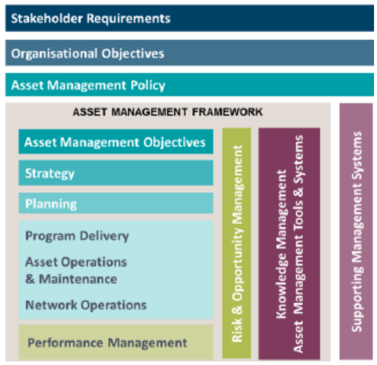
Transmission Line Earthing Design

Design Standard



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RESPONSIBILITIES

Western Power's Engineering and Design Function is responsible for this document

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Revision Details

Version	Date	Summary of change	Section
0	30/03/2017	Initial release	
1	30/08/2023	Change to AMS format.	

1. Introduction

The purpose of this standard is to set criteria for the earthing design of Western Power's transmission lines. Earthing that are designed consistently with these criteria will eliminate the variability in design outcomes and ensure that Western Power complies with its obligation under the Electricity (Network Safety) Regulations 2015.

2. Purpose and scope

This standard provides the minimum requirements for earthing design of Western Power's transmission lines in order manage the transfer of fault energy in such a manner as to limit the risk to people, equipment and system operation to acceptable levels.

2.1 Acronyms

Acronym	Definition
ALARP	As low as reasonably practicable
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis
EPR	Earth potential rise
HMR	Hazard Management Register
SFAIRP	So far as is reasonably practicable
VoSL	Value of statistical life

2.2 Definitions

Term	Definition
ALARP	The underlying risk management principle whereby risk is reduced to 'as low as reasonably practicable' within a risk cost benefit framework.
ARGON	A safety assessment software used for risk based earthing design.
Clearing Time	The time taken for the protective devices and circuit breaker(s) to isolate the fault current.
Earth electrode	Uninsulated conductor installed vertically in contact with the earth (or an intermediate material) intended for the conduction and dissipation of current. One part of the earthing system.
Earth fault	Fault caused by a conductor or conductors being connected to earth or by the insulation resistance to earth becoming less than a specified value.
Earth fault current	Current that flows from the main circuit to earth or earthed parts at the fault location (earth fault location).
Earth potential rise (EPR)	Voltage between an earthing system and reference earth.
Earth rod	Earth electrode consisting of a metal rod driven into the ground.
Earthing conductor	Conductor intended to provide a conductive path for the flow of earth fault current for the control of voltage rise and reliable operation of protection devices. Where a conductor is intended to also carry neutral return current (under normal load) it is not usually called an earthing conductor.

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.
Electrical equipment	Any item used for such purposes as generation, conduction, conversion, transmission, distribution and utilisation of electrical energy.
ENA	Electricity Networks Australia
Hazard	Potential to cause harm.
Induced voltage	The voltage on a metallic structure resulting from the electromagnetic or electrostatic effect on nearby powerline.
Probability	A measure of the chance of occurrence expressed as a number between 0 and 1.
Risk	The chance of something happening that will have an impact on objectives. Potential for realisation of unwanted, adverse consequences to human life, health, property or the environment.
Risk assessment	The overall process of identifying, analysing and evaluating the risk.
Risk treatment	Process of selection and implementation of measures to modify risk.
SFAIRP	The underlying risk management principle whereby risk is reduced to 'so far as is reasonably practicable' within a risk cost benefit framework.
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/m2). Values tabled are normalised to 1 amp flowing into a one metre cube of material yielding units of ohm-metre (Ωm).
Step voltage (prospective)	Voltage between two points on the earth's surface that are 1 m distant from each other, which is considered to be the stride length of a person. The term step voltage refers to prospective step voltage unless otherwise stated.
Touch voltage (prospective)	Voltage between simultaneously accessible conductive parts when those conductive parts are not being touched. The term touch voltage refers to prospective touch voltage unless otherwise stated. When comparing calculated or measured touch voltages with touch voltage limits, the touch voltage is taken as the potential difference between the conductive part and any point on the surface of the earth within a horizontal distance of one metre from the vertical projection of the point of contact with the conductive part
Transmission lines	Overhead lines and underground cables with system voltages of 66 kV and above.
Transferred potential	Potential rise of an earthing system caused by a current to earth transferred by a means of a connected conductor into areas with low or no potential rise relative to reference earth resulting in a potential difference occurring between the conductor and its surrounding.
Value of statistical life (VoSL)	The cost of a human death used in statistical studies and insurance.

2.3 References

References which support implementation of this document

Table 2.1 References

Reference No.	Title
AS 2067:2016	Substations and high voltage installations exceeding 1 kV a.c.
AS/NZS 3835.1:2006	Earth potential rise – Protection of telecommunications network users, personnel and plant, Part 1: Code of practice
AS/NZS 4853:2012	Electrical hazards on metallic pipelines
AS 5577-2013	Electricity network safety management systems
AS/NZS 7000:2016	Overhead line design
	Electricity (Network Safety) Regulations 2015
BS EN 50122-1: 2011	Railway applications — Fixed installations — Electrical safety, earthing and the return circuit Part 1: Protective provisions against electric shock
ENA Doc 025-2022	Power System Earthing Guide (EG-0) Part 1: Management Principles
HB 101-1997	Coordination of power and telecommunications - Low Frequency Induction (LFI): Code of practice for the mitigation of hazardous voltages induced into telecommunications lines
HB 102-1997	Coordination of power and telecommunications - Low Frequency Induction (LFI): Application Guide to the LFI Code
IEC 62561-7:2018	Lightning protection system components (LPSC) - Part 7: Requirements for earthing enhancing compounds
IEEE Std 80-2013	IEEE Guide for Safety in AC Substation Grounding
IEEE Std 81-2012	IEEE Guide for Measuring earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System

3. Compliance

Western Power shall demonstrate due diligence as required by AS 5577 by ensuring the risk on the network is minimised so far as is reasonably practicable (SFAIRP).

4. Functional Requirement

The purpose for earthing a transmission line are:

1. **Safety of personnel and public:** manage any hazardous potential differences to which personnel or members of the public may be exposed. These potential differences include:
    - Touch voltages (including transferred touch voltages)
    - Step voltages
    - Hand to hand voltages
2. **Protection of electrical network equipment:** Limit the level of transient voltage and power frequency voltage impressed on electrical equipment and thus prevent extensive damage to equipment

3. **Ensure correct system operation:** ensure proper operation of protective devices such as surge arresters and surge voltage limiters to maintain system reliability within acceptable limits

The earthing system is required to perform this function for the life of the line.

5. Earthing Design Philosophy

Western Power has adopted the risk based approach to earthing as outline in ENA EG-0. The risk exposed to personnel or members of the public is:

$$\boldsymbol{P_{fatality} = P_{coinc} \times P_{fib}}$$

Where

$P_{fatality}$ the likelihood of a fatality occurring (ie. the risk of the earthing system)

P_{coinc} the probability that a person will be present and in contact with an item at the same time that the item is affected by a fault

P_{fib} the probability that the heart will enter ventricular fibrillation due to contact with an external voltage

The risk based approach shall not be set up to achieve a predetermined risk target, but to assess all practicable and reasonable mitigation options to reduce the risk. A risk cost/benefit analysis shall be used to demonstrate that the cost to mitigate is not grossly disproportionate to the risk reduction benefit.

A risk of $\geq 10^{-4}$ must be prevented regardless of cost.

5.1 Voltage Safety Curves

The series of standard voltage vs time curves as outlined in ENA EG-0, AS/NZS 7000 and AS 2067 shall not be used for Western Power's transmission line earthing design as they are based on achieving a risk target.

5.2 Detailed Earthing Assessment

All transmission line earthing design shall use a detailed earthing risk assessment approach. The Argon tool shall be used to assist in the determination of risk.

The detailed earthing risk assessment shall be based on the following methodology shown in Figure 5.1.

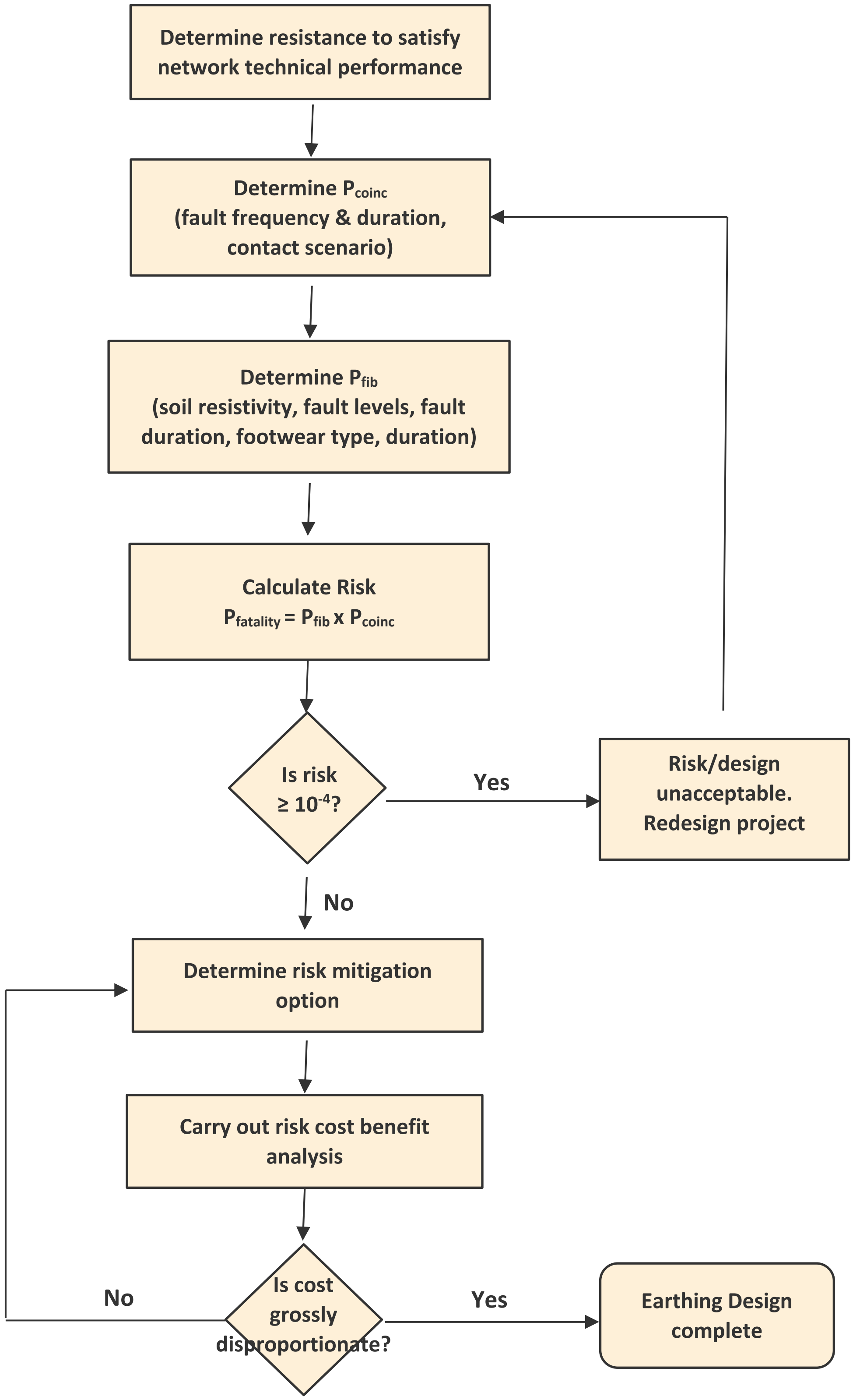

Figure 5.1: Earthing Design Methodology

6. Earthing Design Parameters

The following design parameters shall be used to complete the earthing assessment as per Figure 5.1. By ensuring design parameters are well defined and not ambiguous, earthing designs will be conducted in a consistent and reproducible manner.

6.1 Network Technical Performance

The network technical performance is the target resistance required to meet two of the functional earthing system requirements as outlined in section 5, which is to *protect the electrical network equipment* and *ensure correct system operation*.

Due to the various factors involved, standardising on one target resistance value is not possible. The values provided in Table 1 are typical values which designers may use as a starting point. These values were selected based on maintaining acceptable reliability and network performance while considering practicality and costs implications.

In rocky or high soil resistivity areas, deviations from these recommendations are permissible provided adequate reasoning with its impact on reliability documented.

Table 6.1: Typical target earth resistance values[1]

Situation	Target earth resistance (Ω)
Wood pole overhead line structures	30
Steel pole/tower overhead line structures	10
Underground cable to overhead transition structure	10
3 structures (wood or steel) immediately next to a transition structure	10
Underground cable joint bay link box	10

Soil resistivity plays an important role in determining the effort required to achieve the target earth resistance and is discussed further in section 6.3.1.

6.2 Probability of Coincidence

6.2.1 Fault Frequency

In the absence of substantiated network fault data, the typical fault rates listed in Table C-2 of ENA EG-0 may be used.

6.2.2 Earth Fault Duration

The fault clearing time of primary protection relays and circuit breakers shall be used for touch and step potential assessments. Actual fault clearance times shall be used.

This value is used for both the determination of the probability of coincidence and the probability of fibrillation.

[1] These values only apply to new earths and may not be representative of existing earths in the network. Where it is critical to know the existing earth resistance value, testing may be required.

For fault duration to be used for earthing conductors, refer to section 10.2.

6.2.3 Contact Scenario – Exposure Rates and Duration

The exposure rates and durations shall be applied in all designs that meet the contact scenario assumptions as per ENA EG-0 table C-1.

For other contact scenarios cases, site specific data proposed to be used shall be substantiated and documented.

6.3 Probability of Fibrillation

6.3.1 Soil Electrical Resistivity

Soil resistivity testing must be carried out for all detailed earthing designs. Where practicable, a Wenner four-electrode method shall be used. The testing shall be carried out in accordance with *IEEE Std 81* with at least two long orthogonal traverses.

Sensitivity to soil electrical resistivity variations due to seasonal changes must be taken into consideration. As a guide, a maximum of 20% variation on the soil resistivity shall be allowed for seasonal variations.

6.3.2 Fault Level

The earthing design shall consider future increases which could be reasonably expected and thus as a minimum be based on an actual 10 year maximum fault level forecast.

For fault levels to be used for earthing conductors, refer to section 10.2.

6.3.3 Footwear Type

The footwear type shall be selected as per Table 6.2.

Table 6.2: Footwear Type

Footwear Type	Situation
No Footwear (Barefeet)	Swimming pools, beaches, parks, bodies of water ie. rivers, lakes
Electrical Footwear	Inside substations or employees at or near a Western Power asset that is not accessible to the public.
Standard Footwear	Used for areas not covered by *"No Footwear"* or "*Electrical Footwear*"

In the case of swimming pools and bodies of water, the "Wet" button in Argon shall be selected as the body will be submerged in water or water-wet and therefore use a different body impedance curve in the calculation.

7. Risk Treatment

Risk control measures or treatments shall be applied in accordance with the standard hierarchy of controls.

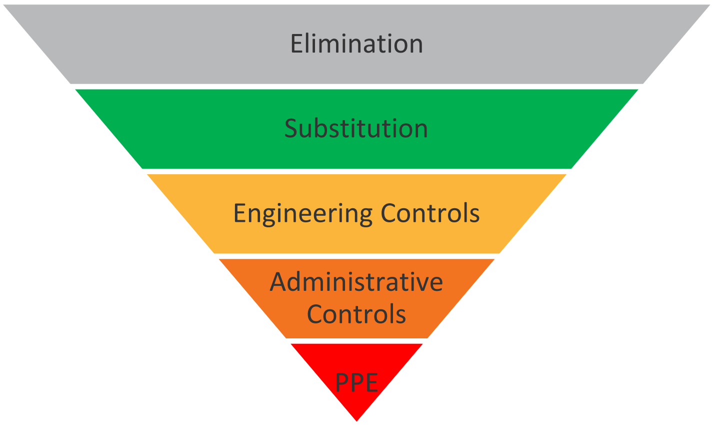

Figure 7.1: Standard Hierarchy of Controls

Where reasonably practicable, the hazards shall be eliminated as the first preference. This may involve moving the asset (power pole, towers, cable joint bays) away from hazardous locations or relocation of non-compliant infrastructure (e.g. telecommunication pits).

Replacing (substituting) the asset producing the hazard with one which does not should then be considered. This may involve substituting the steel pole/structure with a non-conductive structure (eg. wooden poles).

Where it is not reasonably practicable to eliminate the risk, engineering controls may be considered taking into account the risk reduction and cost involved. These may include reduce earth system impedance, installation of grading control conductors (grading rings), installation of overhead earthwires and earthing conductors, and reduction of fault clearance times. Surface insulating layer is not preferred due to ongoing maintenance. Insulating covers around conductive assets is effective in managing touch voltages, however their aging and ongoing maintenance requirements is still unknown.

With assets being easily accessible by the general public, administrative controls such as installation of warning signs/labels should not be considered unless it can be substantiated that it can reduce the probability of coincidence. It should be noted that it is Western Power and general industry practice to install danger signs on power assets regardless.

Personal protective equipment (PPE) should only be considered for electrical workers and not the general public.

8. Risk Cost Benefit Analysis

To determine whether a risk mitigation option is reasonably practicable, a cost benefit analysis shall be applied using the amount by which the probability has been reduced to.

Western Power's liability (*L*) per year (dollars) based on the value of statistical life (VoSL) is:

$$L = VoSL \times P_{fatality}$$

The present value (PV) of liability (risk) is determined using the remaining lifespan of the asset, the liability per year and the expected rate of interest on an alternative investment.

$$PV = \frac{n \times L}{D}\left[1 - \left(\frac{1}{1+D}\right)^{Y}\right]$$

Where

PV Present value (dollars)

L Asset owner’s liability per year

D Discount rate (fractional rate of interest)

Y Number of years which the asset will remain potentially hazardous (years)

The present value benefit after risk treatment is the difference between the present values of the initial liability against the liability after risk mitigation.

$$PV_{benefit} = PV_{initial\ liability} - PV_{liability\ after\ risk\ mitigation}$$

The cost is deemed to be grossly disproportionate to the risk if the ratio of the mitigation cost to the present value benefit after risk treatment is greater than the disproportion factor (DF).

$$Disproportion\ factor\ (DF) > \frac{Mitigation\ Cost}{PV_{benefit}}$$

The mitigation cost shall include both the capital cost to mitigate the risk and any present value future operating expense.

Refer to *Network Standard – Earthing Systems Functional Requirements* (EDM #4479188) for the values to be used in the risk cost benefit analysis.

9. Hazardous Voltages on Surrounding Assets

In addition to the hazardous voltages which may appear on the transmission line, hazardous voltages on surrounding assets as a result from transfer voltages, capacitive coupling and inductive coupling, must also be considered.

Other affected asset operator must be consulted as they may have other Standards and Code of Practice which needs to be considered (eg. AS/NZS 3835.1, BS EN 50122-1, HB 101, HB 102, AS 4853 etc)

Voltage compliance for control of corrosion (e.g pipeline) must also be met and in some cases may be more stringent than the requirements assessed for human safety.

10. Earthing Material and Sizing

The material used for the earthing system needs to be selected and sized to achieve a level of robustness for the life of the installation.

10.1 Earth electrodes

Pole earth electrodes shall be placed as close as possible to the pole and parallel (longitudinal direction) with the direction of the line to minimise the risk of transferring voltages to surrounding conductive structures/assets.

Any drilled bores must be backfilled with a conductive and contact improving compound in accordance with IEC 62561-7.

10.2 Earthing and bonding conductors

Where practicable, earthing conductors shall be rated to Western Power's standardised ultimate fault levels[2]. The ratings must be calculated using the backup protection operating time plus circuit breaker operating time.

The current rating may be determined using the formulae obtained from *IEEE Std 80* or *ENA EG-1*. The following parameters in Table 10.1 shall be used.

Table 10.1: Earthing conductor sizing parameters

Description	Initial Temperature
Underground or embedded conductors	25 °C
Aboveground conductors	40 °C
Description	**Final Temperature**
Conductors – bolter or compression joints	250 °C
Conductors – welded or brazed	450 °C
PVC insulated conductors	160 °C
XLPE insulated conductors	250 °C

10.3 Theft and vandalism protection

To prevent theft and/vandalism, exposed component of the earthing system shall not be made of copper or they must be concealed. Downleads may be installed with an aluminium conductor before transitioning into a stainless steel conductor (to prevent corrosion) as it goes underground to connect onto the earth rod.

For all wooden poles, the downlead is to be housed in a non-conductive casing for a typical height of 3.0 m above ground.

10.4 Foundation embedded earthing

For difficult earthing situations where the steel reinforcing bars is required to be used as part of the earthing system, the following must be adhered to:

- Electrical designers and civil designers to coordinate the design of the embedded earthing to prevent concrete spalling and corrosion
- Reinforcement to be welded and bonded to provide electrical continuity
- Sufficient concrete cover over the steel reinforcement to minimise corrosion
- Thermal ratings of earthing conductors and joints (excluding contribution from the embedded earthing) are not to be exceeded

[2] See Western Power internal document

11. Lightning and Transient Design

For lightning and transient design of overhead lines and underground cables, refer to Western Power's internal document.

12. Commissioning

Commissioning of new earthing systems is essential as a validation step for the design and installation process and for the design inputs. As well as design compliance purposes, it will provide a benchmark or baseline figures for future maintenance activities.

All earthing system design shall include the following field tests:

- Visual inspection
- Continuity test
- Earth resistivity testing

For significant earthing systems, earth potential rise measurement, current distribution measurement and transfer, touch and step voltage testing may be considered.

13. Design Documentation

The final design documentation shall be provided with the following as a minimum:

- Earthing design report including the following details:
  - Design assumptions and inputs
  - Design calculations and decisions
  - Selection of size and material of earthing system
  - Risk cost benefit analysis
  - Final design solution
- Soil earth resistivity test results
- Earthing system layout drawing
- Commissioning data
- Any monitoring and maintenance requirements

CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis) is the preferred software for conducting earthing studies and must be provided together with the report as part of the design.

14. Safety in Design

The earthing design must consider all safety aspects that can arise from the construction, operation, maintenance and decommissioning of the transmission line and other activities within the line corridor.

The *Transmission Lines Earthing Design Hazard Management Register (HMR)*[3] captures and document what risks have been controlled by this standard, and what residual risks may remain that should be considered at the project design stages and construction.

Every design is required to have its own project specific Hazard Management Register.

3 See Western Power's internal document