# Lightning Protection for Transmission Substations

## Design Standard


### DOCUMENT HIERARCHY

This document resides within the Planning component of Western Power's Asset Management System (AMS).

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Record of endorsement, approval, stakeholders, and notification list is provided in EDM# 54288453 appendix

### RESPONSIBILITIES

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

### CONTACT

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# Contents

## Revision Details

| Version | Date | EDM Version | Summary of change |
|---|---|---|---|
| 0 | 28/02/2010 | 1 | Original Issue – Shell Standard |
| 1 | 09/03/2010 | 3 | Approved Standard |
| 2 | 20/10/2020 | 9 | Updated to AMS format – Standardised design recommended |
| 4 | Oct 2023 | 10 | Standard Online Update |
| | | | |

# 1. Introduction

## 1.1 Background

The purpose of this Engineering Design Instruction (EDI) is to assist with understanding lightning protection design principles and provide a clear understanding of lighting stroke formation, specifically within transmission substations.

Zone substations are typically shielded by lightning masts and terminal switchyard substations are shielded with overhead earth wires or a combination of both. Any tall earthed structures such as floodlight masts or microwave towers, however, can also contribute to the shielding of a substation.

The design criterion is based on the rolling sphere methodology using a strike radius of 24 meters. That is, an assumed charged sphere with a 24m radius shall come into contact with either lightning masts, overhead earth wires or any earthed object prior to getting low enough to come into contact with any substation conductors or equipment.

## 1.2 Purpose and Scope

This Engineering Design Instruction sets out the lightning protection requirements for Transmission Zone and Terminal Substations, on both Greenfield and Brownfield sites.

Lightning protection of substations is provided to minimise danger to people, damage to expensive primary plant, thereby providing reliability of supply.

There are two aspects to lightning protection in substations:

- Shielding the area by providing routes for the lightning stroke to travel to earth and
- Providing a safe route for any induced overvoltages or overvoltages resulting from a direct strike on overhead lines entering the substation

This design instruction does not include methods to remove voltage surges on overhead lines entering the substation; this is covered by the 'Network Standard - Insulation Coordination'. This standard sets out the relevant methods used to minimise the risk of substation equipment being damaged by a direct lightning strike.

## 1.3 Acronyms

| Acronym | Definition |
|---|---|
| | |
| | |
| | |

## 1.4 Definitions

| Term | Definition |
|---|---|
| Stepped Leader | Static discharge that propagates from a cloud into the air. |
| Striking distance | The length of the final jump of the stepped leader as its potential exceeds the breakdown resistance of this last gap; found to be related to the amplitude of the first return stroke. |
| Basic Insulation Level (BIL) | Developed method to coordinate insulation levels in the substation and lines. Assurance that the breakdown or flashover strength of all substation equipment will be equal or exceeded. |
| Standard lightning impulse withstand level | Levels determined through equipment voltage surge withstand testing. |
| Keraunic Level | The average number of thunderstorm days for an area. The average number of days per year on which thunder will be heard during a 24-hour period. (T) |
| Ground flash density | The average number of strokes per units of time at a location. Roughly proportional to the keraunic level (0.1 T to 0.19 T) |
| Greenfield | A site that has not previously been developed to contain a new substation. |
| Brownfield | A site that already contains a substation and some substation equipment. Projects at these sites are mostly extensions or refurbishment of selected equipment. |

## 1.5 References

References which support implementation of this document

**Table 1.1 References**

| Reference No. | Title |
|---|---|
| | |
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| | |

# 2. Supporting Documentation[1]

1 See Western Power Internal Document

# 3. Compliance[2]

The Engineering Design Instruction should encompass all requirements of the relevant Australian Standards which are current at the time. A period will be set when the standard needs to be reviewed. If significant changes occur on an Australian Standard that affects safety, an out of cycle review can be completed.

The Engineering Design Instruction must comply with higher level Western Power technical documents such as relevant Network Standards. The relevant Network Standards and other relevant documentation are listed in Table 3.1.

| | Document Title |
|---|---|
| | Network Standard – Insulation Coordination |

**Table 3-1: Relevant Documentation**

The relevant Australian Standards are listed below in the table below.

| Standard Number | Standard Title |
|---|---|
| AS1768:2007 | Lightning Protection |
| IEEE998-2012 | IEEE Guide for Direct Lightning Stroke Shielding of Substations |

**Table 3-2: Australian and International Standards**

Compliance to this Engineering Design Instruction is necessary to provide a safe working environment within a substation. All lightning protection requirements must be implemented where applicable to ensure full compliance.

# 4. Safety in Design[3]

Safety in Design (SID) must be considered when completing all substation design work. SID focuses on making the design safer and easier to understand, with the aim to eliminate and mitigate potential hazards during the design phase of a project.

Some examples of Safety in Design in lightning design include:

- Will the lightning mast be used for lighting? If so, have safety and maintenance access clearance been considered?
- Will the lightning mast location impede access to other equipment in the yard?

Any identified hazards shall be documented in the Hazard Management Register (HMR) and shall be eliminated, or have risks reduced to ALARP. The HMR and relevant design drawings shall undertake a construction, operation and maintenance (C.O.M) review at relevant stages of the project.

[2] See Western Power Internal Document
[3] See Western Power Internal Document

# 5. Design Methods

The Electro Geometric model (EGM) shall be used for lightning protection design. This is achieved via the rolling sphere method which can be proven by means of 3D modelling of the substation. The previous empirical method for lightning protection is no longer used.

## 5.1 Electro Geometric Model (EGM)[4]

Electro geometric modelling is a valid approach for the design of lightning protection systems. A modified version of electro geometric modelling is known as the rolling sphere method by which:

1) The strike is assumed to arrive in a vertical direction;
2) Different striking distances are taken into consideration; and
3) The model is not tied to a specific form of striking distance equations.

In electro geometric modelling, the protective area of a lightning mast or earthing wire depends on the strike current for which protection is needed. This means that if a mast is installed to protect equipment against a strike current of $I_S$, the equipment might not be protected against strike currents of less than $I_S$, because of shorter strike distances. This concept has been further discussed in Appendix A.

The lightning protection system is designed to intercept lightning strikes that can cause flashover of insulation and thus damage to equipment. This involves the calculation of the smallest allowable strike current and the strike distance for this lightning strike.

Allowable strike current is calculated using the equation of Gilman and Whitehead, which considers the basic insulation level (BIL) for the substation[5] and the surge impedance of the station. The calculations can be found in IEEE998.

### 5.1.1 Application of EGM – Rolling Sphere

With application of the rolling sphere method of EGM, the aim is to provide protection to equipment for a specified lightning stroke current, $I_S$. The lightning stroke current being the current that would cause a flashover across insulation. Western Power uses 3D software to model the rolling sphere.

The method involves rolling an imaginary sphere over the surface of a substation. The sphere rolls over grounded metallic objects such as masts and fences that would provide lightning shielding. Equipment is seen as being inside the protected zone if the sphere rolls over without touching it, as seen in Figure 5-1.

For further details on the theory of the EGM refer to Appendix A.

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4 See Western Power Internal Document

5 BIL of Post insulator normally used.

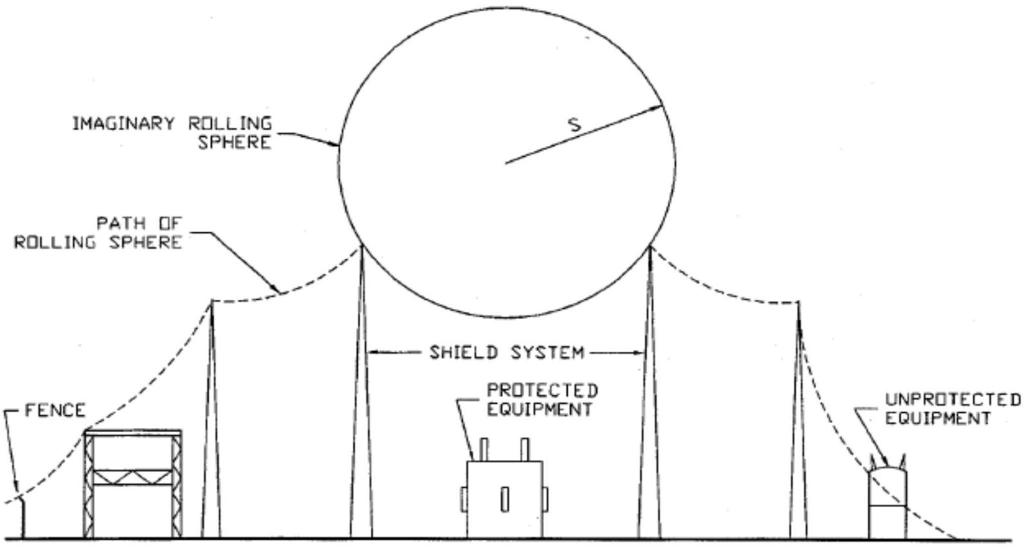


Figure 5-1: Principle of the rolling sphere

### 5.1.2 Lightning Damage Probability[6]

When the minimum strike current is used to determine the sphere size used for the rolling sphere EGM, the substation and its equipment should theoretically be protected against direct lightning strikes. If larger sphere sizes are used for the design of the lightning protection systems, the following method is recommended to determine the risk and probability of failure due to lightning:

1) Determine the required strike distance (S);
2) Determine the alternative bigger strike distance (S1) i.e. the size of the rolling sphere being considered;
3) Calculate the probability of a lightning strike current bigger than S but less than S1;
4) Calculate the area not protected by the S1;
5) Using the ground flash density for the substation area, determine the strokes per year expected on the substation area; and
6) The product of items 3) and 5) will provide the calculated failures per year for the lightning protection design.

The value received from 6) will need to be evaluated for each design where standard values cannot be applied. However, it is anticipated that the standard rolling sphere can be applied in the majority of cases. Section 6 of this document provides guidance on when the standard rolling sphere can be applied.

[6] See Western Power Internal Document

# 6. Lightning Design Criteria

## 6.1 Tolerable Risk

Lightning design strategies have been developed for greenfield and brownfield sites. This section shows how the standard design may be applied to both greenfield and brownfield sites, and result in a level of tolerable risk of failure. Guidance on the level of tolerable risk can be found in AS1768 and is shown below in Table 6.1.

| Type of Risk | Tolerable Risk per Year ($R_a$) |
|---|---|
| Loss of human life | $10^{-5}$ |
| Loss of service to the public | $10^{-3}$ |
| Loss of cultural heritage | $10^{-4}$ |

**Table 6-1: Typical values of tolerable risk**

For a lightning strike on a transmission substation, whilst it may not result in direct loss of human life, the loss of service to the public is considerable and greater than what is considered in AS1768. As such a conservative failure rate of one failure every 10,000 years is applicable for transmission substations. The risk of equipment failure for a substation lightning protection system shall not exceed $1 \times 10^{-4}$.

## 6.2 Standard Design

AS1768 defines four levels of standard levels of lightning protection which are shown in Table 6.2.

| Protection Level | Sphere Radius | Interception Current |
|---|---|---|
| **PL** | **Meters** | **$I_{MIN}$, kA** |
| I | 20 | 2.9 |
| II | 30 | 5.4 |
| III | 45 | 10.1 |
| IV | 60 | 15.7 |

**Table 6-2: AS1768 Lightning Protection Levels**

AS1768 also provides alternative increased sphere radii for each protection level, however these are applicable to large flat surfaces and therefore do not apply to outdoor electrical high voltage equipment,

Western Power has historically used a rolling sphere of radius 24m for lightning protection, which falls between level I and level II protection as defined in AS1768. A 24m radius sphere provides interception for stroke currents above 4.1kA. This design instruction demonstrates the suitability of this chosen sphere radius and recommends its use for standard design.

## 6.3 Greenfield Sites[7]

A risk calculation is performed for both standard terminal and zone substation designs, for all voltage levels and the expected failure rates using the standard 24m sphere are presented below.

Standard designs considered are based on standard layouts for zone and terminal substation yards.

### 6.3.1 Zone Substations[8]

The risk calculation input parameters for the standard zone substation design are as follows:

| Voltage Level | Maximum conductor height | Conductor Radius (of highest conductor) | BIL | Exposed Area | Ground Flash Density |
|---|---|---|---|---|---|
| 132kV | 6m | 50mm | 650kV | 5,400m$^2$ | 5 flashes/km$^2$/year |
| 22kV | 4m | 5mm | 125kV | 230m$^2$ | 5 flashes/km$^2$/year |

**Table 6-3: Zone Substation risk calculation input parameters**

Note: A ground flash density of 5 flashes/km$^2$/year is used as this is the highest level possible for the area covered by the South West Interconnected System (SWIS) and is used for all substations in the SWIS.

The results from the risk calculation for the standard zone substation design, using the standard rolling sphere radius of 24m with strike current of 4.1kA are as follows:

7 See Western Power Internal Document
8 See Western Power Internal Document

| Voltage Level | Strike Current | Strike Distance | Probability of stroke less than 4.1kA but greater than strike | Expected Failures per year | Expected years between failures |
|---|---|---|---|---|---|
| 132kV | 4.6kA | 25.9m | 0% (-0.18%) | 0 | No failures<br>0.18% Overlap |
| 22kV (Capacitor Banks) | 0.7kA | 7.4m | 0.51% | $5.32 \times 10^{-6}$ | 188,036 |

**Table 6-4: Zone Substation risk calculation results**

The standard sphere completely protects the 132kV switchyard of the standard zone substation design, and adequately protects the 22kV capacitor banks with an acceptable level of probability of failure.

### 6.3.2 Terminal Switchyard[9]

The risk calculation input parameters for the standard terminal switchyard design are as follows:

| Voltage Level | Maximum conductor height | Conductor Radius (of highest conductor) | BIL | Exposed Area | Ground Flash Density |
|---|---|---|---|---|---|
| 330kV | 19m | 16mm (twin @ 380mm centres) | 1175kV | 32,000m$^2$ | 5 flashes/km$^2$/year |
| 132kV | 12m | 13mm (twin @ 380mm centres) | 650kV | 14,000 m$^2$ | 5 flashes/km$^2$/year |

**Table 6-5: Terminal Switchyard risk calculation input parameters**

Note: A ground flash density of 5 flashes/km$^2$/year is used as this is the highest level possible for the area covered by the South West Interconnected System (SWIS) and is used for all substations in the SWIS.

The results from the risk calculation for the standard terminal switchyard design, using the standard rolling sphere radius of 24m with strike current of 4.1kA are as follows:

9 See Western Power Internal Document

| Voltage Level | Strike Current | Strike Distance | Probability of stroke less than 4.1kA but greater than strike current | Expected Failures per year | Expected years between failures |
|---|---|---|---|---|---|
| 330kV | 6.5kA | 32.5m | 0% (-1.2%) | 0 | No failures 1.2% Overlap |
| 132kV | 3.6kA | 22.1m | 0.15% | $1.55 \times 10^{-5}$ | 64,341 |

**Table 6-6: Terminal Switchyard risk calculation results**

The standard sphere completely protects the 330kV switchyard of the terminal design, and adequately protects the 132kV switchyard with an acceptable level of probability of failure.

## 6.4 Brownfield Sites[10]

This section evaluates the lightning performance of the standard 24m sphere on worse case parameters that may be encountered at brownfields sites.

When performing works at a brownfields site, the standard 24m sphere design can be applied without the need for a new risk calculation if the following conditions are met:

- BIL equal or higher than the value shown in Table 6.7.
- Highest conductors at or lower than the height shown in Table 6.7.
- Highest conductor radius equal to or larger than that shown in Table 6.7.
- Equipment area equal to or less than that shown in Table 6.7.

| Voltage Level | Maximum conductor height | Conductor Radius (of highest conductor) | BIL | Exposed Area (see note) | Ground Flash Density |
|---|---|---|---|---|---|
| 330kV | 20m | 10mm | 1050kV | 45,000 $m^2$ | 5 flashes/$km^2$/year |
| 220kV | 16m | 8mm | 850kV | 25,000 $m^2$ | 5 flashes/$km^2$/year |
| 132kV | 12m | 8mm | 550kV | 40,000 $m^2$ | 5 flashes/$km^2$/year |
| 66kV | 8m | 5mm | 325kV | 8,500 $m^2$ | 5 flashes/$km^2$/year |
| 33kV | 7m | 5mm | 170kV | 2,000 $m^2$ | 5 flashes/$km^2$/year |
| 22kV | 5m | 5mm | 125kV | 1,500 $m^2$ | 5 flashes/$km^2$/year |

**Table 6-7: Brownfields substation worse case lightning risk parameters**

[10] See Western Power Internal Document

Note: Exposed areas are expected worse case scenarios and are based on ultimate development at the following brownfield sites; 330kV – Southern Terminal, 220kV – West Kalgoorlie Terminal, 132kV – Southern Terminal, 66kV – Cannington Terminal, 33kV – Geraldton, 22kV – Canningvale.

The results from the risk calculation using the standard rolling sphere radius of 24m with strike current of 4.1kA are as follows:

| Voltage Level | Strike Current | Strike Distance | Probability of stroke less than 4.1kA but greater than strike current | Expected Failures per year | Expected years between failures |
|---|---|---|---|---|---|
| 330kV | 5.6kA | 29.2m | 0% (-0.61%) | 0 | No failures 0.61% Overlap |
| 220kV | 4.5kA | 25.5m | 0% (-0.14%) | 0 | No failures 0.14% Overlap |
| 132kV | 2.9kA | 19.3m | 0.30% | $2.14 \times 10^{-4}$ | 4,674 see below |
| 66kV | 1.7kA | 13.5m | 0.46% | $1.34 \times 10^{-4}$ | 7,464 see below |
| 33kV | 0.9kA | 8.7m | 0.51% | $4.40 \times 10^{-5}$ | 22,705 |
| 22kV | 0.6kA | 7.2m | 0.51% | $3.49 \times 10^{-5}$ | 28,690 |

**Table 6-8: Brownfields substation risk calculation results**

The above table shows that the standard rolling sphere of 24m will adequately protect the worse case scenarios which could be encountered at brownfields substations at all voltage levels except for 132kV and 66kV.

For 132kV substations, the combination of the lower BIL (550kV) and large area size results in a failure rate of more than 1 in 10,000 years. However, a BIL of 550kV is not common in Western Power substations. Using the more common BIL of 650kV with other values remaining the same, the failure rate decreases to an acceptable 1 in 16,313 years. Should work be required on a brownfield 132kV substation with a BIL of 550kV, a site-specific lightning risk calculation should be performed.

For 66kV substations, a large substation area can result in a failure rate of more than 1 in 10,000 years. The maximum substation area required to achieve an acceptable failure rate using the above parameters is approximately 6000m$^2$. If performing works on a 66kV brownfield substation of larger area than this, a site-specific lightning risk calculation should be performed. If a site-specific risk calculation is performed, actual site values should be used for the above parameters. If the risk calculation still results in an unacceptable failure rate, a smaller rolling sphere size shall be considered.

A rolling sphere size of 24m is preferred for brownfield installations for site consistency and future lightning studies. However, if this sphere size requires additional lightning protection that is not practical or feasible, other sphere sizes can be considered as long as the failure rate does not exceed the tolerable risk value shown in Section 6.1.

# 7. Installation Requirements

## 7.1 Lightning Masts

The spacing of lightning masts inside the substation will be determined by:

1) A lightning design produced from the criteria outlined in Section 6;
2) Practical placement not to interfere with operations and equipment access; and
3) Required safety clearance from equipment (e.g. clearances from tilt-down mast swing)

Lightning masts can be used to mount floodlights for switchyard lighting. Where this is the case, tilt-down lightning masts shall be used. If no lights are required on a lightning mast, then a fixed mast should be used. Lightning masts may also be used to mount outdoor GPOs where required.

In order to minimise the surge impedance of lightning masts, the following should be observed:

Use of multi-prong lightning interceptor spikes at the top of lightning masts. These should be installed on all fixed masts and tilt-down masts. In general 600mm long spikes should be used as standard, unless the masts has floodlights installed for which then 1500mm long spikes should be used, to provide protection to the lights. Where masts are used for lighting purposes only and are sufficiently protected from lightning strikes by overhead earth wires, lightning spikes are not required.

All tilt-down masts shall have an earth braid installed across the mast hinge for earthing and lightning protection. Earthing of masts to the earth grid shall be in accordance Engineering Design Instruction - Earthing Design. Refer to Substation Design Drawing Register for the full list of standard lightning mast drawings.

## 7.2 Overhead earth wires

Where overhead earth wires are used to provide lightning protection within a substation, a conductor with a minimum strand size of 3mm diameter should be used to ensure ability of the conductor to withstand a lightning strike.

To minimise surge impedance, overheard earth wires should be bonded to the steelwork at the top of the gantry or pole they are connected to. The gantry or pole should then be earthed to the earth grid in accordance with Engineering Design Instruction - Earthing Design.

Should overheard earth wires terminate on wood or concrete poles, the earth grid risers should extend up the pole to connect directly to the overhead earth wire.

## Appendix A: : Electro Geometric Model (EGM) [11]

[11] See Western Power Internal Document

## Appendix B: : Comparison Between AS 1768 and IEEE998[12]

12 See Western Power Internal Document

## Appendix C: : Lightning Stroke Formation[13]

[13] See Western Power Internal Document

## Appendix D: Approval Record and Document Control[14]

[14] See Western Power Internal Document