



Assets Planning and Delivery Group
Engineering

DESIGN STANDARD DS 23

Pipeline AC Interference and Substation Earthing

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FOREWORD

The intent of Design Standards is to specify requirements that assure effective design and delivery of fit for purpose Water Corporation infrastructure assets for best whole-of-life value with least risk to Corporation service standards and safety. Design standards are also intended to promote uniformity of approach by asset designers, drafters and constructors to the design, construction, commissioning and delivery of water infrastructure and to the compatibility of new infrastructure with existing like infrastructure.

Design Standards draw on the asset design, management and field operational experience gained and documented by the Corporation and by the water industry generally over time. They are intended for application by Corporation staff, designers, constructors and land developers to the planning, design, construction and commissioning of Corporation infrastructure including water services provided by land developers for takeover by the Corporation.

Nothing in this Design Standard diminishes the responsibility of designers and constructors for applying the requirements of the Western Australia's Work Health and Safety (General) Regulations 2022 to the delivery of Corporation assets. Information on these statutory requirements may be viewed at the following web site location:

[Overview of Western Australia's Work Health and Safety \(General\) Regulations 2022 \(dmirs.wa.gov.au\)](https://dmirs.wa.gov.au)

Enquiries relating to the technical content of a Design Standard should be directed to the Senior Principal Engineer, Electrical Engineering, Electrical Standards Section, Engineering. Future Design Standard changes, if any, will be issued to registered Design Standard users as and when published.

Head of Engineering

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REVISION STATUS

The revision status of this standard is shown section by section below:

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DESIGN STANDARD DS 23

Pipeline AC Interference and Substation Earthing

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1 Introduction

1.1 Purpose

The Water Corporation has adopted a policy of outsourcing most of the electrical engineering and electrical detail design associated with the procurement of its assets. The resulting assets need to be in accordance with the Corporation's operational needs and standard practices.

This design standard (i.e. Electrical Design Standard No. DS 23) sets out design processes and engineering practice which shall be followed in respect to the analysis and mitigation of AC touch voltage hazards on metallic pipelines and high voltage substation earthing systems acquired by the Corporation.

This design manual does not address all issues that will need to be considered by the Designer in respect to a particular AC interference or substation scenario.

It is the Water Corporation's objective that its assets will be designed so that they are safe, have a minimum long-term cost and are convenient to operate and maintain. In respect to matters not covered specifically in this manual, the Designer shall aim their designs and specifications at achieving this objective.

This design standard is intended for the guidance and direction of electrical system designers and shall not be quoted in specifications for the purpose of purchasing electrical equipment or electrical installations except as part of the prime specification for a major design and construct (D&C) contract.

1.2 Scope

This standard (i.e. Electrical Design Standard No. DS 23) covers:

- AC Interference – Analysis and mitigation of the electrical hazards on metallic pipelines due to inductive, conductive and capacitive coupling with nearby high voltage power lines. In addition, safety in design, safety in construction, documentation and mitigation earthing system validation requirements are defined.
- Substation Earthing System Design – Design of HV earthing systems to ensure touch voltages, step voltages, EPR and transfer voltages are within defined acceptable limits. In addition, safety in design, safety in construction, documentation and earthing system validation requirements are defined.

This standard also addresses the contradictions between AS/NZS 4853:2012 (including AS 2067 – 2008) and the 2011 Work Health and Safety Act. Essentially the target level of risk approach adopted by these Australian standards is in conflict with the WHS act and arguably the precautionary nature of the Australian legal system. The Act requires demonstration that all reasonably practicable precautions (due diligence) have been taken and are in place. Although AS/NZS 4853:2012 and AS 2067 – 2008 stipulates that probabilistic target level of risk methods are to be used to determine safe touch voltage limits, this standard (DS 23) takes the precautionary approach as described in the Work Health and Safety Act. In this standard, touch voltage limits have therefore been computed using traditional deterministic methods focusing on body impedances and fibrillation curves presented in AS/NZS 60479.1:2010.

1.3 Pipeline and Substation Interrelationship

For projects that comprise both High Voltage substation earthing design and pipeline AC interference design, the same specialist earthing design consultant shall be used for both design packages due to the possible complex interactions and similar parameters associated with each earthing investigation and design.

1.4 References

Reference shall be made also to the following associated Design Manuals, Acts and Standards:

1.4.1 Design Manuals

DS 20 – Design process for electrical works
DS 21 – Major Pump Station – Electrical
DS 22 – Ancillary plant and minor pump stations
DS 24 – Electrical drafting

1.4.2 Acts

Model Work Health and Safety Act

1.4.3 Australian Standards

AS/NZS 4853:2012 – Electrical Hazards on Metallic Pipelines
AS 2067-2008 – Substation and High Voltage Installation Exceeding 1kV a.c.
AS/NZS 60479.1:2010 – Effects of current on human beings and livestock, Part 1: General Aspects
AS/NZS 3835.1 – 2006 Earth Potential Rise Code of Practice
AS/NZS 3835.2 – 2006 Earth Potential Rise Application Guide
AS/NZS 1768:2007 – Lightning Protection
AS 2225-1994 - Insulating gloves for electrical purposes
AS/NZS 3000:2007 – Wiring Rules

1.4.4 International Standards

IEEE Standard 80 – 2000 – Guide for Safety in AC Substation Grounding
IEEE Standard 837:2014 – Standard for Qualifying Permanent Connections Used in Substation Grounding
IEEE Standard 81 – 2012 – IEEE guide for measuring earth resistivity, ground impedance and earth surface potentials of a grounding system
IEC/TR 60479-5 Ed 1.0 - Effects of current on human beings and livestock – Part 5 touch voltage threshold values for physiological effects
IEC 61936-1 Ed. 2.0 - Power installations exceeding 1 kV AV - Part 1- Common rules
EN 50522:2010 Earthing of power installations exceeding 1kV AC
EN15280 – Evaluation of AC corrosion likelihood of buried pipelines—Application to cathodically protected pipelines

1.4.5 Other Documents

Australian Energy Market Commission - National Electricity Rules
CIGRE TB 290 – Guide for ac corrosion on metallic pipelines due to influence from AC power lines
ENA EG1-2006 Substation Earthing Guide
Implications for Designers of the Engineers Australia Safety Case Guideline (3rd Edition) Gaye Francis and Richard Robinson Directors, R2A Due Diligence Engineers.
Water Corporation – ‘Guideline – Electrical safety in Pipeline Construction’
Water Corporation – ‘Pipeline Voltage Mitigation Procedure’

1.5 Definitions

ABS – Air Break Switch.

Asset Manager - The Water Corporation officer responsible for the operation of the asset being acquired.

CDEGS - Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis, An integrated software package for power system grounding/earthing, electromagnetic fields and electromagnetic interference design and analyses. Produced by Safe Engineering Services and Technologies Ltd (SES).

CIT - Current Injection Test.

Corporation - The Water Corporation (of Western Australia).

DBYD - Dial Before You Dig.

Decrement Factor - An adjustment factor used in conjunction with the symmetrical ground fault current parameter in safety-oriented grounding calculations. It determines the rms equivalent of the asymmetrical current wave for a given fault duration, therefore accounting for the effect of initial dc offset and its attenuation during the fault.

Designer - The consulting engineer carrying out the electrical design.

Earth Grid – An interconnected system of bare copper conductors and electrodes buried in the earth, providing a local ground for electrical equipment and metallic structures.

Earth Potential Rise (EPR) - The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, EPR, is equal to the maximum grid to ground current multiplied by the grid impedance.

Earthing System - Comprises the local earth grid with the included effect of all grounding facilities connected via cable screens, overhead earth wires, metallic pipelines, etc.

EG-0 – Power System Earthing Guide (Energy Networks Association).

Electrode - A bare conductor installed vertically in the earth to a typical depth of between 1 and 20 metres, however longer electrodes may be required subject to soil structure. Electrodes assist in reducing the impedance of an earth grid by making contact with deeper soil layers that often have a lower resistivity.

FOP – Fall of Potential test. An earthing test whereby the resistance to earth of an earth grid is measured.

GIS – Geographic Information System

Grading Conductors (Grading Rings) – Bare conductors installed horizontally in the earth at a typical depth of 500mm however shallower or deeper conductors may be required depending on the soil structure. Grading conductors form the basis of the equipotential bonding system, reduce earthing system impedance and raise the local soil potential to minimise touch voltages.

Heart Current Factor – Proportion of total body current that flows through the heart.

HIFREQ - A CDEGS software module that can solve any electromagnetic problem involving a network of arbitrarily oriented aboveground and buried conductors energized by any number of current and voltage sources.

Holiday – A small defect in a non-conductive pipeline coating.

LFI - Low Frequency Induction. Phenomenon whereby the magnetic field produced by a current carrying conductor induces a potential on a nearby parallel conductor such as a pipeline. The induced potential is proportional to the length exposed to the magnetic field and both underground and above ground pipelines are affected.

MALZ - A CDEGS software module that analyses the frequency domain performance of buried conductor networks and calculates the following quantities: earth potentials, conductor potentials, longitudinal and leakage currents.

OHEW - Overhead Earth Wire.

OHEW Saturation – Due to the magnetic properties of Steel OHEWs, the high currents that flow during earth faults will saturate the conductor causing the series impedance to be considerably different to that during low current conditions such as normal load or current injection testing.

PPE - Personal Protective Equipment

Senior Principal Engineer Electrical – Senior Principal Engineer - Electrical, Engineering, Water Corporation.

RCD - Residual Current Device

RESAP - A CDEGS software module used for the inversion of soil resistivity test data to produce multilayer resistivity models of the earth structure.

ROW – Right-of-Way CDEGS engineering software used for modelling long transmission line / pipeline parallelisms and computing induced voltages.

RRJ – Rubber Ring Joint

Step Voltage - The difference in surface potential experienced by a person bridging a distance of 1m with the feet and legs without contacting any grounded object.

Surface Material - A material installed over the soil consisting of, but not limited to, gravel, asphalt or man-made materials. The surface material depending on its resistivity, may significantly impact the body current by varying foot contact impedance for touch and step voltages.

Touch Voltage - The potential difference between a grounded structure and a point on the soil surface 1m away. Refer to Section 4.2.

Loaded Touch Voltage – The voltage drop across the body impedance only. Loaded touch voltage is measured during a CIT using a high impedance voltmeter that has a resistor equal to the body impedance connected across the terminals.

Open Circuit or Prospective Touch Voltage – The total voltage drop across the combined body/feet impedances. Measured during a CIT using a high impedance voltmeter. Open circuit voltage limits are always supplied as a function of the resistivity of the soil surface layer that a person is standing. For example, the open circuit touch voltage limit for a person standing on a 100mm thick layer of gravel is 300V.

Transfer Voltage - A high potential that is transferred away from a substation via long metallic structures such as a pipelines, cable screens, fences, etc.

WHS - Work Health and Safety.

WJ – Welded Joint.

X/R ratio - Ratio of the system reactance to resistance. It is indicative of the rate of decay of any dc offset. A large X/R ratio corresponds to a large time constant and a slow rate of decay.

1.6 Mandatory Requirements

In general, the requirements of this manual are mandatory. If there are special circumstances which would justify deviation from the requirements of this manual, the matter shall be referred to the Senior Principal Engineer Electrical for consideration. No deviation from the requirements of this manual shall be made without the written approval of the Senior Principal Engineer Electrical.

1.7 Quality Assurance

It is a requirement of the Corporation that the following QA systems be applied to electrical equipment manufacturers and electrical installers.

1.7.1 Equipment Suppliers

Suppliers of electrical equipment used for earthing purposes (such as earthing connectors, AC/DC decouplers, sheath voltage limiters, prefabricated copper meshes, pipeline insulating materials, etc.) shall only supply equipment from a manufacturer that has in place a Quality Management System certified by an accredited third party to AS/NZS ISO 9001:2000 or an approved equivalent.

1.7.2 Installers

Installers of electrical equipment used for earthing purposes (such as earthing connectors, AC/DC decouplers, sheath voltage limiters, prefabricated copper meshes, pipeline insulating materials, etc.) shall have in place a Quality Management System certified by an accredited third party to AS/NZS ISO 9001:2000 (excluding Clause 7.3 Design & Development) or an approved equivalent.

1.7.3 Acceptance Tests

In tender documents in which acceptance tests are specified, the cost of providing works tests (including associated test certificates) and site tests (including associated test certificates) shall be shown as separate items in the Bill of Quantities so that:

- a) it can be verified that sufficient funds have been allowed to carry out such testing satisfactorily; and
- b) it is clear that works tests and site tests are separate critical deliverables

1.8 Modelling Software

CDEGS modelling/simulation software package, from SES Canada, shall be used for analysis and design of pipeline AC interference and high voltage substation earthing systems as it provides for:

- Consistency of approach
- Consistency of output
- High levels of confidence
- Accurate modelling resulting in minimal mitigation costs
- World leader approach as used by the majority of power utilities both in Australia and the world.

1.9 Change Control and Documentation

1.9.1 Consultant Roles

- The Primary Consultant (Primary Designer) is defined as the Project Consulting Engineer responsible for the whole multidiscipline project.
- The Specialist Earthing Design Consultant is defined as the Engineering Designer responsible for the earthing design associated with the work outlined in sections 2 and 3 of this Design Standard.

1.9.2 Documentation

- Drawings produced by the Specialist Earthing Design Consultant during the course of the design shall be given a Water Corporation drawing number and registered in the Corporation's drawing management system by the Primary Consultant.
- For High Voltage substations, the Primary Consultant shall ensure that the basic earthing design criteria (from the Specialist Earthing Design Consultant's report) are shown on the earthing Design Summary Drawing(s) in tabular form. Such data shall include soil model, earth fault levels, earth fault clearing times, touch and step voltage limits, calculated earthing system impedance, calculated earth potential rise, calculated touch voltages, calculated step voltages and final verification test results (touch & step voltages, EPR and earthing system impedance as a minimum).

- All reports prepared by the Specialist Earthing Design Consultant shall be referenced on the Design Summary Drawings (or pipeline design drawings for AC interference projects) either by the Primary Consultant or the Specialist Earthing Design Consultant to aid traceability.

1.9.3 Change Control

- If following the issue of the Final Design Report (substations) or the Mitigation Design Report (AC Interference) a change is made to the site layout (moved structures, fences, equipment etc.) or pipeline alignment (including relocated appurtenances, additional appurtenances or change of pipe material) the Primary Consultant shall immediately refer these changes to the Specialist Earthing Design Consultant for review and, if necessary, design modification and reissue of the design report.
- If following the issue of the Final Design Report (substations) or the Mitigation Design Report (AC Interference) a change is made to the electrical system (fault level, clearance time, configuration etc.) the Primary Consultant shall immediately refer these changes to the Specialist Earthing Design Consultant for review and, if necessary, design modification and reissue of the design report.
- Any changes detected by the Specialist Earthing Design Consultant during the course of the project shall be reviewed by the Specialist Earthing Design Consultant and design modifications made as appropriate with reissue of the report. Prior to commissioning tests the Specialist Earthing Design Consultant shall verify that critical design parameters (e.g. fault level, clearance time etc.) are current.

1.10 Specialist Earthing Design Consultant Requirements

1.10.1 In-House Capability

The Corporation requires that the Specialist Earthing Design Consultant has all service capabilities and equipment required by this Design Standard (DS23) in house. That is, soil resistivity field testing, modelling, investigation, design and simulation and verification field testing capability. Outsourcing any of these capabilities or equipment is not acceptable.

The Specialist Earthing Design Consultant shall have a team of personnel capable of performing the capabilities outlined above and have critical mass capable to handle multiple projects and provide engineering technical support within the team. Specialist Earthing Design Consultant shall have dedicated and committed longstanding personnel whom carry out this specialist work on a regular basis.

1.10.2 Knowledge and Experience

Extensive experience and a high degree of knowledge relating to safety earthing associated with pipeline AC interference and High Voltage substation earthing is essential.

Extensive knowledge and experience in the use and application of CDEGS® modelling/simulation software package, from SES Canada. The Specialist Earthing Design Consultant shall own and maintain a copy of this software and ensure it is kept up to date.

Extensive knowledge and experience in the use and application of field test equipment necessary to carry out the services as described in this Design Standard DS23. The Specialist Earthing Design Consultant shall own and maintain this test equipment and ensure it is regularly third party calibrated with certification.

1.11 Specialist Earthing Panel

All modelling, mitigation design and design verification work associated with Pipeline AC Interference (LFI and EPR) and Substation Earthing (EPR) shall be carried out strictly in accordance with this Design Standard only by those Specialist Earthing Design Consultants approved on the Corporation's 'Panel for Specialist Earthing Design Services'. Clause 3.18 of design standard DS20 - Design Process for Electrical Works provides further detail in this regard.

1.12 Process for Pipeline AC Interference & Substation Earthing

The process for Pipeline AC Interference (LFI and EPR) and Substation Earthing (EPR) is laid out in section 2 and 3 respectively of this design standard and shall be adhered to for all related projects.

For pipeline AC Interference projects, it may be unclear at the very early stages of a particular project as to whether a study is required to be completed. This may be due to a myriad of factors regarding the technical aspects associated with the pipeline route, materials and electrical technical aspects.

Should this be the case for a particular project, the Design Manager or the Project Manager shall refer this to the Senior Principal Engineer Electrical for direction. The Senior Principal Engineer Electrical, based on consultation with specialist earthing consultants, review of the first pass guidelines of AS/NZS 4853, review of the pipeline route and calling upon the Senior Principal Engineer's knowledge and experience will provide direction as to whether the project should proceed to stage 1, namely the AC Interference analysis and associated report (Clause 2.1).

The Senior Principal Engineer Electrical will document the decision by email to the Design Manager and/or Project Manager.

Substation Earthing (EPR) has very clear boundaries with respect to safe touch voltage requirements and therefore is not in the same situation as for Pipeline AC Interference.

1.13 Hazop Requirements

The Specialist Earthing Design Consultant shall participate in Hazop meetings arranged by the Project Manager in order to provide specialist knowledge of the issues presented. This will ensure the integrity of the process and that duty of care is applied to the installation, operation and maintenance of the facility.

2 Process and Technical Requirements for Pipeline AC Interference

2.1 Introduction

Water Corporation owned metallic pipelines located in the vicinity and/or within the same easement as high voltage transmission and distribution power lines* may be subject to unacceptable touch voltages. The designer shall ensure that a study is carried out to investigate, analyse and mitigate by design, as required, any exposure to touch voltage hazards by the public and operational personnel through the application of AS/NZS 4853 and this standard or as directed by the Senior Principal Engineer Electrical.

The process shall consist of three stages, namely:

1. AC Interference analysis and associated report,
2. AC Interference mitigation design and associated report and drawings,
3. Verification testing and associated report.

It is a requirement of this standard that all 3 stages shall be implemented for all AC Interference projects.

*Note: Transmission and distribution power lines apply to both aerial and cable.

2.1.1 Inductive Coupling Hazard

In joint use corridors, or separate parallel corridors, where both metallic pipelines and power lines are present a portion of the energy contained in the magnetic field surrounding the high voltage power line is captured by the pipeline resulting in induced AC voltages which vary in magnitude throughout the length of the pipeline. Voltages will appear on the pipeline both during the steady state and the transient state (fault condition) however the voltage present during the transient state will be considerably more severe. A touch voltage hazard exists between the earth and the pipeline.

2.1.2 Conductive Coupling Hazard

During an earth fault on a power line, energisation of the earth by the supporting structures near the fault can result in large voltages appearing locally between the earth and the steel pipeline. A touch voltage hazard exists between the soil at high potential and the pipeline at remote earth potential.

High potentials can also be transferred directly to connected pipelines from pumping stations and treatment plants with incoming HV supplies.

2.1.3 Capacitive Coupling Hazard

Pipelines suspended above the ground underneath high voltage power lines are subject to capacitive coupling. The voltage (with respect to earth) on the suspended pipe section, due to the strong electric field from the power line, can be quite high and a person touching the pipe provides a much lower resistance path to earth and therefore subject to static and capacitive discharges. Capacitive touch voltages are usually only of concern during construction when the pipe sections are lifted into position. The capacitive effect of installed pipes is normally negligible compared to the inductive and conductive effects.

2.1.4 Pipeline AC Corrosion

Steady state LFI may result in high current densities at holidays in the pipeline coating causing localised corrosion. The AC corrosion is more pronounced for local soil resistivity of less than 25 Ω m. Australian and international standards and guidelines recommend minimising the steady state pipeline potential to combat AC corrosion.

2.1.5 Mitigation

In order to reduce the touch voltages to safe levels and comply with the requirements of AS/NZS 4853 and this standard, earthing and bonding by virtue of strategically placed and specifically designed earth electrodes, equipotential mats, cancellation wires and gradient control wires are applied.

It should be noted that insulated pipeline sections may be applied at strategic locations within the pipeline to reduce LFI provided such sections are based on experimental field data confirming the adequate technical performance.

For buried insulated steel pipelines only the appurtenances (section valves, air valves, scour valves, etc.) shall be mitigated for hazardous touch voltages. Operational access to the buried sections will be via the application of safe work procedures (Refer Water Corporation's 'Pipeline Voltage Mitigation Procedure'). For above ground steel pipelines the whole pipeline shall be mitigated for hazardous touch voltages.

2.2 AC Interference Study

2.2.1 Design Personnel

Soil testing, AC interference analysis, mitigation design and verification testing shall be completed by the same organisation.

2.2.2 Preliminary Data Gathering

The following engineering information shall be obtained at the commencement of the AC interference study.

2.2.2.1 Site Visit

An engineer shall attend the site of the pipeline to obtain the following information:

- Transmission feeder names and structure numbers that are deemed to affect the pipeline.
- Distribution feeder names and pole numbers of conductive poles and earthed HV equipment that is deemed to affect the pipeline.
- Since a substantial amount of data is collected for a typical AC interference study, it is recommended that photographs of earthed transmission and distribution equipment closest to the pipeline are catalogued. Geotagged photos, which are digital photographs with GPS information automatically embedded in the file, are recommended.
- Soil resistivity tests, Refer to Section 2.2.4
- Fall of potential tests should be performed on earthing systems of interest in close proximity to the pipeline in order to quantify the resistance to earth. Equipment such as substations, towers, poles, transformers, air break switches, underground to overhead transition poles, pad mount substations, ring main units, etc. should be considered. Refer to Section 2.2.5.1.
- Fall of potential tests should be performed at locations of interest along the pipeline if it has already been installed. The shunt impedance of bare buried metal offtakes, anode beds, valve complexes, pumping stations, water treatment plants, etc. should be measured. Refer to Section 2.2.5.1.
- If the pipeline has already been installed, take steady state measurements of the pipeline potential. Refer to Section 2.2.5.2.
- If RRJs are installed on the existing pipeline, measure the resistance across a selection of them when the pipeline is full of water. Refer to Section 2.2.5.3.
- If the pipeline has already been installed, record the location of small offtakes that may have been installed along the route in which bare metal pipe is buried in the soil effectively acting like an earth.

- Details of metallic fencing that runs close to valve locations.

2.2.2.2 Pipeline Information

- Chainage and route drawings in CAD or GIS (Geographic Information System) format including any major offtakes.
- Cathodic protection system drawings.
- General arrangement drawings for earth grids installed at valve complexes, pumping stations, water treatment plants, cathodic protection anode beds, etc.
- Pipeline material information including wall thickness, joint type, coating type, depth, valve types and locations. Note whether rubber ring joints are shorted via a bonding conductor as part of the cathodic protection design.
- Geotechnical borehole information (where available).

2.2.2.3 Power System Information

- Distribution and transmission feeder routes (both aerial and cable) in CAD or GIS format. The drawings should cover at least several kilometres either side of the pipeline route and clearly show the location of all terminal substations (i.e. star-points).
- Phase conductor types, overhead earth wire (OHEW) conductor types, height, sag, transposition scheme, tower arrangement, pole equipment locations, down conductor locations and pole earth grids.
- Transmission lines: Single phase to earth fault levels and primary clearance times for faults at the terminal substations and at equally spaced distances (minimum of three at 25%, 50% and 75% of feeder length) along each feeder that has conductive towers or poles. It is important that both magnitude and phase angle are obtained for each fault location as well as the contributions from each terminal.
- Distribution lines: Single phase to earth fault levels and primary clearance times for faults at the terminal substations and at locations of interest close to the pipeline at earthed distribution equipment such as transformers, air break switches, underground to overhead transition poles, pad mount substations, ring main units, etc.
- Present and future maximum steady state load currents.
- Information on reclosers, circuit breakers, fuses or other earth fault interrupting devices.

2.2.3 Portable Earth Test Meters

A portable earth test meter will be required to measure the soil resistivity, measure the resistance of earthing systems via the FOP method and to measure the resistance of any RRJs or isolation sections in the pipeline.

There are two types of soil resistivity test meters generally available – alternating current (AC) and direct current (DC). AC test meters generally run at or around 128Hz and are generally not suitable for AC interference studies because:

- Inductive coupling between the current leads and voltage leads, especially when the bottom layer soil resistivity is low (for example, at the water table), results in large errors and overestimation of the bottom layer soil resistivity.
- AC meters are generally low power and therefore not well suited to large electrode spacings or dry sandy surface layers.

For consistent and accurate readings (high signal to noise ratio), a high power switched DC soil tester such as an Iris Instruments Syscal or Advanced Geosciences Inc. (AGI) Sting should be used.

2.2.4 Soil Testing

2.2.4.1 Test Locations

Wenner method soil resistivity tests shall be carried out at regular intervals along the pipeline. Test locations shall be chosen to coincide with:

- Valve complexes, pumping stations, water treatment plants, cathodic protection anode beds, etc.,
- HV infrastructure close to the pipeline such as substations, towers, poles, transformers, air break switches, underground to overhead transition poles, pad mount substations, ring main units, etc.
- Changes in topography such as valleys, plains, hills, mountains, etc.

All soil tests shall be analysed with CDEGS RESAP while on site and the resulting multi-layer soil models should be compared with each other to determine trends resulting from changes in the local topography / landscape. The total number of soil resistivity tests required along a given pipeline will depend on how much variation is observed among the soil models.

GPS coordinates direction of traverse and a brief summary of the soil surface conditions (wet, dry, recent rain history, muddy, sandy, etc.) shall all be recorded for all chosen test locations.

2.2.4.2 Wenner Four-pin Method Soil Resistivity Test

The most commonly used and effective method of measuring the soil resistivity structure is via the Wenner four-pin method. As shown in Figure 2-1, four temporary electrodes are driven into the ground in a straight line a metres apart and b metres deep. Current, I is driven between the two outer electrodes and the voltage, V , is measured between the two inner electrodes. The resistance, R , is simply the voltage divided by the current. It is important that the centre point of the test remains fixed, that is, all electrodes are to be moved symmetrically with reference to the fixed centre point.

If b is small compared to a ($b < a/20$), then the resistivity can be calculated from the following formula:

$$\rho = 2\pi aR$$

Since LFI is mainly a function of the bottom layer resistivity, it is important to ensure that the maximum spacing, a , of the test is as large as possible in order for the Wenner method test to detect the lower soil layers. An inter-electrode spacing of 80 to 100 metres shall be achieved for each test.

Assumed soil resistivities shall not be used.

The following electrode spacing's are recommended.

Electrode Spacing, a (m)	Electrode Depth, b (m)
0.5	0.05
1	0.1
2	0.2
4	0.2
6	0.2
8	0.2
10	0.2
20	0.2
30	0.2
40	0.2
60	0.2
80	0.2
100	0.2

Table 2-1: Recommended Wenner Method Electrode Spacing

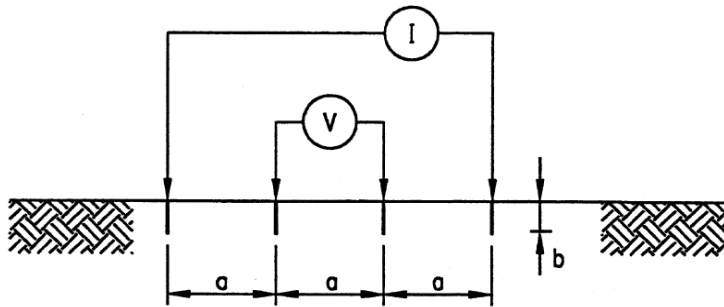


Figure 2-1: Wenner Method Circuit

2.2.5 Additional On-Site Measurements

2.2.5.1 Fall-of-Potential Resistance Measurements

Where possible, the shunt resistance of earthing systems connected to the pipeline, the transmission or distribution systems should be measured.

The fall-of-potential method is commonly used to measure the resistance to earth of small earthing systems. Testing is performed with the same switched DC earth tester described in Section 2.2.3.

The most accurate results are obtained when the FOP method is used to measure the resistance of a small earthing system in isolation of all other earth grids that may be connected by cable screens, OHEWs and the pipeline itself. If the earthing system is not isolated then all details regarding the connection to remote earth grids shall be recorded and used for correction modelling in MALZ or HIFREQ as described in Section 2.2.6.2.

Often, power lines will remain in service during fall-of-potential testing; therefore, all precautions must be taken to eliminate touch voltage hazards at the pole, pipelines or connected test equipment.

Refer to Figure 2-2 for a simple FOP circuit for a stand-alone (isolated) small earth grid. Typically, a temporary current electrode is installed at a distance, D , equal to 7 to 10 times the largest dimension of the earth grid under test. Test current, I , is injected around the earth return loop. The potential difference, V , between the earth grid and the soil is then measured along a straight line profile between the earth grid and the current stake at regular spacings, X , typically equal to $0.05D$, $0.2D$, $0.4D$, $0.6D$, $0.8D$ and $0.95D$. The resistance, $R = V / I$ can then be plotted as a function of distance. If D is large enough, the curve should nearly be horizontal at the centre which gives the resistance to earth of the grid. If no horizontal section is achieved, then D is too short or there are errors due to soil heterogeneity. Either increase D and repeat the test or use MALZ or HIFREQ to correct the test results as described in Section 2.2.6.2.

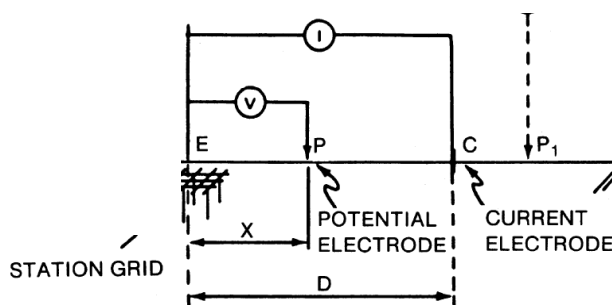


Figure 2-2: Fall-of-Potential Circuit

2.2.5.2 Steady State Pipeline Potential Measurements

Where an existing pipeline valve is not earthed, use a digital multimeter to measure the AC voltage between the valve and the soil 1m away.

Where the existing pipeline has earthing systems installed at the valves then use a digital multimeter to measure the AC voltage between the valve and the soil along a straight line profile running perpendicular to the pipeline. Multiple measurements shall be taken along this profile out to a distance where the measured voltage levels off.

It is important that the power utility is contacted prior to these measurements being taken to ensure accurate feeder load monitoring data will be available during the period of testing.

2.2.5.3 Pipeline Joint Impedance

Where an existing pipeline has rubber ring joints (RRJs), insulating flanges or other permanent discontinuities, the resistance of a selection of the joints should be measured while the pipeline is full of water. Analysis and computer modelling of the tests should be used to account for earthing systems installed on the pipeline to avoid false continuity readings. A high powered switched DC portable test meter should be suitable for this purpose.

2.2.6 Computer Modelling (CDEGS®)

2.2.6.1 Soil Model: CDEGS® RESAP Module

CDEGS RESAP module shall be used for the inversion of the soil resistivity test results. RESAP utilises numerical methods to interpret the measured apparent resistivity and determine an equivalent multi-layer soil model that is used by the other CDEGS engineering modules for the analysis of LFI and EPR.

Soil models in a common geographical location that are similar can be grouped together in regions. An average soil model for a region can be obtained from RESAP by inputting more than one set of test data into a single RESAP run. Using average soil models saves considerable engineering time during the AC interference analysis and mitigation design. Where soil models are dissimilar, each soil model shall be used separately in subsequent inductive and conductive coupling simulations.

2.2.6.2 Fall-of-Potential Correction Model: CDEGS® MALZ or HIFREQ Modules

For computer modelling purposes, it is necessary to enter shunt impedances representing towers, pumping stations, valve earthing systems, substations, etc. It is therefore important to accurately measure the stand-alone shunt impedances of earthing systems if possible during the site visit.

Usually a transmission line may have many shunt impedances (towers) connected together by the overhead earth wire. Similarly, pipelines may be earthed at multiple locations including offtakes, valves, pumping stations, valve complexes etc. Often it is impossible to easily disconnect each earthing system in order to perform a FOP, so it must be tested while it remains connected to a larger earthing network. In order to calculate accurate stand-alone impedance from the measured total system impedance, it is necessary to use computer modelling. To do this, simulate the FOP circuit in MALZ or HIFREQ utilising the measured soil model for that location. Include the earth grid under test, OHEWs, cable screens, other connected earthing systems, current and potential electrodes, test current, etc. Simulation results should yield a curve that is very close to the curve measured for the total system impedance. Remove the test circuit and interconnections to OHEWs and cables screens, etc. and re-simulate to obtain the stand-alone earth grid impedance.

2.2.6.3 Inductive and Conductive Coupling Model: CDEGS® Right-of-Way (ROW) Module

CDEGS ROW module should be used when modelling long parallelisms between transmission lines and pipelines. ROW is generally not suited to short parallelisms or modelling distribution feeders.

ROW is typically used when:

- Modelling long transmission feeders >50km
- Relative separation of transmission lines and pipelines remains relatively constant
- Transmission and pipeline route traverses many different regions with different soil structures

If ROW is used for inductive coupling computations, conductive coupling must be performed using the MALZ module. MALZ can be invoked from within the ROW program or it can be used separately as required. The phase difference between the magnetically induced potential and the soil potential rise due to conductive coupling is generally in the range 100° to 150°. A phase difference of 180° may be used conservatively if required.

2.2.6.4 Inductive and Conductive Coupling Model: CDEGS® HIFREQ Module

CDEGS HIFREQ module should be used when modelling short parallelism between transmission and distribution lines and pipelines or generally any geometrically complex arrangement of feeders and

pipelines. HIFREQ computes inductive and conductive coupling at the same time with input via a three dimensional CAD interface. Run times however are much longer than those of ROW.

2.2.6.5 Modelling Power Lines

It is important to use accurate conductor data for the computer modelling of feeders, especially the OHEWs. Conductor types should be obtained from the utility, and the physical and electrical properties can be looked up in a number of catalogues provided by manufacturers. Particular attention shall be paid to obtaining accurate conductor permeability.

If overhead conductors are modelled as horizontal conductors, conductor height above ground should be derated to account for sag according to the following approximation:

$$H = h + \text{sag}/3$$

Where:

H is the derated height for the model

h is the minimum height at max sag

Simulations shall be run for both transient conditions (phase to earth faults) and steady state load conditions. As per the National Electricity Rules, steady state loads shall have an unbalance applied as follows:

- Feeders $\geq 30\text{kV}$, maximum steady state load current unbalance of 2%
- Feeders $< 30\text{kV}$, maximum steady state load current unbalance of 5%

2.2.6.6 Modelling Pipelines

Pipeline data should be obtained from the manufacturer. Typical pipeline characteristics are given below:

- Steel relative resistivity, $\rho_r = 10$
- Steel relative permeability, $\mu_r = 100$ to 300
- Coating relative permittivity, $\epsilon_r = 2.5$
- HDPE coating resistivity, $\rho = 2 \times 10^7$ to $2 \times 10^8 \Omega\text{m}$
- Bituminous coating resistivity, $\rho = 2 \times 10^5$ to $2 \times 10^6 \Omega\text{m}$

2.2.7 Touch and Step Voltage Limits

2.2.7.1 AS/NZS 4853:2012

AS/NZS 4853:2012 introduced probabilistic touch voltage limits where the target level of probability of fatality has been set to 1×10^{-6} where

$$P_{\text{Fatality}} = P_{\text{Coincidence}} \times P_{\text{Fibrillation}}$$

Essentially, very high touch voltages are deemed “safe” if the chance of a person touching a pipeline during a fault is low enough. If the target level of probability of fatality is $\leq 1 \times 10^{-6}$ then no mitigation earthing systems are required.

2.2.7.2 2012 WHS Legislation

The WHS act which commenced in 2012 essentially reverses the target level of risk approach used in many Australian standards and guidelines including AS/NZS 4853:2012 and EG-0. Instead, a precautionary approach focussing on due diligence is favoured. In terms of mitigating touch voltage safety hazards on pipelines, one must start with what can be done and only do less if it is justified.

2.2.7.3 DS 23 Touch Voltage Limits

It is a Water Corporation mandatory requirement that earthing designers follow the precautionary approach in regard to earthing system design and voltage limits in accordance with the WHS act. To ensure DS 23 complies with the WHS act, the probabilistic touch voltage limits presented in AS/NZS 4853:2012 and derived from EG-0 (using Argon Software) have been disregarded by Water Corporation in favour of deterministic voltage limit calculation methods covered in AS/NZS 60479.1:2010 – Effects of current on human beings and livestock, Part 1: General Aspects.

Probability of coincidence shall not be considered.

AS/NZS 60479.1:2010 focuses mainly on the non-linearity of the impedance of the human body. Experimental evidence has shown that the impedance of the human body varies with applied voltage which is a significant paradigm shift when compared to the traditional constant 1000 Ω body resistance used in IEEE Standard 80.

The non-linearity of the body impedance makes the calculation of allowable touch and step voltage limits more difficult however much more control is afforded to the engineer allowing for voltage limits to be tailored to each specific situation.

2.2.7.4 Body Impedance

In DS 23, the hand-to-hand body impedance shall be determined from Table 2 of AS/NZS 60479.1:2010 for large surface areas of contact in water-wet conditions not exceeded for 50% of the population.

Conservatively ignoring skin impedance and using the simplified schematic of Figure 3 of AS/NZS 60479.1:2010, the body impedances are as follows:

- Hand-to-feet body impedance is 75% of hand-to-hand impedance
- Foot-to-foot body impedance is 100% of hand-to-hand impedance

2.2.7.5 Foot Contact Resistance

Utilise IEEE Standard 80:2000 methods taking into consideration the surface layer derating factor. Washed 20mm minimum aggregate size gravel shall be assumed to have a wet resistivity of 3000 Ω m and hot-mix asphalt shall be assumed to have a resistivity of 10000 Ω m. Gravel and asphalt thicknesses are typically 100mm and 30mm respectively however these can be increased in the design specification to 150mm and 50mm if needed. Wet concrete shall be conservatively assumed to have a resistivity of 20 Ω m. Cold-mix asphalt shall not be used due to its tendency to absorb water.

Note: Foot contact resistance is based on the surface soil resistivity layer as per IEEE Std 80-2000. The lowest measured surface soil resistivity shall be used for the calculation of foot contact resistance.

2.2.7.6 Fibrillation Current

Fibrillation current limits shall be in accordance with Curve C1 of AS/NZS 60479.1:2010 (Figure 20) for all areas of the pipeline. This corresponds to a minimal chance of fibrillation with no organic damage. Total primary clearance time shall be used for determination of fibrillation current.

Note: Fault levels and clearance times shall not be assumed.

2.2.7.7 Stepped Faults

Usually on a transmission line, the local and remote feeder protection will operate at different times resulting in a stepped fault. For the purposes of this discussion, assume the local protection operates first followed by the remote protection. Analysis of the safety criteria is therefore a two-step procedure as described in ENA EG1 – 2006 Section 6.4.2:

1. For first part of the fault where both terminals are contributing to the fault current, the total fault current and local protection clearance time shall be used.
2. For the second part of the fault where only the remote terminal is supplying fault current, the equivalent r.m.s. value of the earth fault current shall be used along with the remote protection

clearance time. The r.m.s. value of the earth fault current shall be computed using Equation 6-8 from ENA EG1 – 2006:

$$I_{r.m.s.-eq} = \sqrt{\frac{I_1^2 t_1 + I_2^2 t_2 + I_3^2 t_3 + \dots}{t_1 + t_2 + t_3 + \dots}}$$

Where t_1 is the duration of current contribution I_1 , t_2 the duration of I_2 , etc.

2.2.7.8 Heart Current Factor

The proportion of total body current that actually flows through the heart is known as the heart current factor. The heart-current factors from Table 12 of AS/NZS 60479.1:2010 shall be used. Common heart current factors are shown below.

- Hand-to hand HCF = 0.4
- Hand-to feet HCF = 1.0
- Foot-to-foot HCF = 0.1 (although HCF = 0.04 is given in Table 12 of AS/NZS 60479.1:2010, 0.1 shall be used to increase the safety factor by reducing the chance of cell damage known as electroporation).

2.2.7.9 Decrement Factor

The decrement factor is calculated using the X/R ratio and is used to determine the rms equivalent of the asymmetrical component of the fault waveform accounting for the initial DC offset for a given fault duration.

The decrement factor is calculated using Equation 79 from IEEE Standard 80-2000:

$$D_f = \sqrt{1 + \frac{T_a}{t_f} (1 - e^{-\frac{2t_f}{T_a}})}$$

Where:

$T_a = \frac{X}{\omega R}$ is the dc offset time constant

t_f is the fault duration (s)

The decrement factor can be accounted for in two ways:

1. Multiply the rms fault current by the decrement factor thus increasing the fault current or,
2. Divide the touch and step voltage limits by the decrement factor thus decreasing (derating) the voltage limits.

Method 2 shall be used in which the voltage limits are derated while all calculations are performed using the original rms fault current. This method has been chosen by Water Corporation to maintain consistency with the voltage limits calculated using CDEGS Safety Module (in which voltage limits are a function of X/R and decrement factor by default).

2.2.7.10 Boot Impedance

No additional boot impedance shall be assumed (i.e. assume bare feet).

2.2.7.11 Touch and Step Voltage Limit Calculation: Graphical Method

Touch and step voltage limits are to be calculated in accordance with the procedure illustrated in Appendix A.

2.2.7.12 Touch and Step Voltage Limit Calculation: CDEGS® Safety Module

The above voltage limit calculations including foot impedance calculations are automated in CDEGS (version 14) Safety module in the output toolbox. Only heart current factor is not considered.

- Choose 'C1-IEC' for the Fibrillation Current Calculation Method.
- Choose 'IEC' for Body resistance.
- Note the terminology of the 5% and 95% body resistance curves in CDEGS are opposite to those described in AS/NZS 60479.1:2010. The '5% of population exceeds' curve in CDEGS is equivalent to the 'are not exceeded for 95% of the population' curve in AS/NZS 60479.1:2010.
- Choose IEEE Std 80-2000 foot resistance calculation method
- Choose IEC Standard revision of 2005
- Choose '50% population exceeds' curve.
- Choose contact moisture 'water-wet'
- Frequency 50Hz
- Enter X/R (Note: Default X/R is set to 20)
- Choose IEC Percentage (hand to feet 75%, step 100%)

- Choose surface layer properties
- Click “Generate Safety Threshold Limits and Report” button
- As appropriate, manually multiply touch or step voltage by $\frac{1}{HCF}$

2.2.7.13 Fault Levels

To account for fault levels varying from the normal operational mode (switching from other sources under abnormal conditions etc.) and growth of the network over say 5 years, a 20% margin shall be added to the supplied maximum single phase to earth fault level during the study.

Note: It is understood Horizon Power make such a statement (20% added) when providing fault levels and Western power do not (however WP add caveats to the information).

2.2.8 AC Corrosion

Steady state LFI may result in high current densities at holidays in the pipeline coating resulting in localised corrosion. AS/NZS 4853:2012 utilises the acceptable pipeline potentials stated in CIGRE TB 290 and EN15280 namely,

- 4V AC for soil resistivity $\leq 25\Omega\text{m}$
- 10V AC for soil resistivity $> 25\Omega\text{m}$

It should be noted that under some circumstances the AC corrosion limits may be more stringent than the human safety limits from the previous sections.

2.2.9 Investigation Report and Recommendations

A single AC Interference report shall be supplied that covers the following:

- Voltage hazards safety assessment criteria
- Analysis input parameters
- Supplied fault levels, clearance times, fault locations, feeder information and load currents
- Soil resistivity testing and soil model
- Supplied information and drawings used as basis for analysis
- Methodology
- Analysis software
- Diagrams and explanation of how each of the CDEGS models were created
- Simulation results
- Hazard assessment
- Pipeline touch voltages during fault conditions and safety assessment
- Appurtenance step voltages spot plots if there are existing earthing systems.
- Steady state pipeline potential for AC corrosion

If a large number of fault locations have been considered, CDEGS output data can be exported as a spread sheet and this may help to condense data into “envelope plots” which are the maximum pipeline touch voltages at any given location along the pipeline with all fault scenarios having been considered. There should be one envelope plot per feeder.

2.3 AC Interference Mitigation Design

2.3.1 Mitigation Measures

2.3.1.1 Compliance with the WHS Act

In addition to robust technical design, the designer must also fulfil the legal requirements of the WHS Act. The designer must demonstrate due diligence in the mitigation of voltage hazards on any Water Corporation asset. The designer must ensure, so far as is reasonably practicable, the safety of workers and the general public coming in contact with an affected asset.

2.3.1.2 Common Law Approach to AC Interference Mitigation Design

The following process shall be used when designing mitigation for Water Corporation assets.

1. Identify Critical Hazards – Perform detailed AC Interference Analysis as described in Section 2.2.
2. Identify all practical precautions for each critical hazard by following the hierarchy of controls – Recognised mitigation measures are summarised below.
 - a. Elimination
 - i. Eliminate need for pipeline appurtenance
 - ii. Non-conductive bollards
 - b. Substitution
 - i. Install underground pipeline instead of above ground
 - ii. Move pipeline appurtenance to lower risk location
 - iii. Replace manually operated valves with electric powered / remote operated
 - iv. Replace metallic above ground valves with underground valves
 - v. Replace accessible metallic appurtenances with non-conductive materials
 - c. Isolation
 - i. IP2X cathodic protection test points installed in non-conductive enclosures
 - ii. Using UV stabilised painted Sintakote pipeline for above ground sections to insulate pipeline
 - iii. Pits, barricades or security fencing
 - d. Engineering
 - i. Reduce earth fault clearance time
 - ii. Reduce earth fault level
 - iii. Install or upgrade overhead earth wire on feeder or bonding of cable screens on feeders (cooperation with utility) to take advantage of return current that reduces EPR and induced voltages
 - iv. Install grading ring / mesh / electrode (i.e. pipeline earthing system)
 - v. Equipotential bonding (including bonding to concrete reinforcement)
 - vi. Insulated fence sections in metallic fences running close to valves
 - vii. Voltage limits as described in Section 2.2.7
 - viii. High resistivity surface layers such as gravel or hot-mix asphalt
 - ix. Install non-conductive pipeline sections (Sintaline ® or GRP)

- x. Non-conductive spindle extensions
 - e. Administrative Controls
 - i. Worker training
 - ii. Safe work procedures
 - iii. Signage
 - f. Personal Protective Equipment
 - i. Non-conductive valve operating handles
 - ii. Insulating gloves
 - iii. Insulating boots
 - iv. Temporary equipotential mats and bonding
- 3. Determine the reasonableness of each of the practical precautions
 - a. Dialogue between mitigation designer, pipeline owner, pipeline designer, cathodic protection designer, stakeholders, etc.
- 4. Implementation of reasonably practicable precautions
 - a. Electrical safety during construction documentation to be supplied by the designer
- 5. Monitoring and review.
 - a. Commissioning testing and ongoing maintenance

2.3.2 Mitigation Design Modelling (CDEGS®)

2.3.2.1 CDEGS® Right-of-Way (ROW) Module

When using ROW for mitigation design, the method in Figure 2-3 should be used for each fault scenario.

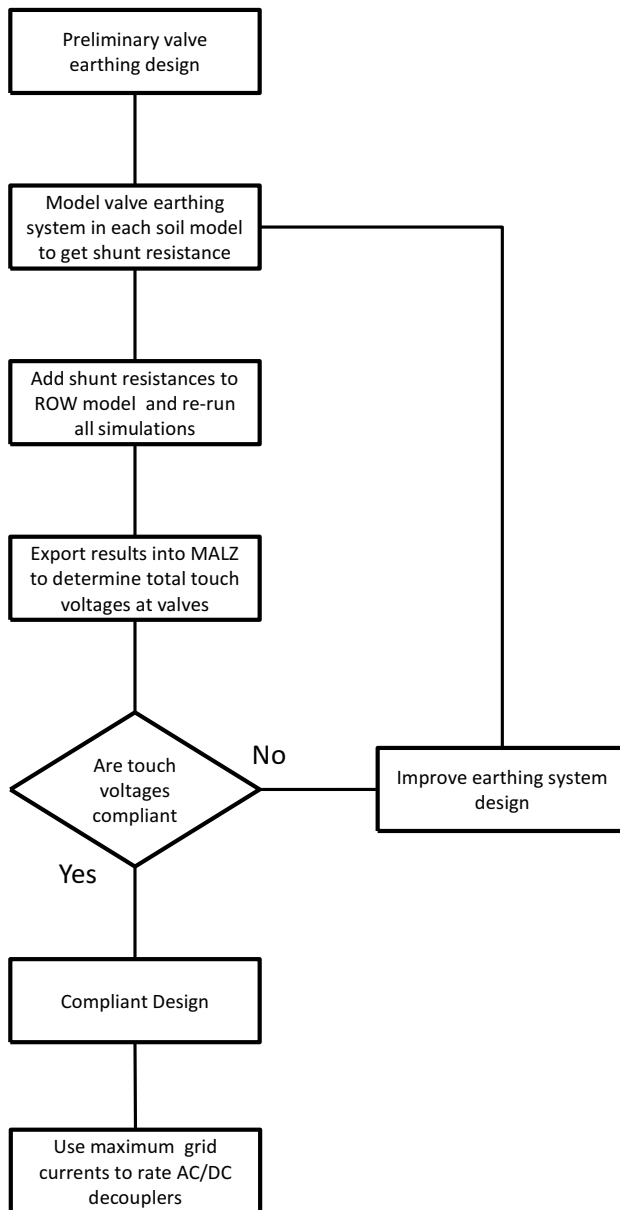


Figure 2-3: ROW Design Process

2.3.2.2 CDEGS® HIFREQ Module

Earthing systems designed to mitigate touch voltages at appurtenances should be tested for suitability by updating the HIFREQ model with the new earthing systems and rerunning all simulation scenarios.

Reduce the run time by using equivalent shunt impedances for majority of the earthing systems and only modelling detailed grids and meshes at the areas of interest.

2.3.3 Voltage Mitigation Design Drawings

The following drawings shall be supplied for each earthing system required:

- Earthing system general arrangement
- Earthing connection diagram
- Earthing installation details

Drawings shall be in accordance with Water Corporation Standards DS24 Electrical Drafting and DS80.

2.3.4 ‘Safety in Design’ Documentation

Earthing design is carried out to ensure the safety of the public from accidental contact with the installed pipeline and appurtenances and also to protect maintenance personnel while working on the pipeline. It is important that additional hazards are not introduced by the design and installation of the pipeline earthing systems or the failure of the installed earthing systems. The following aspects should be considered as part of the design:

Constructability

- Prefabricated copper mesh
- Steel reinforced pit liners and base slabs with prefabricated reinforcement bonding tabs; make equipotential bonding intrinsic to the pit construction.

Access / Egress

- Equipotential bonding conductors should not impede access to valves or pit causing slips, trips and falls.

Environmental

- Flooding of the pit or surrounding land should not interfere with the performance of the earthing system or operation of the AC/DC decoupler. Install decoupler and earth bar in above ground pillar.
- IEEE 837 - 2002 compliant bonds shall be used for all buried permanent earthing connections.
- Bonding conductors and decoupler rated for lightning impulses.

External Safety

- Vandalism or copper theft. Earth risers to above ground valves should be covered for mechanical protection or connection made completely underground.
- Redundancy in earth connections

Utilities and Services

- Touch voltage hazards at nearby metallic fences, metallic structures, water taps, communications pits, etc. due to proximity to valve earthing system.

Robustness

- Bonding conductors and decoupler rated for induced and steady state currents.

- Materials chosen to minimise corrosion (i.e. copper earth risers PVC insulated at the soil/air interface)

Inspection / Testing / Maintenance

- Ease of inspection and testing – where possible eliminate need to climb into pit to perform earthing testing.
- Design earth bar so clamp earth tester can be used so earth grid does not have to be disconnected.

2.3.5 ‘Safety in Construction’ Documentation

A number of electrical hazards will exist during the construction of a pipeline and the installation of valve mitigation earthing systems. Additionally, earthing systems installed along an existing pipeline will not protect workers who have excavated a pipeline for maintenance and repairs. During these critical times, workers will be exposed to unmitigated touch voltage hazards due to inductive, capacitive and conductive coupling. As a result, temporary equipotential bonding and/or insulation techniques described in the Water Corporation document ‘Guideline – Electrical Safety in Pipeline Construction’ must be followed. The following safety in construction considerations must be documented in the design report for all specific construction scenarios.

2.3.5.1 Insulation Techniques

Insulation techniques aim to maximise the series resistance in the touch voltage circuit thus minimising the body current. All tasks must be carried out treating the pipeline metal as live. Appropriately rated insulated gloves, boots or overboots must be worn at all times as well as following work procedures that are designed to prevent circumvention of the insulation. These work procedures include:

- Do not kneel on the ground or lean on the pipeline
- Use double insulated power tools
- Do not work while standing in water
- Exclusion zone of 2.4m from pipeline metal set up around work area using non-conductive barrier
- Site specific pre-work risk assessment

Insulating gloves for electrical purposes are rated for use according to nominal working voltage, unless otherwise specified insulating glove rating shall be taken to be for a nominal working voltage of 1000V in accordance with AS 2225-1994. This definition shall include the use of both glove liners and protective gloves for the insulating gloves so as to afford them the maximum possible mechanical protection.

Where insulated gloves, boots or overboots are used, there is no requirement for equipotential bonding.

2.3.5.2 Temporary Equipotential Bonding

Equipotential bonding techniques may be used in situations where the use of insulating gloves and boots is impractical. Work procedures shall be followed to prevent circumvention of the safety system.

All work shall be carried out on temporary equipotential mats bonded to the pipeline. The mats shall be prefabricated with flexible PVC insulated 70mm² copper bonding conductors and earth clamps which are fit for purpose and fully insulated. Install equipotential bonding of pipeline segments as required.

Connection of mats to the pipeline shall be done while wearing insulated gloves, boots or overboots.

Do not work while standing in water.

Exclusion zone of 2.4m from metal objects at pipeline potential set up around work area using non-conductive barriers. Items such as generators and single insulated power tools such as drills and welders will be at pipeline potential. Multiple tools supplied by the same generator represents a possible transfer voltage hazard.

Site specific pre-work risk assessment must be implemented.

2.3.5.3 Temporary Earthing Systems

Vehicles on rubber tyres or elevated pipeline sections that are well insulated from earth (either sitting on non-conductive supports or hoisted using non-conductive slings) underneath energised high voltage transmission lines will experience capacitive coupling. This phenomenon involves the unearthed metallic structure accumulating an electric charge due to the coupling with the overhead phase conductors. When the metallic structure is intentionally or accidentally earthed, the stored charge is discharged to the earth. The current flow due to capacitive coupling typically consists of a fast transient discharge of duration of several microseconds followed by a steady state current flow. Typically, the transient current is of the order of 10A while the steady state current through a 1000 Ω human body drops to around 1mA for an object the size of a car under a HV transmission line. Both discharges can be shown not to cause ventricular fibrillation however they can be quite painful and may represent a significant nuisance on site. Additionally, care must be taken to ensure the capacitive discharges cannot ignite flammable materials.

Typically, any sort of earthing with a resistance to earth of less than 1000 Ω is sufficient to prevent capacitive charge building up. Bare copper trailing cables, chains, or shallow earth rods are sufficient to eliminate the transient discharge associated with capacitive coupling. It should be noted that in most cases, the measures described in the previous sections to minimise the risk due to inductive and conductive coupling will also mitigate capacitive coupling hazards during construction.

2.3.5.4 Lightning

Pipelines represent a significant collection area for lightning both through direct strike to the pipeline or plant bonded to the pipe and through induction on the pipe due to lightning electromagnetic pulse. As the pipeline itself is generally well insulated from earth, the effects of lightning can propagate over large distances along the pipeline to be shunted to earth mainly via discrete earthing systems bonded to the pipe.

As the occurrence of power line faults and lightning-induced surges is increased during lightning activity, work shall be suspended whenever thunderstorms have been detected in the area surrounding the entire pipeline.

2.3.6 Mitigation Design Report

A single AC interference mitigation design report shall be prepared and it shall include the following topics:

- Summary of safety assessment criteria, fault levels, clearance times, fault locations, feeder information, load currents, soil test results, soil models, touch and step voltage hazards and reference to details within the AC interference study report.
- Description of the earthing techniques utilised to mitigate touch voltages to acceptable levels.
- Design drawings
- Simulation results
- Hazard assessment
- Pipeline touch voltages during fault conditions and safety assessment
- Appurtenance step voltages spot plots
- Steady state pipeline potential for AC corrosion
- Earthing system impedances for use in post construction validation tests
- Safety in design documentation
- Safety in construction documentation
- Proposed earthing system validation procedure (test plan)

2.3.7 Specification

2.3.7.1 Earthing Conductors

Copper conductors shall only be used. Zinc conductors shall not be used under any circumstances.

2.3.7.2 Equipotential Bonding

Equipotential bonding shall be implemented at all appurtenances. The internal equipotential bonding of the pits (scour valve, air valve, flow meter, etc.) shall be implemented as standard. However, the decision on whether a grading ring or grading mat (with or without electrodes etc.) is to be deployed must be made by the specialist earthing design consultant.

All conductive items such as step irons, pit liner concrete reinforcement, concrete pit base, etc. shall be bonded together via insulated 70mm² soft drawn copper conductors.

All bonding conductors are to be terminated in a compression lug.

A suitably sized galvanised steel tab shall be welded to all steel items requiring bonding. Refer to Figure 2-4 for the typical bonding method for a pit. Refer standard drawings EG20-5-4 & EG20-6-7 for below ground air valve pit and scour valve pit earthing detail.

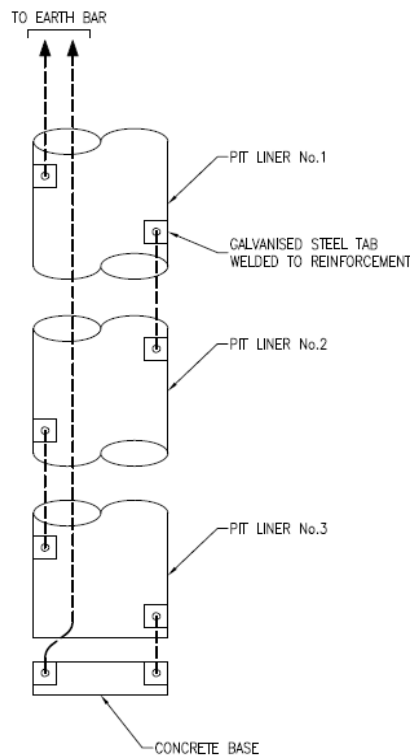


Figure 2-4: Equipotential Bonding of Pit Liners.

2.3.7.3 AC/DC Decoupler

So as to not affect the cathodic protection system (or create a corrosion cell between the pipeline steel and copper earthing) via the installation of valve earthing systems, an AC/DC decoupler shall be installed at each earthed valve. The decoupler simultaneously passes AC current and blocks DC current. The minimum fault current rating shall be determined from CDEGS computer simulations.

Dairyland Electrical Industries (DEI) Solid State Decoupler (SSD), Auscor Type 1016D or similar. A suitably sized copper earth bar shall be installed to accommodate all required earthing connections. The decoupler shall be installed inside a connection pillar AUSCOR Type AUS5063 or similar. Refer to Figure 2-5 for a typical pillar arrangement.

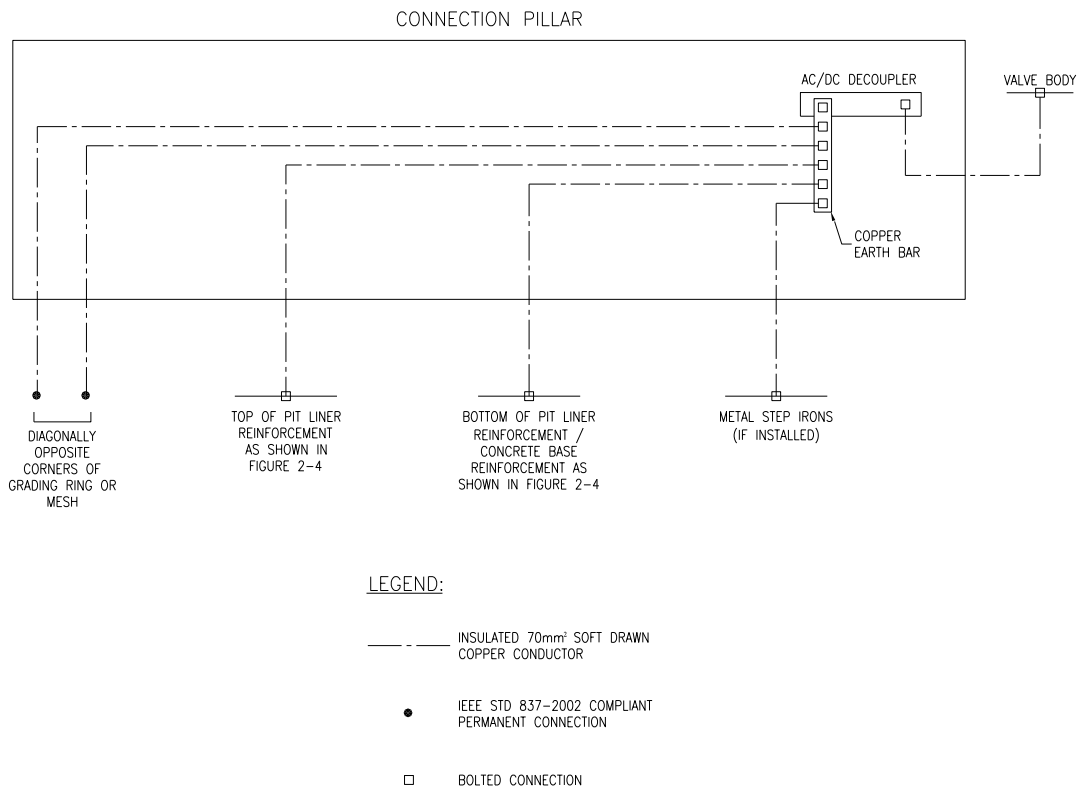


Figure 2-5: AC/DC Decoupler Connection Diagram.

2.3.7.4 Equipotential Grading Conductors

Valves that can be accessed by a person standing on the surface using a metal spindle extension require equipotential grading conductors buried around the valve out to a distance such that the valve operator is always standing within the earthing system. Depending on the magnitude of the touch voltage hazard, potential grading can be achieved using copper grading conductors, buried copper meshes or concrete slabs where the steel reinforcement is bonded to the valve earthing system. Two connections shall be made between the opposite corners of the potential grading conductors and the earth bar.

Grading rings shall be constructed from 70mm² bare soft drawn copper or 35mm² bare hard drawn copper installed at a depth of 500mm. The depth may be as shallow as 300mm if required by CDEGS computer simulation results. Quality fill is to be compacted in maximum 200mm thick layers to 95% standard in accordance with AS 1289.1.1. Refer to Figure 2-6.

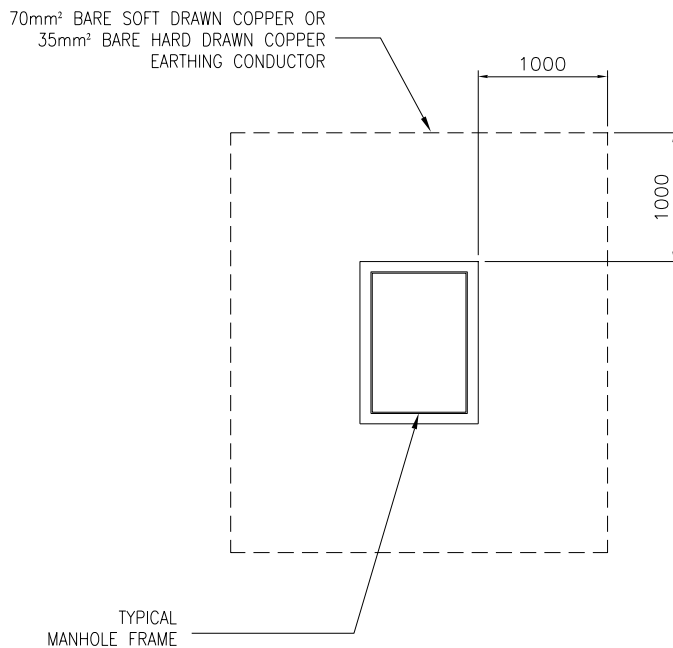


Figure 2-6: Grading Ring.

A 200 × 200 copper mesh shall be Erico prefabricated wire mesh, Auscor 5080 Equipotential Copper Earthing Mesh or equivalent. Minimum mesh conductor diameter to be 4.11mm (#6 AWG). Depth of mesh to be determined by computer simulation. Quality fill is to be compacted in maximum 200mm thick layers to 95% standard in accordance with AS 1289.1.1. Refer to Figure 2-7.

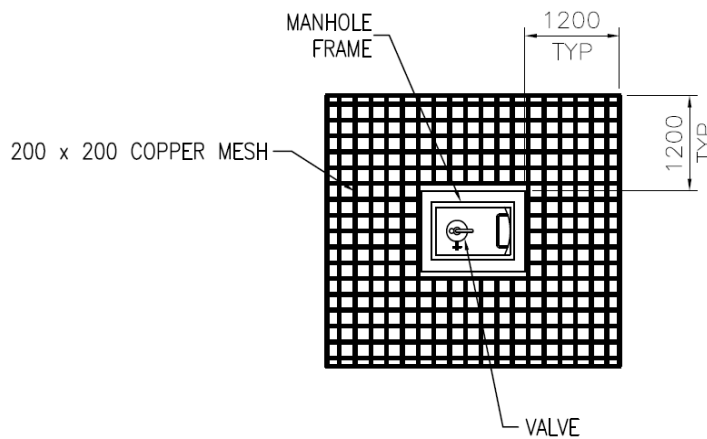


Figure 2-7: Copper Mesh.

2.3.7.5 Electrodes

Electrodes may be required to reduce the overall shunt impedance of the pipeline to lower induced pipeline potential.

Where appropriate, 15mm OD copper clad steel electrodes shall be driven into the ground. Alternatively, electrodes shall be lengths of bare 70mm² soft drawn copper installed in 75mm diameter drilled holes and backfilled with a slurry mixture of 50% bentonite, 45% gypsum and 5% sodium sulphate or equivalent earthing compound such as Good Earth by Fulton Industries. Consideration should be given to earthing compound in regard to suitability for constant contact with the water table.

2.3.7.6 Earthing System Connections

All earthing system connections under finished ground level (e.g. direct buried, within earth pits, etc.) shall be made with IEEE Standard 837- 2002 compliant connectors.

Accepted connector suppliers are:

- CADWELD
- Groundlok
- Panduit (connectors using only the enhanced crimp process consisting of 3 crimps per connector)

Connections inside pits or plinths shall be utilise compression lugs and appropriately sized stainless steel bolts.

2.3.7.7 Non-conductive Pipeline Sections

Sintalined ® pipeline is steel pipe lined externally and internally with Tyco Sintakote. Where it has been determined through computer simulation that a discontinuity is required in a pipeline, a minimum 24m long section (4 × 6m lengths) of Sintalined ® pipeline may be used.

To protect the insulation against lightning transients, an appropriately rated surge protection device (SPD) shall be installed across each flange/joint. The SPDs are to be installed as close as possible to the respective insulating flange and connected to the pipelines either side of the insulating flange using the shortest length leads as is practical. The SPD shall be sized such that under the maximum expected 50Hz potential difference across a given flange, it remains open circuit. The SPDs shall also have a residual

voltage during lightning impulse currents of less than the breakdown voltage of the components making up the insulating flange. Where the isolating pipe sections comprise of an entirely non-conductive construction (e.g. glass reinforced plastic pipe), SPDs are not required.

Sintalined® pipeline sections are typically joined using the rubber ring joint method and therefore may not be able to be installed in areas where welded joint pipeline is required. Sintalined® flanged pipeline and insulating sleeves and washers should be considered in this case.

Insulating flanges or gaskets that have been specified for cathodic protection purposes and rubber ring joints are not to be relied upon for the electrical segmentation of a pipeline to mitigate voltage hazards arising from inductive and conductive coupling with distribution and transmission lines.

2.3.7.8 Non-conductive Air Valve Risers

Above ground air valves in close proximity to metallic property fences represent a hand-to-hand touch voltage hazard. In addition, the installation of a valve earthing system in close proximity to existing structures or services susceptible to EPR may be undesirable. To eliminate the hazard and the need for installing a valve earthing system and replacing a portion of the fence with non-conductive materials, an insulated riser may be considered.

50mm OD Impact Modified Polypropylene (PP-B) has been tested and found to be suitable for the purpose of insulating air valves.

For 12Ωm water a 0.5m length of 50mm PP-B installed on the air valve side of the gate valve has been shown to add sufficient impedance to the touch voltage circuit to limit the body current to acceptable levels for a given touch voltage scenario. The remainder of the riser between the PP-B section and the surface may be metallic however it must be electrically insulated by a suitable pipeline coating.

The length of the PP-B section shall be based on measured local water resistivity, riser diameter and computed touch voltage hazard. The resistance of the chosen PP-B section shall be tested prior to implementation on the pipeline.

Note: Insulating flanges, although suitable for cathodic protection purposes, shall not be relied upon for human safety.

2.3.7.9 Insulating Fence Sections

Where touch voltage hazards have been identified on an existing metallic fence affected by the EPR of a nearby pipeline earthing system, an insulating fence section may need to be installed subject to approval from the property owner.

Insulating fence sections in properties not owned by the Water Corporation shall be of entirely wooden construction.

Suitably engineered insulating fence sections in properties owned by the Water Corporation may be constructed from non-reinforced masonry, fibre reinforced plastic or from combination wood/steel. Insulating fence type shall be approved by the Senior Principal Engineer Electrical prior to construction.

2.3.7.10 High Resistivity Surface Layers

To increase foot contact impedance, a high resistivity surface layer may be installed such as:

A minimum 100mm thick layer of 3000Ωm (wet resistivity) washed gravel with minimum aggregate size of 20mm

Minimum 30mm thick layer of hot-mix asphalt (no metallic additives). Asphalt shall be installed upon a suitable stabilised/compacted base layer to prevent movement, cracking and erosion.

Due to the maintenance concerns associated with high resistivity surface layers installed along pipelines, high resistivity surface layers shall only be used as a last option and only applied under controlled conditions.

2.3.7.11 Above Ground Pipelines

Due to considerable difficulty and cost to effectively mitigate above ground pipelines, consideration shall be given to using Sintakote[®] pipe with protective UV resistant paint. The designer shall discuss such requirements with the civil pipeline designer during the initial stage.

2.3.7.12 General Installation Requirements

1. All cables to be labelled with stainless steel labels and fixed with stainless steel cable ties.
2. All de-coupler domes and pits to have labels with the following information:

WATER CORPORATION
VOLTAGE MITIGATION
TEL: 131375

Label Size: 100mm x 50mm x 2mm stainless steel OR appropriate proprietary stick on label with lettering size: 6mm high.
3. Steel bollards are to be installed where the de-coupler dome or pit is in a position where it can be damaged by vehicular traffic.
4. All connections in manholes, cable pits, de-coupler domes and on pipes to be wrapped with Denso tape. Stainless steel bolts and studs shall be used for the connection points.
5. Pipeline installations to have 50mm high Test Point Numbers stencilled on the pipe approx. 50mm above the test point connection for ease of location on long pipeline installations. Black paint is to be used for the numbers.

2.3.8 Recognised Mitigation Measures Exhausted

If all reasonably practical mitigation measures of Section 2.3.1 have been exhausted and hazardous touch voltages cannot be mitigated to levels defined in Section 2.2.7, then a formal submission shall be made to the Senior Principal Engineer Electrical outlining the situation for consideration of what other practical measures can be taken to reduce the risk.

2.4 AC Interference Mitigation Earthing System Validation

The validation of earthing systems installed to protect against AC interference in pipelines is typically achieved using the following six key activities. Appropriate verification testing shall be performed.

- Current injection testing
- Visual inspection / physical integrity check
- Fall-of-Potential testing
- Continuity testing
- Steady state pipeline potential measurement
- Computer modelling and correction

2.4.1 Current Injection Testing

It is possible to simulate an earth fault by injecting a low current off frequency test signal (such as 58 or 60Hz for a 50Hz power system) around an earth return loop. Depending on how the circuit is set up, induced pipeline potential, touch voltages and step voltages may be directly measured for inductive and/or conductive coupling scenarios.

Current injection test (CIT) methods described in IEEE Standard 81 – 2012 should be followed.

It is typically impractical to perform CITs for every valve, feeder and HV tower along a given right-of-way. CITs shall be performed:

- At sites where simulation results show that extreme touch voltages are expected.
- At safety critical locations where there is an increased frequency of access by Water Corporation staff and/or the general public. These sites include, valve complexes, pumping stations, assets near places where the public gather such as schools, shopping centres, pools, sportsgrounds, etc.
- Opportunistically using feeder outages should they be made available by the utility.

The CIT circuit shall be chosen to suit the main mechanism of AC interference affecting that particular asset. For example:

- Voltage hazards at the pipeline appurtenances themselves due to the magnetically induced potential. Either of the two CIT circuits described in Sections 2.4.1.1 and 2.4.1.2 may be used.
- Voltage hazards transferred via the soil to nearby objects due to the magnetically induced potential on a pipeline earthing system. Either of the two CIT circuits described in Sections 2.4.1.1 and 2.4.1.2 may be used.
- Voltage hazards at a pipeline appurtenance due to conductive coupling from a nearby HV tower or pole. Only the CIT circuit described in Section 2.4.1.3 may be used.

2.4.1.1 Injecting Over a Parallel Feeder

Injecting test current between two substations over an out-of-service feeder that runs parallel to a pipeline allows for the inductive coupling component of the AC interference to be directly measured at the pipeline. Since earth faults at all towers along a pipeline route cannot be simulated due to their large number, this method neglects the conductive component of the pipeline touch voltages. This method may however be suited to situations where the conductive influence of the towers on the pipeline is negligible due to large pipeline/feeder separations or favourable soil structures. During the injection of the test current, touch voltages, step voltages and induced pipeline potentials can be directly measured at appurtenances along the pipeline route. Correction modelling will be required to account for the influence of the test circuit on measured results as well as any nonlinearity associated with saturation of steel OHEWs during high current fault conditions.

Current injection testing over out-of-service feeders to validate AC interference mitigation designs is generally considered impractical once time, cost, availability of suitable feeders and the large number of possible earth fault scenarios along a typical right-of-way are accounted for.

2.4.1.2 Injecting Directly into a Pipeline Appurtenance Earthing System

An alternative CIT circuit involves injecting the test current between an earthed pipeline appurtenance (disconnected from the pipeline) and a temporary network of electrodes installed at a remote location. The EPR of the grid is measured by performing a fall-of-potential test by running out a potential lead in a direction at 90° relative to the test current. Touch, step and transfer voltages can then be measured at the appurtenance and at surrounding infrastructure such as fences, water taps and telecommunications pits.

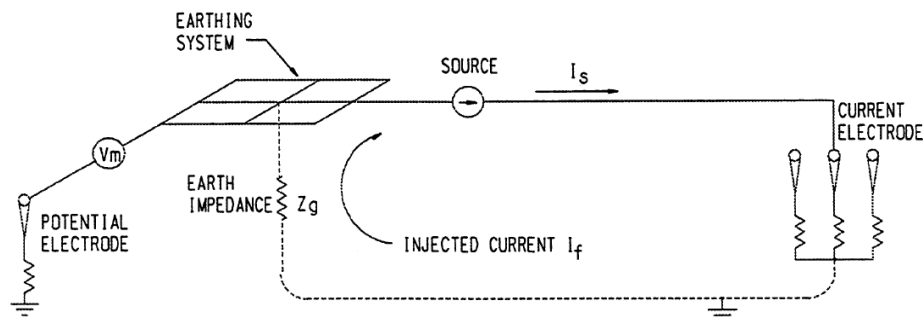


Figure 2-8: Typical CIT Test Circuit.

It should be noted that this test method does not allow for any of the inductive effects to be simulated or measured. Additionally, it does not allow for the conductive component of the touch voltage due to proximity to nearby HV poles or towers. Measured results must be scaled up to full system fault levels and therefore are heavily reliant on CDEGS simulation results.

2.4.1.3 Injecting Directly into a Nearby HV Pole or Tower Earth

With cooperation from the asset owner, the conductive coupling between a HV pole or tower and a pipeline appurtenance can be measured by injecting the test current between the HV tower or pole and a temporary network of electrodes installed at a remote location. The EPR of the tower is measured by performing a fall-of-potential test by running out a potential lead in a direction at 90° relative to the test current. The soil voltage gradients surrounding the tower and resulting touch voltages to the pipeline appurtenance can be measured. The testing can be done with the feeder in service however safe work practices must be employed due to the possibility of high EPR that may appear on feeder earths during fault conditions.

2.4.2 Visual Inspection

A visual inspection is mandatory and shall be carried out for all earthing systems installed along a pipeline.

The visual inspection shall include but is not limited to:

- Design compliance and as built drawing accuracy
- Condition and size of earthing conductors
- Condition and size of earthing connections
- Condition of high resistivity earth surface covering layer if installed
- Presence of equipotential bonding to reinforcement in pit liner, step irons, etc.
- Installation and connection to AC/DC decoupler

- Identification of areas where secondary mitigation may be required due to unforeseen hazards at the design stage

2.4.3 Fall-of-Potential Testing

A fall-of-potential (FOP) test is mandatory and shall be performed on every valve earthing system prior to connection to the valve. This testing shall be performed as described in IEEE Standard 81 – 2012 using a high power switched DC portable earth tester.

The primary reason for conducting a FOP on a stand-alone valve earthing system is to obtain the earthing system impedance to earth such that the pipeline shunt impedances in the CDEGS model can be updated to actual measured values.

2.4.4 Continuity Testing

Continuity testing is mandatory and shall be performed on every valve earthing system. Measurements shall be made with a low resistance ohmmeter between the main earth bar and all bonded items. Pass / fail criteria should be determined by analysis of the distribution of all continuity measurements at the site under test in conjunction with the size of the bonding conductors.

If Sintalined® or other pipeline isolation sections have been installed, use a high power switched DC earth tester or other appropriate meter to measure the series impedance of the isolated pipeline section (filled with water). Note that significant errors can be introduced by the test current flowing in parallel earth return paths. These errors must be accounted for through analysis and computer simulation.

2.4.5 Steady State Pipeline Potential Measurement

Steady state 50Hz induced pipeline potential measurement is mandatory and shall be measured at each appurtenance using a high impedance voltmeter. The pipeline potential should be recorded along a straight line profile running 90° relative to the transmission lines. The length of the profile should be extended until the potential reading levels off. Note that all pipeline earthing systems are to be completed and connected to the pipeline at the time of testing.

By obtaining feeder loading data from the utility corresponding to the time of testing, the test measurements can be compared to the CDEGS simulation results to form part of the validation process.

2.4.6 Computer Modelling and Correction

Due to the complexity of inductive and conductive interactions inside a typical right-of-way, comprehensive validation of a pipeline earthing system via testing alone is impractical. Instead, a practical range of tests as described in the previous sections shall be carried out with the measured data being used to update, rerun and check the original computer models essentially producing an “as-built” CDEGS model.

The computer modelling component of the validation process is as follows:

- If current injection tests were carried out, update original CDEGS model to reflect measured values taking care to correct for any errors introduced into the measurements by the test circuit itself (off-frequency test signal, saturation of OHEWs during high current faults, test circuit arrangement).
- If the series impedance of isolation sections has been measured, update model with measured values.
- Update shunt impedances in the computer model with measured values and rerun all simulations.
- If steady state pipeline potentials have been measured compare measured values and simulation results.
- Verify that computed touch and step voltages are within the allowable limits.
- If practical, design secondary mitigation to account for any additional hazards identified on site.

2.4.7 Commissioning Report

All details associated with the validation tests shall be documented in the commissioning test report which shall include:

- Test circuits
- Correction modelling and comparison to design values
- Updated simulation results
- Test results
- Updated hazard and risk assessment

3 Process and Technical Requirements for Substation Earthing

3.1 Earthing System Design

3.1.1 Compliance with the WHS Act

In addition to robust technical design, the designer must also fulfil the legal requirements of the WHS Act. The designer must demonstrate due diligence in the mitigation of voltage hazards on any Water Corporation asset. The designer must ensure, so far as is reasonably practicable, the safety of workers and the general public coming in contact with an affected asset.

3.1.2 Common Law Approach to HV Substation Earthing Design

The following process shall be used when designing earthing systems for Water Corporation HV assets.

1. Identify Critical Hazards – Perform detailed earthing system design as described in Section 3.
2. Identify all practical precautions for each critical hazard by following the hierarchy of controls – Recognised mitigation measures are summarised below.
 - a. Elimination
 - i. Eliminate need for substation
 - ii. Fibre reinforced plastic instead of metal handrails, grates, etc.
 - iii. Non-conductive bollards
 - b. Substitution
 - i. Relocate substation to lower risk location
 - ii. Relocate substation to location with lower soil resistivity
 - iii. Use underground cables instead of overhead feeders
 - iv. Choose HV supply with highest reliability
 - v. Use non-conductive poles for incoming supply
 - vi. Non-conductive kiosk substation enclosures
 - c. Isolation
 - i. Ensure sufficient space around outside of substation boundary fence to minimise soil potential transfer voltage hazards to neighbouring properties
 - ii. Use pole mounted hook/stick operated switching equipment
 - iii. Apply insulating coating to conductive poles
 - iv. Security fencing, barricades
 - d. Engineering
 - i. Earth fault limitation
 - ii. Reduce earth fault clearance time
 - iii. Install or upgrade overhead earth wire on feeder or bonding of cable screens on feeders (cooperation with utility) to take advantage of return current that reduces EPR and induced voltages
 - iv. Install grading ring / mesh / electrode (i.e. substation earthing system)
 - v. Equipotential bonding (including bonding to concrete reinforcement)

- vi. Insulated fence sections in metallic fences of adjacent properties
- vii. Voltage limits as described in Section 2.2.7
- viii. High resistivity surface layers such as gravel or hot-mix asphalt
- e. Administrative Controls
 - i. Worker training
 - ii. Safe work procedures
 - iii. Signage
- f. Personal Protective Equipment
 - i. Insulating gloves
 - ii. Insulating boots
 - iii. Temporary equipotential mats and bonding
- 3. Determine the reasonableness of each of the practical precautions
 - a. Dialogue between substation earthing designer, owner, substation designer, cathodic protection designer, stakeholders, etc.
- 4. Implementation of reasonably practicable precautions
 - a. Electrical safety during construction documentation to be supplied by the designer
- 5. Monitoring and review.
 - a. Commissioning testing and ongoing maintenance

3.2 Earthing Design Technical Review Process

Earthing system design for high voltage Water Corporation assets shall follow the technical review process in Figure 3-1, with all stages carried out by the same organisation.

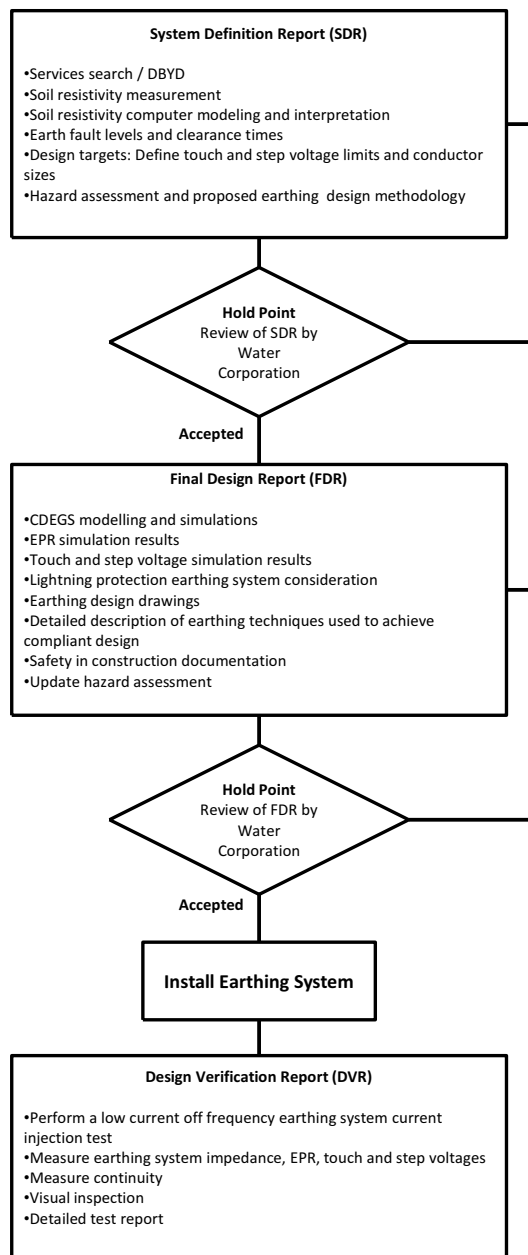


Figure 3-1: Earthing System Design Technical Review Process.

3.3 System Definition Report (SDR)

3.3.1 Data Gathering

The following information must be obtained at the commencement of a substation earthing design:

- An engineer shall attend the site of the proposed substation perform soil resistivity tests. Refer to Section 3.3.2.

- Proposed substation general arrangement drawings, concrete footing drawings, fencing drawings.
- Surveyed property boundary drawings including existing property fences.
- Dial-before-you-dig (DBYD) drawings for water pipes, gas pipes, telecommunications, etc.
- Single line diagrams for the substation itself and for the utility's network that feeds it.
- Single phase to earth and double phase to earth fault levels and primary and backup feeder protection clearance times from the power utility.

3.3.2 Soil testing

At least two Wenner Method soil resistivity tests (100m maximum spacing) shall be carried out in perpendicular directions over the proposed substation site. Additional tests and analysis may be required to account for earthworks (benching / cut and fill). SDR shall not be submitted until all earthworks have been completed and bench soil information has been accounted for. Refer to Section 2.2.4.2 for soil test method.

Assumed soil resistivities shall not be used.

3.3.3 Touch and Step Voltage Limits

Refer to Section 2.2.7 for touch and step voltage limit calculation methods.

The lowest top layer resistivity measured on site shall be used to calculate the 'natural surface layer' foot impedance for all voltage limit calculations. Care should be taken not to rely on thin natural top layers for safety.

3.3.4 Conductor sizing

Conductor sizes are to be calculated as per IEEE Standard 80 using maximum future earth fault levels and backup total clearance time.

- Lugged and bolted connections shall have a maximum allowable temperature of 250°
- IEEE Standard 837 compliant connections shall have maximum allowable temperature of 350°
- Minimum earthing system conductor size shall be 70mm² soft drawn copper

Note: Only copper conductors to be used.

3.3.5 Preliminary Design Modelling (CDEGS®)

3.3.5.1 CDEGS RESAP

All soil resistivity test results shall be analysed with CDEGS RESAP module. Since more than one soil must be obtained per site, all available test data must be used to choose a soil model that best represents the site. The following process demonstrates how to choose the most conservative soil model for use in the final design.

- Analyse each soil test individually in RESAP.
- Enter all soil test results into a single RESAP run to obtain an average.
- Utilise MALZ to simulate a typical earthing system in each of the above soil models to determine which of the generated soil models yields the most conservative results in terms of impedance, EPR, touch voltage and soil voltage gradients.

3.3.5.2 CDEGS MALZ

The preliminary proposed earthing system should be modelled as described in Section 3.3.5.1 only as a means to determine which soil model will be the worst-case.

3.3.6 Documentation

A System Definition Report (SDR) shall be submitted to Water Corporation and this forms a hold point in the technical review process. Detailed design shall not progress until the SDR has been approved by Water Corporation. The SDR shall include:

- Services search / DBYD drawings with the proposed substation location clearly highlighted and affected services identified.
- Soil resistivity measurements, RESAP and MALZ simulation results with discussion on how worst-case soil model was chosen.
- Documented fault level and clearance time data supplied by the utility.
- Preliminary design earthing system impedance.
- Calculated touch and step voltage limits (include calculations)
- Hazard assessment highlighting possible earthing hazards located:
 - Inside the substation boundary: equipotential bonding, concrete reinforcement bonded or not bonded to earthing system, lightning protection, etc.
 - Outside the substation: boundary fence bonded or not bonded to earthing system, UGOHs, external services, Telstra, etc.
 - Along connected pipelines
 - In neighbouring residential or industrial properties: transfer voltage hazards at fences, MEN connected equipment, pools, etc.
- Identification of the standard best practice earthing techniques that will be used to mitigate touch and step voltage hazards identified above. These may include (but are not limited to):
 - Grading conductors
 - Electrodes
 - Equipotential bonding
 - Bonding of concrete reinforcement
 - Insulating fence sections on external fences
 - Metallic boundary fence bonded to or isolated from the substation earthing system

- Non-conductive boundary fence around the substation such as masonry
- Use of fibre reinforced plastic (FRP)
- High resistivity surface layers such as hot-mix asphalt or gravel
- Isolation of incoming services and pipelines
- Avoiding building all the way out to the allocated property boundary to allow an EPR buffer zone from neighbouring properties if required.

3.4 Final Design Report (FDR)

3.4.1 Detailed Earthing System Design Process

The detailed earthing system design shall follow the process outlined in the flowchart of Figure 8.1 of AS 2067 – 2008 (reproduced in Figure 3-2).

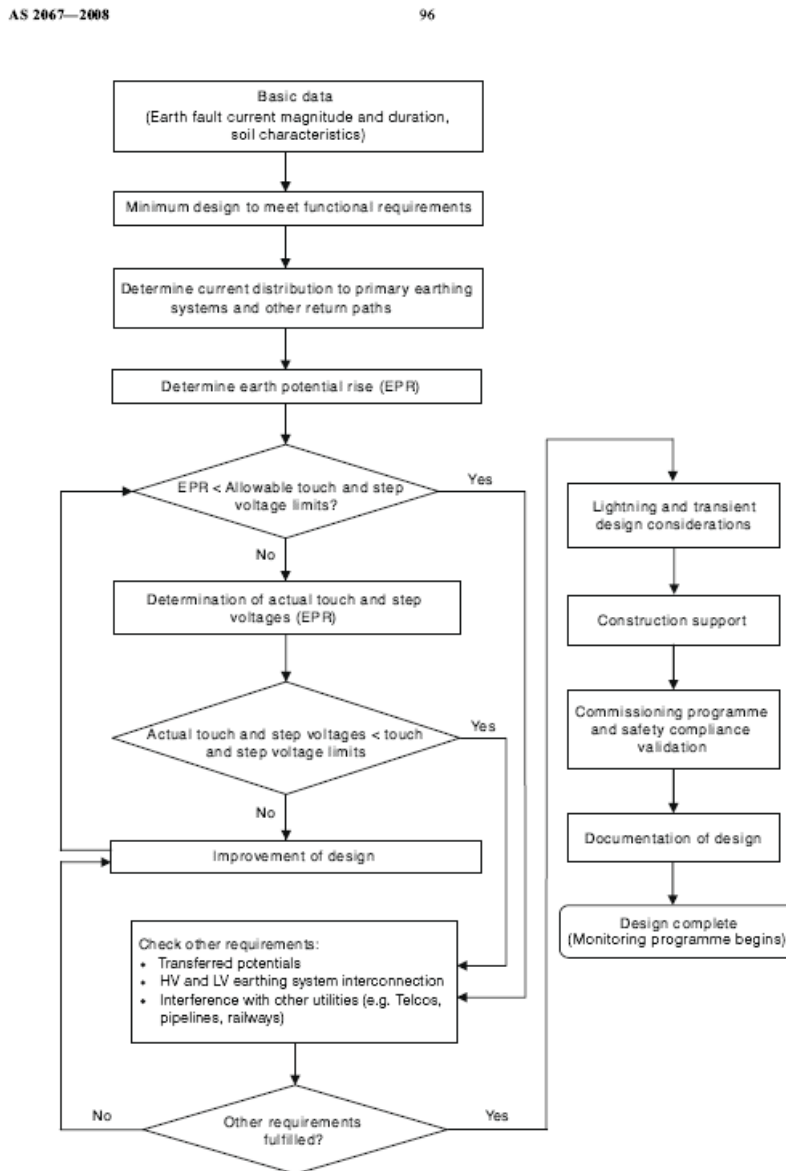


FIGURE 8.1 EARTHING SYSTEM DESIGN FLOW CHART

Figure 3-2: AS 2067 – 2008 Earthing System design Flowchart

3.4.2 Final Design Modelling (CDEGS®)

CDEGS MALZ or HIFREQ module should be used for all simulation of the buried earth grid. The following CDEGS outputs should be included in the final design report:

- Touch and step voltages inside and around the boundary of the substation
- Touch voltages at surrounding metallic infrastructure affected by the substation
- Touch voltages at pipelines entering or leaving the installation
- Soil potential
- Earth potential rise
- Earthing system impedance

All output plots shall only be two dimensional.

If required and approved by the electricity utility and Water Corporation, use CDEGS HIFREQ, FCDIST, TRALIN or SPLITS modules to compute the current distribution in the incoming HV feeders. It should be noted that currently Western Power does not allow for customer earthing systems to rely on connection to the utility earthing system via OHEWs and cable screens. As per Western Power Technical Rules, touch and step voltage compliance of Water Corporation substations shall be based on stand-alone earthing systems (i.e. assuming the full fault current is injected through the substation earthing system with no reliance on the earth return to the Western Power network).

3.4.3 Lightning

The earthing system shall be suitable for use as a lightning protection system earth termination. Typically, the resistance should be less than 10Ω to achieve compliance with AS/NZS 1768:2007.

The need for lightning protection air terminations to protect HV equipment, buildings and structures shall be determined in accordance with AS/NZS 1768:2007.

3.4.4 Earthing System Impedance

There is no target earthing system impedance for HV earthing systems. The key compliance criteria are touch voltage, step voltage, transfer voltages, EPR and insulation coordination.

Although bonded reinforced concrete foundations help reduce the overall impedance of an earthing system, waterproof membranes, compressive strength and concrete additives may impede the current flow to earth thus reducing the effectiveness of concrete encased earthing.

3.4.5 Earthing System Design Drawings

Earthing design drawings shall include:

- Earthing system general arrangements
- Bonding schematic diagrams
- Installation detail drawings
- Safety criteria limits
- All performance parameters

3.4.6 Safety in Design

Earthing systems are primarily installed for the protection of equipment during transient and fault conditions. In this regard, the key aspects of earthing systems are conductor sizes, conductor joints and earth grid impedances to ensure mechanical damage is eliminated, protection systems operate correctly and insulating ratings are not exceeded.

By the application of the process and design techniques in DS 23 with particular emphasis placed on human safety by the analysis and mitigation of touch and step voltage hazards, 'safety in design' requirements are addressed. It is important that additional hazards are not introduced by the design and installation of the substation earthing systems or the failure of the installed earthing systems. The following aspects should be considered as part of the design:

Constructability

- Concrete slab reinforcement electrical continuity complementary with civil plans. Adequate continuity achieved using the minimum number of welds.

Access / Egress

- Equipotential bonding conductors should not impede access to switchrooms, transformer bunds, etc. causing slips, trips and falls.

Environmental

- IEEE 837-2002 compliant bonds shall be used for all buried permanent earthing connections.
- Bonding conductors and AC/DC decouplers rated for lightning impulses.

External Safety

- Vandalism or copper theft. Earth risers to boundary fences should be installed on the inside of the fence
- Redundancy in earth connections

Utilities and Services

- Touch voltage hazards at nearby metallic fences, metallic structures, water taps, communications pits, etc. due to proximity to substation earthing system.

Robustness

- Bonding conductors and AC/DC decoupler rated for induced and steady state currents.
- Materials chosen to minimise corrosion (i.e. copper earth risers PVC insulated at the soil/air interface)

Inspection / Testing / Maintenance

- Ease of inspection and testing – where possible eliminate need to climb into pits to perform earthing testing.
- Design earth bars and electrodes so clamp types CTs can be used to easily measure current distributions in cable screens, electrodes, etc. during current injection tests.

3.4.7 Safety in Construction

Earthing systems are designed for the long term protection of equipment and human safety. During the construction process however, especially around existing installations, construction workers may be exposed to touch and step voltage hazards before the mitigation measures are installed.

General and site specific safety procedures must be documented by the earthing designer and may include (but are not limited to):

- PPE – Appropriately rated insulating boots, gloves and mats where appropriate
- Temporary equipotential bonding and working mats
- Temporary earthing
- Order of installation

- Work procedures, exclusion zones
- Use of double insulated electrical tools
- Protection against capacitive coupling for suspended metalwork under overhead power lines
- Prevention of direct contact with overhead lines
- Suspension of work during lightning
- Site specific pre-work risk assessment

3.4.8 Documentation

A Final Design Report (FDR) shall be submitted to Water Corporation and this forms a hold point in the technical review process. Earthing system construction shall not proceed until the FDR has been approved by Water Corporation. The FDR shall include a summary of all material presented in the SDR plus:

- Detailed step and touch voltage simulation results
- EPR simulation results
- Current distribution simulation results if required
- Simulation results focussing on interaction with connected pipelines
- Soil potential contours
- Safety in design documentation
- Safety in construction documentation
- Assessment of suitability of earthing system to be used as a lightning protection system earth termination as per AS/NZS 1768:2007.
- Updated hazard assessment with confirmation from simulation results that design safety targets have been met.
- Earth potential rise coordination with telecommunications network – Compliance to AS/NZS 3835:2006
- Earthing design drawings that include critical information such as:
 - EPR and supplied fault levels
 - Soil model
 - Voltage limits and clearance time
 - Calculated touch and step voltages at critical points within the installation
 - Reference to appropriate design report for further reference
 - Performance of design for stand-alone and for connection to OHEWs and/or cable screens.

3.4.9 Installation Specification

3.4.9.1 Redundancy

No reliance on a single wire connection to any part of the earthing system which may result in non-compliance if it is broken or removed.

3.4.9.2 Earthing System Connections

All earthing system connections under finished ground level (e.g. direct buried, within earth pits, etc.) shall be made with IEEE Standard 837- 2002 compliant connectors.

Accepted connector suppliers are:

- CADWELD
- Groundlok
- Panduit (connectors using only the enhanced crimp process consisting of 3 crimps per connector)

Above ground, bolted connections shall be used for equipment, earth bars, etc. Green/yellow PVC insulated soft drawn copper risers shall be terminated in a suitably sized compression lug. M12 grade 316 stainless steel nuts, washers and bolts shall be used for bolted connections. Only one earth cable connection per bolt/tab is permitted. An anti-seizing / anti-galling compound shall be used. Note care must be taken to ensure the electrical connection itself is free from the anti-seizing compound.

Where required appropriately sized hot dipped galvanised steel tab shall be welded to any structure, pipeline, etc. requiring a bolted earth connection.

3.4.9.3 Conductor sizing

- Conductor sizes are to be calculated as per IEEE Standard 80 using maximum future earth fault levels and backup total clearance time.
- Lugged and bolted connections shall have a maximum allowable temperature of 250°
- IEEE Standard 837 compliant connections shall have maximum allowable temperature of 350°
- Minimum earthing system conductor size shall be 70mm² soft drawn copper.
- Only copper conductors shall be used

3.4.9.4 Combined Earthing System

Where possible a combined HV/LV earthing system in accordance with AS/NZS 3000:2007 shall be used. Note: For small sites, special provisions may apply where a separated HV/LV is necessary. Refer Design Standard DS22.

3.4.9.5 Grading Conductors

70mm² bare soft drawn or 35mm² bare hard drawn copper grading conductors shall be installed at a depth of 500mm with a minimum trench width of 75mm. The conductor is to be laid on 25mm layer of quality fill and the trench is to be backfilled with 500mm of quality fill which is compacted in maximum 200mm thick layers to 95% standard in accordance with AS1289.1.1. The grading conductor depth may be adjusted based on results of the detailed design.

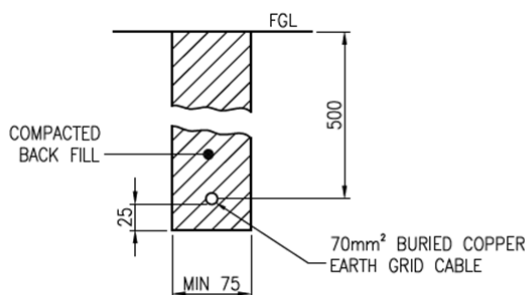


Figure 3-3: Grading Conductor Installation

Typically grading rings shall be installed and spaced 1m around transformer kiosks, prefabricated substations, HV switchrooms, unfenced kiosk substations, HV substation perimeter fences and aerial switch poles. Grading rings may be omitted under some circumstances as dictated by computer simulation results.

3.4.9.6 Electrodes

Electrodes are to be driven where possible using 15mm diameter extendable copper clad Fulton Industries type CDR15xx or equivalent. Appropriate accessories are to be used as required.

Where conditions do not favour driven rods, electrodes shall be installed in 75mm drilled holes. The holes shall be backfilled with a slurry mixture of 50% bentonite, 45% gypsum and 5% sodium sulphate by mass or equivalent commercially available earthing compound such as Fulton Industries Good earth or similar. Other appropriate earthing compound may be required if the hole extends into the water table. Copper clad steel electrodes, bare stranded copper or a combination of the two may be installed in the drilled holes.

A plastic earth rod inspection box, Erico PIT T416D or equivalent, is to be installed for each earth electrode in non-trafficable areas. A 100mm loop is to be formed at the top of the electrode to allow a portable tong meter to be used to measure the electrode impedance.

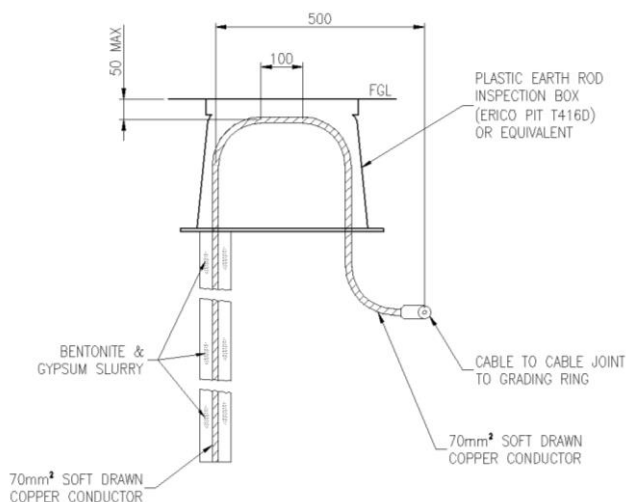


Figure 3-4: Electrode Installation

3.4.9.7 Concrete Reinforcement Bonding

All steel concrete reinforcement is to be bonded to the earthing system. A minimum of 2 x 70mm² bare soft drawn copper conductors shall be installed from diagonally opposite corners of each slab to the earthing system.

The topmost layer of steel reinforcement of all new concrete slabs is to be made electrically continuous via welding. An electrically continuous ring shall be created around the perimeter of each slab via welding of steel reinforcing bars. Electrical continuity shall be provided by welding the inner reinforcing bars to the perimeter ring at maximum spacings of 2000mm along all sides of the slab. The inner reinforcing bars that are welded to the perimeter ring shall also be made longitudinally continuous via end-to-end welding of the bars for the entire distance across the slab. Earth risers to equipment, structures, earth bars or to the earthing system itself shall only be connected to reinforcement bars that are part of the welded network. Refer to Figure 3-5.

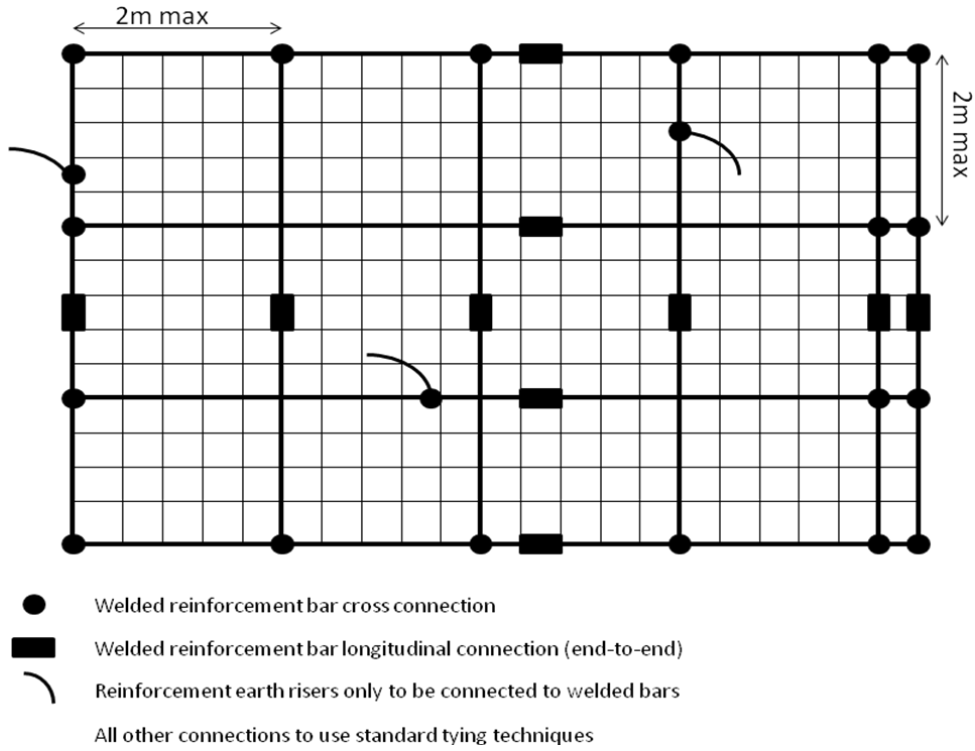


Figure 3-5: Reinforcement Bar Welding

Electrical continuity is to be provided across all sawn and expansion (construction) joints as shown in

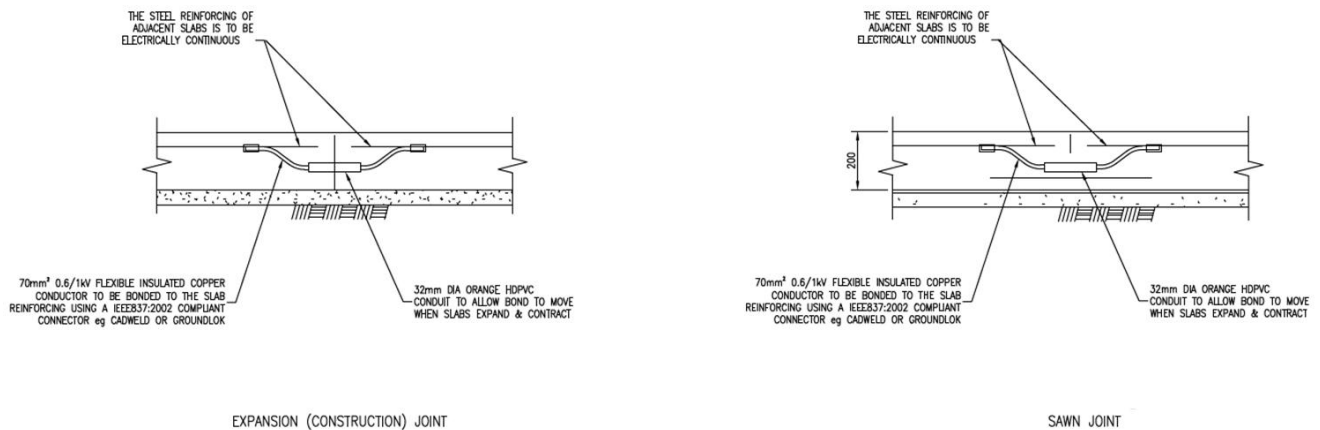


Figure 3-6. Where more than one layer of steel reinforcing is used, the above shall be applied to the topmost layer of reinforcing. All other joints between reinforcing bars may be made using typical jointing methods.

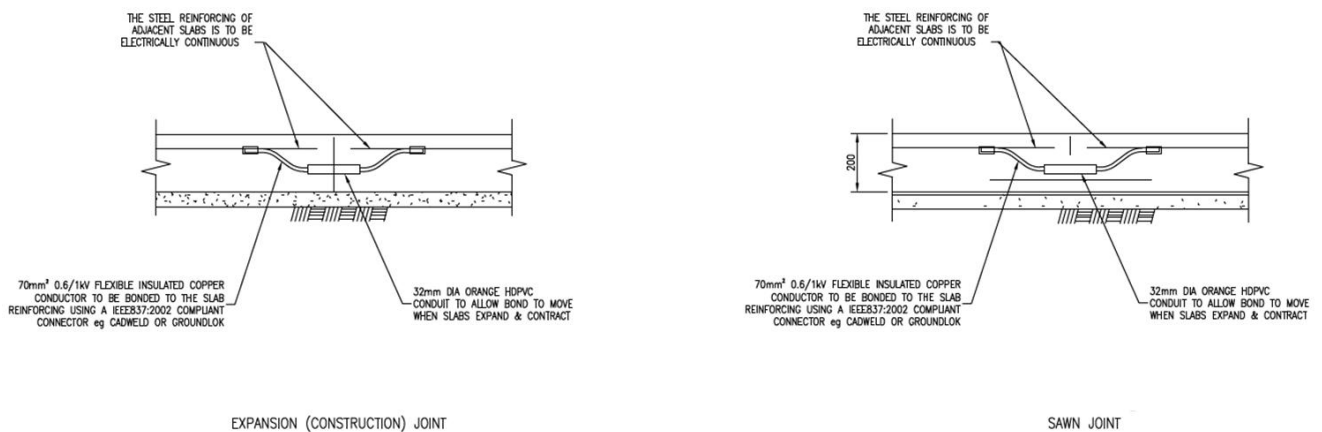


Figure 3-6: Reinforcement continuity across concrete joints

The electrical continuity of the steel reinforcing in each slab shall be inspected and proven by test prior to concrete being poured. The test shall be carried out by a trained technician using a calibrated micro-ohmmeter. The test results shall be recorded in an inspection test plan. The inspection test plan shall be approved by the site electrical supervisor prior to concrete being poured.

A section of steel reinforcing shall be considered 'electrically continuous' if the measured electrical resistance between both pairs of diagonally opposing corners of the reinforcement does not exceed 20mΩ (subject to size of slab and reinforcement bar). If the measured resistance exceeds this value, the designer shall be consulted to determine if further action is necessary.

A section of steel reinforcing shall be considered 'electrically continuous' with another section of steel reinforcing or structure (such as structural columns) if the measured electrical resistance between the two does not exceed 20mΩ. Example tests include between column hold down bolts and the reinforcement welded perimeter ring or between two adjacent slabs. If the measured resistance exceeds this value, the designer shall be consulted to determine if further action is necessary.

6mm fillet welds shall be used for all welds.

Suitably sized galvanised steel tabs or Dulmison C-70 shall be welded to the reinforcement for connection to the earth riser.

3.4.9.8 Metallic Fences and Gates Connected to the Main Earthing System

Every fourth post, every corner post and every gate post shall be bonded to the earthing system. The earth bonds shall be made on the inside of the fence. Galvanised steel tabs suitably sized to receive an M12 bolted connection shall be welded to all equipment requiring an earth connection.

All gates shall have one 70mm² PVC insulated flexible soft drawn copper bonding conductor or equivalent sized flexible braid fitted between the gate and the gate post. Where gates swing outwards, grading conductors shall be installed 1m outside the gates arc.

Where required, a grading conductor and/or asphalt are to be installed 1m around the outside of the boundary fence. The grading ring is to be bonded directly to the main earthing system via multiple connections running in conduit under the fence utilising IEEE Standard 837 compliant connectors. Under no circumstances shall the grading ring be bonded to the main earthing system via the fence. Ensure the substation fence is at least 1m inside the boundary line to avoid encroachment onto neighbouring properties.

3.4.9.9 Metallic Fences and Gates Separated from the Main Earthing System

Sometimes it may be necessary to separate the metallic boundary fencing from the main earthing system in order to reduce touch voltages to safe levels. The fence earthing shall be designed to suit the specific installation using CDEGS software. Special consideration shall be given to electric gate openers, electronic access systems, CCTV, lighting, switchboards, etc. to ensure earthing separation is maintained.

3.4.9.10 Insulated Fence Sections

The substation fence shall be isolated from neighbouring metallic fences using fence sections constructed out of wood, non-reinforced masonry or fibre reinforced plastic. The minimum length of an isolation fence panel is to be 3m with the maximum length determined as part of the detailed design. Refer to Section 2.3.7.9 for further design options.

3.4.9.11 Earth Bars

All transformers, switchboards, switchrooms, control rooms, etc. shall have earth bars installed. Earth bars are to be mounted in a location so as to avoid trip hazards.

Cross sectional area of copper earth bars are to be sized as described in Section 3.4.9.3 and must also be sized to accept all required earthing connections via M12 bolts. A minimum of two spare holes shall be provided to ensure sufficient room is available for future connections. Only one lug per bolt is permitted.

All bonding cables shall be permanently marked indicating to which piece of equipment they are attached.

3.4.9.12 Equipment Bonding

Bonds shall be made between equipment and the earthing system according to Table 3-1. Where two bonds are listed, they shall be made from diagonally opposite corners of the item to different locations on the earth grid. If the cable design specification allows, all cable screens are to be bonded to the earthing system at both ends. If cables must be run single point bonded then an appropriately sized earth continuity conductor must be run with the cable. All major earth connection cables shall be clearly labelled at both ends.

Table 3-1: Equipment Bonding

Item	Number of Bonds to HV Grid
Transformer tank	1
Earth bar	2
Transformer neutral	1
NER	1
Outdoor active steel work such as surge arrestors, circuit breakers, CTs, VTs, ABS, earth switches, landing structure, etc.	2
Indoor switchgear	2
Concrete slab reinforcement	2 per slab
Passive steel work such as hand rails, fence posts, grate flooring, stairs, ladders, deluge showers, etc.	1 per location as required
Cable trays	1 at each end
Lightning air terminations	1 for each air termination
Steel tanks, towers, etc.	Subject to AS/NZS 1768 lightning protection risk assessment
Incoming earth associated with utility	0 The utility earth is to be separated from Water Corporation earth unless computer simulations show that bonding is essential for safety reasons and accepted by the Water Corporation and the utility. Connection to the utility earth shall not be to the detriment of the Water Corporation earthing system (and vice versa). Transfer voltages between earthing systems shall be quantified.
Pipeline Mounted Instrumentation	0 Instrumentation to be electrically isolated from pipe work and earthed separately to the instrumentation earth bar in accordance with DS 25

3.4.9.13 Services Isolation

Incoming water mains from the street supply shall be broken by a 6m section of nonconductive pipeline where the pipe crosses the fence line entering the HV installation (3m either side of the fence).

A street LV supply entering a HV installation shall be isolated using an appropriately rated isolation transformer located inside the HV installation boundary. The secondary earth shall be bonded to the HV installation earthing system.

Optical fibre should be used where possible to eliminate the voltage hazards associated with copper wires. If copper must be used, the need for isolation of copper phone lines entering a HV installation shall be determined as part of the design based on:

- Maximum computed EPR of the HV earthing system
- Insulating rating of phone equipment
- AS/NZS 3835: 2006 - Protection of telecommunications network users, personnel and plant – All Parts.

3.4.9.14 High Resistivity Surface Layers

To increase foot contact impedance, a high resistivity surface layer may be installed such as:

- A minimum 100mm thick layer of 3000Ωm (wet resistivity) washed gravel with minimum aggregate size of 20mm
- Minimum 30mm thick layer of hot-mix asphalt (no metallic additives). Asphalt shall be installed upon a suitable stabilised/compacted base layer to prevent movement, cracking and erosion.

3.4.9.15 Cathodic Protection

All earthing system design shall be performed in consideration of cathodic protection design requirements. The effect of AC/DC decouplers, insulating flanges and associated surge diverters shall be taken into account in the HV earthing system design. Note that insulating flanges and associated surge diverters for cathode protection purposes are not suitable for the EPR associated with high voltage earth faults.

3.5 Earthing System Design Validation

The validation of Water Corporation HV earthing systems is achieved by carrying out the following four key activities.

- Current injection testing to measure EPR, touch voltages, step voltages and current distribution
- Visual inspection / physical integrity check
- Continuity testing
- Computer modelling and correction

3.5.1 Current Injection Testing

It is possible to simulate an earth fault by injecting a low current off frequency test signal (such as 58 or 60Hz for a 50Hz power system) around an earth return loop. EPR, current distribution, touch voltages and step voltages may be directly measured during a current injection test.

Current injection test methods described in IEEE Standard 81 – 2012 should be followed.

The basic CIT circuit involves injecting the test current between a HV substation earthing system and a remote earthing system. The remote earthing system can either be temporary network of electrodes or a distant substation earthing system and the test current can be injected over an out-of-service feeder or over temporary test leads.

The EPR of the grid is measured by performing a fall-of-potential test by running out a potential lead in a direction at 90° relative to the test current. Touch, step and transfer voltages can then be measured at the substation and at surrounding infrastructure such as fences, water taps and telecommunications pits. The current distribution in any OHEWs or cables screens must also be measured. Refer to Figure 3-7 for a typical CIT circuit. Open circuit touch and step voltages shall only be measured (refer to Section 4.2 for details).

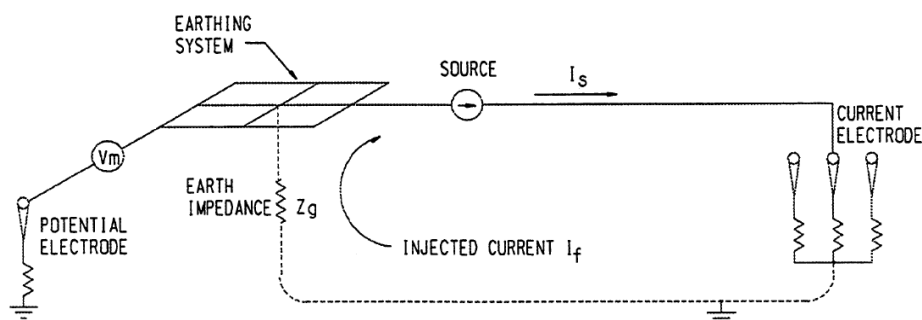


Figure 3-7: Typical CIT Test Circuit.

3.5.2 Visual Inspection

The visual inspection shall include but is not limited to:

- Design compliance and as built drawing accuracy

- Condition and size of earthing conductors
- Condition and size of earthing connections
- Condition of earth electrodes
- Condition of high resistivity earth surface covering layer
- Fences and any other external transfer voltage hazards
- Assessment of impact on nearby telecommunications infrastructure
- Assessment of impact on associated pipelines
- Identification of areas where secondary mitigation may be required due to unforeseen hazards at the design stage

3.5.3 Continuity Testing

Continuity measurements shall be made with a low resistance ohmmeter between the main earth bar and all bonded items of plant. Pass / fail criteria should be determined by analysis of the distribution of all continuity measurements at the site under test in conjunction with the size of the bonding conductors.

3.5.4 Computer Modelling and Correction

A CDEGS HIFREQ model of the current injection test circuit shall be created for the following reasons:

- To ‘double check’ the test measurements. Modelling the test circuit in HIFREQ will highlight any anomalies that may be encountered in the test results.
- To correct for the interaction between the test circuit and the earthing system under test and the interactions within the test circuit itself. When performing a current injection test (CIT) it is necessary to set up a test circuit using many long temporary leads. These leads generally sit on the soil surface and sometimes they run parallel to cable screens or OHEWs that are carrying test current. Therefore, it is often found that even with an optimal test circuit, errors due to inductive, capacitive and conductive coupling are unavoidable.
- To correct for the use of a non-power frequency test signal. A test signal other than 50Hz in the range 40-60Hz is commonly used to avoid interference from background 50Hz noise. Since earthing systems are not purely resistive and can sometimes contain a significant reactive component, the test results must be converted from the test frequency back to 50Hz.
- To validate the soil model that was used for the design. At the design stage, Wenner Method soil resistivity test results are processed with CDEGS RESAP module to determine the multi-layer soil model at the proposed substation site. By comparing measured soil voltage gradients from the CIT with simulation results allows for the chosen multi-layer soil model to be validated.
- To validate the HIFREQ models used for computing EPR and current distribution for actual fault scenarios. It is often impractical to perform a current injection test (CIT) using a real earth fault circuit that often extends tens of kilometres back to the star point. It is also impractical to perform a CIT for each of the many feeding arrangements that can exist at a given substation. The method recommended to validate the calculated EPR and current distribution at a substation is summarised below:
 - Perform a CIT preferably using feeders that will be in service once the substation is commissioned.
 - Use HIFREQ to model the substation earthing system, all feeders, cable screens, etc. All interconnections to other earthing systems via cable screens must be included. All feeders should be modelled exactly.
 - Simulate the test circuit in the above HIFREQ model.

- Compare the simulation results with measured results. Once good agreement is observed for all measurements of EPR, soil voltage gradient and current distribution then the HIFREQ model can be considered validated.
- Remove the test circuit from the validated model and energise with 50Hz fault current and simulate every possible fault circuit.
- If practical, design secondary mitigation to account for any additional hazards identified on site.

3.5.5 Commissioning Report

All details associated with the validation tests shall be documented in the commissioning test report which shall include:

- Executive summary
- Analysis input parameters
- Test circuits and location (shown on drawings)
- Test results complete with comparison to original earthing design
- Correction modelling and comparison to design values
- Weather conditions during and leading up to the test which may affect the soil condition and test results
- Updated hazard and risk assessment
- Touch and step voltage measurement locations identified on drawings (may include satellite photo).
- Test instrumentation and calibration certificates
- Reference to original design report so that assumptions, calculations, supplied fault levels, clearance times and decisions can be reviewed.
- Summary and conclusion

4 Theory and Principles

4.1 Mechanisms of interference (inductive, conductive, capacitive) and the hazards

4.1.1 Inductive Coupling

Long metallic structures located in transmission line easements are subject to induced potentials due to the magnetic fields associated with high-voltage energy transmission. A pipeline running parallel to a transmission line will intersect the alternating magnetic field line resulting in an induced longitudinal emf on the pipeline metal. The pipeline essentially acts as the secondary of an air core transformer. The induced emf is referenced to earth via the capacitance of the pipeline coating and by any earthing systems installed along the pipeline; the pipeline therefore represents a touch voltage hazard to personnel should the induced potential rise to high levels. It is important to note that both above ground and underground pipelines are affected by magnetic induction.

During normal load conditions magnetically induced potentials are relatively small due to:

- Relatively low normal load line currents
- Balanced line currents causing low resultant magnetic field at the victim conductor.

Any residual induced potential during normal load is due to the incomplete cancellation of the magnetic fields because of slightly unbalanced line currents and the unequal distance between each transmission line phase conductor and the victim conductor.

During single phase to earth faults, one of the three phases carries a large fault current while the other two phases carry negligible current. Due to the large magnitude fault current and the associated large current imbalance, single phase to earth faults represent the worst-case fault scenario.

The worst-case touch voltage due to inductive interference occurs when a person touches an unearthed metallic appurtenance of a well-insulated pipeline. The touch voltage hazard is the potential difference between the high potential pipeline and the low potential soil. Therefore, when the local soil potential near a well-insulated pipeline is zero, the maximum inductive touch voltage is equal to the pipeline potential.

4.1.2 Conductive Coupling

When phase to earth faults occur at towers, large currents are injected into the soil through the tower's earthing systems raising the potential of the surrounding soil. The soil potential decreases as the distance from the tower increases and the rate of drop off is a function of the multi-layer soil model. If an OHEW installed, a proportion of the fault current will return to the star point via the OHEW thus not contributing to the EPR.

The worst-case touch voltage at a pipeline due to conductive interference occurs when a well-insulated and remotely earthed pipeline passes near a faulted pole or tower. Assuming the pipeline is unearthed near the tower, the touch voltage hazard is the potential difference between the low potential (remotely earthed) pipeline and the high potential soil. The maximum conductive touch voltage therefore occurs when the pipeline potential is zero. It is equal to the local soil potential adjacent to the pipe.

4.1.3 Total Effect of Inductive and Conductive Coupling

The phase difference between the magnetically induced potential and the soil potential rise due to conductive coupling is generally in the range 100° to 150° . Since the total pipeline touch voltage is the difference between the two potentials, the total touch voltage hazard can be conservatively taken to be the sum of the inductive and conductive touch voltage magnitudes.

4.1.4 Capacitive Coupling

Electric charges will accumulate on any ungrounded metallic object close to an energised overhead power line. This accumulation of charge which is a result of the capacitive coupling between the object and the phase conductors is a function of the size of the object and the distance to the phase conductors.

The shock from a capacitively charged object under a HV feeder is a two-stage shock. Before contact the open circuit potential on the object can be up to several tens of kilovolts. For a typical situation, the initial transient discharge of the order of 10A flows through the human body to earth when contact is made. This transient lasts of the order of several microseconds and the sensation is similar to that of a static electric shock. It can be conservatively shown using AS/NZS 60479.2:2002 Effects of current on human beings and livestock - Special aspects that ventricular fibrillation will not occur as a result of the initial transient shock.

If contact with the metallic object continues then a steady state current of the order of milliamps can then flow to earth indefinitely through the person touching the object. The steady state loaded potential is typically of the order of several volts.

As per AS/NZS 4853:2012, generally the handling of individual pipe lengths at a safe distance will not give rise to conditions electrically harmful to personnel. Cars and trucks with rubber tyres parked in transmission easements may also experience capacitively coupled voltages and static shocks may represent a nuisance to personnel. Simple temporary earthing such as a short trailing lead on the ground will be enough to dissipate the static charge. Any considerable length of insulated pipeline in a transmission easement will most likely have an LFI voltage hazard which is more severe than the capacitive voltage hazard. Therefore treatment of the LFI hazard will also treat the capacitive hazard.

4.2 Loaded and Unloaded Touch Voltages

4.2.1 Introduction

Touch voltages can be measured two different ways during a current injection test:

1. Unloaded: Also known as Open circuit or Prospective
2. Loaded

It is important to understand the difference between the two and the relationship between measured touch voltages, CDEGS simulation results, and calculated touch voltage limits.

4.2.2 Permissible Touch Voltage Circuit

Consider the touch voltage scenario in Figure 4-1 in which a bare foot person is touching a metallic structure energised by an earth fault.

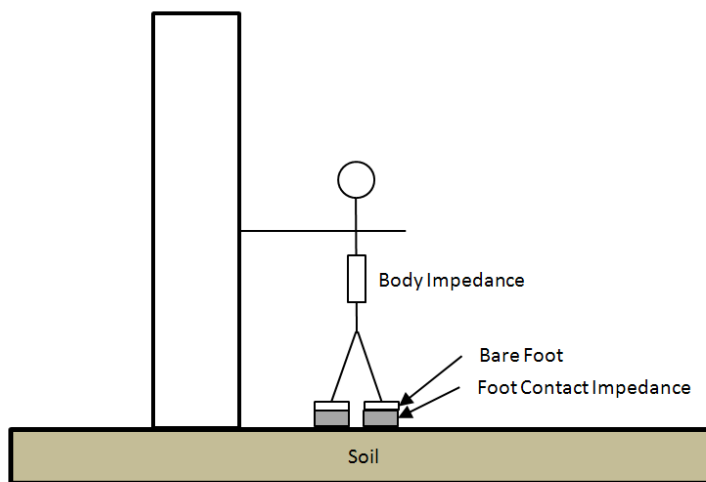


Figure 4-1: Touch voltage during earth fault.

This touch voltage scenario can be represented by the circuit diagram shown in Figure 4-2.

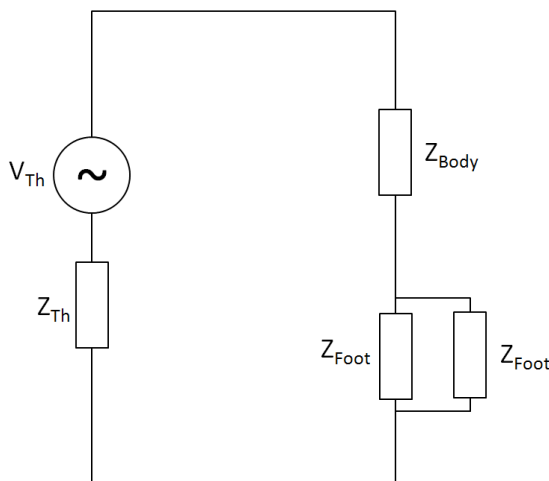


Figure 4-2: Equivalent touch voltage circuit.

Where,

V_{Th} is the Thevenin equivalent of the touch voltage

Z_{Th} is the Thevenin equivalent of the touch voltage source impedance

Z_{Body} is the body impedance calculated using AS/NZS 60479.1

Z_{Foot} is the contact impedance of a bare foot on the soil surface computed using Equations 19 and 27 of IEEE Standard 80 – 2000. Traditionally a metallic circular plate of radius 8cm is used to represent one foot.

For the purposes of this discussion, the circuit in Figure 4-2 can be simplified as follows:

- $Z_{Feet} = Z_{Foot}/2$
- Assume $Z_{Body} + Z_{Feet} \gg Z_{Th}$ therefore V_{Touch} can be considered an ideal voltage source

The simplified touch voltage circuit is shown in Figure 4-3.

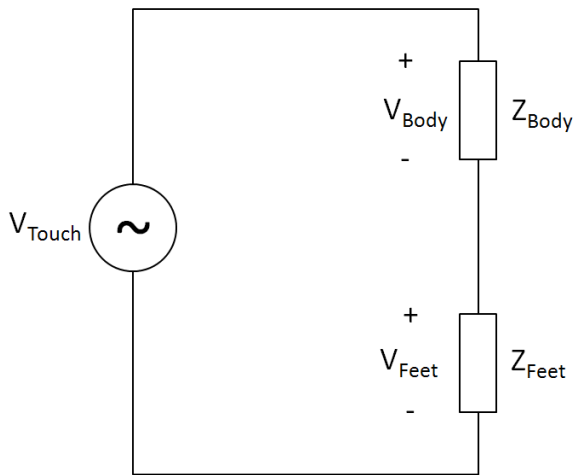


Figure 4-3: Simplified touch voltage circuit.

Using Kirchhoff's voltage law it can be seen from Figure 4-3 that the open circuit touch voltage, $V_{Touch} = V_{Body} + V_{Feet}$. The open circuit touch voltage is simply divided across the body and feet impedances.

Permissible touch voltage limits can be expressed as either the voltage across the combined body/feet impedance or across the body alone as shown in Figure 4-4. When the voltage limit corresponds to the voltage drop across the body only then it is called a loaded touch voltage. When the voltage limit corresponds to the total voltage drop across the combined body/feet impedance it is called an unloaded, open circuit or prospective touch voltage.

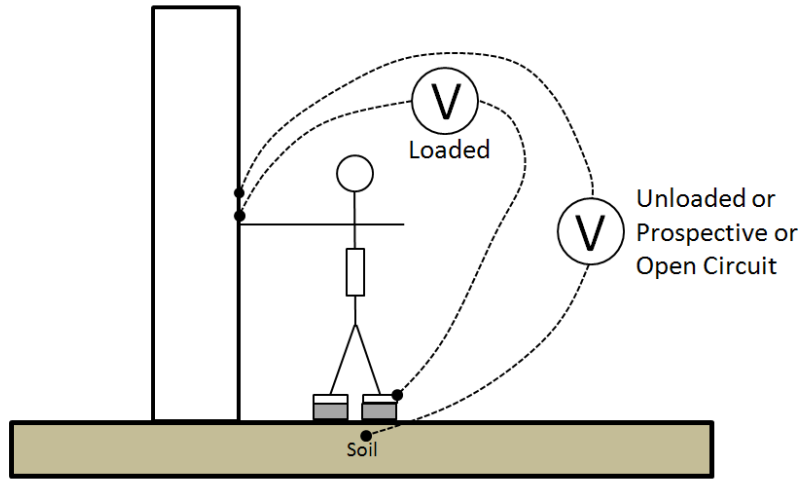


Figure 4-4: Loaded vs Unloaded touch voltage limits.

It is important to understand how touch voltages are measured in order to understand how to apply calculated permissible touch voltages.

4.2.3 Unloaded, Prospective and Open Circuit Touch Voltages

As shown in Figure 4-5, when measuring a touch voltage with a high impedance voltmeter, no current flows through the voltmeter. Hence there is no voltage drop across the probe or metal disc on the ground and the high impedance voltmeter only measures the open circuit touch voltage. Since no current flows in this circuit, the measured voltage is not dependant on the contact impedance with the soil therefore a metal plate or a short stake hammered to a very shallow depth may be used.

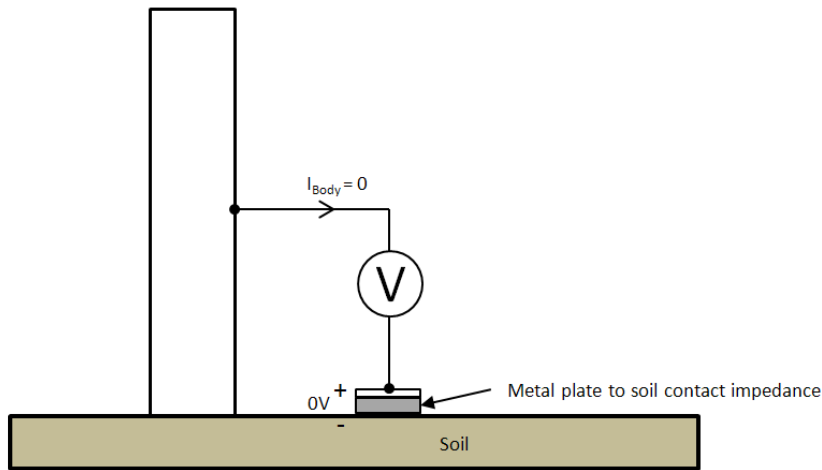


Figure 4-5: Measuring an open circuit touch voltage.

When a high resistivity top layer material such as gravel or asphalt is present, the surface potential on top of the natural soil is transferred through the thin top layer. The surface potential on top of the natural soil is therefore the same as that on top of the asphalt or gravel. Again, since no current is flowing through the test circuit, the measured voltage is the same irrespective of the presence of the surface layer.

Open circuit touch voltages measured as per Figure 4-5 should only be compared to theoretical permissible voltage limits that are the sum of the voltage across the body and the voltage across the theoretical foot impedance calculated as per IEEE standard 80 – 2000 Equations 19 and 27.

Open circuit touch voltage limits are supplied as a function of the resistivity of the soil surface layer that a person is standing.

CDEGS only computes touch voltages as open circuit touch voltages.

4.2.4 Loaded Touch Voltages

Loaded touch voltages are measured using the circuit of Figure 4-6. In this configuration, current will flow around the loop causing voltage drops across the body impedance resistor and across the contact impedance of the metal plate on the ground.

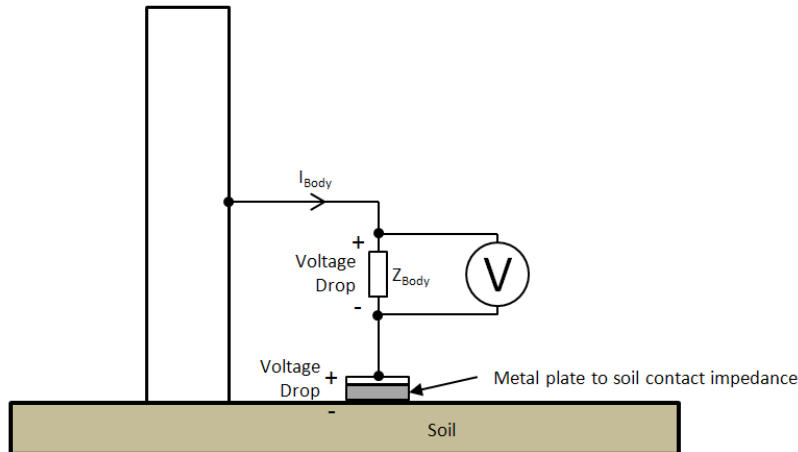


Figure 4-6: Measuring a loaded touch voltage.

Loaded touch voltages are generally much smaller than open circuit touch voltages because only the voltage drop across the body is being measured. Higher contact impedances between the metal plate and the ground will result in more voltage drop across that contact impedance and therefore the voltage drop across the body will be reduced.

While the loaded touch voltage method has the advantage of accounting for the *actual* contact impedance of the feet on the soil, it has the following disadvantages:

When IEEE Standard 80 – 2000 was in wide use throughout Australia, a 1000 Ω resistor was typically used to measure loaded touch voltages because the 1000 Ω body impedance is one of the fundamental assumptions in this standard. Australia is now moving away from IEEE Standard 80 in favour of the European approach described in AS/NZS 60479.1 in which the body impedance is a function of applied voltage. It is therefore not clear which resistor should be used.

Common earthing software such as CDEGS only outputs open circuit voltages and therefore it is impractical to compare loaded voltage measurements against computer simulation results.

The measured loaded voltage is highly dependent on the contact impedance of the metal plate with the soil and will vary widely if the surface is wet, dry, rocky or sandy. Additionally, the amount of weight applied to the metal plate will affect the loaded touch voltage reading. This measurement technique is not repeatable.

4.2.5 Permissible Touch Voltage Examples

Unloaded / open circuit / prospective touch voltage limits should always be specified as a function of the soil surface layer a person will be standing on. For example for a clearance time of 0.5 seconds, IEC curve C1, water-wet hand contact impedance and 50% population exceeds body impedance curve the open circuit touch voltage limits are:

- Standing on 20 Ω m wet concrete – 104V
- Standing on 100 Ω m natural soil – 115V
- Standing on 3000 Ω m 100mm thick gravel – 404V
- Standing on 10000 Ω m 50mm thick hot-mix asphalt – 808V

For the same conditions the loaded touch voltage limit would be 101V in which case 3V, 14V, 303V and 707V are dropped across the respective feet contact impedances with the wet concrete, natural soil, gravel and asphalt.

It is important that care is taken not to “Double Dip”. That is, one should not measure a loaded touch voltage and then compare it against an open circuit voltage limit. For areas with high surface layer resistivity, this can lead to dangerous underestimation of the magnitude of voltage hazards.

4.3 Pipeline Characteristics

4.3.1 RRJ Impedance

Modern pipelines have bonds installed across the RRJs as part of the cathodic protection system therefore modern RRJ pipelines have low series impedance much the same as welded joint pipelines.

Older pipelines such as the Stirling Trunk Main have no bonds across RRJs so in these pipelines, RRJ sections tend to have higher series impedance. Although on a new dry pipeline a RRJ can have very high joint impedance, in practice it is shorted out by the water in the pipeline, reinstated cement lining and sediment build up. For AC interference studies carried out on existing RRJ pipelines, it is important to account for the RRJ impedance by using data obtain from site testing.

4.3.2 Pipeline Coating Resistivity

In the absence of manufacturer data, the following typical values are to be used:

- Polyethylene (Sintakote) typical resistivity 2×10^7 to $2 \times 10^8 \Omega\text{m}$
- Bituminous typical resistivity 2×10^5 to $2 \times 10^6 \Omega\text{m}$

5 Appendix A

Method of calculating permissible touch and step voltages.

Adapted from EN 50522:2010 and IEC 61936-1 Ed2.

5.1 Loaded Touch and Step Voltage

Formula:

$$U_L = I_B(t_f) \cdot \frac{1}{HF} \cdot Z_T(U_T) \cdot BF \cdot \frac{1}{D_f} \quad \text{Equation A-1}$$

Factors:

Touch voltage	U_T	
Loaded permissible voltage (touch or step)	U_L	
Fault duration	t_f	
Body current limit	$I_B(t_f)$	c1 in Figure 20 and Table 11 of AS/NZS 60479.1-2010.
Heart current factor	HF	Table 12 of AS/NZS 60479.1-2010, 1.0 for left hand to feet, 0.4 for hand to hand and 0.1 for foot to foot (step voltage). Note: 0.1 used instead of 0.04 to reduce chance of electrocution.
Body impedance	$Z_T(U_T)$	Table 2 and Figure 3 of AS/NZS 60479.1-2010, large surface areas of contact in water wet conditions. Z_T not exceeded by 50% of the population. Z_T depends on touch voltage.
Body factor	BF	Figure 3 of AS/NZS 60479.1-2010 i.e. 0.75 for hand to both feet, 1.0 for foot to foot (step).
Decrement Factor	D_f	Calculated using Equation 79 of IEEE Standard 80 – 2000. Used to derate the voltage limit to account for the initial DC offset of the fault current waveform.

5.2 Prospective (Open Circuit) Touch and Step Voltage

For specific consideration of additional foot and hand resistances the formula to determine prospective (open circuit) permissible voltage becomes:

$$U_{OC} = I_B(t_f) \cdot \frac{1}{HF} \cdot (Z_T(U_T) \cdot BF + R_H + R_F) \cdot \frac{1}{D_f} \quad \text{Equation A-2}$$

Additional factors:

Open circuit permissible voltage (touch or step) U_{OC}

Additional hand resistance R_H

Additional foot/feet resistance R_F

Foot impedance calculated as per IEEE standard 80 – 2000 Equations 19 and 27. Note: No additional foot impedance is to be added for Water Corporation assets.

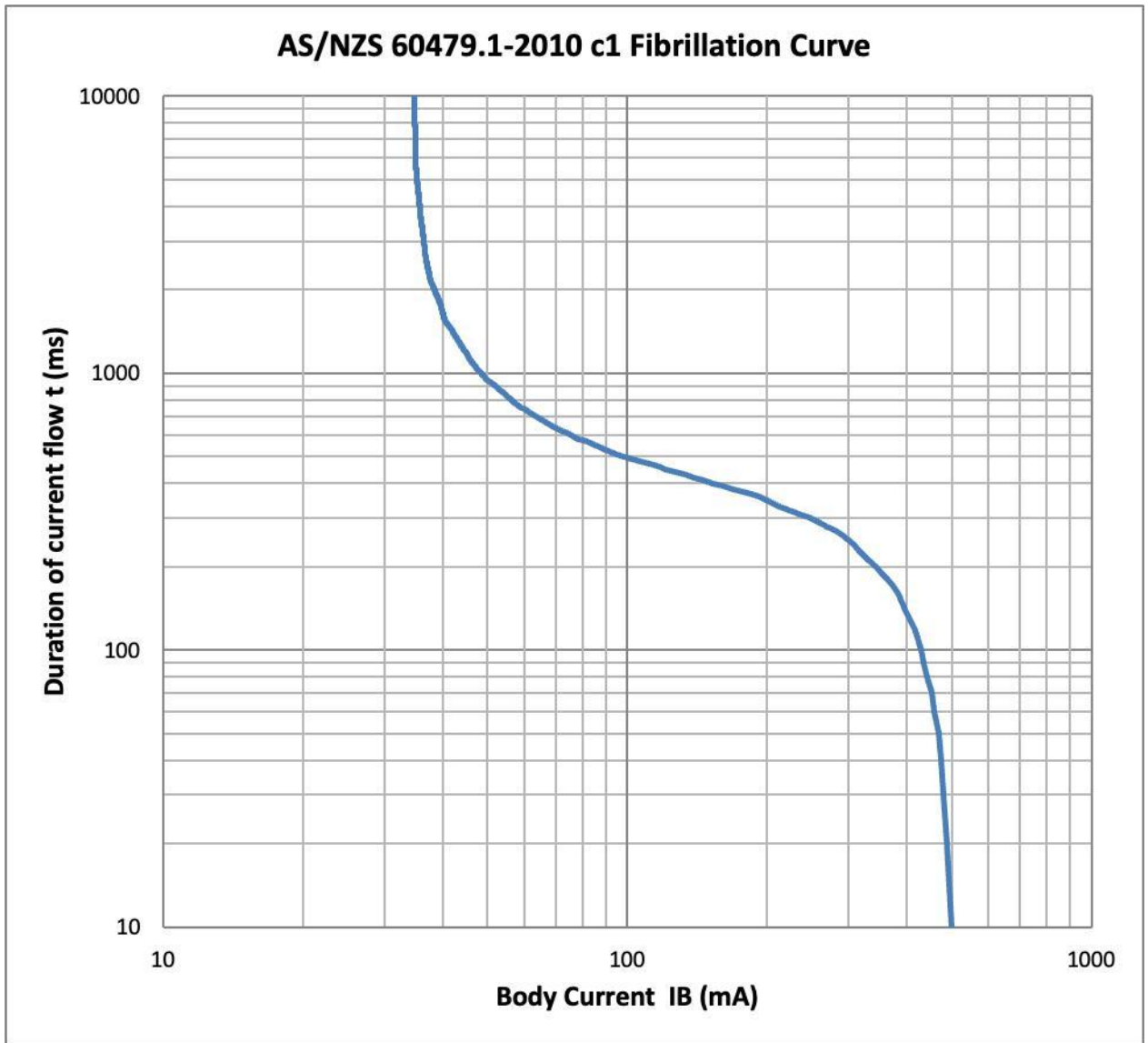


Figure A-1: c₁ fibrillation curve from Figure 20 of AS/NZS 60479.1-2010.

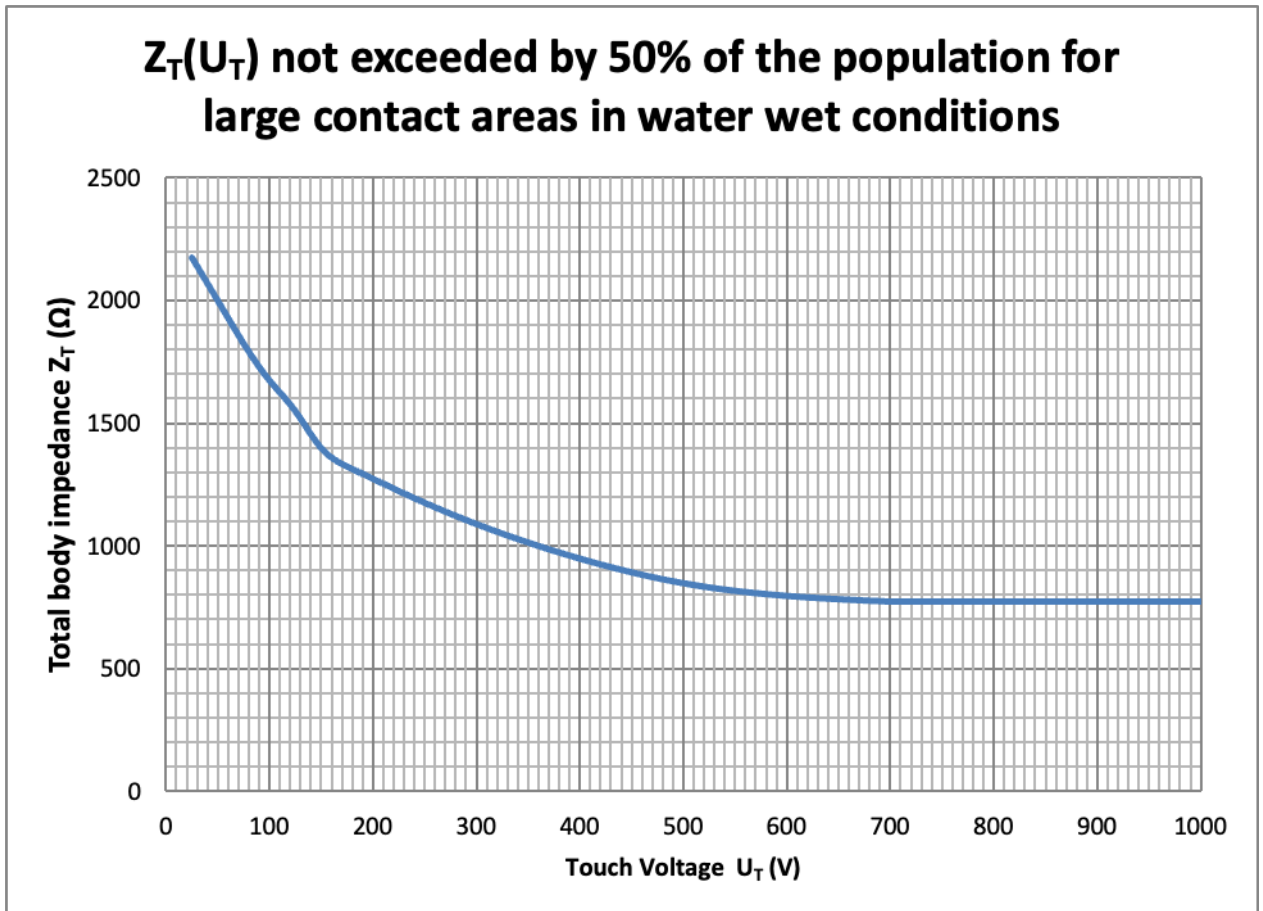


Figure A-2: Total body impedance from Table 2 of AS/NZS 60479.1-2010.

5.3 Examples.

Example 1

Calculate loaded hand to feet touch voltage and step voltage limits for 500ms clearance time and X/R=20 (50Hz).

Look up fibrillation current from curve c_1 (Figure A-1).

$$I_B(500) = 98.58 \text{ mA}$$

As shown in Figure A-3, using ohms law plot the straight line equation $U_T = 98.58 \times Z_T$ on the $Z_T(U_T)$ graph in Figure A-2.

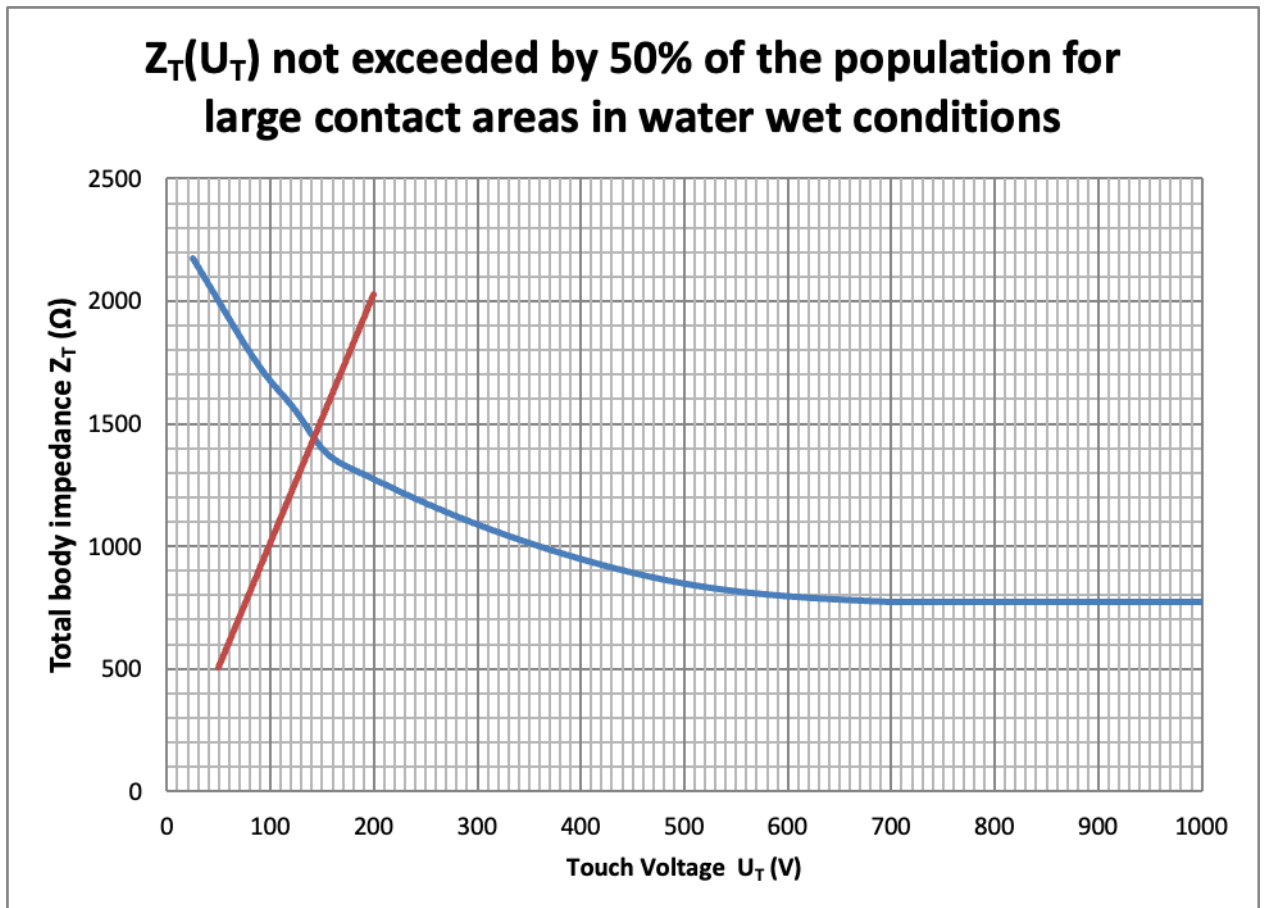


Figure A-3: Example 1.

Total body impedance of 1443Ω is found at the intersection of the two curves.

Calculate Decrement Factor, $D_f = 1.062$

Calculate hand to feet touch voltage from Equation A-1.

$$U_L = I_B(t_f) \cdot \frac{1}{HF} \cdot Z_T(U_T) \cdot BF \cdot \frac{1}{D_f} = 0.09858 \times \frac{1}{1} \times 1443 \times 0.75 \times \frac{1}{1.062} = 100 \text{ V}$$

Calculate step voltage from Equation A-1.

$$U_L = I_B(t_f) \cdot \frac{1}{HF} \cdot Z_T(U_T) \cdot BF \cdot \frac{1}{D_f} = 0.09858 \times \frac{1}{0.1} \times 1443 \times 1.0 \times \frac{1}{1.062} = 1339 \text{ V}$$

Example 2

Similarly, the prospective (open circuit) touch and step voltages can be calculated from equation A-2
(NB: A calculation example will be documented here at the next revision of this standard).

END OF DOCUMENT