by the Fluke 179 and Hioki 3283 instruments. The Resistivity curves in figures 18 to 21, indicate significant variation when the Resistivity is calculated using the measured resistance versus the Resistivity calculated from the measured voltage and current signals. The curves all display significant variation as the test probe spacing is increased, particularly as the probe spacing exceeds ≈10 Metres**.**

Further inspection of figures 18 to 21 indicates that the orientation of the test leads, also has an effect on the magnitude of the variation in Calculated Resistivity readings. Consider the 3 curves shown in Figure 18, for example and note the variation in the Resistivity curves for the 90°, Parallel 0°, and Parallel 180° test lead configurations. From these curves the variation due to test lead configuration, and parallel lead orientation soon becomes apparent.

It is not accurate to say that all of the variation we have found can be attributed solely to the effects of test lead coupling, however, the results for both sites and both instruments, indicate the effects of coupling are indeed present. External factors such as environmental noise must be considered, however, are assumed to be non-significant in this case, based on the selection of the test sites. Because of the careful selection of the test sites as areas well clear of any infrastructure such as fences, powerlines, pipelines, etc. any environmental noise present, is therefore considered as normal or “background” noise, as would be encountered in almost any situation.

6.5 Further Testing Based on Results of Initial Tests. (Stage 2 Tests)

Using the information obtained from the results of the initial (stage 1) tests, further testing was deemed necessary. The intent was to more accurately determine the coupling effects on the injected current and measured voltage signals for tests conducted using a large probe spacing, in this case, 32 Metres.

Using a digital scope meter (a digital version of a Cathode Ray Oscilloscope) and the Fluke 1625 Instrument, a Wenner Array with probe spacing of 32 Metres was prepared. The scope meter selected was a Philips PM97 Scopemeter, based on availability through Downer EDI Engineering.

Using this equipment, a Resistivity test was conducted using each of the 3 test lead layout configurations, and the Resistance displayed together with the waveform of the injected current and voltage signals were obtained. The injected current and measured voltage waveforms were obtained using the “hold” function of the scope meter, and recorded using a Digital Camera. The Philips PM97 does have a facility for connection to a Laptop computer, however neither the interface lead, nor the required software were available at the time of testing.

As before, the results obtained from these further tests, have been included, and are as shown in below, in section 6.4.

6.5.1 Results Obtained from Stage 2 Tests

The Resistivity results and photographs of the scope meter display, for each test are as shown in Table 4 below and figures 22 to 24. It should be noted, these pictures have been colour adjusted for clarity of the waveform displays. For the waveform results displayed, Channel A is connected to the Measured Voltage signal, and channel B is the Injected current signal.

Test Lead Orientation	Probe Spacing	Instrument	Resistance
90°	32m	Fluke 1625	347 Ω
Parallel 0°	32m	Fluke 1625	348 Ω
Parallel 180°	32m	Fluke 1625	348 Ω

Table 4: Variation in Resistance readings for stage 2 tests (probe spacing of 32 metres)

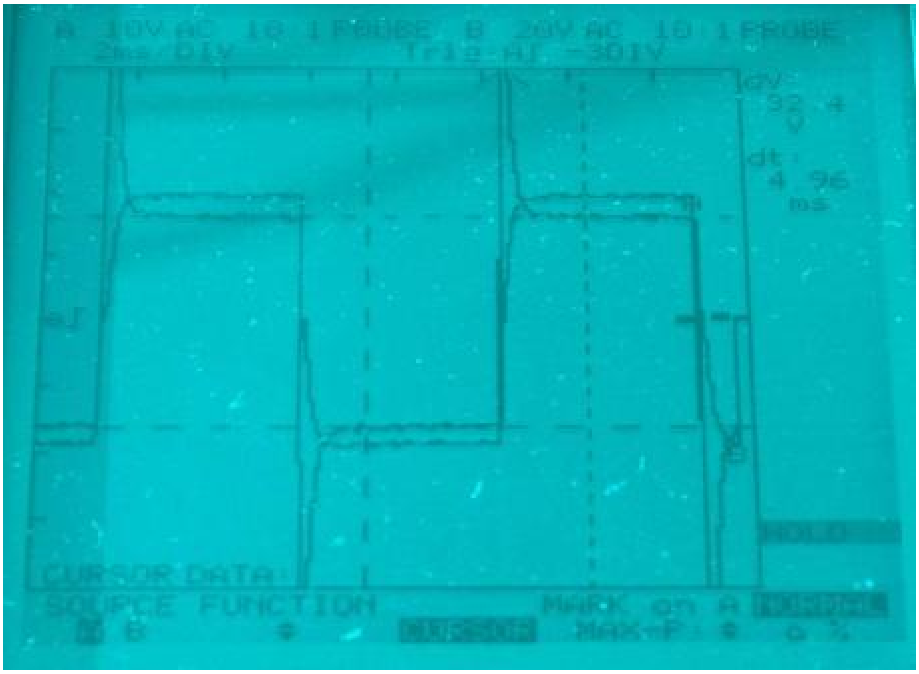


Figure 22: Voltage and Current Waveforms, 90° Test lead Orientation:

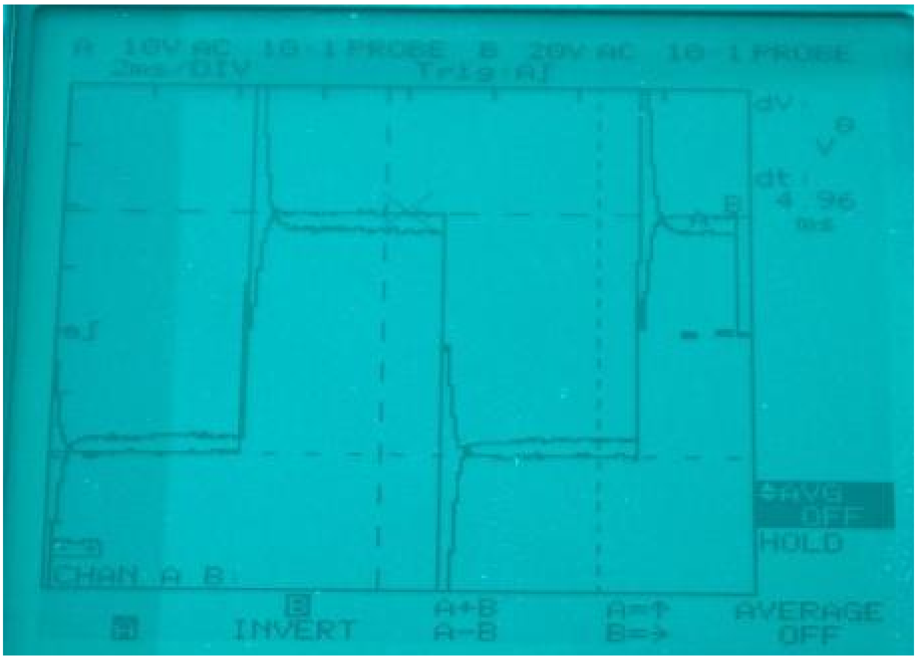


Figure 23: Voltage and Current Waveforms, Parallel 0° Test lead Orientation:

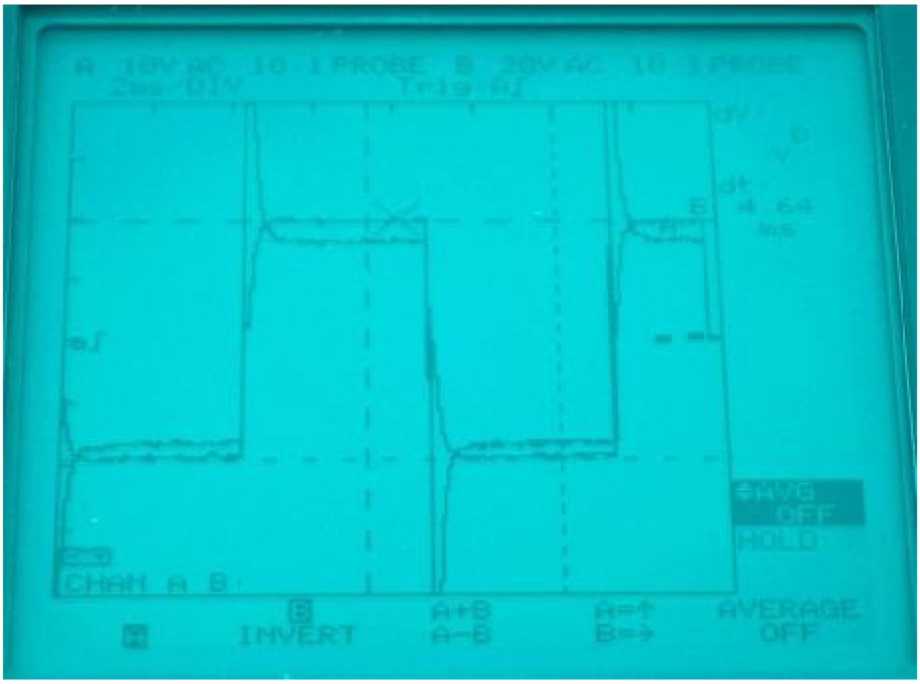


Figure 24: Voltage and Current Waveforms, Parallel 180° Test lead Orientation

6.6 Discussion of Stage 2 Test Results

From the waveforms displayed for channel A and B, as indicated in figures 22 to 24, the measured voltage and injected current signals appear consistent with a series R-L circuit. For clarity, the injected current and measured voltage signals have been recorded separately, and an example of their shape is provided in figures 25 and 26. For the injected current waveform, the wave shape appears consistent with and inductive-resistive load, as can be seen by the rounded leading edges of the waveform in figure 26. Similarly the voltage waveform (figure 25) clearly denotes the voltage spike as characteristic of an inductive discharge in an R-L circuit.

It is possible that the source of the inductive effects of the associated waveforms may be considered as a combination of inductance from two separate inductive sources. Two possible sources that may be present are:

1. The self inductive effect of the injected current with respect to the current test leads, as they are run across the test site, I.e. the flow of current through the test leads and the return current through the earth to create an inductive loop. The current path through the earth may have a self inducing effect on the current injection test leads.

2. Inductance between the test current and voltage leads, as originally anticipated through the tests conducted for the stage 1 tests.

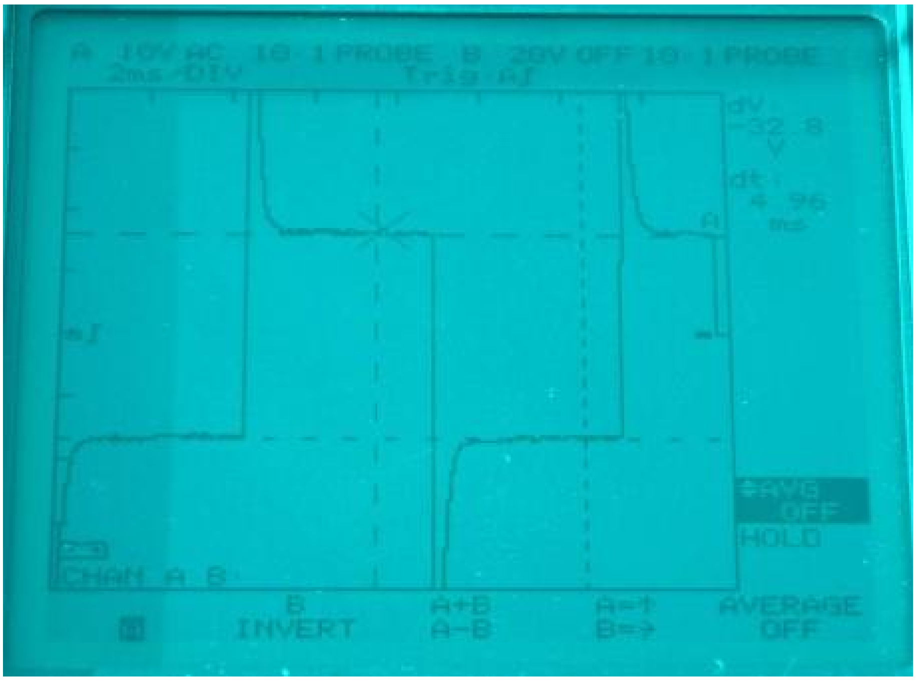


Figure 25: Typical Voltage Waveform (Channel A)

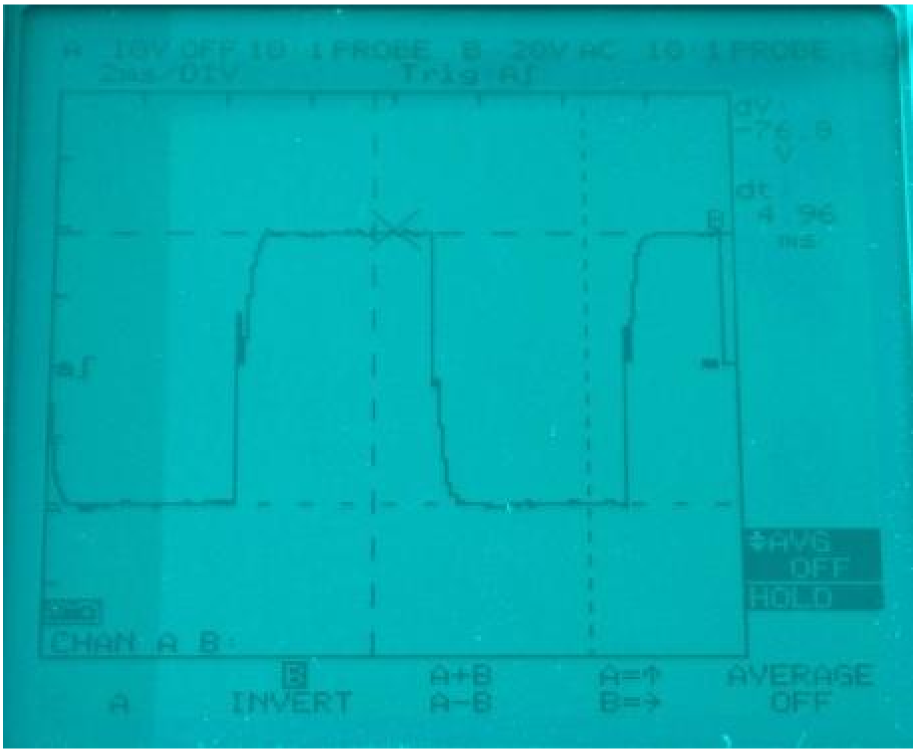


Figure 26: Typical Current Waveform (Channel B)

A very useful feature of the PM97 Scope-meter is the ability to measure the change in voltage signal between selected areas of the displayed waveform, using the cursor function. Refer to figure 25 and note the dV value in the upper right corner of the display. This value is the voltage difference between the points denoted by the horizontal and vertical dotted cursor lines of the display. The large horizontal and vertical dotted lines intersect at an upper horizontal section of the channel A waveform, and the small dotted lines intersect at a lower horizontal section of the same waveform. The voltage difference between these points is then as displayed by the dV value indicated. Selection of channel B allows similar measurements to be taken for the channel B waveform.

For each of the tests conducted, the relevant dV measurements were taken for the measured voltage and injected current signals (channels A and B). The scope meter displays were taken using a 10:1 probe for both channels, hence the measured dV values are multiplied by a factor of 10. The results obtained have been included below in table 5.

Test Lead Orientation	**Signal (Channel A or B)**	**dV Measured (V)**	**dV Corrected**	**Resistance Displayed (Ω)**
90°	Voltage (Ch A)	32.4	3.24	347
	Current (Ch B)	76.8	7.68	
Parallel 0°	Voltage (Ch A)	33.2	3.32	348
	Current (Ch B)	76.8	7.68	
Parallel 180°	Voltage (Ch A)	32.8	3.28	348
	Current (Ch B)	77.0	7.76	

Table 5: dV measurements for stage 2 tests (probe spacing of 32 metres)

As indicated by the results in table 5, the effects of inductive or capacitive coupling do not have a significant effect on the “flat” portions of the waveforms as shown. As reasonably expected, the “flat” portions of the waveforms correlate to DC current flow only, after the effects of any inductance or capacitance have dissipated, and would therefore not logically be altered by the effects of coupling.

Recall from the test results obtained for the stage 1 tests, the RMS values of injected current and measured voltage showed significant change, depending on the test lead configuration. If we consider the wave shapes as indicated by the stage two tests, the inductive and resistive components can be represented separately. The Resistive portion of the circuit accounts for the flat periods as shown, and the inductive portion, for the voltage spike and current “buildup” as indicated in figure 27. These inductive and resistive waveforms therefore give an insight into the effect on the RMS voltage readings obtained, depending on the Inductive portion of the circuit under test.

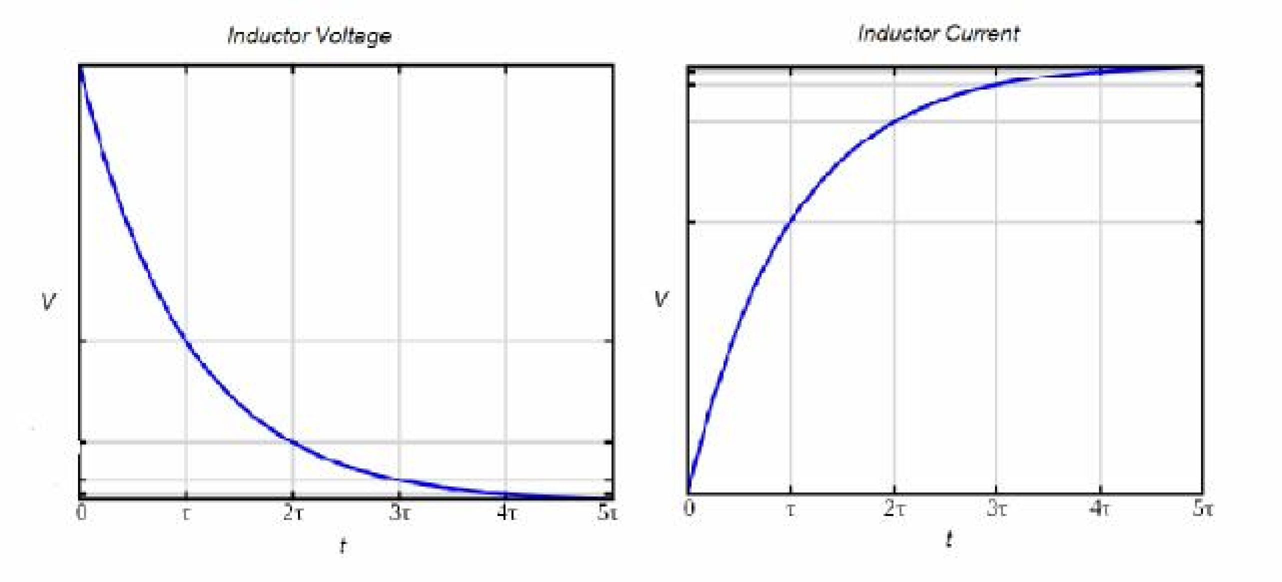


Figure 27: Typical Inductive Voltage and Current Waveforms for a voltage applied at time t= 0

For a circuit with minimal inductance present (as is the case for the 90° test lead orientation) the inductive portion of the circuit will be at a minimum, and the resulting inductive voltage spike will be smaller in magnitude and shorter in duration, due to the low inductance and short time constant of the R-L circuit. From basic electrical theory, the time constant of an R-L circuit represents the time for the current to reach 63% of the final steady state (DC) value and can be calculated from:

$$t = \frac{L}{R}$$

Where τ = Time Constant (sec)

L = Inductance in Henrys

R = Resistance of circuit

This equation therefore indicates that with an increase in inductance (L), and constant resistance (R) the time constant of the circuit will increase. The increase in time constant leads to a longer duration voltage spike, which in turn will increase the True RMS value of the waveform under test.

This alteration of the circuit inductance, while measurable with the scope meter and True RMS meter, appears to be allowed for in the algorithm used by the test instruments. As previously indicated by the results of the stage 1 and 2 tests, the displayed resistance value from the test instruments is not significantly affected by the alteration in lead layout. The signal processing algorithm used by the instruments to calculate the soil resistance, must "filter out" the interference of the inductive component of the circuit, and possibly therefore utilise the DC components of the injected and measured waveforms to calculate the resistance of the soil under test.

This filtering, or noise rejection property of the equipment, then leads to the question at what point will the self inductance of the test leads have an effect on the resistance displayed by the test instruments

Based on this question, further testing was deemed necessary, to determine the coupling effects for a very long lead length and probe spacing.

6.7 Further Testing Based on Results of Stage 1 and 2 Tests. (Stage 3 Tests)

The Pittsworth site, as used for part of the initial tests, was selected for the final stage of tests. This site provided ample space for tests to be conducted using a very large probe spacing, and as previously stated, was well clear of any potential sources of interference.

The Fluke 1625 instrument, together with the Philips PM97 Scope meter, Fluke 179 and Hioki 3283 instruments were all used again, to conduct the tests and record the required data. Four cable reels, each with approximately 500 metres of 2.5 mm^2 cable were available through Downer EDI Engineering, and these were used for test leads as required.

Using this equipment, a Resistivity test was conducted at a probe spacing of 150 meters, using the parallel and 90 º lead configurations as detailed in section 6.2.2. The Parallel 180º test lead configuration was not used, due to difficulty in setting out such a configuration for probe spacing of 150m.

As was conducted in previous tests, the Resistance displayed on the test instrument, waveforms of the injected current and voltage signals, and the true RMS values of current, voltage and frequency were obtained for the lead layouts discussed above. The test probes were not disturbed between tests, in order to limit any variation in results that may be introduced due to changes in electrode contact resistance or position. To avoid any variation due to the resistance of the test leads themselves, the same test leads were used for each test, with the only change to the test leads being their orientation, as required for the parallel and 90 º lead configurations.

As before, the results obtained from the stage 3 tests, have been included, and are provided in section 6.6.1.

6.7.1 Results of Stage 3 Tests

As shown below the measured Resistance, injected signal frequency, measured voltage and injected current have been included in table 6. Figures 28 and 29 detail a screen "shot" image of the injected current and measured voltage waveform signals, taken from the Phillips PM97 scope meter using a RS232 interface lead to a laptop computer.

Measured Parameters – Resistivity test using Fluke 1625 with 150m probe spacing						
Lead Layout	**Measured Resistance**	**RMS Voltage**	**RMS Current**	**Frequency**	**Resitivity calculated from R**	**Resistivity calculated from V & I**
Parallel 0º	0.128Ω	1.264 V	91.9 mA	111 Hz	120.6 Ωm	12962 Ωm
90°	0.145Ω	92.0 mV	97.5 mA	111 Hz	136.6 Ωm	889 Ωm

Table 6: Recorded measurements for stage 3 tests (probe spacing of 150 metres)

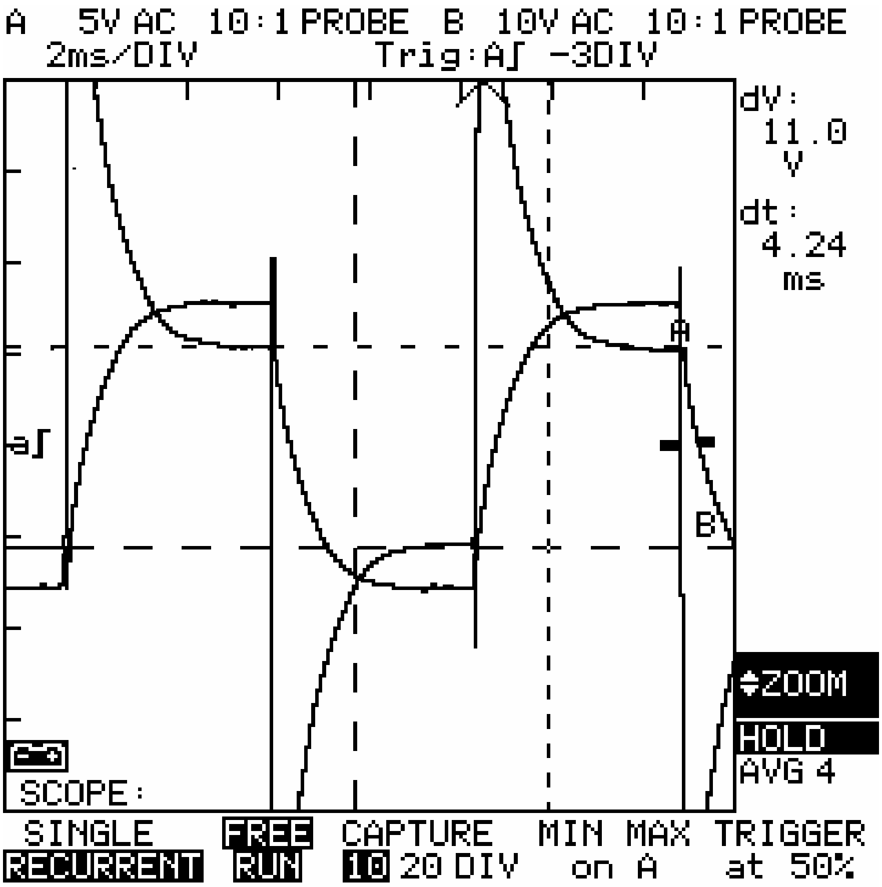


Figure 28: Voltage and Current Waveforms for Resistivity test with probe spacing of 150m, test leads in parallel Ch A: Measured Voltage, Ch B: Injected Current

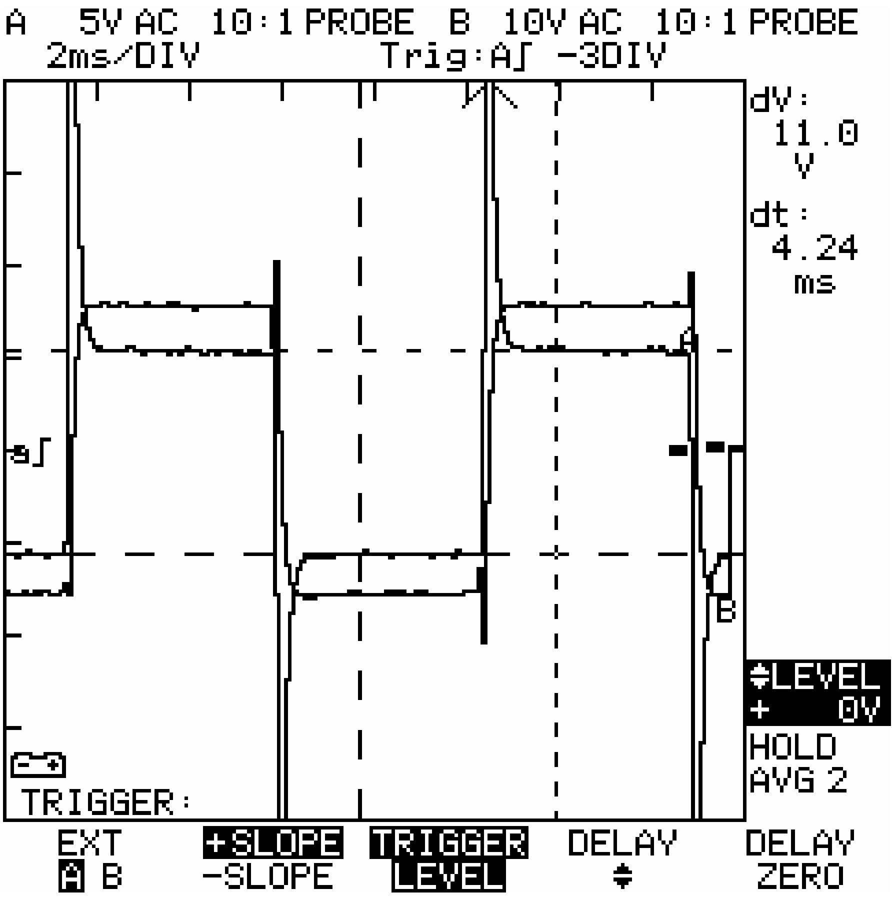


Figure 29: Voltage and Current Waveforms for Resistivity test with probe spacing of 150m, test leads 90° separated. Ch A: Measured Voltage, Ch B: Injected Current

6.8 Discussion of Stage 3 Test Results

Review of the results recorded in Table 6 shows a major difference in measured voltage, between the parallel and 90° test lead configurations. Parallel lead configuration yielded a measured RMS voltage of 1.264 V compared to 92mV for the 90° configuration. The injected current signals also showed variation, with the parallel lead configuration yielding a current signal of 91.9mA compared to 97.5mA for the 90° lead configuration. The reasons for the variation witnessed in test current and Voltage, can be considered due to a number of factors, as follows.

From ohms law, any alteration of the injected current will alter the measured voltage however it can be reasonably assumed that the variation in measured voltage in this case, is not solely due to the alteration in injected current. The measured voltage signal for the parallel lead configuration, exhibits an increase of approximately 13 times that of the measured voltage for the 90° lead configuration, which is clearly too large an increase for the corresponding change in injected current. Some form of coupling appears present in the circuit, for such a large variation in measured voltage, as has been recorded in this case.

The variation in the injected current also gives an indication of the presence of coupling, as the level of injected current for the parallel lead configuration is less than the injected current for the 90° lead configuration. From basic electrical theory, for a constant source and load impedance, alteration of the impedance of the connecting cables alters the current flow through the entire circuit. An increase in impedance will reduce the circuit current, and conversely, a reduction in impedance will result in an increase in circuit current.

Both tests conducted for the stage 3 tests were completed using same test instrument, identical test lead lengths and probe locations, therefore the change in injected current (and hence the change in circuit impedance) can be attributed to the coupling effects between the test leads. The absence or minimisation of any coupling effects when using the 90° lead configuration, accounts for a reduced test circuit impedance due to the theoretical absence of any inductive or capacitive components. Introduction of an inductive or capacitive component into the test circuit, by using the parallel lead configuration leads to an increase in the impedance of the test circuit, resulting in a reduction in circuit current.

The significant alteration of the injected current and measured voltages, when using long test leads, indicates that the calculation of soil resistivity from measured RMS values will yield incorrect results. The results obtained for stage 3 testing appear consistent with the results of the stage 1 and 2 tests, where the calculation of soil resistivity from the measured voltage and current yields a result that is significantly different from the values displayed by the test instrument.

The resistance displayed on the test instrument also showed significant variation, as can be seen in column 2 of table 6. Using the resistance displayed for the parallel lead configuration as the reference, the resistance values shown indicate a resistance increase of approximately 13 % between the Parallel and 90° lead configurations. It appears the coupling effects of the test leads, has become too great for the signal processing algorithm of the Fluke 1625 to adequately correct. Recall from the tests conducted as part of the stage 2 tests, the variation between resistance readings for a probe spacing of 32m, was not significant, possibly due to the algorithm within the Fluke 1625 instrument, adequately compensating, or “correcting” the measured voltage and current signals.

As can be seen from fig. 28 and fig.29, the waveforms of the injected current and measured voltage signals indicate significant alteration dependant on the test lead layout chosen. Figure 28 seems to indicate a test circuit which is much more inductive when test leads are run in parallel, as characterised by the shape of the current and voltage waveforms as shown. The current (Ch. B) waveform in fig.28 clearly shows an exponential rise characteristic consistent with that expected for a series R-L circuit, and similarly, the measured voltage signal (Ch. A) shows an exponential decay characteristic, as would also be seen in a series R-L circuit.

By comparison, the waveforms for the 90° test lead layout (fig.29), show greatly reduced “rounding” of the leading edges of the current waveform, and a much faster decay of the measured voltage signal to the steady state, or DC value. Given that the only change between tests, to obtain these waveforms, was the alteration of the lead layout, it can be concluded that the inductive or capacitive properties of the test circuit, have been significantly altered by the layout of the test leads used.

7. Theoretical Effects

In order to obtain a more meaningful relationship between the test current and measured voltage signals, the effects of low frequency induction need to be investigated further. The aim is of this investigation, is to obtain a relationship between the test lead layout and the injected current and voltage signals as used for a soil resistivity test. By obtaining this relationship, the resistance results obtained are able to be assessed for accuracy. Tests conducted with a can be assessed based on the calculated injected current waveshape and those test results likely to have significant coupling effects, may be re-tested or corrected, as applicable.

The coupling effects introduced by the layout of the test leads can be considered as two fold and as having a inter-related effect on the injected current and voltage signals, by virtue of two separate means. The first effect in the relationship described above, is the effect of the complex circuit impedance on the injected test current signal. Any inductance or capacitance introduced into the test current circuit will have an effect on the shape of the injected square wave current signal. As discussed in previous sections, an inductive or capacitive element in the current loop will alter the leading and/or trailing edges of the injected current square wave signal. The second effect to be considered is the shape of the induced voltage signal, as dependant on the shape of the injected current waveform. An alteration of the injected current waveform will naturally affect the shape of the measured voltage signal, and thus the two effects can be considered as inter-related.

To clarify the above statement, think of the injected current loop as one portion of the test circuit. The injected current will be dependant on the properties of the circuit, based on the resistive, inductive and capacitive properties of the test circuit. Alteration of the current circuit properties will in turn lead to alteration of the magnitude and shape of the injected current waveform, as shown by the field tests conducted. This alteration in the magnitude and shape of the injected current waveform, will therefore alter the magnitude and shape of the voltage induced onto the voltage measuring leads, by the injected current signal. By initially calculating the circuit properties, I.e. the resistance, capacitance and inductance present, the injected current waveform can be calculated, which in turn allows the shape and presence of any induced voltage signal, to be determined. It should be noted at this point that the measured voltage signal is not easily calculated from the shape of the injected current signal, as the voltage signal is a combination of the actual measured voltage between the voltage probes and the induced voltage signal from the adjacent current leads.

Regardless of this difficulty in calculating the voltage signal, the level of distortion of the current waveform is still able to be assessed and is useful in indicating the likely accuracy of the tests conducted. The greater the distortion of the current waveform, the more inaccurate the test results can be assumed to be.

For the following theoretical analysis, the test lead layout of Parallel 0° (refer section 5.2.2) has been used as the circuit model. The selection of the Parallel 0° lead layout was due to this configuration being the most logical layout used by a Technician when completing tests, and the most likely configuration to suffer from the effects of inductive coupling. The 90° lead layout will theoretically not suffer from the effects of coupling, due to the orientation of the test leads and the Parallel 180° lead layout (refer section 5.2.2), while still valid, is not a practical layout for repeated use, and hence will not be considered further in the following analysis.

Using a MATLAB computer program, the calculation of the circuit inductance and capacitance can be calculated, and then the expected current waveform is determined, based on a number of user entered input values. This expected current waveform can then be useful to in assessing the accuracy of the results obtained, and thus indicate the accuracy of the resistance reading obtained from the instrument.

7.1 Calculation of Circuit Inductive and Capacitive Effects - Parallel Test Lead Layout.

7.1.1 Calculation of Circuit Inductance Effects

For the calculation of the theoretical inductive effects, Consider the voltage and current leads of one half of a Wenner test array. The voltage and current leads can be considered as a two wire transmission line, with current flow in one conductor only. Each conductor is connected together at the remote ends, via a common point (in this case the earth electrodes) . Figure 28 outlines this circuit configuration, including the radii of the circuit conductors, the distance between them and the magnetic field as a result of current flow in one conductor only.

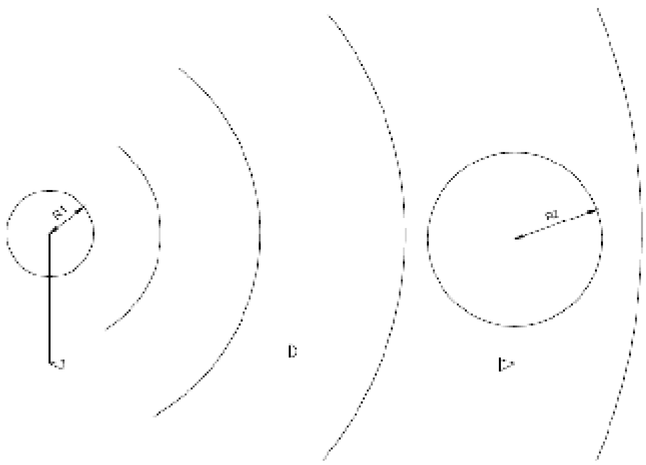


Figure 30: 2 Wire transmission line and magnetic field due to current in one conductor only

Grainger and Stevenson (1994) provides a useful equation for determining the inductance of such a circuit, due to the current in one line only, defined as:

$$L = \left(\frac{1}{2} + 2\ln\frac{D}{R1} \right) \times 10^{-7} \quad H/m$$

Where

L = Inductance in Henrys per metre,

D = Distance between the two conductor centres (m)

R1 = Radius of current carrying conductor (m)

It should be noted that this equation assumes an air dielectric and that the conductors are equally sized, single, solid conductors, which is appropriate for this discussion. The tests conducted for stage 1, 2 and 3 tests, all used copper test leads using conductors of 2.5 mm^2 size, hence the single solid conductor assumption is satisfactory in this case.

Using the above equation with user supplied values of D and R1, the inductance per metre can be easily determined. The entire circuit inductance is then obtained by multiplying the result of the above equation, by the probe spacing of the test array used.

Using the value of inductance calculated from the above formula and the resistance reading from the test instrument, the time constant of the R-L circuit can be determined by the formula given in section 6.3.2, i.e.

$$t = \frac{L}{R}$$

Where τ = Time Constant (sec)

L = Inductance in Henrys

R = Resistance of circuit

The circuit inductance and time constant for the 150m probe spacing array have been calculated using the above formulae, for several values of D. These results are as shown in table 7:

Parallel Lead Length (m)	Lead Spacing (m)	Lead Radius (m)	Resistance (Ω)	Inductance (H)	R-L Time Constant (sec)
150	0.01	0.0012	0.128	7.11E-05	9.10E-06
150	0.05	0.0012	0.128	1.19E-04	1.53E-05
150	0.1	0.0012	0.128	1.40E-04	1.79E-05
150	0.5	0.0012	0.128	1.88E-04	2.41E-05

150	1	0.0012	0.128	2.09E-04	2.68E-05

Table 7: Inductance and R-L time constant values of Wenner Array with 150m probe spacing

From inspection of the inductance and time constant values shown in table 7, the inductive components of the test circuit can be expected to have a significant effect on the injected current signal, based on the length of the time constant values. Considering the period of one cycle at test frequency of 111Hz, is approximately 9.01 milliseconds (from t = 1/*f*), the time constant values obtained in table 7 will form a significant portion of one cycle period, and hence will result in a significant distortion of the injected square wave current waveform. Based on this rationale, the inductance of the circuit is a significant quantity, as calculated above and will need to be included when considering the distortion effects on the injected current signal.

7.1.2 Calculation of Circuit Capacitance Effects

Capacitance of a transmission line is the result of the potential difference between the two conductors, causing them to operate in the same manner as the plates of a capacitor. The two wire transmission line, as used for the Wenner array will therefore have the same capacitive effect as a capacitor, for the parallel sections of current and voltage leads.

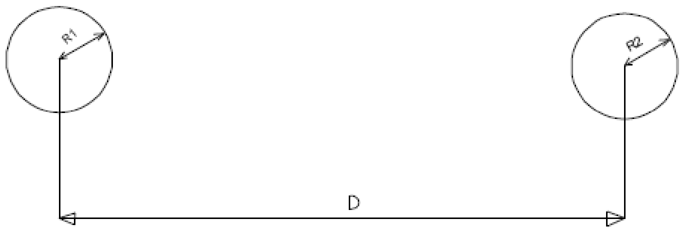


Figure 31: 2 Wire transmission line

Grainger and Stevenson (1994) again provides a useful equation for determining the capacitance of the two wire transmission line, with conductors of equal size, defined as:

$$C_{12} = \frac{pk}{\ln(D/R)} \;\; F/m$$

Where

C_{12} = Capacitance between conductors 1 and 2
k = permittivity of insulating material between conductors (for dry air k = 8.898 x 10^{-12})

D = the distance between the two conductor centres (m)

R = Radius of carrying conductors (assuming R1= R2) (m)

By using the above equation with user inputs as defined for the inductance calculation in section 7.1.1, the capacitance of the test circuit array can be determined. Several calculated capacitance values have been calculated using the above formula, and the results have been included below, in table 8. Similar to the calculations in section 7.1.1, the time constant of the R-C portion of the test circuit has also been calculated by using the formula:

$$t = RC$$

Where:

τ = Time Constant (sec)

C = Capacitance in Farads

R = Resistance of circuit

Parallel Lead Length (m)	Lead Spacing (m)	Lead Radius (m)	Resistance	Capacitance	R-C Time Constant
150	0.01	0.0012	0.128	1.32E-11	1.69E-12
150	0.05	0.0012	0.128	7.49E-12	9.59E-13
150	0.1	0.0012	0.128	6.32E-12	8.09E-13
150	0.5	0.0012	0.128	4.63E-12	5.93E-13
150	1	0.0012	0.128	4.16E-12	5.32E-13

Table 8: Capacitance and R-C time constant values of Wenner Array with 150m probe spacing

From inspection of the capacitance and time constant values shown in table 8, the capacitive components of the test circuit can be expected to have minimal effect on the injected current signal. The R-C time constant values shown in table 8 are in the picosecond range, and hence do not form a significant portion of one cycle period of the injected current signal. With a very short time constant as calculated above, the distortion effects of the capacitive components of the circuit will not have a major impact on the injected current waveform.

When considering the capacitive effects, the physical connection arrangement of the current and voltage test leads, also gives an indication that the capacitance value of the line should be omitted from the calculations. Since the remote ends of the test leads are connected to a common conductor (via the earth electrodes), any capacitance between the test leads is therefore short circuited and hence can be considered negligible.

Capacitance may become a consideration where extremely high test signal frequencies are used, however due to the frequency of the injected signal in this case, the capacitance is considered not applicable.

For the reasons outlined above, remainder of this analysis and theoretical discussion, the capacitive effects have been considered negligible and have therefore been omitted from further consideration.

7.2 Calculation of Equivalent Current Injection Circuit and Injected Current Waveform Shape.

By using the circuit inductance as calculated in section 7.1.1, an equivalent circuit can be deduced, from which the estimated current waveform can be determined. It should again be noted at this point, that the inductive components of the circuit are considered far greater than the capacitive effects for the Wenner array circuit, and hence the capacitive effects have been considered negligible.

The calculation of the current waveform is achieved through the use of a MATLAB program written by the author. This program uses the Inductance equation detailed in section 7.1.1 together with several user entered values, to determine the inductance of the circuit. From the calculated inductance value, the time constant of the circuit is calculated and the injected current waveform deduced by an iterative process. The iterative process initially uses the user entered value of measured RMS current, as the steady state current value, or DC portion of the injected current waveform, as shown in figure 32. From the calculated waveform, the True RMS value of the theoretical current waveform is obtained, and the error between this and the user entered value is calculated. The calculation process is repeated until the error between the calculated True RMS current value, and the user entered current value is less than 0.5%. The final waveform shape is plotted together with the user entered and calculated values of Injected current.

In the first stage of this calculation process, the user is required to enter several test values to allow the theoretical inductance of the test circuit to be calculated. The required variables are:

1. Wenner Array probe spacing (m)
2. Resistance measurement as displayed by the test instrument (Ω)
3. Circuit RMS current value, as recorder using a True RMS Clamp Meter (A)
4. Spacing between parallel sections of test leads (m)
5. Radius of test lead conductor used (m)
6. Frequency of injected current signal (Hz)

Based on the user entered values of probe spacing, test lead radius and parallel section spacing, the inductance of the circuit is calculated using the inductance equation stated in section 7.1.1. Using this calculated inductance value together with the resistance value as entered by the user, the time constant is determined by:

$$t = \frac{L}{R}$$

On initial inspection, the resistance displayed by the test instrument may or may not be affected by the effects of test lead coupling, however this consideration is not important at this stage, as the MATLAB program will allow the current waveforms to be recreated, and the effects of coupling assessed as significant or non-significant, based on the shape of the resultant waveform.

The next step uses the injected current signal frequency to determine the time period of one half cycle of the current waveform, and this half cycle period is then split into a calculation intervals, based on the time constant value calculated. By using the time constant period as the sample time, the calculation of the current waveform at these sample points can be easily achieved by using the 63% relationship as is defined by the time constant value. Recall that the time constant is the time taken for a series R-L circuit to reach 63% of the final steady state current value. By using the user entered RMS value of current as an initial guess of the steady state DC value, the current waveform value at $t = 1\tau$, $t = 2\tau$, etc can be calculated.

As an explanation of the above, consider the first sample time, as sample *m* at time $t = 0$, and the second sample, as sample *n*. at time $t = 1\tau$. By setting sample *m* value equal to the -1 times the RMS current as entered by the user, the corresponding value of sample *n* is calculated by taking 63% of the difference between the positive and negative RMS current values. The time constant of the circuit details the time taken for the current to reach 63 % of the final steady state value, therefore with positive and negative steady state values equal to +/- the user entered RMS current value, the corresponding value of sample *n* is then easily calculated as 63% of the difference.

With these known values of sample *m* and *n*, we can assume the curve characteristic between these points, as a straight line. It is noted that this straight line approximation approach is not strictly accurate, as the current waveform will not be a perfectly straight line relationship between points *m* and *n*, however the straight line approximation will be sufficiently accurate for our purposes.

By using the calculated value for point *n* as the starting value for the next sample period and the user entered RMS value as the steady state current value, the next sample (at $t = 2\tau$) can be calculate using the 63% relationship again. This process is repeated until sufficient multiples of τ have elapsed for the equivalent time of one half cycle of the injected current.

By the same method, the second half of the current waveform cycle is calculated using the positive value of user entered RMS current as the starting point, and the negative value of the user entered RMS current as the steady state value. The sample points are again calculated using the 63% relationship of the time constant, and hence the end result is a full cycle of injected current waveform with steady state DC values equal to +/- the user entered RMS value. This process is illustrated below in Figure 32.

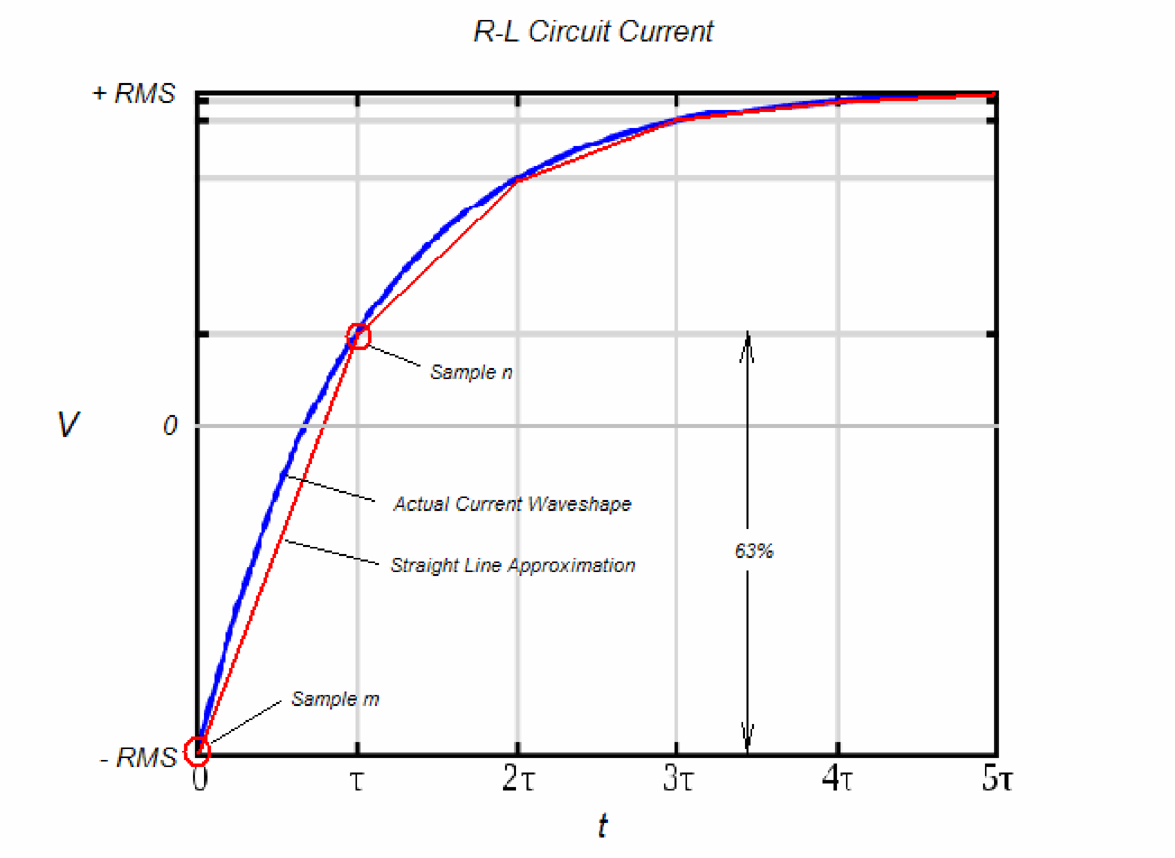


Figure 32: R-L Circuit current showing actual and calculated curve characteristics

With the wave shape of the injected current now calculated, the RMS value of the calculated current signal can be obtained by integrating the area between the current curve and the x axis for one cycle of the current waveform. The calculated area between the curve and the x axis is the multiplied by the injected current signal frequency to obtain the RMS value of the complex waveform for a one second period. This value is then compared to the user entered value, and the difference, or error is then calculated between them. Based on the error, the steady state current value as used in the calculation process is increased and the entire curve calculation process repeated. This process is repeated continuously, until the error between the user entered RMS and calculated RMS are within 0.5% of each other.

Once calculated to the required accuracy, a plot of the theoretical injected current waveform is shown, with the corresponding values of theoretical and actual RMS current shown.

Figure 33, as shown below, details a program flow chart of the above process. The program code listing has been included in appendix F

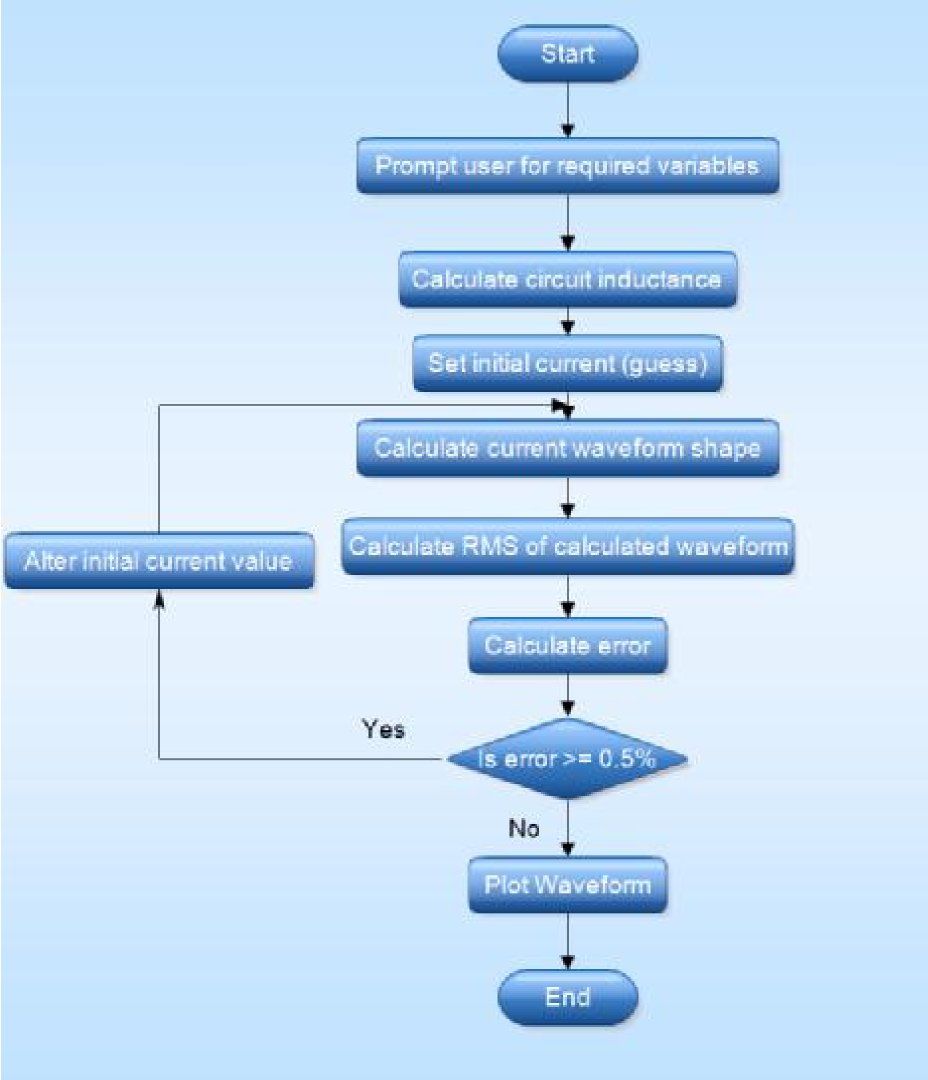


Figure 33: Program flowchart for calculation of R-L circuit current waveform

7.3 Sample Results Obtained From MATLAB Program

Using the MATLAB program as detailed in the previous sections, several sample calculations have been completed and the resulting waveforms have been produced. From the shape of the current waveforms, the user can determine the likely presence of induced voltages, and hence determine if tests need to be repeated. The program also allows easy calculation of a suitable test lead parallel section spacing to ensure sufficiently accurate test results.

Several examples of the calculated current waveforms are as shown in figure 33. These results were obtained by using the following the input variables as shown adjacent to each current waveform plot.

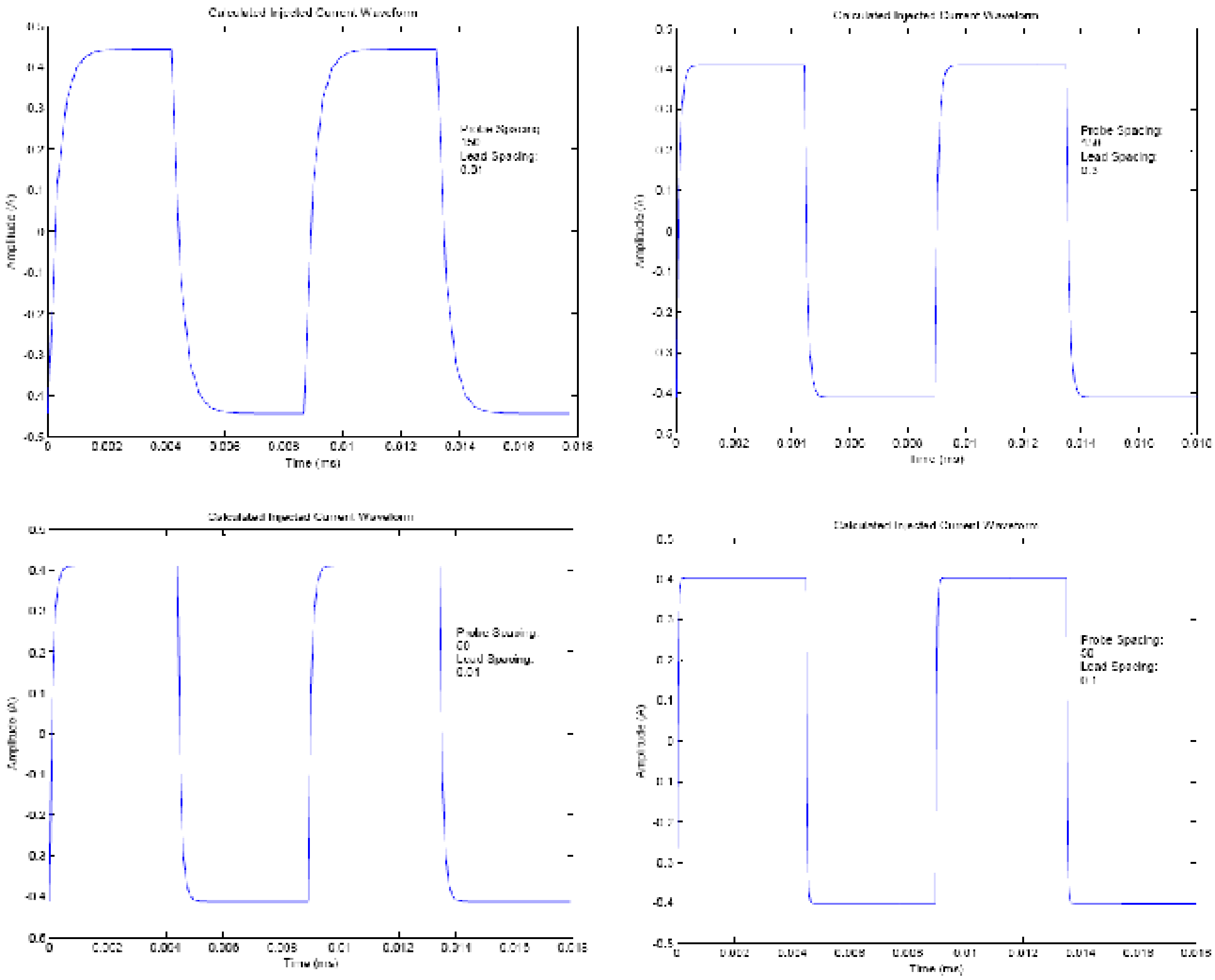


Figure 34: Sample output calculations of current waveform from MATLAB rogram

From the Graphs displayed in figure 34, the inductive effects can be easily seen, depending on the length of parallel lead section and the spacing of the parallel lead sections. The upper Graphs show the effect of increasing the spacing of the parallel sections of test lead, and the lower graphs, the same effect for a smaller test probe spacing, and hence a shorter parallel section of test lead.

8. Conclusions

8.1 Achievement of Project Objectives

The aim of this project was initially to investigate the effects of test lead coupling for a variety of tests conducted as part of the testing process of a high voltage substation earthing system. The intent was to investigate the effects of self coupling of the test leads themselves, and not the effects of external interference and induced voltage from a separate source. Several tests were to be investigated, and from this investigation, recommendations for improvement of testing practices be deduced.

Due to equipment availability and realistic timeframes, Earth Resistivity testing using a wenner array was selected for analysis. Other tests, test methods and alternative test lead types were not investigated due to time and scope constraints.

From the investigation conducted, the effects of test lead self coupling appear evident, when using long test leads and leads in close proximity. An approximation was obtained for the calculation of these inductive effects on the injected current waveform and several testing practice recommendations were deduced.

The accurate calculation of the induced voltage signal was not achieved, due to difficulty in calculation of an induced signal for a non sinusoidal waveform. The vast majority of reference material available assumes a sinusoidal current signal, which allows the use of well established electrical theory, however the mechanism of induction characteristics for a complex waveform, is not well known. One approach considered was the interpretation of the injected signal as a Fourier series of sinusoidal components, however an analysis of this nature could realistically be a research project in itself.

8.2 Recommendations

From the research conducted, the following recommendations are able to be drawn:

- Calculation of soil Resistivity using measured values of Current and Voltage may lead to inaccurate results. Test configurations such as those shown in figure 5.1 of the relevant Australian standard (ENA EG1 (2006)) detail the use of a separate current source and voltage measurement instrument, which will yield different results, to a purpose built earthing test instrument. As shown by the results of stage 1 testing, significantly different resistance results were obtained when comparing resistance calculated from measured Voltage and current and the resistance obtained from the earthing test instrument.

- When conducting soil Resistivity tests using a Wenner array, careful selection of test lead layout will reduce the effects of coupling between test leads, and hence improve the accuracy of test results. Select separated lead layouts where possible, and where long probe spacing is used for tests, ensure the maximum possible separation between the test leads. Inductive effects are proportional to the length of parallel lead sections, and therefore parallel lead spacing needs to be considered for all test probe spacings above approximately 32 metres. This spacing recommendation is based on the use of the Fluke 1625 and Megger DET2/2 test instruments, and may vary for other test instruments.

- Where Wenner array tests are conducted and adequate parallel lead spacing is not easily achieved, calculation of the distortion effects of the current waveform due to coupling of the test leads can be achieved through the use of the MATLAB program. This program is intended to act as a guide for the distortion effects present and therefore highlight areas where re-testing may be required.

8.3 Further Work and Potential Future Research Projects

Based on the findings of the research completed through this project, several possible future projects include:

- Research into the coupling effects of a sinusoidal test signal, or a 50Hz induced signal from a nearby source such as a high voltage power line. This project was initially intended to research a broader range of signals including 50Hz and non-50 Hz signals, and their effect on a range of tests conducted, however time constraints and the need for a realistic scope limited the investigation conducted to soil Resistivity testing. The Resistivity testing instruments investigated utilise a square wave signal as previously discussed, and hence this project became focussed on the coupling effects of a non- 50 Hz signal.

- Investigation into the mechanisms of AC and DC current flow through soil. Recall from the discussion in section 6.5, there appears to be some research into the mechanisms of AC and DC electric current flow through soil, and the different conductive properties, depending on frequency.

8.4 Conclusion

As a result of the research work completed in this project, a better understanding of the effects of test lead coupling has been obtained, as well as several practical methods to reduce these effects and improve accuracy of results. Testing procedures which are outlined in a current Australian Standard may prove inaccurate, based on the suggested use of non-specific test instruments.

Although there is considerable scope for further investigation into the effects of coupling from test signals and external sources, this research project has provided an insight into the effects of coupling on Resistivity test results, and can be used as a starting point for future work.

On a personal note, through the completion of this project, the author has gained much knowledge about the testing of High voltage earthing systems and the calculation and analysis of results obtained from field testing. This information will prove valuable for future work commitments, and possible career paths.

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Appendix A - Project Specification

University Of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **Cameron John Brandis**

TOPIC: High Voltage Substation Earthing Testing -Investigation Into the Effects of Test lead Coupling

SUPERVISOR: Les Bowtell

PROJECT AIM: To investigate and analyse the effects of test lead coupling when conducting tests on, or for High Voltage Substation Earthing Grids, and the implication of such results on improved testing methods, or alternative test equipment.

PROGRAMME: (Draft For Negotiation)

1. Research the different methods of earthing testing, including the purpose for testing, various test methods, and use of results obtained.
2. Analyse the test methods and deduce those tests which are likely to suffer from coupling effects between test leads. (i.e tests using an AC signal, measuring very low level signals, or similar)
3. Design a schedule of tests and, using suitable test equipment, conduct field experiments with varied layout to quantify coupling effects.
4. Analyse and evaluate the data obtained to deduce results
5. Investigate, and if possible, derive a mathematical relationship to predict or quantify coupling effects.
6. Submit an academic dissertation on the research.

As time permits:

7. Investigate the use of alternative test lead types
8. Provide recommendations for likely situations, or methods for detecting when coupling effects are present.

AGREED: _________________(student) ____________________(supervisor)

Date ____ / ____ / ____ Date ____ / ____ / ____

Examiner/Co-examiner: ____

Appendix B - Risk Assessment and Workplace Health and Safety

Risk Assessment

Standard AS/NZS 4360 (Standards Association of Australia) states that risk assessment is recognised as an integral part of good management. Risk assessment is effectively a logical and systematic method of establishing the context, identifying, analysing, evaluating, monitoring and communicating risks associated with any activity.

The Downer EDI Engineering Job Safety Analysis (JSA) procedure will be used, due to the research and testing works being performed in part, during work hours. Appendix A shows the Job Safety Analysis to be used in to analyse and control the foreseeable and present risks. This is a tool used within Downer EDI Engineering for the specific identification and control of risks associated with a task or job, I.e. their form of risk assessment.

The crux of the JSA is the risk matrix which is a useful tool for determining the level of risk associated within the task to be carried out. The risk matrix is composed of a Likelihood criteria, and a Consequence or Impact criteria. These two criteria are then used to determine a Risk Rating Score.

These are explained below.

Likelihood Criteria

The Likelihood Criteria essentially asks the question "How often are people being exposed to the hazard being assessed, and how likely is it that these circumstances can and will lead to an accident". Generally speaking this defines the level of exposure of a particular hazard and the likelihood of harm occurring as a result. Each hazard identified, is initially assessed in terms of the likelihood criteria, and the result used in conjunction with the consequence or impact criteria.

Consequence or Impact Criteria

The consequence or impact criteria asks the question "What type of impact do you expect could result from exposure to this hazard?" The consequence or impact is then categorised as Catastrophic, Major, Moderate, Minor or Insignificant as determined by the person(s) conducting the analysis.

Risk Rating Score

Using the Likelihood Criteria and Consequence or Impact Criteria, the Risk Rating Score is obtained from the matrix shown in the bottom left corner of page 1 of the JSA. The Risk Rating obtained will be categorised according to the relevant rating i.e.

Extreme: 8 – 10

Significant: 6 – 7

Medium: 4-5

Low: 1 - 3

Using the risk ranking and action/responsibility table defines the actions to be taken as a result of the calculated risk.

Refer to the completed JSA Contained in Appendix B, for a list of the hazards identified, risk ratings and control measures implemented.

Risk Assessment – Conclusions

The risk assessment performed on the "Earth Grid Testing" portion of the project has not highlighted any potential hazards that are ineffectively controlled by the control measures listed. For a detailed listing of the hazards identified as well as the relevant control measures allocated, refer to the completed JSA attached in appendix B.

The concept of reducing risks to an acceptable level, is seen as an ongoing process and hence incorporates the concept of continual improvement. Continual improvement, as the name implies, involves continual reduction of the levels of risk associated with a given task or activity. Risk assessment and management is therefore to be done at all stages of the project, particularly when new "unforseen" hazards are encountered throughout the project during the life of the project:

- During the testing phase, i.e. whilst conducting field experiments
- During any re-testing or additional testing as required;

Appendix C – Schedule Of Tests

Schedule of Tests

Earth Resistivity Tests

Stage 1 Tests: Conduct Resistivity tests for variable probe spacing for 3 different lead layouts:

Probe spacing required(m): 1,2,3,4, 8, 12,16, 24, 32

Use salt water solution to minimise contact resistance

Sample results sheet:

Resistivity Measurements – Stage 1							
Soil type	Loam over clay						
Comments							
Probe Spacing (m)							
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity from R**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2						
Parallel 0	DET2/2						
Parallel 180	DET2/2						
90 Degrees	Fluke 1625						
Parallel 0	Fluke 1625						
Parallel 180	Fluke 1625						

Stage 2 Tests: Conduct Resistivity tests at 32 metre probe spacing and record current and voltage waveform characteristics for 0, 90 and 180 degree lead orientations.

Use PM97 Scope meter with hold function to obtain waveforms - record with digital camera

0°orientation- Ensure test leads are run in parallel as close as possible – use wooden stakes with a V notch cut in the top to support test leads. Fix leads together with plastic clothes pegs where required

90° orientation – Ensure maximum possible separation between parallel sections of test leads.

Avoid disturbance of test probes as much as possible when altering lead layout between lead orientations.

Stage 3 Tests: Conduct resistivity tests at 150m Probe spacing and record current and voltage waveforms with PM97 scopemeter

Record V, I, f, R values of tests conducted.

Save waveform results to computer using RS232 opto isolated interface lead (approx $ 600)

Use 0 and 90 orientations only. 180 orientation is difficult and time consuming to set up.

Use wooden pegs as per stage 2 tests

Appendix D – Multimeter and Clamp Meter Accuracy Specifications

Hioki Clamp On Leak HiTester 3283

- Wide bandwidth, 5 Hz to 15 kHz (Waveform output)
- High-sensitivity with a full scale of 10 mA (resolution:10 µA)
- High-accuracy at ±1 %
- True RMS measurement
- Analyzer functions, for filtering and output signals

Basic specifications	
AC Current range	10.00 mA to 200 A AC, 5 ranges (±1.0 % rdg. ±5 dgt. at 50 or 60Hz), and 200 A AC, 1 ranges (±1.5 % rdg. ±5 dgt. at 50 or 60Hz), Effective value rectifier
Frequency measurement	100.0 or 1000 Hz, 2 ranges (±0.3 % rdg. ±1 dgt.)
AC Voltage range	None
Other functions	**Filter function:** 180 Hz ±30 Hz /-3 dB
Analog output	DC, or AC 1 V /f.s. ,**Level output:** with REC mode, **Waveform output:** with MON mode
Frequency characteristics (at AC current / voltage)	40 to 2 kHz
Display section	Digital / 1000 dgt. Bar graph / 35 seg.
Sampling rate	2 or 4 times/sec (Slow: 1 time/3 sec)
Crest factor (RMS)	2.5 (1.5 at 200 A range)
Max. circuit voltage	300 V AC rms (insulated wire)
Power supply	6F22(006P) × 1, Continuous use 40 hours, or AC adapter
Core jaw dia.	Ø40 mm(1.57 in)
Dimensions, mass	62 mm(2.44 in)W × 225 mm(8.86 in)H × 39 mm(1.54 in)D, 400 g (14.1 oz)
Accessories	CARRYING CASE 9399 (1), Hand strap (1)

Fluke 170 Series Digital Multimeters

- True RMS voltage and current measurements
- 0.09% basic accuracy (177, 179)
- 6000 count resolution
- Digital display with analog bargraph and backlight (177, 179)
- Manual and automatic ranging
- Display Hold and Auto Hold
- Frequency and capacitance measurements
- Resistance, continuity and diode measurements
- Temperature measurements (179)
- Min-max-average recording
- Smoothing mode allows filtering of rapidly changing inputs
- Easy battery exchange without opening the case
- Closed case calibration through front panel
- Ergonomic case with integrated protective holster
- EN61010-1 CAT III 1000V / CAT IV 600V
- Measures twice as fast as other multimeters

Specifications	
Voltage DC	**179 - Accuracy*** ± (0.09%+2) **Max. Resolution** 0.1 mV **Maximum** 1000 V
Voltage AC	**Accuracy*** ± (1.0%+3) **Max. Resolution** 0.1 mV **Maximum** 1000 V
Current DC	**Accuracy*** ± (1.0%+3) **Max. Resolution** 0.01 mA **Maximum** 10 A
Current AC	**Accuracy*** ± (1.5%+3) **Max. Resolution** 0.01 mA **Maximum** 10 A
Resistance	**Accuracy*** ± (0.9%+1) **Max. Resolution** 0.1 Ω **Maximum** 50 MΩ
Capacitance	**Accuracy*** ± (1.2%+2) **Max. Resolution** 1 nF **Maximum** 10,000 µF
Frequency	**Accuracy*** ± (0.1%+1) **Max. Resolution** 0.01 Hz **Maximum** 100 kHz
Temperature	**179 - Accuracy*** ± (1.0%+10) **Max. Resolution** 0.1°C **Range** -40°C/400°C

Appendix E – Resistivity Results for Caboolture and Pittsworth Sites – Stage 1 Tests

E.1 Initial Test Results – Caboolture Site

			c				
Soil type	Loam over clay						
Comments							
Probe Spacing (m)	1						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	16	1497	95	128	596.90	587.87
Parallel 0	DET2/2	16	1496	95.1	128	597.53	587.48
Parallel 180	DET2/2	16	1497	95.1	128	597.53	587.87
90 Degrees	Fluke 1625	36	3370	95	111.1	596.90	588.18
Parallel 0	Fluke 1625	36.1	3372	95	111.1	596.90	586.89
Parallel 180	Fluke 1625	36.1	3381	95.1	111.1	597.53	588.46
Probe Spacing (m)	2						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	14	209.6	15.14	128	190.25	188.14
Parallel 0	DET2/2	14.9	221.9	15.21	128	191.13	187.15
Parallel 180	DET2/2	15	211.3	15.17	128	190.63	177.02
90 Degrees	Fluke 1625	30.8	462	15.2	111.1	191.01	188.50
Parallel 0	Fluke 1625	32.8	482.2	15.2	111.1	191.01	184.85
Parallel 180	Fluke 1625	33.0	490.1	15.1	111.1	189.75	186.63
Probe Spacing (m)	3						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	13.4	62.4	4.66	128	87.84	87.78
Parallel 0	DET2/2	13.7	64	4.66	128	87.84	88.06
Parallel 180	DET2/2	14	64.8	4.64	128	87.46	87.25
90 Degrees	Fluke 1625	29.6	137.2	4.51	111.1	85.01	87.33
Parallel 0	Fluke 1625	30.3	133.6	4.55	111.1	85.77	83.18
Parallel 180	Fluke 1625	30.9	140.1	4.54	111.1	85.58	85.35
Probe Spacing (m)	4						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	12.2	40.7	3.18	128	79.92	83.84
Parallel 0	DET2/2	12.3	42.8	3.19	128	80.17	87.45
Parallel 180	DET2/2	12.4	45.8	3.19	128	80.17	92.83
90 Degrees	Fluke 1625	28.1	89.3	3.11	111.1	78.16	79.98
Parallel 0	Fluke 1625	28.3	99.4	3.13	111.1	78.67	88.31
Parallel 180	Fluke 1625	28.5	98.8	3.12	111.1	78.41	87.07
Probe Spacing (m)	8						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	17.7	25.6	1.277	128	64.19	72.70
Parallel 0	DET2/2	17.3	32.7	1.281	128	64.39	95.01
Parallel 180	DET2/2	17.5	32.5	1.281	128	64.39	93.35
90 Degrees	Fluke 1625	40.0	61.2	1.28	111.1	64.34	76.90
Parallel 0	Fluke 1625	39.1	74.2	1.28	111.1	64.34	95.39
Parallel 180	Fluke 1625	39.6	73.1	1.28	111.1	64.34	92.91

Probe Spacing (m)	12						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	22.3	19.2	0.779	128	58.74	64.92
Parallel 0	DET2/2	22.1	29.5	0.781	128	58.89	100.64
Parallel 180	DET2/2	22.3	28.6	0.782	128	58.96	96.70
90 Degrees	Fluke 1625	50.4	39.1	0.78	111.1	58.81	58.49
Parallel 0	Fluke 1625	50.5	46.7	0.79	111.1	59.56	69.72
Parallel 180	Fluke 1625	50.3	43.7	0.79	111.1	59.56	65.51
Probe Spacing (m)	16						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	21.2	18.5	0.58	128	58.31	87.73
Parallel 0	DET2/2	21.9	32.7	0.583	128	58.61	150.11
Parallel 180	DET2/2	21.9	30.3	0.584	128	58.71	139.09
90 Degrees	Fluke 1625	46.7	28.1	0.58	111.1	58.31	60.49
Parallel 0	Fluke 1625	47.6	51.7	0.59	111.1	59.31	109.19
Parallel 180	Fluke 1625	48.3	46	0.59	111.1	59.31	95.74
Probe Spacing (m)	24						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	20.5	16	0.473	128	71.33	117.69
Parallel 0	DET2/2	20.6	29.3	0.477	128	71.93	214.48
Parallel 180	DET2/2	20.9	23.1	0.476	128	71.78	166.67
90 Degrees	Fluke 1625	44.1	22	0.48	111.1	72.38	75.23
Parallel 0	Fluke 1625	44.2	47.6	0.49	111.1	73.89	162.40
Parallel 180	Fluke 1625	45.6	35	0.48	111.1	72.38	115.74
Probe Spacing (m)	32						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	26.1	16.5	0.211	128	42.42	127.11
Parallel 0	DET2/2	26.6	28.2	0.213	128	42.83	213.16
Parallel 180	DET2/2	26.7	20.9	0.216	128	43.43	157.39
90 Degrees	Fluke 1625	63.7	22.3	0.22	111.1	44.23	70.39
Parallel 0	Fluke 1625	64.8	48.5	0.22	111.1	44.23	150.49
Parallel 180	Fluke 1625	66	34.5	0.22	111.1	44.23	105.10

E.2 Initial Test Results – Pittsworth Site

Resistivity Measurements - Pittsworth							
Soil type	Black Clay						
Comments							
Probe Spacing (m)	1						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	19.1	78.4	4.12	128	25.89	25.79
Parallel 0	DET2/2	19.1	79.9	4.17	128	26.20	26.28
Parallel 180	DET2/2	19.1	79.8	4.21	128	26.45	26.25
90 Degrees	Fluke 1625	39.6	161.2	4.08	111.1	25.64	25.58
Parallel 0	Fluke 1625	39.7	163.4	4.13	111.1	25.95	25.86
Parallel 180	Fluke 1625	39.3	162.8	4.17	111.1	26.20	26.03
Probe Spacing (m)	2						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	20.9	24.5	1.146	128	14.40	14.73
Parallel 0	DET2/2	21	24.6	1.147	128	14.41	14.72
Parallel 180	DET2/2	21.1	24.8	1.148	128	14.43	14.77
90 Degrees	Fluke 1625	45.9	52	1.15	111.1	14.45	14.24
Parallel 0	Fluke 1625	46	52.4	1.15	111.1	14.45	14.31
Parallel 180	Fluke 1625	46.3	52.7	1.14	111.1	14.33	14.30
Probe Spacing (m)	3						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	21.2	14.5	0.649	128	12.23	12.89
Parallel 0	DET2/2	21.2	14.7	0.649	128	12.23	13.07
Parallel 180	DET2/2	21.2	14.7	0.649	128	12.23	13.07
90 Degrees	Fluke 1625	46.7	30.1	0.65	111.1	12.25	12.15
Parallel 0	Fluke 1625	46.6	30.3	0.65	111.1	12.25	12.26
Parallel 180	Fluke 1625	46.7	30.2	0.65	111.1	12.25	12.19
Probe Spacing (m)	4						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	26.6	13.7	0.497	128	12.49	12.94
Parallel 0	DET2/2	26.7	14	0.5	128	12.57	13.18
Parallel 180	DET2/2	26.6	14.1	0.505	128	12.69	13.32
90 Degrees	Fluke 1625	67.1	33	0.51	111.1	12.82	12.36
Parallel 0	Fluke 1625	67	33.2	0.5	111.1	12.57	12.45
Parallel 180	Fluke 1625	67.2	33.3	0.5	111.1	12.57	12.45
Probe Spacing (m)	8						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	25.8	8.4	0.299	128	15.03	16.37
Parallel 0	DET2/2	26.1	10.1	0.298	128	14.98	19.45
Parallel 180	DET2/2	26	8.9	0.306	128	15.38	17.21
90 Degrees	Fluke 1625	64.1	19.2	0.3	111.1	15.08	15.06
Parallel 0	Fluke 1625	64.3	22.2	0.31	111.1	15.58	17.35
Parallel 180	Fluke 1625	63.6	19.3	0.29	111.1	14.58	15.25

Probe Spacing (m)	12						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	26.6	8.5	0.245	128	18.47	24.09
Parallel 0	DET2/2	26.6	10.4	0.245	128	18.47	29.48
Parallel 180	DET2/2	26.7	7.7	0.245	128	18.47	21.74
90 Degrees	Fluke 1625	67.3	17.2	0.25	111.1	18.85	19.27
Parallel 0	Fluke 1625	67.1	19.9	0.25	111.1	18.85	22.36
Parallel 180	Fluke 1625	67.8	17.4	0.25	111.1	18.85	19.35
Probe Spacing (m)	16						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	22.4	9.1	0.223	128	22.42	40.84
Parallel 0	DET2/2	22.4	14.7	0.225	128	22.62	65.97
Parallel 180	DET2/2	22.4	12	0.224	128	22.52	53.86
90 Degrees	Fluke 1625	43.1	11.3	0.22	111.1	22.12	26.36
Parallel 0	Fluke 1625	43.1	24	0.22	111.1	22.12	55.98
Parallel 180	Fluke 1625	43.2	19.2	0.23	111.1	23.12	44.68
Probe Spacing (m)	24						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	19.5	8.3	0.187	128	28.20	64.19
Parallel 0	DET2/2	19.6	12.9	0.187	128	28.20	99.25
Parallel 180	DET2/2	19.5	13.5	0.187	128	28.20	104.40
90 Degrees	Fluke 1625	41.4	10.1	0.2	111.1	30.16	36.79
Parallel 0	Fluke 1625	41.4	23	0.2	111.1	30.16	83.78
Parallel 180	Fluke 1625	40.8	20	0.21	111.1	31.67	73.92
Probe Spacing (m)	32						
Lead Orientation	**Instrument**	**I (mA)**	**V (mv)**	**R Measured**	**f**	**Resistivity**	**Resistivity Calculated from V&I**
90 Degrees	DET2/2	23.3	11.9	0.175	128	35.19	102.69
Parallel 0	DET2/2	23.6	27.5	0.187	128	37.60	234.29
Parallel 180	DET2/2	23.7	16.9	0.182	128	36.59	143.37
90 Degrees	Fluke 1625	54.1	18.4	0.18	111.1	36.19	68.38
Parallel 0	Fluke 1625	54.3	54	0.19	111.1	38.20	199.95
Parallel 180	Fluke 1625	54.7	26.2	0.19	111.1	38.20	96.30

Appendix F Code Listing – MATLAB Current Waveform Calculation Program

```
% Matlab file for calculating the induced current effects between parallel
% sections of the voltage and current leads of a wenner array.

% Written by Cameron Brandis
% student # 0050008387

% This program assumes a resistivity test has been conducted with a
% portable test instrument, using an alternating DC current signal as the
% injected test current. The user is required to record and enter as
% prompted, the values of
% 1. Measured Resistance
% 2. spacing between current and voltage test leads (metres
% 3. radius of test lead (metres)
% 4. injected test current (true RMS value) in A
% 5. frequency of injected alternating DC current signal
% 6. length of parallel test lead sections

clc;
clear;

% define the variable for the circuit


R=input('Enter the resistance displayed on the test instrument (ohms): ');
D=input('Enter the spacing between the test leads (metres): ');
CSA=input('Enter the CSA of the test leads (mm^2):');
I=input('Enter the RMS current measured (A):');
f=input('Enter the test signal Frequency (Hz):');
l=input('Enter the probe spacing (m):');

% calculate the raduis of the test lead conductors

r=(sqrt(CSA/pi))/1000;

% based on the user data entered, calculate the inductance of the circuit

L=((0.5+2*log(D/r))*10^-7)*l;                 %Equation 4.22 Grainger &
Stevenson

% calculate the time constant of the inductive portion of the circuit

tau=L/R;

% using tau as sample interval, calculate the number of samples of per cycle

s=(1/f)/tau;

% calculate the response curve of the injected current for 2 cycles of
% injected current signal for the inductive portion of the circuit

st=tau;             % calculate the sample time
t=(0:st:2*(1/f));           % array of time values
icurve=[-I] ;              % open matrix of values and set starting value for
current

% using an iterative process, determine the shape of the current waveform,
% and obtain the actual RMS value of the calculated current waveform
% using trapezoidal integration. If the calculated and user measured values
% are within 0.5% of each other, the calculated waveform is sufficiently
```

```
% accurate and can be used for the calculation of the induced voltage,
% otherwise alter the initial value, and recalculate

error=1;                      % set initial error value to 1 for first pass
k=[]  ;                       % loop counter
while error>=0.005;
    inew=abs(icurve(1));
    for k=2:round(length(t)/4);
        icurve(k)=icurve(k-1)+ abs((inew-icurve(k-1))*0.63);
        k=k+1;
    end
    for k=round(length(t)/4)+1:round(length(t)/2);
        icurve(k)=icurve(k-1)- abs((-inew-icurve(k-1))*0.63);
        k=k+1;
    end
    for k=round(length(t)/2)+1:round(length(t)*(3/4));
        icurve(k)=icurve(k-1)+ abs((inew-icurve(k-1))*0.63);
        k=k+1;
    end
    for k=round(length(t)*(3/4))+1:length(t)
        icurve(k)=icurve(k-1)- abs((-inew-icurve(k-1))*0.63);
        k=k+1;
    end
    % calculate the RMS Value of the calculated waveform
    newIcurve=abs(icurve);
    RMS=trapz(t,newIcurve)*(f/2);
    % Calculate the error between user entered and calculated values
    error=1-(RMS/I);
    % if error is less than 0.5%, end program, else recalculate
       if error>=0.005;
           icurve(1)=icurve(1)-0.001;
       end
end
% display the User entered and calculated RMS values
disp('The Calculated RMS Current Value is: ')
disp(RMS)
disp('The User entered RMS Current Value is: ')
disp(I)

plot (t,icurve)
xlabel('Time (ms)');
ylabel('Amplitude (A)');
title('Calculated Injected Current Waveform');
hold
str1(1) = {'Probe Spacing: '};
str1(2) = {(l)};
str1(3) = {'Lead Spacing: '};
str1(4) = {(D)};
text(0.014,0,str1)

% end of program
```