TS 00006:1.0

ETN 11/02

Standard

HV Earthing Design

Issue date: 22 February 2023

Effective date: 22 February 2023

© State of NSW through Transport for NSW 2023

Disclaimer

This document has been prepared by Transport for NSW (TfNSW) specifically for its own use and is also available for use by NSW public transport agencies for transport assets.

Any third parties considering use of this document should obtain their own independent professional advice about the appropriateness of using this document and the accuracy of its contents. TfNSW disclaims all responsibility and liability arising whether directly or indirectly out of or in connection with the contents or use of this document.

TfNSW makes no warranty or representation in relation to the accuracy, currency or adequacy of this document or that the document is fit for purpose.

The inclusion of any third party material in this document, does not represent an endorsement by TfNSW of any third party product or service.

For queries regarding this document, please email Transport for NSW Asset Management Branch at standards@transport.nsw.gov.au or visit www.transport.nsw.gov.au

© State of NSW through Transport for NSW 2023

Document information

Owner: Director Energy Networks and Systems
Asset Management
Safety, Environment and Regulation

Mode: Multimodal

Discipline: Electrical

Document history

Revision	Effective date	Summary of changes
1.0	12 February 2013	First issue as *ETN 11/02 Earthing Designs for RailCorp's High Voltage AC System*.
1.0	22 February 2023	First issue as TS 00006. Version recommenced in line with new designation.

© State of NSW through Transport for NSW 2023

Preface

This document is a first issue and supersedes electrical technical note ETN 11/02 *Earthing Designs for RailCorp's High Voltage AC System*. This document specifies the requirements for conducting earthing designs.

When a fault occurs on an electrical network, particularly, a phase to earth, or a phase to phase to earth fault, electrical current will flow from the source to the point of the fault and through the general mass of earth as it returns to the source (typically the star point of an earthed star transformer). The characteristics of the electrical circuit formed, and particularly the zero sequence impedance of the electrical path to the source, will lead to the presence of a voltage on earthed electrical infrastructure, and voltage contours on the surrounding soil structure. This can expose the general public and workers to an unacceptable level of risk associated with electrical hazards if not appropriately managed.

This standard aligns with Australian standards, industry best practice, and is fundamentally based on the established practices published in ENA EG-0 and ENA EG-1, which are widely used in the electricity distribution industry.

This standard describes the process for managing risks associated with high voltage (HV) ac earthing systems on Transport for NSW HV ac electrical networks in order to appropriately manage the safety of the general public, customers, and TfNSW staff.

This will ensure that the risks associated with the earthing systems on TfNSW HV ac network are managed so far as is reasonably practicable (SFAIRP).

© State of NSW through Transport for NSW 2023

Table of contents

1 Scope ... 6
2 Application ... 6
3 Referenced documents ... 7
4 Terms, definitions and abbreviations ... 8
5 General requirements ... 10
5.1 Risk management ... 11
5.2 Functional requirements ... 11
5.3 Earthing conductor ratings ... 12
5.4 Redundancy of connections ... 12
6 Whole-of-life design philosophy ... 13
7 Data gathering ... 13
7.1 Soil resistivity ... 14
7.2 Fault levels and protection information ... 14
7.3 Hazard locations ... 16
7.4 Existing earthing system testing ... 16
8 Power frequency design ... 16
8.1 Earthing system design ... 16
8.2 Earthing system modelling ... 17
8.3 Risk assessment criteria ... 17
8.4 Engineering controls ... 25
9 Lightning and transient design ... 27
10 Construction Support ... 27
11 Testing and commissioning ... 27
11.1 Earth grid resistance testing ... 28
11.2 Continuity testing ... 28
11.3 Current injection testing ... 28
12 Asset handover ... 29
Appendix A Quantification of earthing risks ... 30
Probability of fibrillation ... 30
Probability of coincidence ... 31

© State of NSW through Transport for NSW 2023

1 Scope

This standard covers the requirements for earthing design risk management on all TfNSW high voltage (HV) alternating current (ac) networks.

This standard provides the following:

- risk assessment variables for typical design situations including:
  - publicly accessible areas for typical distribution fault scenarios and major substation secondary scenarios
  - operators in substations
  - special locations (for example, aquatic centres)
- a risk assessment process (aligned to ENA EG-0) for a designer to follow if the scenarios in the preceding list do not fit
- functional requirements for all earthing systems
- guidance on the use of testing to validate a design

This standard does not provide requirements for the following:

- dc networks, traction return bonding arrangements, or low voltage earthing
- specific requirements for the earthing of a particular asset (for example, bus bar requirements, cable crimping requirements and so on)
- testing methodologies.

2 Application

The requirements of this standard apply to all new and modified earthing systems within TfNSW HV ac electrical networks.

This standard applies to all traction substations, HV ac switching stations, distribution substations, HV ac aerial lines and cables.

This standard also applies to conductive or metallic non-power system infrastructure parallel to or within the zone of influence of the TfNSW electrical networks and systems.

Existing installations may not be consistent with the requirements of this document. Due to the changes in the surrounding environment and the deterioration of earthing systems over time, an earthing installation may no longer perform as it was designed. For these reasons, modification of interfacing systems can lead to challenging considerations for the Technically Assured Organisation (TAO). Where the requirements of this standard cannot be practically met, alternative solutions aligned to the philosophy of this standard may be acceptable subject to consultation and acceptance from the relevant authority within the operator and maintainer.

© State of NSW through Transport for NSW 2023

In addition to the requirements of this standard, asset decisions should take into account the life cycle cost considerations specified in T MU AM 01001 ST.

If, when using this standard, it is considered that the intent of any requirement is not clear, clarification should be sought from the AMB.

3 Referenced documents

The following documents are cited in the text. For dated references, only the cited edition applies. For undated references, the latest edition of the referenced document applies.

International standards

IEEE Standard 80 *IEEE Guide for Safety in AC Substation Grounding*

Australian standards

AS 1768 *Lightning Protection*

AS 2067 *Substations and high voltage installations exceeding 1 kV a.c.*

AS/NZS 3835.1 *Earth potential rise – Protection of telecommunications network users, personnel and plant – Part 1: Code of practice*

AS 3851–1991 (R2015) *The calculation of short-circuit currents in three-phase a.c. systems*

AS/NZS 4853 *Electrical hazards on metallic pipelines*

AS/NZS 7000 *Overhead line design*

AS/NZS 60479.1 *Effects of current on human beings and livestock – Part 1: General aspects*

AS/NZS ISO 31000:2009 *Risk management – Principles and guidelines*

Transport for NSW standards

TS 03726 (EP 12 10 00 10 SP) *HV Earthing for Substations and Distribution Systems*

T HR EL 12004 ST *Low Voltage Distribution and Installations Earthing*

T HR EL 12005 ST *Bonding for 1500 V DC Traction Systems*

T HR EL 10001 ST *HV Aerial Line Standards for Design and Construction*

T HR EL 12002 GU *Electrolysis from Stray DC Current*

T HR EL 21001 ST *Lightning Protection and Insulation Coordination*

T HR EL 99001 ST *Substation and Sectioning Hut Commissioning Tests and Processes*

T MU AM 01001 ST *Life Cycle Costing*

T MU AM 01005 ST *Asset Handover Requirements*

TS 00003.1:1.0 (T MU MD 00011 ST) *Concessions to Transport Standards Part 1 – Concessions Process*

© State of NSW through Transport for NSW 2023

T MU MD 20003 GU *Quantified Safety Risk Assessment*

T MU MD 20001 ST *System Safety Standard for New or Altered Assets*

Legislation

Electricity Supply Act 1995 (NSW)

Rail Safety National Law (NSW)

Work Health and Safety Act 2011 (NSW)

Other referenced documents

Energy Networks Association 2022, *Substation Earthing Guide (EG-1)*, ENA DOC 045-2022

Note: Shown as ENA EG-1 in this document.

Energy Networks Association 2022, *Power System Earthing Guide (EG-0) Part 1: Management Principles*, ENA DOC 025-2022

Note: Shown as ENA EG-0 in this document.

4 Terms, definitions and abbreviations

The following terms, definitions and abbreviations apply in this document:

ac alternating current

ALARP as low as reasonably practicable

AMB Asset Management Branch

clearing time the time taken for the protective devices and circuit breaker(s) to isolate the fault current (source ENA EG-0:)

conductive part a part capable of conducting current, although it may not necessarily be used for carrying service current

Note: For the purpose of this document conductive parts can include but are not limited to elements built from conductive materials, for example, steel fences, steel horizontal safety screens, steel vertical safety screens and steel balustrades.

dc direct current

earth (verb) to make an electric connection between a given point in a system or in an installation or in equipment and local earth

earth fault occurrence of an accidental conductive path between a live conductor and the earth

earth grid interconnected uninsulated conductors installed in contact with the earth (or an intermediate material) intended for the conduction and dissipation of current and or for the provision of a uniform voltage reference. One part of the earthing system. (source ENA EG-0:)

© State of NSW through Transport for NSW 2023

earth potential rise (EPR) voltage between an earthing system and remote earth (source ENA EG-0:)

Note: For the purpose of this standard the term EPR is considered equivalent to the earth grid voltage rise (EGVR) and grid potential rise (GPR).

earthing system arrangement of earth conductors, typically including an earth grid, earth electrodes and additional earth conductors such as overhead earth wires (OHEWs), cable sheaths, earth continuity conductors (ECCs) and parallel earthing conductors (source ENA EG-0:)

electrolysis an electrochemical reaction involving an electrolyte and metals which are carrying a dc current

GST galvanised steel troughing

HV high voltage

MEN multiple earthed neutral

NER neutral earth resistor

NEX neutral earth reactor

PEN protective earthed neutral

power frequency 50 Hz ac

remote a location where the contact frequency is sufficiently low that the fault/ contact coincidence probability is less than the target fatality probability. Typically, it is a location with few people around such as a rural area. For this case there is no touch voltage target required (source ENA EG-0)

remote earth part of the Earth considered as conductive, the electric potential of which is conventionally taken as zero, being outside the zone of influence of the relevant earthing arrangement (source ENA EG-0)

SFAIRP so far as is reasonably practicable

soil resistivity specific resistivity of a material is used to define the resistance of a material to current flow, and is defined as the electric field strength (V/m) divided by the current density (A/m^2). Values tabled are normalised to 1 A flowing into a one metre cube of material yielding units of ohm-metre (Ωm). (source ENA EG-0)

step voltage the voltage between two points on the earth's surface that are 1 m distant from each other while a person is making contact with these points (source ENA EG-0)

TAO Technically Assured Organisation, previously known as Authorised Engineering Organisation (AEO)

TfNSW Transport for NSW

© State of NSW through Transport for NSW 2023

touch voltage the voltage between conductive parts when touched simultaneously (source ENA EG-0)

NOTE: The value of the effective touch voltage may be appreciably influenced by the impedance of the person in electric contact with these conductive parts.

transferred earth potential the potential rise of an earthing system caused by a current to earth transferred by means of a connected conductor (for example, a metallic cable sheath, PEN conductor, pipeline, rail) into areas with low or no potential rise relative to reference earth resulting in a potential difference occurring between the conductor and its surroundings.

NOTE: The definition also applies where a conductor, which is connected to reference earth, leads into the area of the potential rise. (source ENA EG-0)

5 General requirements

TfNSW HV ac networks may be either solidly earthed, earthed through a resister or a reactor to limit earth fault levels.

A solidly earthed system can be beneficial in limiting insulation requirements of network equipment due to the reduced impact of over-voltages during fault conditions, and can provide for improved protection grading and sensitivity.

To limit the earth fault levels and to improve the safety of workers and the public a NER can be implemented on the TfNSW Network subject to consultation with AMB to demonstrate the following:

- appropriate stakeholder consultation and agreement has occurred with the operator maintainer
- due consideration is given to the whole-of-life costs and the secondary insulation levels in the electrical network.

During earth fault conditions, the surface of the earth, and any electrically conductive surface in the area around the electrical infrastructure may be subject to hazardous voltages. Within a direct current (dc) rail environment, metallic infrastructure can also be subject to stray currents. The design of the earthing arrangements for conductive infrastructure in a dc environment requires careful consideration. Refer to the following standards and guideline for more information:

- T HR EL 12004 ST
- T HR EL 12005 ST
- T HR EL 12002 GU

When assets are modified, the integrity and safety of the existing earthing system shall be evaluated in accordance with this standard.

© State of NSW through Transport for NSW 2023

5.1 Risk management

In all situations, the designer shall understand the legislative frameworks that apply to a particular situation, and the implications for safety in design and management of risk. The overarching legislative framework that applies in NSW is the *Work Health and Safety Act 2011* and related regulations.

Electrical infrastructure within a rail context is also subject to the following legislation:

- *Rail Safety National Law (NSW)*
- *Electricity Supply Act 1995*, and related regulations.

These legislations require designs to manage safety risks to workers and the general public SFAIRP (known as ALARP in the *Electricity Supply Act 1995*).

In an earthing context, designers are required to consider all foreseeable earthing risks, and develop and implement risk mitigation for each of them.

Where a proposed risk mitigation methodology introduces a new risk, such as an electrolysis risk or trip hazard in a public location, the designer shall consider the likelihood and consequences of all relevant hazards to determine relative risks and achieve the lowest risk outcome overall.

Within the scope of this standard, the principles provided in ENA EG-0 apply as adopted in AS 2067, and AS/NZS 7000.

> Note: AS/NZS 60479.1 *Effects of current on human beings and livestock*, is based on IEC 60479.1 *Effects of current on human beings and livestock*. Whilst describing and setting limits on electrical current through the human body in various situations, it is acknowledged that there are other aspects to be considered, such as probability of faults, probability of contact with live or faulty parts, ratio between touch voltage and fault voltage, experienced gained, technical feasibilities and economics. The intent of this standard is to consider these other aspects and apply this in a design context that allows a designer to appropriately consider risk in line with legislative requirements.

5.2 Functional requirements

The earthing system shall be designed to be ‘fit for purpose’ for the life of the asset that it is protecting.

Specifically, over the life of the asset, the earthing system shall fulfil the following:

- conduct fault current (including any known changes in fault levels) without damage to components of the earthing system
- minimise the risk of mechanical damage both due to movement during fault conditions and due to external forces

© State of NSW through Transport for NSW 2023

- minimise the risk of theft through selection of materials, and securing and locating conductors appropriately
- manage the risk of chemical corrosion and electrolytic corrosion from stray current
- manage the safety risks associated with EPR in accordance with this document.

An asset shall be designed to the conditions and configuration that are reasonably expected on the network over the life of the asset. The TAO should consider known future configuration changes that can impact the earthing system risk profile including fault level changes, encroachments from surrounding developments and so on.

5.3 Earthing conductor ratings

The earthing system shall be designed so that all conductors are rated to carrying all foreseeable fault scenarios for the asset it is protecting. That is, the design shall take into account all fault scenarios foreseeable including known network configuration changes.

Conductor ratings shall be determined using back up fault clearing times.

The designer shall determine the appropriate conductor ratings for the earthing system being designed using the following ambient temperatures:

- 25 °C buried or concrete encased conductors
- 40 °C aerial and aboveground conductor.

Under fault conditions the temperature of the earthing system that shall not be exceeded is as follows:

- bolted or compression joints: 250 °C
- welded (Cadweld) or brazed joints: 450 °C
- steel reinforcing embedded in concrete (where bonded into the earthing system): 90 °C (unless higher temperatures are determined to be appropriate in the concrete design)
- insulated conductors (unless specified by the manufacturer as being suitable for higher temperature operation): 160 °C.

For requirements relating to conductor ratings for standard electrodes refer to TS 03726. Conductors shall be rated to achieve the appropriate current rating without compromising insulation integrity due to temperature rise.

5.4 Redundancy of connections

Redundancy of N-1 shall be provided for earthing of critical equipment but is not required for equipment, structures and infrastructure that is not likely to represent a primary conductive path. See TS 03726 for further information.

© State of NSW through Transport for NSW 2023

6 Whole-of-life design philosophy

Following safety in design requirements and in line with good design practice, the designer shall take into account all stages of the asset life cycle, including commissioning and decommissioning.

The design process presented in Figure 1 has been adapted from the process identified in ENA EG-1 and ENA EG-0. In line with this example, the designer shall provide support throughout the construction phase of a project, to allow for adjustments due to on site conditions.

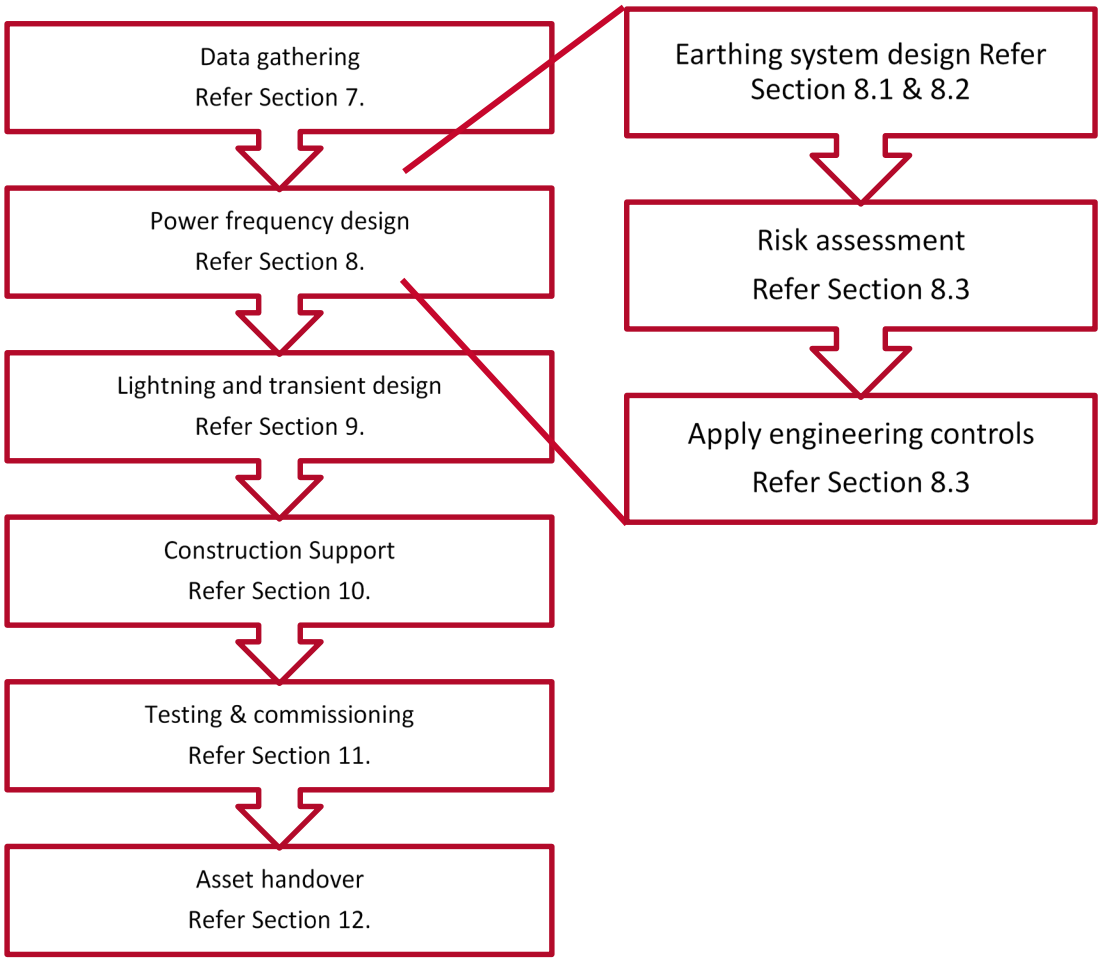

Figure 1 – Design process – Adapted from ENA EG-1 and ENA EG-0

7 Data gathering

A key component of the earthing design process is the gathering of site-specific data applicable to the design. The process for data gathering will typically involve onsite investigation as well as desktop review of site specific information including the following:

- Dial Before You Dig (DBYD)
- Detailed Site Survey (DSS)

© State of NSW through Transport for NSW 2023

- Geographic Information System (GIS).

7.1 Soil resistivity

The soil electrical resistivity model is a critical component of any earthing system design.

Soil electrical resistivity testing shall be carried out for all earthing designs at a location as close as practical to the proposed earthing system using an industry recognised testing methodology (examples are provided in ENA EG-1 and IEEE Standard 80). Soil testing is typically undertaken using the Wenner method. Where soil testing is impractical to carry out at the same location as the proposed earthing system (this is often the case in brownfield situations due to the proximity to existing services and safety implications of testing in the live railway environment), at least two test locations in the surrounding area shall be used to establish a representative model. Orthogonal arrays shall be used where practicable. Further testing or test locations may be required if the two surrounding tests show significantly different soil structures or the soil conditions at the test location are not considered to be reliable representations of the site location.

Previous soil resistivity testing data can be useful for comparison to field testing results; however this shall not be used as a substitute for field testing as part of the design process.

To account for seasonal variations in soil resistivity, and to ensure that the earthing system performs under all reasonably expected environmental conditions, the designer shall carry out sensitivity analysis. The sensitivity analysis should identify a best case and worst case soil structure. The likely worst case soil resistivity should be considered to ensure that the protection system will operate. Conversely the best case soil resistivity should be used for the calculation of safety criteria.

A multi-level soil model shall be prepared to adequately model the earthing system performance and to perform an appropriate earthing risk assessment. This shall be done, unless the soil testing and modelling determines that a homogenous soil profile is appropriate.

Where there is opportunity to validate or calibrate soil models by testing existing earthing systems this shall be done in accordance with Section 7.4.

7.2 Fault levels and protection information

Fault level information shall be captured for the proposed asset, including alternative and future proposed operating configurations. This information shall be sourced from the operator and maintainer, and be reflective of the network configuration when the proposed earthing system will be installed, and any committed future configuration changes that would affect fault levels.

To allow for sensitivity analysis during the design phase, the maximum and minimum short circuit phase to earth fault currents shall be determined in accordance with AS 3851 factoring in the ‘c’ factor and the asymmetrical components. For fault locations close to the secondary side

© State of NSW through Transport for NSW 2023

of a transformer, the maximum earth fault current may occur for a phase-to-phase to earth short circuit scenario. In this case, the maximum and minimum phase-to-phase to earth short circuit currents shall also be determined.

For the purpose of an earthing risk assessment the worst case foreseeable operating configuration should be used to model the earthing system performance. However, the designer shall confirm that the protection system adequately operates under all alternative supply configurations. Protection clearing times shall be adjusted by taking into account the earthing system impedance.

For the purpose of earthing conductor rating calculations, the supply arrangement resulting in the highest thermal energy ($I^2 t$) shall be used, with the maximum short circuit current and back-up protection clearing times to ensure system integrity is maintained. This may not necessarily be the highest fault level if the clearing time under an alternative supply arrangement is substantially slower.

The effects of both conductive and inductive coupling shall be considered in determining the earth fault current resulting in the highest EPR. Where there are multiple earth fault scenarios the highest fault level may not always result in the worst case EPR in particular when the return paths back to the source include inductive coupling such as cable screens.

7.2.1 Stepped fault

In many cases on the electrical network, fault current will be supplied from multiple sources (for ring fed configurations) supplying a location. The fault level and protection clearing time can be different for these different sources, and as each protection system operates, the short circuit current flowing into the earthing system can step down. In these scenarios an equivalent fault current and fault duration shall be calculated using the methodology described in ENA EG-1: or an equivalent methodology.

7.2.2 Fault current asymmetry

ENA EG-1 describes the effects of electrical current on human bodies which is determined based on root mean squared (RMS) symmetrical current, while due to the nature of a power system, fault current will be asymmetrical, particularly immediately after the fault is initiated.

Fault currents on systems 33 kV or higher shall be adjusted based on the decrement factor provided in ENA EG-1: (or equivalent) to account for the asymmetrical or aperiodic nature of short circuit faults.

Due to the longer clearing times, and lower X/R ratio seen on the 11 kV system, fault current asymmetry should be considered but typically would not significantly impact the fault current value.

© State of NSW through Transport for NSW 2023

7.3 Hazard locations

The location and types of hazards at the location shall be captured and recorded to allow for a desktop design assessment to calculate the prospective voltage hazards at these locations. The designer shall conduct both an onsite visual inspection and desktop study in order to identify all the relevant hazards in the area of influence. The designer shall aim to ensure that all hazards within the EPR zone are identified. The minimum detail that shall be captured includes the following:

- distance from the proposed asset
- applicable contact scenarios
- location relative to proposed asset (marked up on a drawing or map)
- type of voltage hazard (for example, fence, publicly accessible tap, swimming pool, and so on).

7.4 Existing earthing system testing

Where the design is associated with an existing asset or an existing earthing system the designer may assess the performance of the existing earthing system by carrying out current injection testing, or more simple earth impedance testing methods such as fall of potential and clamp testing.

Current injection testing on existing assets can be a costly exercise, and lead to operational impacts. The decision to carry out this testing should be based on the risks associated with the earthing system such as the location of the asset and associated earthing system, the sensitivity of the performance of the earthing system to unknowns (for example, buried services, soil resistivity and so on). Current injection testing may not be justifiable for example, on transmission lines or distribution substation earthing systems in remote locations; see Section 4.

Where the designer identifies this form of testing as necessary, they shall coordinate with the operator and maintainer to arrange for access to the assets, and any necessary outages.

8 Power frequency design

8.1 Earthing system design

The designer shall design an earthing system appropriate for the asset that it will protect, in accordance with the relevant standards. An earthing system shall not be modified or installed without an earthing design risk assessment undertaken in accordance with this standard.

Refer to TS 03726, for specific requirements related to earthing of substation areal lines and cables.

© State of NSW through Transport for NSW 2023

In a rail environment the presence of stray current can have a detrimental effect on the performance and integrity of earthing systems. Reasonable effort has been made to minimise the corrosive impacts of stray current on earthing systems however the risk is unable to be eliminated. The risk of stray current has also resulted in the inability to implement a significant interconnected MEN system as is established in other electricity supply networks.

Earthing systems shall be designed in consideration of the increased risk due to stray current. This can include considerations related but not limited to the following:

- impacts to the stray current risk profile
- appropriate redundancy
- proximity to 1500 V dc infrastructure
- configuration and arrangement of an earthing system.

8.2 Earthing system modelling

The earthing design process shall use analytic earthing system modelling software to model the performance of the designed earthing system such as CDEGS or equivalent software. The model shall utilise the soil model, and fault levels determined in the data gathering stage (see Section 7.1 and Section 7.2). The earthing system model shall account for alternative fault current paths including (not limited to) cable screens, supplementary earthing conductors, and overhead earth wires.

As a minimum requirement the model shall show the following:

- the design EPR of the earthing system
- the earthing system impedance (accounting for the effects of mutual coupling)
- hazardous soil, step, touch and transfer voltages on the earthing system and surrounding infrastructure determined in the data gathering stage (see Section 7.3)
- current splits (the current flowing in all parts of the earthing system) including the effects of mutual inductance.

In some cases, multiple modelling systems may be required to analyse and determine these design variables. The designer shall ensure that all models are aligned.

8.3 Risk assessment criteria

The *Work Health and Safety Act 2011* aims to eliminate risks to health and safety, SFAIRP. Where it is not reasonably practicable to eliminate risks to health and safety, then the intent is to minimise those risks SFAIRP. *Rail Safety National Law (NSW)* includes the same requirement.

The design of an earthing system shall be a key component to the overall design of an asset, or system at a given location. Earthing designs are often considered last after other decisions in

© State of NSW through Transport for NSW 2023

the asset design have been committed. This practice reduces the number of risk management opportunities, and leaves the earthing designer with limited options for risk management.

Designers make the following considerations for minimising risk SFAIRP:

consideration of alternative design options, including alternative supply arrangements, relocation of the infrastructure to a location that would represent a lower risk, and the use of lower risk configurations

where the earthing system is required, the management of hazardous voltages through the earthing design in accordance with this standard and industry best practice

the identification and consideration of all reasonable mitigation solutions that could reasonably be used to further reduce the risks.

The legislation requires the designer to consider all practical mitigation techniques and only rule out mitigation strategies where the cost is grossly disproportionate to the benefit gained. Where a mitigation strategy introduces a new, different risk such as a trip hazard, then the designer shall weigh this new risk against the reduction in earthing risk. The asset operator and maintainer shall be consulted on proposed risk mitigation strategies. The methodology in this standard is intended to assist designers in this process.

By ensuring that the voltage hazards for an earthing system are below the touch voltage curves provided in this standard, or are determined to be low risk in accordance with the risk assessment process described in this standard, any further mitigation (that is not required for other reasons) will not typically be warranted. It does not mean that there is zero risk or that the risk has been eliminated, but it will typically be grossly disproportionate to the benefit gained to invest significant time and effort to further reduce the risk.

This methodology uses a quantified safety risk assessment methodology. Refer to T MU MD 20003 GU for more information on the use of quantified safety risk assessments in the TfNSW context.

T MU MD 20001 ST describes the system safety requirements placed upon TAOs delivering a change to the TfNSW Network, including the hierarchy of controls required to demonstrate that a risk has been reduced SFAIRP.

8.3.1 Key risk assessment variables

The mathematical equation that describes the level of risk in an earthing context for a given scenario is set out in Appendix A. This equation, and therefore the risk assessment process described in this standard, relies on a set of key assumptions that can be difficult to accurately determine on a case by case basis by a designer. In the absence of contact scenarios and fault frequencies that are specific to railway assets the variables described in this section are based on the research and analysis behind the development of ENA EG-0, and current industry best practice. Provisions have been made in Section 8.3.2 to address the specific issues

© State of NSW through Transport for NSW 2023

encountered near to dc traction locations. The use of this framework, and in general, compliance with a standard does not relieve a designer's due diligence requirements.

In all cases, a designer needs to satisfy themselves that the variables described are reasonable in their particular scenario. If the designer determines that an alternative set of variables are required in a particular design scenario, the Argon tool (or an equivalent alternative) shall be used to assess the risk level on the site. Alternative design variables may be used subject to the submission of a request for concession to AMB.

8.3.2 Safety criteria and earth system performance in dc railways

The presence of stray current poses challenges in achieving the required earthing system performance within TfNSW dc railway networks and increases the risk associated with the occurrence of EPR by the following:

- limiting the use of a global connected MEN system
- reducing the effective life and performance of earthing systems through excessive electrolytic corrosion.

For these reasons designers should attempt to develop robust and resilient earthing systems with appropriate redundancy by utilising the following:

- standard earthing arrangements where appropriate with additional earthing as required in order comply with safety criteria and reduce risk SFAIRP
- a conservative approach when determining safety criteria to assess earthing system performance.

The standard earthing arrangements represent the minimum earthing system requirements for substations, aerial lines and cables are documented in TS 03726. These arrangements are intended to achieve a minimum level of reliability and redundancy and are representative of a balanced approach to performance, cost and risk in line with SFAIRP principles.

Initially the safety criteria shall be determined using the following fault frequency and contact scenarios:

- the applicable fault frequency in accordance with Section 8.3.3
- the highly frequented MEN contact scenario for all situations not related to swimming pools and wet areas which shall use the aquatic scenarios.

Where the designer has demonstrated that compliance with the initial safety criteria cannot be achieved using a standard earthing arrangement (without increasing the overall footprint) then other applicable contact scenarios in accordance with Section 8.3.4 may be used to determine the extent of additional earthing.

© State of NSW through Transport for NSW 2023

8.3.3 Fault frequency

The fault frequency variable describes the number of earth faults per year that will affect the asset or area. ENA EG-0 takes into account a range of locations in their recommendations.

A fault that can result in a hazard on or around an earthing system will be categorised for the purpose of this standard as either a primary fault or a secondary fault.

A primary fault is directly associated with the asset that sees fault current driven into the local earthing system.

A secondary fault is a fault on an asset downstream of the asset being designed that will see fault current return to the local earthing system through the neutral point of a transformer.

In many cases, the primary fault scenario is all that will be applicable. The secondary scenario applies to a substation that feeds downstream HV assets at a lower voltage by a transformer, such as 33 kV/11 kV substations.

Specific fault frequency and durations shall be supplied by the operator maintainer where available. Were specific fault data cannot be sourced from the operator maintainer alternative fault frequencies may be calculated using the number of downstream earthing systems connected to a particular feeder as proposed in ENA EG-0.

A request for concession to AMB is required where the calculated fault frequencies are lower than the following:

- one fault in 10 years for primary fault scenario
- two faults per year for secondary fault scenario.

  Note: A concession is not required where specific fault data is supplied by the operator and maintainer (O&M).

8.3.4 Contact scenarios

The contact scenario describes the frequency and duration of a contact with the potential hazard being assessed, which would be expected from the behaviour of an average person.

A designer shall determine the appropriate contact scenario for a given hazard based on the description of the following scenarios:

1. Remote: A location where the contact frequency is very low; for example, a pole in a remote bushland easement, or on a rural roadside with no footpaths nearby
2. Urban interface: Asset outside normal public thoroughfare with low frequency of direct contact by an individual
3. Backyard: An area with a contactable metallic structure in a location that is frequented by the public such as a fence or gate

© State of NSW through Transport for NSW 2023

4. Highly frequented / MEN: Contact with either LV MEN interconnected metalwork such as household taps or highly frequented public locations such as stations, bus stops or public facilities
5. Aquatic: An area within close proximity to or within premises where there is a high likelihood that shoes will not be worn. Examples include aquatic centres, recreational swimming areas and beaches. May also be used as a conservative scenario for schools, pre-schools, and day care centres
6. Operators and workers inside substations: The area within a substation that is not accessible to the general public. In this scenario the earth fault is not independent of the presence of an individual, as the fault may occur due to the individual's actions or the work they are performing.

The contact frequency and contact duration that can reasonably be used for the preceding scenarios are shown in Table 1. When using these variables a designer shall satisfy themselves that the variables used are appropriate.

Table 1 – Contact frequency and duration variables

Contact scenario	Contact frequency and duration	Footwear
Urban	135 contacts/year for 4 seconds	Standard
Backyard	416 contacts/year for 4 seconds	Standard
Highly frequented / MEN	2000 contacts/year for 4 seconds	Standard
Remote	<60 contacts/year for 4 seconds	Standard
Aquatic	In accordance with societal based gathering with a population size of 50 (refer to ENA EG-0)	None/wet
Operators and workers inside substations	1000 contacts/year for 4 seconds	Electrical

Where alternative contact frequencies and/or contact durations are proposed, a detailed analysis shall be conducted to support the proposed scenario and be subject to the submission of a request for concession to AMB.

8.3.4.1 Footwear

The footwear provisions provided in ENA EG-0 shall apply. ENA EG-0 provides the details and electrical characteristics for applicable footwear. The designer shall consider the use of barefoot footwear in public areas where there is an increased risk of barefoot public. Such areas may include but are not limited to coastal urban areas and backyards.

8.3.5 Risk tolerability

The risk level to be used in an earthing design risk assessment is an individual probability of fatality less than 1 in 1,000,000 per year. For the purposes of this standard, this risk level will be defined as 'low risk'.

© State of NSW through Transport for NSW 2023

This level of risk is supported by *NSW Government Hazardous Industry Planning Advisory* papers, as it is considered below the background level of risk that an individual experiences in life.

The designer however shall not stop the risk assessment process once this risk level is achieved. At this point, in accordance with ENA EG-0; risk treatment may be applied if the cost is low and/or a normally expected practice.

If a detailed risk assessment process identifies a risk level greater than 1 in 1,000,000 and the designer can demonstrate that there are not practicable design mitigation options to reduce the risks below this level, a risk level greater than this may be accepted using the concession process described in T MU MD 00011 ST.

In accordance with T MU MD 20003 GU, and aligned to the requirements of ENA EG-0, an individual probability of fatality of 1 in 10,000 per year for a customer or member of the public is considered intolerable and at this point action shall be taken to reduce the risk, regardless of costs and SFAIRP considerations.

8.3.6 Low risk touch voltage curves

The curves described in Figure 2 to Figure 5 represent a low risk touch voltage for the scenarios defined in Section 8.3.4. These curves have been determined using the Argon tool provided with ENA EG-0 for the variables described in this standard. A surface soil resistivity of 50 Ω/m has been used. In areas with different soil resistivity, the designer should use the Argon tool (or an equivalent alternative) to adjust the surface soil resistivity.

8.3.6.1 Customers and the general public

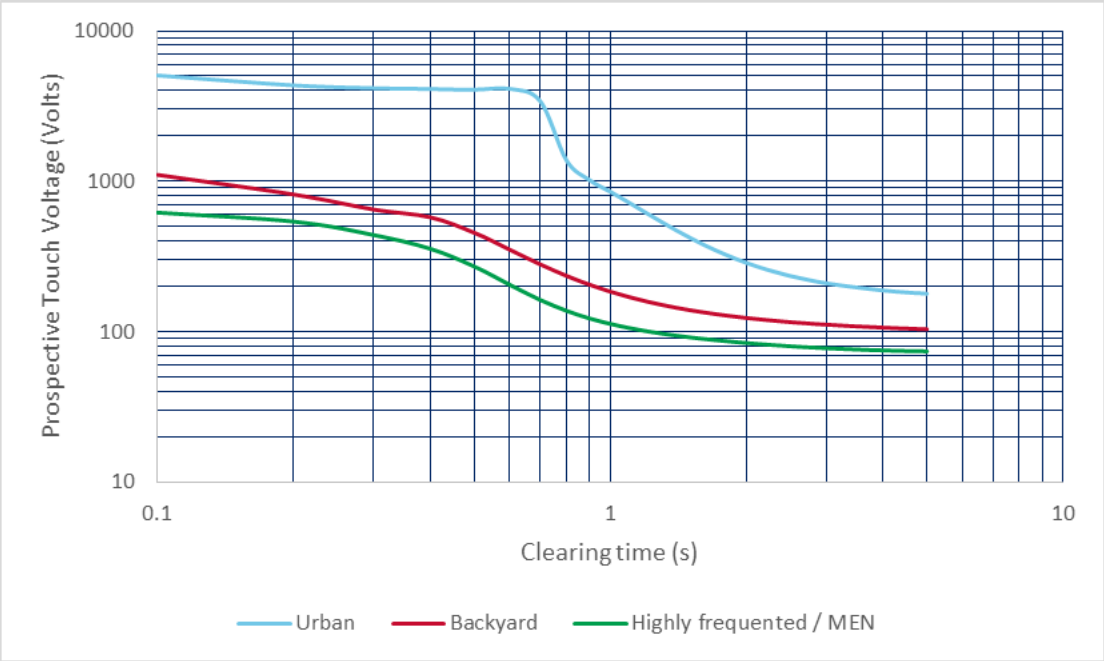

Figure 2 – Primary fault scenario

© State of NSW through Transport for NSW 2023

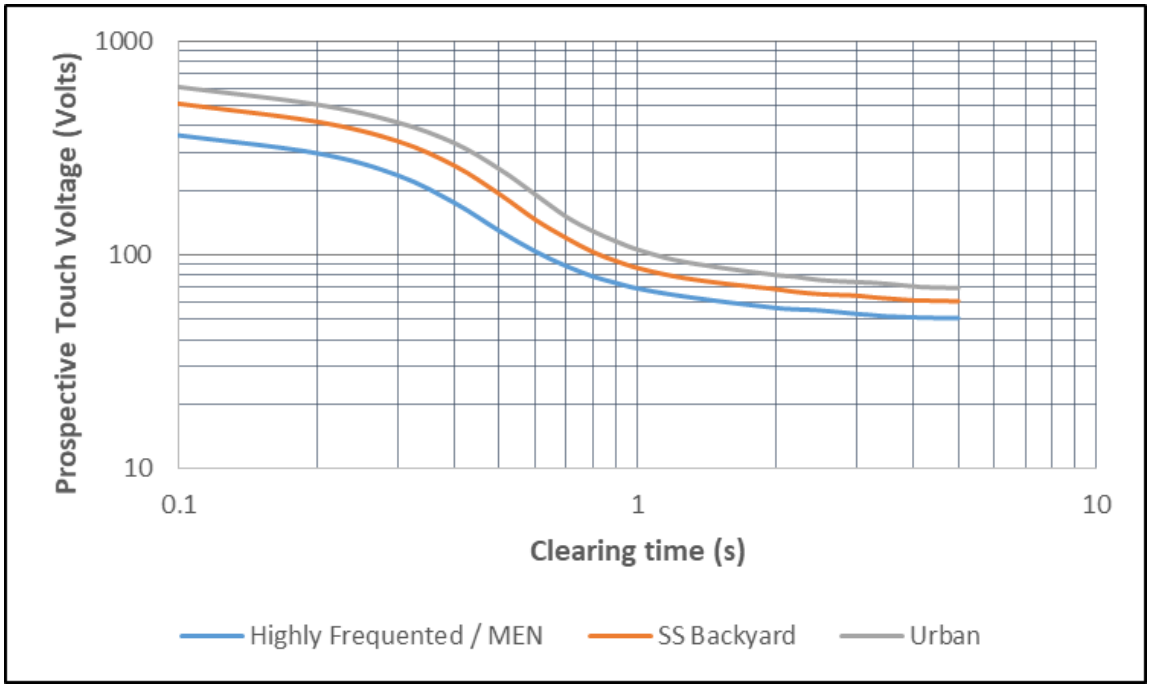

Figure 3 – Secondary fault scenario

8.3.6.2 Aquatic locations

Figure 4 – Aquatic locations

© State of NSW through Transport for NSW 2023

8.3.6.3 Risks to operators and workers

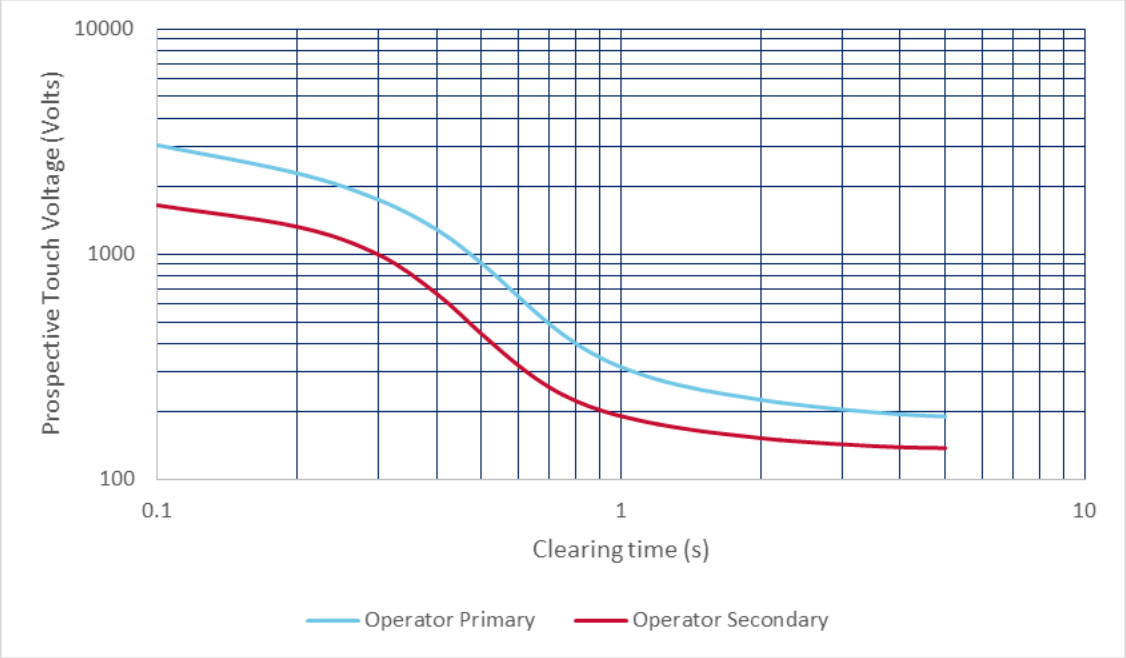

Figure 5 – Primary and secondary operators

8.3.7 Step voltages

Step voltage scenarios should initially be assessed against the equivalent touch voltage curves as a prudent avoidance measure. Where a design step voltage exceeds this limit and typical, low cost risk measures can be implemented, they should be utilised. However, the heart current factor described in AS/NZS 60479.1 implies that the relative proportion of electrical current that will flow through the heart in a step voltage scenario (one foot to another) is 25 times lower than the equivalent touch voltage scenario. For this reason, step voltages represent a significantly lower risk of fibrillation than touch voltages, and the low risk step voltage curves calculated for this scenario typically exceed the system voltages. However, a step voltage may lead to other risks such as causing a person to fall.

The mitigation of all step voltage risks shall be weighed against the introduction of other risks such as those related to surface treatments, see Section 5.1.

8.3.8 Impact on other utilities

The designer shall consider the risks imposed on other utility assets due to transferred earth potentials in accordance with the applicable Australian standards.

Refer to AS/NZS 3835.1 and AS/NZS 4853 for more information.

© State of NSW through Transport for NSW 2023

8.4 Engineering controls

Engineering controls shall be considered to engineer out or reduce hazards determined through the design process to exceed the low risk levels provided in this standard.

In all cases, while demonstrating that a design reduces the risks associated with the earthing system SFAIRP, any reasonable engineering controls should always be considered in accordance with the following hierarchy of control:

- elimination
- substitution
- engineering controls
- administrative controls
- personal protective equipment.

Controls can either be preventative or recovery controls. Preventative controls reduce the likelihood of the unwanted event occurring in the first place, and recovery controls reduce the impact of the event after it occurs. Preventative controls should be preferred over recovery controls; however, in many cases these will be out of the control of the designer.

8.4.1 Preventative controls

Preventative controls that will reduce the likelihood of an earth fault event in the first place include the following:

- reliability, availability, maintainability and supportability (RAMS) considerations in the design of the electrical network and selection of equipment ensuring the network is designed to be reliable
- appropriate maintenance considerations to keep assets in working order, such as periodic maintenance of the earthed equipment, inspection and management of vegetation around aerial lines, renewal of equipment that is no longer fit for purpose.

  Note: These considerations will typically be outside of the earthing designer's control but may be considered when considering the options of replacing equipment at the end of its life vs extending the life of the asset.

8.4.2 Recovery controls

Recovery controls that reduce the impact of the fault after it occurs include, but are not limited to, the following:

- Protection arrangements – the protection design can play a significant role in managing earthing design risk levels as the protection clearing time is a key variable in the risk level associated with the earthing system. Working with the protection designer to ensure that

© State of NSW through Transport for NSW 2023

the protection settings allow for the fastest fault clearance time practical is an efficient engineering control

- Insulating conductive surfaces or substitution for non-conductive materials – the installation of insulated material on a metallic or otherwise conductive surface to engineer out the possibility of a touch voltage at that location. This engineering control requires particular consideration for the susceptibility to corrosion or increased maintenance cost that it may introduce. Examples include coatings (which may be used subject to type approval) or other non-conductive barriers on poles or overhead wiring structures, or the use of non-conductive alternative materials such as timber or plastic, or fibre reinforced plastic materials
- Varying the earth grid impedance – The deliberate altering of the earth grid impedance as a design variable can lead to more (or less) fault current entering the ground at the location. This can change the EPR at the location which can reduce the touch voltage risks. Increasing earth grid footprint can however spread voltage hazards into the surrounding areas. A lower impedance earth grid will not always lead to a lower risk
- Installation of additional current paths (cable screens, counterpoise conductors, supplementary earth grids and so on) – the use of current paths to distribute fault current, and lower the earthing system impedance. This can improve protection operation times, and in some cases significantly limit the fault current flowing into the local earth grid. In a dc electrified rail environment this can have implications for the management of stray currents, and the risks of electrolysis shall be considered
- Equipotential bonding arrangements – the establishment of equipotential zones through electrical bonding to design out the possibility of a touch voltage scenario. This may be done by ensuring that a person's feet will be at the same potential as the surface they are contacting. In a dc electrified rail environment this can have implications for the management of stray currents, and the risks of electrolysis shall be considered
- Breaking long conductive structures such as fences and GST – the installation of insulated or non-conductive sections in long conductive structures to reduce the impact of transferred earth potentials. Long conductive assets may bring a voltage close to remote earth (zero Volts) into a location with an EPR. By installing breaks in these structures, the infrastructure close to the fault location is able to rise in voltage with the local soil reducing the touch voltage risk. In a dc electrified rail environment this can have other benefits in the management of stray currents, and so may be required regardless of the ac earthing risk need
- Regular maintenance of the earthing system – the ongoing maintenance of an earthing system, including inspection, testing and replacement to ensure that the earthing system continues to perform as designed over the life of the asset. This activity can have a substantial impact on the whole-of-life risks associated with the asset.

© State of NSW through Transport for NSW 2023

9 Lightning and transient design

The requirements for the lightning and transient design for electrical infrastructure shall be as specified in the following standards:

- AS 1768
- TS 03726
- T HR EL 21001 ST.

10 Construction Support

Construction support is a critical component of any design activity; however due to the complexity and high levels of unknowns associated with an earthing system, is particularly critical in this area.

The earthing designer shall be contactable by the construction TAO, and may need to adjust the earthing design based on the findings during construction, including the following:

- the presence of buried services or other hazards not previously identified
- mismatches between the design earthing system impedance and what is achieved on site
- any design change associated with system configuration that will impact the performance of the earthing system (for example, protection system configuration, cable screen and/or overhead earth wire configuration).

11 Testing and commissioning

Testing and commissioning of an earthing system is important due to the safety criticality, complexity and unknowns associated with the performance of an earthing system in the real world.

The level of testing and commissioning required for a particular earthing system will depend on the criticality of the particular system, and the sensitivity of the performance of the earthing system to the local environment. The designer shall specify in the design report the type of testing required for the particular asset to satisfactorily verify the performance of the system. Substation commissioning tests shall comply with T HR EL 99001 ST and TS 03726.

© State of NSW through Transport for NSW 2023

11.1 Earth grid resistance testing

As a minimum, an earthing system shall be tested to ensure that the impedance of the earth grid installed matches the designed impedance.

Impedance testing shall be performed using a combination of the following methods were appropriate:

- Clamp method – provided that the earthing system is interconnected with a low impedance earthing system to provide a return path. Clamp tests are also used to take baseline measurements for individual earth electrodes
- Fall of potential (FOP) method – for earthing systems (other than system substations). FOP method is not appropriate for larger interconnected (global) earth systems with auxiliary return paths. Interconnected systems should be disconnected for accurate measurements. Current probe should be located sufficient distance away from the zone of influence of the earth grid under test
- Current injection test (see Section 11.3).

Manufacturers' instructions shall be followed for the use of test equipment.

Note: Current injection testing will also provide an earth grid resistance measurement; where this testing methodology is used, additional FOP testing is not required.

11.2 Continuity testing

For all earthing systems the continuity of all earthing connections to the main earth grid shall be tested using a micro-ohmmeter (or ductor) tester.

11.3 Current injection testing

Current injection testing is a comprehensive testing methodology that simulates the performance of the earthing system.

Current injection testing is required for all system substations but may not be justified on distribution or transmission line earthing systems in remote locations. The decision to carry out this testing shall be based on the risks associated with the earthing system such as the location of the asset and associated earthing system, and the sensitivity of the performance of the earthing system to unknowns such as buried services, soil resistivity and so on.

If current injection testing is utilised, the tester shall determine the following at a minimum:

- the EPR
- touch voltages (including reach touch and hand to hand) at known hazard locations around the earthing system, and any hazard location identified during the test
- step voltages (using FOP method)

© State of NSW through Transport for NSW 2023

- transferred voltages to nearby conductive structures
- the proportion of electrical current, and associated phase angle of the current that flows in all current paths leaving the earthing system (current splits) to determine the resultant electrical current and phase angle of electrical current flowing into the general mass of earth.

The designer or commissioning engineer shall coordinate with the operator and maintainer to arrange for access to the assets, any necessary outages. The designer shall provide assurance that the commissioning test results meet all design requirements.

12 Asset handover

The requirements for asset handover are detailed in T MU AM 01005 ST.

In accordance with this standard, the following shall be provided to the relevant asset steward including the O&M at asset hand over:

- confirmation that relevant stakeholders have been identified and adequately consulted
- asset and operational safety argument demonstrating that the asset ensures safety SFAIRP in its intended operational context
- risk register including identification of residual risks
- commissioning report including test results and inspection test plans (ITP)
- design reports
- as-built drawings.

© State of NSW through Transport for NSW 2023

Appendix A Quantification of earthing risks

The calculation of earthing risk exposed to electrical workers and the general public is based on ENA EG-0. It comprises two fundamental components. The equation is described in Equation 1:

$$\text{Risk} = P_{\text{fibrillation}} \times P_{\text{coincidence}}$$

Equation 1 – Earthing Risk

Where,

$P_{\text{fibrillation}}$ is the probability that a voltage incident will occur in the critical part of the cardiac cycle which is sufficient to cause ventricular fibrillation. This is a value based on the current path through the body, the body impedance and any additional series impedance that can be expected (shoes, asphalt, soil contact resistance and so on).

$P_{\text{coincidence}}$ is the probability based on the frequency and duration of any voltage incident being present at a location as well as a consideration of the frequency and duration of any person being coincident with the voltage hazard.

Risk is the risk being assessed, in this case the probability of an individual fatality which is annualised.

In general, the calculation of the probability of fibrillation is less subjective than the probability of coincidence. For this reason, and in accordance with good risk management practices, the designer should first determine the probability of fibrillation, and put in place measures to minimise this including minimising the voltages on exposed metallic infrastructure, and reducing the protection clearing time where possible.

Probability of fibrillation

The main risk to humans is the exposure of the body to currents that are sufficient to cause ventricular fibrillation. Refer to AS/NZS 60479.1 for further detail on body current risks.

Based on AS/NZS 60479.1 and the assumptions provided in ENA EG-0, a set of expected fibrillation probabilities for a general population are provided in B.3 of ENA EG-0 and may be used to ascertain the risk of fibrillation. Alternatively the Argon tool, released to accompany ENA EG-0 can be used.

Other risks associated with the exposure of the body to power frequency current include risks associated with muscle contraction, muscle damage, respiration difficulties and the risk of falling due to electric shock. These conditions can occur during unbalanced load conditions and should be managed accordingly. For this reason the limits regarding these conditions are more restrictive.

© State of NSW through Transport for NSW 2023

Probability of coincidence

The probability of coincidence is the probability of someone being exposed to the influence of an earthed asset at the same time as the voltage hazard occurring.

A single event coincidence probability is described in Equation 2:

$$P_{coincidence} = \frac{f_n \times p_n \times (f_d + p_d) \times T}{365 \times 24 \times 60 \times 60} \times CRF$$

Equation 2 – Single event coincidence probability

Where;

1. Fault frequency (f_n) – the number of faults per annum of the type being considered

Fault duration (f_d) – the duration of the fault prior to clearance from the closest upstream protection

Contact frequency (p_n) – the number of contacts expected over a year at the asset being considered

Contact duration (p_d) – the duration of time each contact should last each time

T – the number of years (exposure duration) = 1 year

CRF is coincidence reduction factor (set to 1 normally).

This assumes the occurrence of an earth fault is random, independent of the presence of a person, independent of the occurrence of past earth faults, occurs one at a time and has approximately equal probability of occurring at any given time. Where the occurrence of an earth fault is not independent of the presence of an individual, such as operational switching, it is a requirement to consider special precautions and mitigation accordingly based on the associated risks.

© State of NSW through Transport for NSW 2023