Ausgrid

Network Standard

NETWORK	Document No : NW000-S0142 Amendment No : 0 Approved By : Head of AEP&S Approval Date : 08/06/2017

NW000-S0142 **NS264 MAJOR SUBSTATION LIGHTNING PROTECTION AND INSULATION COORDINATION**

ISSUE

For issue to all Ausgrid and Accredited Service Providers' staff involved with the design and installation of components associated with the insulation coordination and lightning protection of the companies major substations, and is for reference by field, technical and engineering staff.

Ausgrid maintains a copy of this and other Network Standards together with updates and amendments on www.ausgrid.com.au.

Where this standard is issued as a controlled document replacing an earlier edition, remove and destroy the superseded document.

DISCLAIMER

As Ausgrid's standards are subject to ongoing review, the information contained in this document may be amended by Ausgrid at any time. It is possible that conflict may exist between standard documents. In this event, the most recent standard shall prevail.

This document has been developed using information available from field and other sources and is suitable for most situations encountered in Ausgrid. Particular conditions, projects or localities may require special or different practices. It is the responsibility of the local manager, supervisor, assured quality contractor and the individuals involved to make sure that a safe system of work is employed and that statutory requirements are met.

Ausgrid disclaims any and all liability to any person or persons for any procedure, process or any other thing done or not done, as a result of this Standard.

All design work, and the associated supply of materials and equipment, must be undertaken in accordance with and consideration of relevant legislative and regulatory requirements, latest revision of Ausgrid's Network Standards and specifications and Australian Standards. Designs submitted shall be declared as fit for purpose. Where the designer wishes to include a variation to a network standard or an alternative material or equipment to that currently approved the designer must obtain authorisation from the Network Standard owner before incorporating a variation to a Network Standard in a design.

External designers including those authorised as Accredited Service Providers will seek approval through the approved process as outlined in NS181 Approval of Materials and Equipment and Network Standard Variations. Seeking approval will ensure Network Standards are appropriately updated and that a consistent interpretation of the legislative framework is employed.

Notes: 1. Compliance with this Network Standard does not automatically satisfy the requirements of a Designer Safety Report. The designer must comply with the provisions of the Workplace Health and Safety Regulation 2011 (NSW - Part 6.2 Duties of designer of structure and person who commissions construction work) which requires the designer to provide a written safety report to the person who commissioned the design. This report must be provided to Ausgrid in all instances, including where the design was commissioned by or on behalf of a person who proposes to connect premises to Ausgrid's network, and will form part of the Designer Safety Report which must also be presented to Ausgrid. Further information is provided in Network Standard (NS) 212 Integrated Support Requirements for Ausgrid Network Assets.

2. Where the procedural requirements of this document conflict with contestable project procedures, the contestable project procedures shall take precedent for the whole project or part thereof which is classified as contestable. Any external contact with Ausgrid for contestable works projects is to be made via the Ausgrid officer responsible for facilitating the contestable project. The Contestable Ausgrid officer will liaise with Ausgrid internal departments and specialists as necessary to fulfil the requirements of this standard. All other technical aspects of this document which are not procedural in nature shall apply to contestable works projects.

INTERPRETATION

In the event that any user of this Standard considers that any of its provisions is uncertain, ambiguous or otherwise in need of interpretation, the user should request Ausgrid to clarify the provision. Ausgrid's interpretation shall then apply as though it was included in the Standard, and is final and binding. No correspondence will be entered into with any person disputing the meaning of the provision published in the Standard or the accuracy of Ausgrid's interpretation.

KEYPOINTS

This standard has a summary of content labelled "KEYPOINTS FOR THIS STANDARD". The inclusion or omission of items in this summary does not signify any specific importance or criticality to the items described. It is meant to simply provide the reader with a quick assessment of some of the major issues addressed by the standard. To fully appreciate the content and the requirements of the standard it must be read in its entirety.

AMENDMENTS TO THIS STANDARD

Where there are changes to this standard from the previously approved version, any previous shading is removed and the newly affected paragraphs are shaded with a grey background. Where the document changes exceed 25% of the document content, any grey background in the document is to be removed and the following words should be shown below the title block on the right hand side of the page in bold and italic, for example, Supersedes – document details (for example, "Supersedes Document Type (Category) Document No. Amendment No.").

KEY POINTS OF THIS STANDARD

Scope and Risks Addressed

This standard defines the requirements for the:

- ☐ Design, construction and documentation of major substation lightning protection systems
- ☐ Minimum equipment insulation requirements for major substations
- ☐ Minimum overvoltage protective requirements (surge arresters and overhead earth wires) for major substations

Where to for more information?

Sections 1.0 and 2.0

Lightning Protection

Equipment, structures and buildings within major substations shall be adequately protected from direct lightning strikes by installing a combination of the following:

- ☐ Lightning spires
- ☐ Associated substation earthing system components

Where to for more information?

Section 0

Tools and Forms

Annexures B and C

Insulation Coordination

Insulation coordination within major substations is required to achieve acceptable service reliability by minimising the risk of equipment failure. This is achieved by a combination of the following:

- ☐ Identification of voltage stresses
- ☐ Minimum equipment insulation levels
- ☐ Overvoltage protection

Where to for more information?

Section 7.0

Tools and Forms

Annexures D and E

Network Standard
NS264
Major Substation Lightning Protection and Insulation Coordination

CONTENTS

1.0 PURPOSE

The purpose of this document is to identify the minimum lightning protection and insulation coordination requirements for design and construction of major substations. The aim is to minimise equipment damage and network outages due to overvoltages as far as reasonably practical.

2.0 SCOPE

This document defines the requirements for:

- Design, construction and documentation of major substation lightning protection systems;
- Minimum equipment insulation requirements for major substations; and
- Minimum overvoltage protective requirements (surge arresters and overhead earth wires) for major substations.

Design, construction and commissioning of earthing systems for major substations are covered in Ausgrid network standard NS222 Major Substation Earthing Layout Design.

Lightning protection and insulation coordination design for overhead and underground transmission and distribution mains are covered in Ausgrid network standards NS109, NS126, NS135, NS168, NS220 and NS260.

3.0 REFERENCES

3.1 General

All requirements covered in this document shall conform to all relevant Legislation, Standards, Codes of Practice and Network Standards. Current Network Standards are available on Ausgrid's Internet site at www.ausgrid.com.au.

3.2 Ausgrid documents

- Electrical Safety Rules
- NEG-SM23 Selection of Surge Arresters within the Sub-transmission Network
- NS135 Specification for the Construction of Overhead Sub-transmission Lines
- NS168 Specification for the Design and Construction of 33kV, 66kV and 132kV Underground Cables
- NS181 Approval of Materials and Equipment and Network Standard Variations
- NS210 Documentation and Reference Design Guide for Major Substations
- NS222 Major Substation Earthing Layout Design
- NS260 Sub-Transmission Feeder Earthing

3.3 Other standards and documents

- AS 1307.2:1996 'Surge arresters - Metal oxide surge arresters without gaps for AC system'
- AS 1768:2007 'Lightning Protection'
- AS 2067:2016 'High Voltage Installations exceeding 1kV a.c'
- AS 7000:2010 'Overhead Line Design – Detailed Procedures'
- AS 4436:1996 'Guide for the selection of insulators in respect of polluted conditions'
- AS 62271.100:2005 'High-voltage switchgear and controlgear Part 100: High-voltage alternating-current circuit breakers'
- IEC 60071-1:2011 'Insulation coordination – Part 1: Definitions, principles and rules'
- IEC 60071-2:1996 'Insulation coordination – Part 2: Application guide'
- IEC 60099-4:2009 'Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems'
- IEC 60099-5:2000-03 'Surge arresters – Part 5: Selection and application recommendations'
- IEEE Std 998:2012 'IEEE Guide for Direct Lightning Stroke Shielding of Substations'
- IEEE Std 1410:2014 'IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Lines'
- IEEE Std 1243:1997 ' IEEE Guide for Improving the Lightning Performance of Transmission Lines'
- IEEE Std 1036:2010 'IEEE Guide for the Application of Shunt Power Capacitors'
- Insulation Coordination for Power Systems, Andrew R. Hileman, 1999 CRC Press
- Insulation Co-ordination in High-voltage Electric Power Systems, W. Diesendorf, 1974

3.4 Acts and regulations

- Electricity Supply (General) Regulation 2014 (NSW)
- Electricity Supply (Safety and Network Management) Regulation 2014
- Work Health and Safety Act 2011 and Regulation 2011

4.0 DEFINITIONS

Air terminal	A vertical or horizontal conductor of a lightning protection system (LPS), positioned so as to intercept a lightning discharge, which establishes a zone of protection.
Back Flashover	A flashover of insulation resulting from a lightning strike to a part of the network which is normally at earth potential to the phase conductor.
Coefficient of Earthing (COE)	The ratio of the line-to-ground voltage (V_{LG}) to the line-to-line voltage (V_{LL}) (expressed as a percentage – (V_{LG} / V_{LL}) x 100) of the highest r.m.s. line-to-ground power frequency voltage, on a non-faulted or healthy phase at a selected location, during a fault to earth affecting one or two other phases.
Continuous Operating Voltage (COV)	The continuous operating voltage of a surge arrester is the designated permissible r.m.s. value of power frequency voltage that may be applied continuously between the arrester terminals (also known as MCOV).
Corona	Partial discharge/incomplete failure of air. Corona occurs when the local electric field near the surface of the conductor is high enough to ionise the gas molecules surrounding the conductor.
Critical Flash Over (CFO) voltage	The amplitude of voltage of a given wave shape that under specified conditions causes a flashover through the surrounding medium on 50% of the voltage applications. CFO typically describes external or self-restoring insulation such as line insulators.
Direct lightning flash	A lightning discharge composed of one or more strokes that strike the structure or its LPS directly.
Down conductor	A conductor that connects an air terminal network with an earth termination. Also known as downlead.
Earth Grid	Interconnected uninsulated conductors installed in contact with the earth (or intermediate material) intended for the construction and dissipation of current and or for the provision of a uniform voltage reference. One part of the earthing system.
Earth fault factor	At a given location of a three-phase-system, and for a given system configuration, the ratio of the highest r.m.s. phase-to-earth power frequency voltage on a healthy phase during a fault to earth affecting one or more phases at any point on the system to the r.m.s. phase-to-earth power frequency voltage which would be obtained at the given location in the absence of any such fault.
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.
Effectively earthed network	Earthed through a sufficiently low impedance (inherent or intentionally added, or both) so that the coefficient of earthing does not exceed 80% (or earth fault factor ≈ < 1.4).
External insulation	Distances in atmospheric air, and the surfaces in contact with atmospheric air of solid insulation of the equipment which are subject to dielectric stresses and to the effects of atmospheric and other environmental conditions from the site, such as pollution, humidity, vermin, etc.
Ferro-resonance	Sustained oscillations involving a capacitance in series with a non-linear inductance, characterised by highly distorted waveforms
Flashover	A disruptive discharge over a solid surface.

Indirect lightning flash	A lightning discharge, composed of one or more strokes, that strikes the incoming services or the ground near the structure or near the incoming services.
Insulation coordination	The selection of the dielectric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available protective devices.
Internal insulation	Internal distances of the solid, liquid, or gaseous insulation of equipment which are protected from the effects of atmospheric and other external conditions.
Lightning flash	An electrical discharge in the atmosphere involving one or more electrically charged regions, most commonly in a cumulonimbus cloud, taking either of the following forms: Ground flash (earth discharge) – A lightning flash in which at least one lightning discharge channel reaches the ground. Cloud flash – A lightning flash in which the lightning discharge channels do not reach the earth.
Lightning (or switching) Impulse Withstand Level (LIWL or SIWL)	The electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions. Also known as BIL (lightning) or BSL (switching). Typically used for internal or non-self-restoring insulation such as transformer winding insulation
Lightning Protection System (LPS)	Complete system used to reduce the danger of physical damages and of injuries due to direct flashes to the structure. It consists of both external and internal LPSs and is defined as a set of construction rules, based on corresponding protection level.
Major Substation	Zone substations, transmission substations and switching stations with transmission voltages (including 33kV and above).
Metal-oxide surge arrester without gaps	An arrester having non-linear metal-oxide resistors connected in series and/or in parallel without any integrated series or parallel spark gaps.
Non-effectively earthed network	Any system or location on a system where the coefficient of earthing exceeds 80%.
Non-self-restoring insulation	Insulation which loses its insulating properties, or does not recover them completely, after a disruptive discharge e.g. XLPE in underground cables
Overvoltage	Any voltage between one phase conductor and earth or between phase conductors having a peak value exceeding the corresponding peak of the highest voltage for equipment.
Pressure relief device of an arrester (short circuit withstand capability)	A design or mechanism for relieving excessive internal pressure in an arrester housing (this includes an arrester housing which ruptures or vents to act as a pressure relief device eg a polymer housing) under normal conditions of either a sustained power follow through current or fault current due to an internal fault.
Protection Level (PL)	Four levels of lightning protection. For each protection level, a set of maximum (sizing criteria) and minimum (interception criteria) lightning current parameters is fixed, together with the corresponding rolling sphere radius.
Rated voltage of an arrester	The maximum permissible r.m.s. value of power frequency voltage between surge arrester terminals at which it is designed to operate correctly under

	temporary overvoltage conditions as established in the operating duty tests. The rated voltage is used as a reference parameter for the specification of operating characteristics. Note that the rated voltage defined within AS 1307.2 is the 10 s power frequency voltage used in the operation duty test after high current or long duration impulses.
Residual voltage on an arrester	The peak value of the voltage that appears between the terminals of an arrester during the passage of discharge current. Also known as discharge voltage.
Rolling Sphere Method (RSM)	A simplified technique for applying the electro-geometric theory to the shielding of substations. The technique involves rolling an imaginary sphere of prescribed radius over the surface of a substation. The sphere rolls up and over (and is supported by) lightning masts, shield wires, fences, and other grounded metal objects intended for lightning shielding. Equipment is protected from a direct stroke if it remains below the curved surface of the sphere by virtue of the sphere being elevated by shield wires or other devices. Equipment that touches the sphere or penetrates its surface is not protected.
Safety factor	Overall factor to be applied to the coordination withstand voltage to obtain the required withstand voltage, accounting for all other differences in dielectric strength between the conditions in service during life time and those in the standard withstand test voltage.
Self-restoring insulation	Insulation which completely recovers its insulating properties after a disruptive discharge e.g. porcelain insulators for bus support in outdoor substation.
Single Wire Earth Return (SWER) network	A HV distribution system consisting of a single active wire, and using the earth as the return path.
Standard short duration power frequency voltage	A sinusoidal voltage with frequency between 48 Hz and 62 Hz, and duration of 60 seconds.
Surge arrester	A protective device for limiting surge voltages on equipment by diverting surge current and returning the device to its original status. It is capable of repeating these functions as specified.
UGOH	Underground to overhead transition point in a feeder.

5.0 OVERVIEW

5.1 Overvoltage protection methods

The following over voltage protection methods shall be incorporated into major substation lightning protection and insulation coordination designs to protect equipment to an acceptable failure rate:

- Shielding of the substation equipment from direct lightning strokes;
- Use of surge arresters to protect substation equipment from incoming surges and substation generated overvoltages;
- Shielding of the overhead lines entering or leaving major substations for a minimum distance.

5.2 Lightning protection and/or insulation coordination design

A new or review of an existing lightning protection and insulation coordination design is required for:

- All new major substations;
- An existing substation that is intended to have a change of structure height and/or structure location where the structure is providing a lightning protection function or is critical to network performance;
- An existing substation that is intended to have a system configuration change impacting overvoltages e.g. replacement of outdoor switchgear with indoor GIS, change to transformer neutral configuration, like for like replacement of equipment where the original equipment had arcing horns mounted to the equipment or supporting structure;

For augmentation or replacement works at existing substations the design works shall extend to the nominated equipment item(s) and associated interfaces only. For pre-existing installed design, where no significant additional costs and/or rework arise, the current Network Standard requirements can be adopted. Otherwise the requirements of the existing design and the standards that were applicable at the original time of installation shall be maintained.

5.3 Design performance criteria

5.3.1 Lightning incidence

The average lightning ground flash density (Ng) may be taken from:

- Average values specified in AS1768 for the area, or
- The Ausgrid Lightning Tracker Database to calculate a site specific ground flash density where this value exceeds the average value specified in AS1768. In this case lightning data from MetService for a minimum 5km radius from a major substation and for a minimum of 3 years shall be used.

5.3.2 Equipment failure rates

The performance of an insulation system is determined by the number of insulation failures while in service (i.e. voltage stresses imposed on equipment which cause damage to equipment insulation or affect continuity of service). IEC 600071-2 provides the following general guidance on acceptable failure rates:

- Substation equipment: 0.001/year to 0.004/year depending on repair times (i.e. a mean time between failure (MTBF) rate of 250 to 1000 years)
- Due to switching overvoltages: 0.01 to 0.001 per operation.
- Overhead lines 0.1 to 20 failures / 100km /year with the greatest number being for distribution lines (i.e. 22kV or lower voltage lines)

In general, lightning protection assessments should use failure rates that fall within these ranges with the exception of substation equipment with nominal voltage less than 132kV which may use slightly higher failure rates. Minimum MTBF design targets to be use for the Ausgrid network are specified in Table 1.

Table 1: Substation equipment minimum MTBF due to lightning

Nominal System Voltage (kV)	Failure Rate / Year	MTBF (years)
11	0.0133	75
33	0.0100	100
66	0.0050	200
132	0.0025	400

The MTBF criterion is used for direct strikes to the substation and determination of a risk based rolling sphere size.

The line flashover rate and the MTBF (of substation equipment) together determine the steepness of the incoming surge imposed on major substation equipment due to line flashovers in the vicinity of the substation.

6.0 LIGHTNING PROTECTION

6.1 Lightning protection objective

All equipment, structures and buildings within major substations, where network performance may be adversely affected by direct lightning strikes, shall be protected as per the requirements of AS1768 by installing a Lightning Protection System (LPS). This is achieved through a combination of elements such as lightning spires, feeder Overhead Earth Wires (OHEW), surge arresters and the earthing system.

6.2 Design inputs

The following components are design inputs to be used when developing a major substation LPS:

- Substation equipment layout detail (e.g. plan and section views indicating building and equipment heights);
- Earthing system design;
- The Protection Level (PL) to provide sufficient protection to the substation against direct lightning strikes identified within Clause 6.4.

6.3 Design outputs

The following components are design outputs to be produced to identify the associated LPS design and installation requirements:

- Earthing layout drawings showing placement and height of lightning spires, any lightning protection elements, and all connections to the earth grid.
- Earthing design report detailing the results of calculations that demonstrate the LPS compliance with the relevant rolling sphere radius as per Clause 6.4.

6.4 Lightning protection levels

6.4.1 General

Major substation LPS shall be designed using the Rolling Sphere Method (RSM) to a PL I as defined in AS 1768 (Table 2 below summarises AS 1768 lightning protection levels). The rolling sphere radius to be used for the substations LPS design is 20m (60m)*.

Table 2: Protection levels

Lightning Protection Level	Sphere Radius (m)	Interception Current (kA)	Interception Efficiency	Sizing Efficiency	LPS Efficiency
I	20 (60)*	2.9	0.99	0.99	0.98
II	30 (60)*	5.4	0.97	0.98	0.95
III	45 (90)*	10.1	0.91	0.97	0.9
IV	60 (120)*	15.7	0.84	0.97	0.8

* The values within the brackets are for an increased sphere radius and apply to large flat surfaces, such as on the roof of a structure and on the sides of tall structures; refer to AS 1768 for further details.

6.4.2 Risk based LPS design

Alternative cost effective designs which achieve the intent of Section 6.4 may be submitted for consideration by an Ausgrid approved design authority. A substation specific design may be developed that can reduce the required PL and hence increase the rolling sphere radius based on an acceptable failure rate for equipment, see Annexure B for example calculation.

A reduced design is not acceptable for main power transformers.

6.5 Protection of buildings/indoor substations

All substation buildings, where network performance may be adversely affected by direct lightning strikes, shall be protected with air terminals unless the building is designed to intercept lightning strikes.

Protection for non-metallic buildings are generally met by placing metal air terminals on the uppermost parts of the building or its projections, with conductors connecting the air terminals to each other and to earth such that the spacing between down conductors does not exceed 20m.

For buildings that are roofed, or roofed and clad with metal, it may be possible to dispense with some or all air terminals provided the supporting roof steelwork is directly connected to down-conductor network or the earthing system. It is unacceptable to incorporate it into the LPS if its main function is adversely impacted by being bonded to the LPS. For instance, a roof being punctured due to lightning strike is unacceptable if it were the only weather proofing above electrical equipment.

For steel reinforced concrete buildings, as far as practical, the reinforcement should be made electrically continuous in all concrete elements. Reference shall be made to embedded earthing section in NS222. Where the steel reinforcing is used as the down conductor system, multiple effective electrical connections shall be made from the air terminal network to the steel reinforcing at the top of the building (i.e. minimum of one at each corner and spaced at no less than 20m).

6.6 Lightning masts, metallic poles and air terminals

The location of air terminals shall be determined by the LPS design. An air terminal may consist of a vertical rod (as for a spire), a single horizontal conductor (as on the ridge of the building), or a network of horizontal conductors for protection of roofs, transformer firewalls etc. Protection may also be provided with overhead shield wires supported independently of the buildings. The design of new overhead shield wires shall not cross over outdoor bare busbars or other circuits.

Lightning air terminals shall not be mounted directly on substation equipment e.g. on transformer.

Lightning masts shall be positioned away from any equipment or structures to reduce the likelihood of side flashes to adjacent equipment or structures and allow future replacement of masts. A minimum of five metres clearance shall be used if the amount of clearance is not determined in the design.

Where a power line provides shielding to a building or substation equipment, lightning masts are not required.

All metallic poles (e.g. light poles, communication poles, and lightning spires) in proximity to live exposed equipment (e.g. busbars, circuit breakers etc) or which have the potential to receive a direct lightning strike shall be earthed in accordance with Section 6.7.

Lightning poles with LV wiring should have the wiring installed internally and a PVC conduit provided to facilitate the underground entry/exit of the wiring to the pole.

Lightning poles shall not be earthed via the LV wiring earth or neutral conductors. Refer to Ausgrid standard construction drawing 162013 for details.

6.7 Down conductors and earthing

Down conductor and earthing conductors/components associated with LPS shall be designed and installed using new materials in accordance with Ausgrid specifications and the associated robustness and testability requirements identified in NS222. Where the proponent wishes to use materials not supplied or already approved by Ausgrid, they must submit details in accordance with the requirements of NS181 Approved Materials and Equipment and Network Variations. Materials approved by Ausgrid under this process are listed in the regularly updated Approved Materials List.

Down conductors between the air terminal and the associated earth termination shall be routed in the most direct path and/or the shortest vertical distance possible to avoid the flashover of lightning to neighbouring components and to minimise impedance to earth. Re-entrant loops are to be avoided. Where possible, down conductors shall be located directly below the associated air terminal.

The minimum copper Cross Sectional Area (CSA) required for a main current carrying component of a LPS taking into consideration surge current carrying capacity, thermal rating, mechanical strength and robustness of the installation is 70mm2. Conductors of other materials may be used provided they are proved to satisfy equivalent surge current carrying capacity and temperature rise, mechanical strength requirements and give due consideration to corrosion.

Lightning spires and OHEW down conductors shall be earthed to a dedicated electrode and directly to the substation earth grid. OHEW terminating on nonconductive landing spans, free standing lightning spires or spires mounted on nonconductive structures shall have a separate connection to an electrode. The electrode shall have a minimum length of 10m unless specified otherwise on the earthing layout drawing. The LPS shall have a combined earthing impedance of less than 10 ohms.

Separation shall be maximised between buried services (i.e. power or control cables, pipes etc.) and LPS earthing equipment (i.e. electrodes, earth grid connections and down conductors). A minimum two metres separation shall be achieved unless specified otherwise in the earthing layout drawing. Where a two metre separation is unable to be achieved, then buried services shall be installed in conduit to increase the insulation of the service within the ionisation zone of the buried LPS earthing.

6.8 Inspection and testing

The commissioning, inspection and testing of any LPS components shall be carried out in accordance with NS222.

6.9 Standard drawings

A list of lightning protection standard drawings is provided in Annexure C.

7.0 INSULATION COORDINATION

7.1 Insulation coordination objectives

The objective of insulation coordination for a major substation is to achieve acceptable service reliability by minimising the risk of equipment failure and outages due to overvoltages. This can be achieved by:

- Identification of voltage stresses from various sources (short circuits, switching and lightning)
- Minimum insulation levels for substation equipment
- Overvoltage protection

Generally, insulation coordination shall be as per IEC 60071. Other standards are referenced where applicable.

7.2 Design inputs

The following items are design inputs for a major substation insulation coordination study and design:

- Substation main connections single line diagram
- Substation equipment insulation withstand level
- Protective device characteristics e.g. surge arresters
- Incoming/outgoing feeder configuration e.g. underground or overhead feeder, OHEW/cable sheath configuration details

7.3 Design outputs

The following items are design outputs to be produced to identify the major substation insulation coordination design and installation requirements:

- Substation equipment clearances
- Locations and details of overvoltage protective devices shown on substation design drawings;
- Minimum OHEW shielding distance of the overhead lines entering or leaving major substations and associated feeder structure footing resistances;

7.4 Identification of voltage stresses

The network configuration and operating practices should be reviewed at the planning stage to identify the magnitude and duration of system overvoltages that may occur due to short circuits, switching and lightning in the network.

7.4.1 Power frequency voltage

The highest voltage for equipment shall be equal or greater than the highest r.m.s phase to phase voltage for the system for which the equipment is intended. The maximum system voltage is taken as the nominal system voltage times 1.1pu (e.g. for 132kV system the maximum system voltage is 145kV).

7.4.2 Temporary overvoltage

Temporary overvoltages (TOV) are power frequency overvoltages of short duration and may cause overheating of gapless surge arresters. They are caused by:

- Earth faults with the overvoltage magnitude dependent on the earth fault factor and the earth fault duration based on the backup protection clearing time.
- Load rejection
- Resonance and ferroresonance

The maximum TOV conditions shall be determined at the project planning stage. The maximum TOV is typically based on the earth fault factor (EFF) which can be determined at an earth fault location by using the system positive and zero sequence impedances, including fault resistance, and referring to the figures provided in IEC60071-2 Annex B. The system is considered effectively earthed if the healthy phases rise to ≤ 80% of the normal line to line voltage during an earth fault. This is defined when the coefficient of earthing (COE) is less than 80%:

$$Earth\ Fault\ Factor(EFF) = \sqrt{3}\frac{COE}{100}$$

$$System\ Effectively\ Earthed\ if\ EFF \leq \sqrt{3}\frac{80}{100} \approx 1.4$$

Other forms of TOV shall be controlled by alternate means at the project planning stage. All forms of TOV shall be kept below the TOV rating of the arresters installed on the system. If TOV voltages occur frequently near the rating of the arrester it may be necessary to use a higher rated arrester for robustness if insulation coordination can still be achieved.

7.4.2.1 Ausgrid network neutral earthing configuration

In the Ausgrid network, the 132kV network is effectively (solidly) earthed.

Depending on the location (e.g. mining areas) the 66kV and 33kV networks may be either solidly earthed or impedance earthed. The typical configurations of impedance earthed networks found within the Ausgrid network are:

- Each individual power transformer secondary star point is earthed via a separate low impedance neutral earthing reactor (typically 3.5Ω). The classification of these systems lie on the border between effectively earthed and non-effectively earthed system. For Ausgrid network and particularly for surge arrester application they are classed as non-effectively earthed.
- All power transformer secondary star points are connected together and earthed via a bank of resistors and classed as non-effectively earthed.

The 11kV network is typically solidly earthed if the transformer secondary winding is Wye connected or earthed via an earthing transformer if the transformer secondary is a delta (i.e. 132kV/11kV transformer). These 11kV networks are classified as effectively earthed for surge arrester application.

There are a few exceptions where the 11kV network supplies mine loads which are classed as non-effectively earthed for surge arrester application.

7.4.3 Switching overvoltage

Switching overvoltages are represented by a standard 250/2500µs impulse voltage for testing of equipment insulation. They are caused by:

- Switching of capacitive and inductive currents
- Line energisation and re-energisation (generally not applicable at Ausgrid nominal system voltages – refer IEC-60099-5 Section 4.2, IEC 60071-2 Section 2.3.3.1.1)
- Faults and fault clearing (considered only for isolated or resonant earthed transformer neutral at Ausgrid nominal system voltages – refer IEC 60071-2 Section 2.3.3.2)
- Load rejection (generally not applicable at Ausgrid nominal system voltages – refer IEC 60071-2 Section 2.3.3.3)

Due to Ausgrid system voltages (highest being 132kV) switching overvoltages is not considered a serious overvoltage problem. The insulation coordination is based on power frequency and lightning strike generated overvoltages.

Switching overvoltages however are determined by an insulation coordination study using the methods outlined in IEC 60071-2 and/or simulation studies. Switching studies maybe required in exceptional circumstances only (e.g. non-standard configuration).

7.4.4 Lightning overvoltage

Lightning overvoltages are represented by a standard 1.2/50µs impulse voltage for testing of equipment insulation. They are caused by:

- Direct strikes to phase conductors, earth wires or equipment
- Indirect strikes to ground or objects in close proximity that induce voltages

Lightning overvoltages at Ausgrid substations will be determined by an insulation coordination study using the methods outlined in IEC 60071-2 and/or simulation studies.

Generally lightning studies are only required in exceptional circumstances (e.g. poor performing reliability or non-standard configuration).

7.5 Minimum equipment insulation levels

The minimum insulation strength for HV equipment installed within major substations shall meet the requirements of Table 3.

Table 3: Equipment minimum insulation levels

Nominal System Voltage L-L (kV rms)	Maximum System Voltage L-L (kV rms)	Standard Short-duration Power Frequency Withstand Voltage L-L (kV rms)	Lightning Impulse Withstand Voltage L-E or L-L (kV peak)
11	12	28	95 (75)
22	24	50	145
33	36	70	200 (170)
66	72.5	140	325
132	145	275	650 (550)

*The values within brackets may be deemed sufficient for equipment, other than transformers, connected by cable

7.5.1 Safety factors

Safety factors are used to provide additional margin to account for unknowns in insulation coordination calculations.

For insulation coordination assessments a safety factor of at least 1.15 for internal insulation and 1.05 for external insulation shall be applied as per IEC 60071-2. For internal and external insulation in parallel a safety factor of at least 1.15 shall be applied.

7.5.2 Clearances

Substation outdoor air insulated equipment electrical clearances shall be in accordance with AS2067. Ausgrid preferred electrical clearances specified on drawing 221830 should be used where practicable.

Where substation equipment has differing insulation rating (i.e. newer 650kV installed adjacent to legacy 550kV LIWL 132kV equipment) clearances for the new equipment shall be based on the higher lightning impulse withstand level (LIWL).

In exceptional cases the clearances for certain equipment may be reduced in accordance with manufacturer's documentation and design assumptions/calculations shall be documented.

When no guidance is provided by manufacturers for clearance between a surge arrester and adjacent equipment on the same phase, a minimum clearance of non-flashover distance to AS2067 shall be used.

7.5.3 Switching impulse withstand

Switching impulse withstand voltages (SIWV) are not typically provided for nominal system voltages used on the Ausgrid network. Where required for an insulation coordination assessment, test conversion factors shall be applied as per IEC60071-2:1996 Table 2 to convert switching impulse overvoltages to power frequency and lightning overvoltages for comparison with specified power frequency and lightning insulation withstand voltages provided.

7.5.4 Pollution

Insulators for HV equipment installed within major substations shall withstand the highest system voltage in polluted conditions continuously with an acceptable risk of flashover in accordance with AS4436. The minimum nominal specific creepage distance requirements are reproduced from AS4436 in Table 4 below.

Table 4: Minimum nominal creepage distances

Pollution Level	Approximate Indication Where Pollution Conditions May Occur	Minimum nominal specific creepage distance (mm/kV)*
Light	Beyond 10km from sea coast or light pollution from other sources	16
Medium	3-10km from sea coast, areas with industries not producing particularly polluting smoke	20
Heavy	1-3km from sea coast, areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution	25
Very Heavy	Less than 1km from sea coast or areas subjected to conductive dusts and industrial smoke producing particularly thick conductive deposits (e.g. Kooragang Island)	31

*Minimum creepage distance of insulators between phase and earth related to the highest system voltage (L-L)

The minimum creepage distance for Ausgrid system voltages is given by:

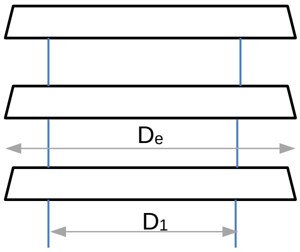
$$Min\ creepage\ distance = min\ specific\ creepage\ distance \times U_m \times k_D,\ \text{(mm)}$$

Where k_D is a factor depending on the insulator average diameter (D_M) which is given in Table 5

Table 5: Factor kD

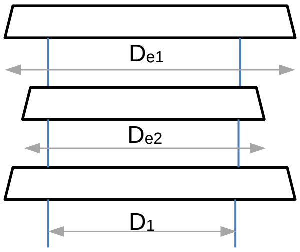
kD	Diameter DM (mm)
1	DM < 300 mm
1.1	300 mm ≤ DM ≤ 500 mm
1.2	DM > 500 mm

AS 4436 provides an approximation for calculating the average diameter D_m as shown in Figure 1 and Figure 2:



$$D_M = \frac{D_1 + D_e}{2}$$

Figure 1: Regular sheds



$$D_M = \frac{D_{e1} + D_{e2} + 2D_1}{4}$$

Figure 2: Alternating sheds

Based on experience and proximity of Ausgrid's network to the sea coast, pollution level "light" is not appropriate for minimum creepage distance calculations. Secondly a diameter factor K_D for insulators used in major substations is generally 1 and as a consequence the minimum creepage distances for Ausgrid system voltages are shown in Table 6.

Table 6: Ausgrid minimum nominal insulator creepage

Nominal Voltage (kV)	Minimum Nominal Creepage (mm)
11	300
33	950
66	1600
132	3350

7.6 Overvoltage protection

7.6.1 Surge arresters

Surge arresters shall be used for overvoltage protection of major substation equipment. Surge arresters shall be metal-oxide surge arresters without gaps and have a polymeric housing, or acceptable non-shattering characteristics. Additionally they shall comply with the requirements of AS 1307.2. Arcing horns, ground lead disconnection devices, gapped arresters or arresters with porcelain housings are not acceptable for future use on the network.

Surge arresters shall be selected such that the maximum residual voltage is as low as possible without compromising the Continuous Operating Voltage (COV) or the Temporary Overvoltage (TOV) limits of the arrester.

7.6.2 Surge arrester selection

Surge arresters selected for the Ausgrid network shall meet the following minimum requirements:

(a) Arrester COV shall be greater than the maximum system phase-to-neutral voltage

The safety factor of 5% for harmonics is considered covered by the arrester power frequency voltage versus time characteristic (for systems with automatic earth fault clearing as per IEC 60099-5). A small margin above maximum system voltage is expected as different arrester manufacturers provide slightly different recommendations.

(b) TOV capability shall be greater than the maximum system phase-to-neutral voltage × Maximum TOV of the network (effectively or non-effectively earthed). Typical minimum duration rating is given in Table 7.

For identification of which existing Ausgrid sub-transmission substations are effectively or non-effectively earthed and the correct selection of surge arresters refer to NEG-SM23.

(c) Short circuit withstand capability (formerly referred to as pressure relief class). The fault current withstand of the arrester should be equal to or greater than the power frequency maximum fault current through the arrester at the installation point of the arrester.

Table 7: Surge arrester typical minimum fault current rating

Nominal System Voltage (kV)	Fault Current Class (kA)	Duration (s)
11 / 66	20*	3.0
33	31.5	3.0
132	40*	1.0

*In exceptional cases these values may be exceeded. Refer to site specific faults levels provided by Sub-Transmission Planning

(d) The minimum arrester nominal discharge current requirement is 10kA.

(e) Line discharge class. Determined by the energy requirements of the arrester when subjected to switching or lightning overvoltages. A minimum line discharge class of 2 is required for nominal system voltages 33kV and above. The minimum specific energy required is 4.5kJ/kV at rated voltage.

In exceptional circumstances when switching large capacitors, such as shunt capacitor banks or unloaded cables, the switching impulse energy capability may require a higher energy rated arrester than typically used, refer Section 7.6.5.3 for further details.

(f) Preference for spark production Class A (spark free) as per AS1307.2 Table 3.1

7.6.3 Surge arrester connections

Surge arrester earthing conductors and connections shall be designed and installed using the recommended equipment and the associated robustness requirements identified in section 7.0 of NS222.

Surge arrester down leads shall be as short and straight as practically possible between the arrester earth terminal and the earth grid to minimise the down lead impedance.

Where the arrester is mounted on equipment the arrester and equipment earth terminals/tank shall be interconnected. The arrester earth down lead shall not be run with LV or signalling cabling associated with the equipment the arrester is mounted on.

Where arresters are mounted on the same structure and the bases earthed together then two down conductors (one either side) shall be connected to the earth grid.

The minimum cross sectional area for a surge arrester down lead is a 70mm2 stranded copper conductor. Double bolted lug connections are not required for surge arrester connections.

Surge arresters shall not be used as busbar supports.

7.6.4 Surge arrester separation distance from protected equipment

Due to travelling wave effects the protection of equipment by an arrester can be guaranteed only for short distances between the arrester and equipment. Otherwise a doubling of the arrester protective level (arrester discharge voltage plus lead length inductive voltage drop) may occur due to surge impedance mismatch (i.e. busbar connection to high impedance transformer or open breaker).

Where surge arresters are unable to be directly mounted on the equipment to be protected the maximum separation distance versus arrester lead length shall be assessed by the approved design authority. An example calculation method for determination of the voltage at protected equipment due to lead length and separation distance for overhead systems is given in Annexure D. Separation versus lead length considerations typically become more onerous the lower the nominal system voltage even though higher reliability criteria is specified for more expensive equipment at higher voltages.

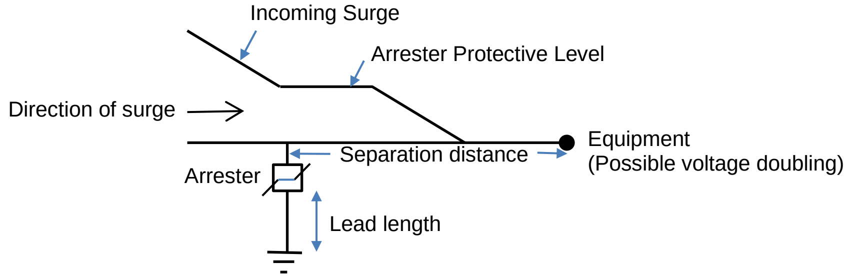


Figure 3: Separation distance between arrester and equipment

7.6.5 Location of surge arresters

Surge arresters shall be fitted at the following locations unless an insulation coordination assessment recommends otherwise:

- All HV incoming and outgoing overhead lines on or near the structure where the overhead line terminates to the substations outdoor busbar.
- At underground to overhead (UGOH) line terminations within or outside the substation, where these overhead lines emanate from the substation. The arresters shall be terminated as close as practicable to the cable termination.
- Power transformers where 132kV, 66kV or 33kV outdoor air insulated bushings. 11kV outdoor air insulated bushings where connected to an overhead line.

  The arresters shall be mounted as close as practical to the transformer bushings i.e. on the adjacent support structure or transformer tank.

Further to the above surge arrester locations, additional requirements for the installation of surge arresters within the following sub-sections shall be assessed by the approved design authority. For these additional requirements the location of surge arresters shall be as close as practically possible to the equipment to be protected.

7.6.5.1 Three winding power transformer tertiaries

All three winding transformers, with delta connected 11kV tertiary supply to the substations auxiliary transformer, shall have 11kV surge arresters fitted near the transformer 11kV outdoor air insulated bushings.

Where 11kV supply is not taken from the tertiary winding (i.e. no auxiliary transformer is connected) then one phase must be connected to earth directly to provide an earth reference point. Surge arresters shall be fitted on the other two phases where the winding is connected to outdoor busbar or where not connected the exposed terminals insulated.

11kV surge arresters shall be suitable for use within a non-effectively earthed network (or nominal 12.7kV arresters as those used on Ausgrid’s Single Wire Earth Return network).

7.6.5.2 Gas insulated switchgear (GIS)

Surge arresters are generally not required at GIS unless the OHEW requirements of Clause 7.6.8 cannot be met and an insulation coordination assessment indicates a need for them. At substations with GIS switchgear where due to system configuration it has been deemed necessary to incorporate surge arresters within the GIS switchgear, these arresters are enclosed within a separate gas filled compartment and are to be fitted with surge counters. The specification of these arresters is encompassed in the relevant switchgear specification.

7.6.5.3 Switching

Switching in power systems may generate large overvoltages under certain conditions and may require application of surge arresters to protect substation equipment.

Worst case overvoltages are generated if restrike across a circuit breaker contacts occurs during opening (tripping) of a circuit breaker.

(a) Shunt capacitor banks

Shunt capacitor banks on the Ausgrid network are typically double unearthed star connected. The switching of shunt capacitor banks produces excessive transient overvoltages on energisation and on de-energisation (if restrike occurs). De-energisation with restrike may cause overvoltages that can damage the capacitor bank and nearby equipment such as connecting power cables, circuit breakers and transformers.

All circuit breakers have a probability of restrike in service. The restrike performance of a circuit breaker is determined by its C1 or C2 class. Class C1 corresponds to a maximum expected probability of restrike per 3-phase operation to be 0.02 and class C2 to be 0.002 (refer AS 62271.1-2005 and IEEE Std. 1036-2010 Clause 6.4 Table 5).

If the circuit breaker switching the shunt capacitor bank corresponds to class C2 then no surge protection is required.

If the circuit breaker switching the shunt capacitor bank corresponds to class C1 then overvoltage limitation shall be considered by the Substations Designer in conjunction with recommendations from the Senior Engineer Transmission Switchgear. Installation of surge arresters to protect shunt capacitor banks has not been standard practice at Ausgrid, however in some instances surge arresters have been fitted (where older class C1 circuit breakers are installed and the risk of multiple restrikes is higher). Surge arresters installed in this scenario can be subject to severe energy absorption duty because of the large energy ($1/2CV^2$) stored in the capacitor bank. For surge arresters protecting shunt capacitor banks the energy absorption requirement shall be assessed. Refer to Annexure E for example calculation.

Another method of limiting capacitive switching overvoltages is by point-on-wave switching which has been used on the Ausgrid 132kV network at Bunnerong and Peakhurst. Surge arresters are not required for overvoltage protection where point-on-wave circuit breakers are installed.

(b) Unloaded feeders

Switching of unloaded or lightly loaded feeders can result in transient overvoltages with energy levels that may thermally stress surge arresters connected to the feeder due to trapped charge. Auto-reclose is not used on the Ausgrid 132kV network therefore increased overvoltages due to trapped charge is less of a concern. For the system nominal voltages used on the Ausgrid network the minimum energy requirement for surge arresters (4.5kJ/kV at rated voltage) are sufficient for line energisation overvoltages, refer Annexure E for example calculation.

7.6.5.4 Series or shunt reactors

Whenever series or shunt reactors are installed on overhead lines, surge arresters shall be installed on the overhead line side of the reactor.

7.6.6 Surge arrester replacement

Where any surge arrester requires replacement on an individual phase of a three phase installation then the other two arresters shall be inspected for damage. Included in an inspection shall be the housing for any cracks or damage and the connections for signs of corrosion or flashover.

7.6.7 Arcing horns

Arcing horns or rod gaps are an older form of overvoltage protection. However, they have the following disadvantages:

- Poor protective performance for steep impulse voltage fronts. The arcing level depends on the overvoltage amplitude which increases sharply for steep wave fronts. Arcing delay also increases as the overvoltage decreases. Therefore steeper surges have the potential to break down the equipment insulation before the gap has had time to operate
- Extinguishing an arc across a gap causes current chopping resulting in a steep front overvoltage which could damage the winding insulation of transformers
- Arcing results in a fault (i.e. outage due to not having reclose on 132kV), thus affecting reliability of supply.
- The gap spacing is a compromise between the protection obtained and the number of outages produced by gap operation. The arcing voltage is dependent on atmospheric conditions and changing characteristics of the arcing horns over times (can result in variations more than 40%). Arcing horns also respond differently to positive and negative surges.

Arcing horns are an older protective technology being phased out by the better performing gapless surge arresters where possible. Generally where overvoltage protection is provided by arcing horns and the equipment is to be replaced then:

- Surge arresters shall be the first option considered
- If it is not cost effective/practical to install surge arresters (i.e. space constraints) then arcing horns may be reinstalled provided they give the same level of protection as the old arcing horns (i.e. correct gap length taking into consideration the insulation withstand of the equipment to be protected may have changed). The gap characteristics must be obtained from the manufacturer or established by test.

Arcing horns shall not be installed on voltage transformers, main power transformers or oil circuit breakers.

Arcing horns shall be avoided on systems below 33kV whenever possible due to the ease with which small gaps are bridged (e.g. by birds).

7.6.8 Overhead earth wires

Equipment installed within a substation that is directly connected to an overhead line is susceptible to direct, indirect and induced lightning overvoltages. Overhead earth wires (OHEW) reduce overvoltages to sufficiently low levels so that they can be safely discharged by the surge arresters located at the entry to the major substation. This also applies to cable connected indoor switchgear which are typically protected with one set of surge arresters at the UGOH end of the cable.

Refer to NS260 Clause 7.2, 7.9.1 and Section 8 for more detail on the earthing requirements of OHEWs.

Arrester separation distances are determined by the magnitude and steepness of the incoming lightning overvoltage surge. The steepness of the overvoltage surge is dependent on the line flashover rate and the substation equipment target in-service reliability known as the mean time between failures (MTBF).

To minimise the line flashover rate due to lightning in the vicinity of the connected major substation the following OHEW lightning performance criteria shall be considered:

7.6.8.1 OHEW shielding angle

To minimise the shielding failure flashover rate the shielding angle used for overhead lines on the Ausgrid network is typically 30deg for 33kV, 66kV and 132kV line constructions and has been incorporated into Ausgrid standard overhead line construction drawings.

7.6.8.2 OHEW minimum length

To prevent direct lighting strikes to the phase conductors, to reduce the incoming overvoltage surge and to limit the surge arrester energy requirements at the substation entrance minimum OHEW lengths from a substation are specified in NS135.

Where the minimum OHEW requirements cannot be met, an insulation coordination assessment using electromagnetic transient analysis software package (e.g. ATP, EMTP-RV) shall be undertaken to determine site specific requirements. In some instances depending on the configuration of the feeder (e.g. span lengths, footing impedances, cable length from UGOH) the OHEW length requirement may be reduced.

7.6.8.3 OHEW down conductor/conductive structure footing resistance

To minimise the back flashover rate due to lightning striking the OHEW/structure and flashing across from earth to phase conductor, the maximum down conductor/conductive structure footing resistances shall be in accordance with Table 8:

Table 8: Maximum footing resistance

Nominal System Voltage (kV)	Maximum Footing Resistance
33	30 ohms
66	20 ohms
132	10 ohms

Footing resistances shall be minimised where cost effective and practical. Extra consideration should be applied to achieve the specified footing resistance for the structures within 800m of the substation.

Where these resistances cannot be achieved (such as in high soil resistivity areas) the approved design authority shall be contacted for advice.

Where surge arresters are installed (i.e. at a UGOH) then the maximum recommended footing resistance is 10 ohms.

Refer to NS260 Section 9 for details on local earthing system commissioning.

For the bonding of an OHEW to the associated substations earth grid refer to Clause 6.7 and NS222 Section 7.0.

7.6.8.4 Line structure minimum insulation

Strikes to ground in the vicinity of the overhead line can cause an induced voltage flashover. The large critical flashover voltage (CFO) for 66kV and 132kV line insulators prevents induced flashovers. Structure insulation design for 33kV lines should be greater than 245kV for lines with an OHEW where practical to minimise induced voltage flashovers (refer IEEE1410).

7.7 Insulation Coordination Summary

Insulation coordination for major substations shall include the items below. If the proposed major substation configuration or equipment does not meet the following process requirements (i.e. non-standard) then an insulation coordination assessment by the approved design authority is required.

Confirm equipment insulation requirements are acceptable

- Equipment insulation withstand, refer Clause 7.5
- Clearances, refer Clause 7.5.2
- Pollution, refer Clause 7.5.4

↓

Confirm arrester rating is acceptable

- Determine the continuous overvoltage (COV) and temporary overvoltage (TOV) stress from data provided by Sub-transmission Planning and the earth fault TOV duration from Protection and Control

  132kV continuous overvoltage (COV) example:

$$COVrating > V_{systemNominal} \times 1.1,$$

$$COVrating > \frac{132kV}{\sqrt{3}} \times 1.1 > 84kV$$

  132kV temporary overvoltage (TOV) example:

$$TOVrating > V_{systemMax} \times TOV$$

$$TOVrating > \frac{132kV}{\sqrt{3}} \times 1.1 \times 1.4 > 118kV\ for\ 0.4s$$

- Select surge arrester suitable for effectively or non-effectively earthed network
- Locate surge arresters as per Clause 7.6.5
- Confirm short circuit withstand capability for the fault current at arrester location

↓

Switching coordination

- Determine surge arrester requirements for switching of capacitive currents as per Clause 7.6.5.3
- Confirm surge arrester energy requirements as per Annexure E.

↓

Lightning coordination

- Confirm separation distance/lead length requirements as per Clause 7.6.4 and Annexure D.
- Confirm outgoing/incoming feeder OHEW minimum requirements as per Clause 7.6.8

Figure 4: Insulation Coordination Summary

8.0 RECORDKEEPING

The table below identifies the types of records relating to the process, their storage location and retention period.

Table 9: Recordkeeping

Type of Record	Storage Location	Retention Period*
Approved copy of the network standard	BMS Network sub process Standard – Company	Unlimited
Draft Copies of the network standard during amendment/creation	TRIM Work Folder for Network Standards (Trim ref. 2014/21250/159)	Unlimited
Working documents (emails, memos, impact assessment reports, etc.)	TRIM Work Folder for Network Standards (Trim ref. 2014/21250/159)	Unlimited

* The following retention periods are subject to change eg if the records are required for legal matters or legislative changes. Before disposal, retention periods should be checked and authorised by the Records Manager.

9.0 AUTHORITIES AND RESPONSIBILITIES

For this network standard the authorities and responsibilities of Ausgrid employees and managers in relation to content, management and document control of this network standard can be obtained from the Company Procedure (Network) – Production/Review of Network Standards. The responsibilities of persons for the design or construction work detailed in this network standard are identified throughout this standard in the context of the requirements to which they apply.

10.0 DOCUMENT CONTROL

Content Coordinator : Head of Asset Engineering Policy and Standards

Distribution Coordinator : Engineering Information and Services Manager

Annexure A –Sample Compliance Checklist

Network Standard Checklist Form

NS264 Major Substation Lightning Protection and Insulation Coordination

Project Identification:	
Prepared by:	Date:

This checklist is for internal Ausgrid use only and does not apply to ASPs or contractors who have specific compliance requirements in relation to Contestable project works. The checklist is unique for each network standard and is available within BALIN and the BMS as a separate form that can be amended as required, completed and saved in TRIM with the other project documentation.

This section is used to identify compliance checks that when applied to the work associated with this Network Standard will satisfy an audit process to establish that the requirements of the standard have been followed. It is expected that applicable items would normally be checked as Comply (Yes) as non-compliance is generally not tolerated.

Where non-compliance is the result of specific site conditions or design decisions this needs to be identified in the notes section of the form for each non-compliance and approval sought from an appropriately authorised Ausgrid manager responsible for design approval.

Should additional information be available to document non-compliance decisions, these can be attached to the checklist form. The checklist and any attached explanatory notes should be saved in the project document repository.

Item	Description	Refer clause	Completed/ Actioned
	Scope		
	This Network Standard identifies the minimum lightning protection and insulation coordination requirements for design and construction of major substations.		
	Performance Criteria		
1	Lightning protection and insulation coordination designed to an acceptable failure rate	5.0	Yes/No/NA
	Lightning Protection		
2	Lightning protection design outputs are documented	6.3	Yes/No/NA
3	Major substation lightning protection designed to acceptable protection level	6.4	Yes/No/NA
4	Building lightning protection requirements met	6.5	Yes/No/NA
5	Lightning masts and air terminal requirements met	6.6	Yes/No/NA
6	Down conductors and earthing requirements met	6.7	Yes/No/NA
	Insulation Coordination		
7	Insulation coordination design outputs are documented	7.3	Yes/No/NA
8	Equipment minimum insulation level requirements are met	7.5	Yes/No/NA
9	Electrical clearance requirements are met	7.5.2	Yes/No/NA

10	Insulator pollution minimum creepage requirements are met	7.5.4	Yes/No/NA
11	Surge arrester selection minimum requirements are met	7.6.2	Yes/No/NA
12	Surge arrester connection requirements are met	7.6.3	Yes/No/NA
13	Surge arrester location requirements are met	7.6.5	Yes/No/NA
14	OHEW requirements for incoming overhead lines are met	7.6.8	Yes/No/NA
15	Insulation coordination process has been followed	7.7	Yes/No/NA

Notes: ……

………

………

………

………

………

_ _ _ _ _ _ _ _ _ _ _ _ _

Prepared by

{Name}
{Position Title}
Date: ____/____/____

_ _ _ _ _ _ _ _ _ _ _ _ _

Endorsed by

{Name}
{Branch Manager Title}
Date: ____/____/____

_ _ _ _ _ _ _ _ _ _ _ _ _

Approved by

{Name}
{Head of Branch Title – where required}
Date: ____/____/____

Annexure B – Risk Based LPS Design

(Informative only)

A risk based lightning protection design example is presented below based on the methodology in IEEE998-2012 Annex G which allows calculation of a rolling sphere radius based on an acceptable failure rate for equipment.

B.1 Lightning exposure area

A substation collects more flashes than its physical area times the ground flash density i.e. is also dependent on the height. A substation exposed area (from Hileman) is given by:

$A = (W + 2R_A)(L + 2R_A)$ (m^2)

Where:

W and L are the width and length of the substation in metres

$R_A = 16h^{0.6}$ (m)

h is the height (m)

Example:

A 6m height 50 x 50m substation, A = 0.0225km^2, Ground flash density (Ng) = 5 flashes/km^2/yr.

Flash collection rate = 5 x 0.0225 = 0.1125 or 1 flash every ≈ 9yrs

B.2 Lightning strike magnitude probability

The probability that a certain peak current will be exceeded in any lightning stroke is given by:

$$P(I) = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}}$$

Where:

P(I) is the probability that the peak current in any stoke will exceed current of magnitude I

I is the specified crest current of the stroke in kA

Example:

If I = 31kA, then P(I) = 0.5, i.e. 50% of lightning strikes have a magnitude > 31kA.

B.3 Surge impedance

A lightning stroke to an overhead line or busbar produces travelling waves of voltage V and current I related be a surge impedance Z = E/I that travels along the conductor at propagation velocity v.

For a single conductor having a radius r located at height h above ground the surge impedance is given by:

$$Z = 60 ln \frac{2h}{r} \Omega$$

Common surge impedance values for an overhead conductor are between 400 to 500 ohms and for a larger radius substation hollow busbar ≈330 to 360 ohms.

B.4 Allowable strike current and perfect shielding

For perfect lightning shielding of a substation the maximum voltage stress imposed is less than the safety factor reduced insulation withstand of the equipment to be protected.

The imposed stress voltage is given by the lightning stroke current divided by two as it hits the busbar multiplied by the surge impedance of the busbar:

$$V_{stress} = \frac{I_{stroke}}{2} Z_{surge} \text{ (kV)}$$

So the allowable strike current for perfect shielding is given by:

$$\frac{V_{withstand}}{SF} > \frac{I_{stroke}}{2} Z_{surge} \text{ (kV)}$$

The maximum allowable stroke current can then be converted into a striking distance (or rolling sphere radius) using Love's equation from AS1768:

$$ds = 10 i_{max}^{0.65} \text{ (m)}$$

Assuming a busbar surge impedance of 400 ohms and using a safety factor (SF) of 1.15 the maximum allowable stroke current for a given system insulation withstand can be calculated as shown in Table 10 below.

Table 10: Perfect Shielding Required Radius

System Voltage	LIWV	LIWV (SF reduced)	Iallowable max (kA)	Required Radius (m)
132	650	565	2.83	19.6
66	325	283	1.41	12.5
33	200	174	0.87	9.1
11	95	83	0.41	5.6

Table 10 shows to achieve perfect shielding for system voltages less than 132kV an impractical rolling sphere radius is the result. If voltage doubling is taken into account at an open point such as an open circuit breaker then the criteria becomes even more onerous. An accepted probability of failure is then required to be included in the rolling sphere criteria calculation.

B.5 Risk based LPS methodology

The risk based lightning protection methodology calculates the rolling sphere radius based on an acceptable failure rate for equipment. A mean time between failures (MTBF) of 400 years for equipment shall be used unless otherwise specified in the design.

The probability of failure due to a lightning strike is given by the probability of a strike magnitude being between the design rolling sphere radius let through current and the maximum allowable stroke current that does not cause insulation failure. The design current and hence rolling sphere radius can be then back calculated.

$$P(acceptable\ failures/flash) = P(I > Iallowable\text{Max}) - \text{P}(\text{I} < \text{Idesign})$$

Therefore:

$$\text{P}(\text{I} < \text{Idesign}) = P(I > Iallowable\text{Max}) - P(acceptable\ failures/flash)$$

Where:

$P(I > Iallowable\text{Max}) = \frac{1}{1+\left(\frac{I_{stroke}}{31}\right)^{2.6}}$, and $I_{stroke} = \frac{2.V_{withstand}}{SF.2.Z_{surge}}$ (kA)

$P(acceptable\ failures/flash) = \frac{Years\ per\ Flash}{MTBF}$, and $Years\ per\ Flash = \frac{1}{Ng.Exposure\ Area}$

$Acceptable\ Rolling\ Sphere\ Radius = 10.Idesign^{0.65}$ (m), and $Idesign = 31\left(\frac{1}{P(I<Idesign)-1}\right)^{\frac{1}{2.6}}$ (kA)

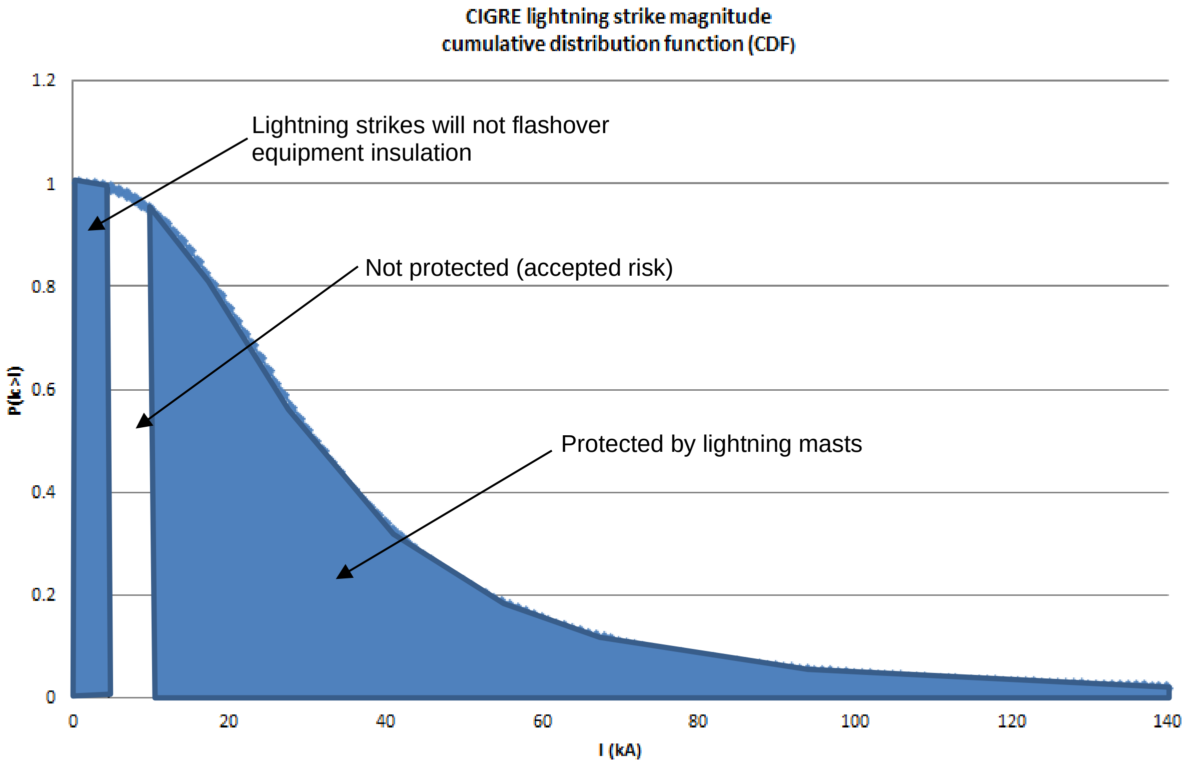


Figure 5: Risk Based LPS Concept

Given the inputs below:

- MTBF = 400 years/failure
- Ng = 4.3 flashes/km^2/year (average value from Ausgrid's Lightning Tracker database of MetService data)
- Safety Factor = 1.15
- Surge impedance = 400 ohms
- Voltage doubling at open breaker

The following rolling sphere sizes shown in Figure 6 can be calculated based on an acceptable failure rate.

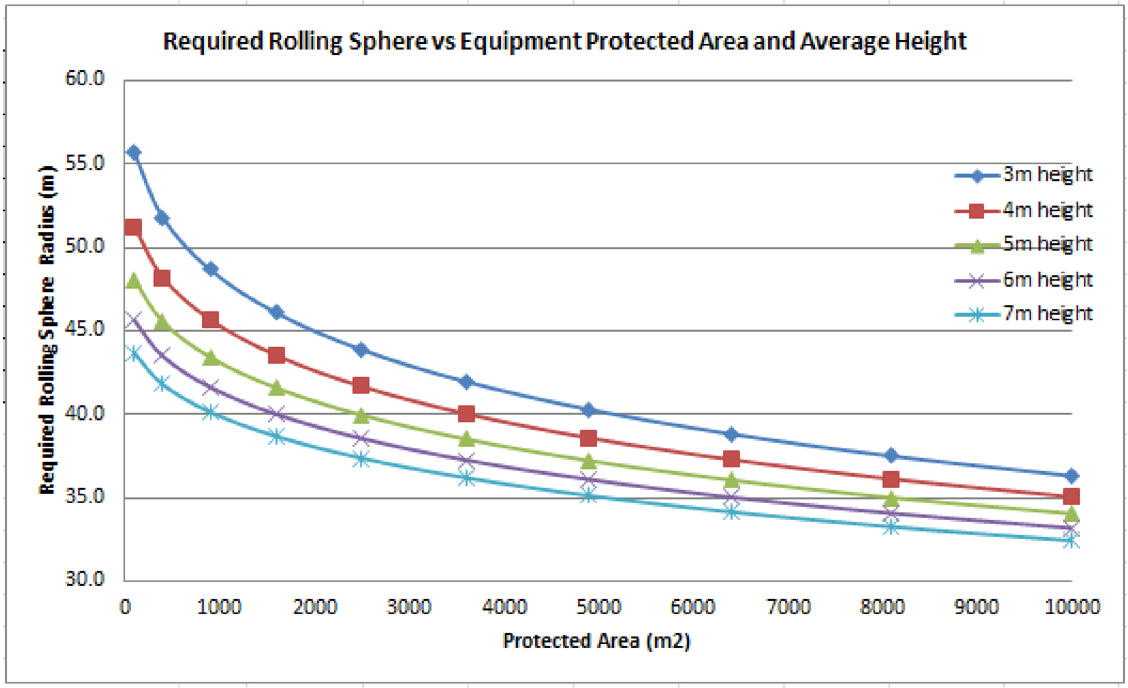


Figure 6: Risked based rolling sphere requirements

Annexure C – Lightning Protection System Standard Drawings

Table C1: Standard drawings

Drawing Number	Drawing Title
161887	Standard Construction Lightning Spire Earth Bar Details
162013	Standard Construction Lightning Spire and Floodlighting 2 Light Assembly General Arrangement
162293	Standard Construction 15m 18m and 20m Lightning Spire Footing Details
162611	Standard Construction Steel Flange Mounted Lightning Spire Earthing Details
162812	Standard Construction 7m Light Pole and 12m Lightning Spire Footing Details
163028	Standard Construction Steel Flange Mounted Lightning Spire Floodlighting Design Crossarm Details
169818	Standard Construction Lightning Spire and Floodlighting 4 Light Assembly General Arrangement
202164	Outdoor Substations Reinforced Blockwork Tx Bay Walls Wall Mounted Lightning Mast Arrangement and Details
202369	Standard Construction 66kV Switching Station Lightning Spire and OHEW Details
211846	Outdoor Substations Reinforced Blockwork Tx Bay Walls Wall Mounted Lightning Mast 6m Spire Arrangement and Details
215497	Standard Construction Steel Flange Mounted Lightning Mast Concrete Pad Footing Detail
516894	Standard Construction Substations Type 2 Pole Mounted Lightning Spire Construction Detail

Annexure D – Surge Arrester Connection Calculation

(Informative only)

The following example calculation, for lightning surges impinging on an overhead fed substation, identifies the surge arrester maximum allowed lead length and maximum separation distance from the protected equipment based on IEC 60071-2 and Hileman.

This calculation is not applicable for cable fed substations or analysis of switching surges.

D.1 Surge arrester voltage protection level:

The surge arrester voltage protection level consists of the residual discharge voltage of the arrester for a given discharge current plus the inductive voltage drop in the arrester leads. The discharge current is conservatively estimated as:

$$Id = \frac{2 \times 1.2 \times CFO_{NS} - V_{dis}}{Zsurge}$$

Where,

Id is the surge arrester discharge current (kA)

CFO_{NS} is the line insulator negative critical flashover voltage (kV)

V_{dis} is the discharge voltage of the arrester (kV)

$Zsurge$ is the surge impedance of the feeder phase conductor (Ω)

The conductor inductive voltage rise can be calculated by the following:

$$V_{ind} = L\, {}^{di}/_{dt}$$

Where:

V_{ind} is the inductive voltage rise (V)

L is the inductance (H), ≈1.2µH/m for a 70mm^2 stranded copper conductor

${}^{di}/_{dt}$ is the rate of current change (A/s)

D.2 Effect of separation distance:

If the arrester is on the line side of the equipment the equipment can be subjected to no more than double the arrester discharge voltage plus lead voltage rise. The voltage stress the equipment is subjected to is determined by the separation distance between the surge arrester and the equipment.

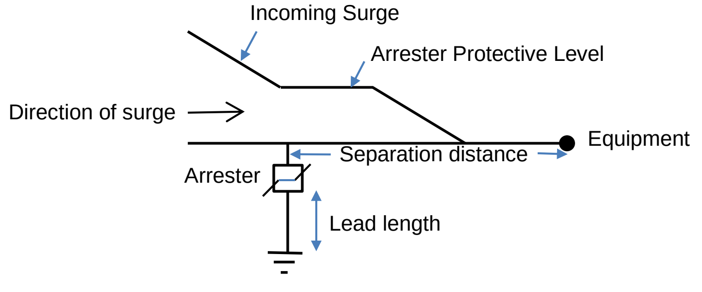


Figure D1: Separation distance D between arrester and equipment

The maximum voltage at the terminals of the protected equipment at a distance D from the surge arrester is given by:

$V(D) = V_p + 2ST$, up to a maximum of $2V_p$

Where:

$V(D)$ is the voltage at a distance D (kV)

V_p is the arrester voltage protection (kV)

S is the steepness of the incoming surge (kV/µs)

T is the travel time (µs)

The maximum allowed separation distance can then be found using the following equation:

$$D = \frac{\left(V(D) - V_p\right) \times v}{2S \times 1000000}$$

Where:

D is the separation distance between arrester and protected equipment (m)

v is the velocity, m/s (≈300 m/µs for an OH line)

D.3 Incoming surge wave shape:

The steepness of the surge at the struck point is assumed to be infinity and as the surge travels towards the substation corona pushes the front back and attenuates the magnitude. The steepness of the incoming surge is dependent on the stroke location and the corona constant. The critical distance to the stroke terminating point is given by:

$$d_m = \frac{1}{LFR \times MTBS}$$

Where:

LFR is the line flashover rate (flashes/100km-yrs)

$MTBS$ is the mean time between surges, yrs. MTBS = MTBF * n

n is the minimum number of in-service lines connected to the substation ($n = 1$ for one line or = 2 for two or more lines)

d_m is the critical distance plus one additional span (km)

The steepness of the incoming surge is then given by:

$$S = \frac{K_c}{d_m}$$

Where:

K_c is the corona damping constant (km-kV/µs) The surge magnitude and is reduced and steepness of the surge pushed back due to corona increasing the line capacitance, refer IEC60071-2 Table F.2 for values, where $A = \frac{2.K_c}{c}(kV)$.

D.4 Line flashover rate:

For lightning strikes to an overhead line, the line flashover rate is dominated by the back flashover rate (BFR) as the majority of lightning strikes and the higher magnitude strikes will terminate on the OHEW. The shielding failure flashover rate (SFFOR) is assumed to be minimised by the shielding angle ≈30deg and the induced voltage flashover rate (IVFOR) is minimised by a structure minimum CFO > 245kV (with OHEW).

A strike to the OHEW/structure will result in a surge on the OHEW and a coupled surge on the phase conductors. The surge split in equal magnitudes in two directions in the OHEW and also will travel down the structure to the footing resistance. A voltage will be created across the insulation between the structure earthing and the phase conductor. If the voltage is greater than the lowest CFO voltage of the structure, a back flashover to the phase conductor will occur. The following simplified method is from Hileman and is applicable to structure heights < 50m.

The line flashover rate can be found from the back flashover rate:

$LFR \approx BFR = 0.6 N_L P(I > I_c)$, flashes/100km/year

Where:

0.6 accounts for the effect of strikes within the span, where the majority of back flashovers occur at the pole/tower due to weaker insulation

$N_L = (28h^{0.6} + S_g)\frac{N_g}{10}$, is the line flash collection rate (flashes/100km/year)

S_g, is the width between OHEWs if there are two or more OHEWs (m)

N_g, is the ground flash density for the area (flashes/km^2/year)

$P(I \geq I_c) = \frac{1}{1+\left(\frac{I_c}{31}\right)^{2.6}}$, is the probability of the strike magnitude exceeding the critical current required to flashover the line insulation

$I_c = \frac{CFO_{NS} - V_{PF}}{R_e(1-C)}$, is the critical current required to cause flashover (kA)

Where:

$CFO_{NS} = \left(0.977 + \frac{2.82}{\tau}\right)\left(1 - 0.2\frac{V_{PF}}{CFO}\right)CFO$, is the nonstandard CFO to account for the difference in shape of the backflashover wave shape compared to standard 1.2/50us waveshape insulators are tested to (kV).

$V_{PF} = \sqrt{2} \times V_{LN} \times K_{PF}$, is the average peak power frequency at time of flashover (kV)

K_{PF}, is the power frequency factor to account for line construction, 0.7 for horizontal, 0.4 for vertical or 0.7 if unknown/other

$C = \frac{Z_{12}}{Z_g}$, is the coupling factor between OHEW and phase conductor

$Z_{12} = 60 ln\frac{D_{12}}{d_{12}}$, is the mutual impedance between OHEW and phase conductor (Ω)

D_{12}, is the distance between the phase conductor and the image of the OHEW below ground (m)

d_{12}, is the distance between the phase conductor and the OHEW (m)

$Z_g = 60ln\frac{2h}{r}$, is the surge impedance of the OHEW (Ω)

$\tau = \frac{Z_g}{R_i}T_s$, is the surge tail time constant (µS)

$T_s = \frac{Span\ Length}{c}$, is the travel time of one span (µS)

$R_e = \frac{R_i Z_g}{Z_g + 2R_i}$, is the equivalent resistance seen by critical current (Ω)

$R_i = \frac{R_o}{\sqrt{1 + I_R/I_g}}$, is the impulse or current reduced footing resistance and is found iteratively (Ω)

$I_R = \frac{R_e}{R_i}I_c$, is the current through the footing resistance (kA)

$I_g = \frac{1}{2\pi}\frac{E_o\rho}{R_o^2}$, the current required to achieve critical breakdown gradient (kA)

$E_o = 400$, is the soil breakdown gradient (kV/m)

ρ, is the soil resistivity (Ω)

R_o, is the measured low current footing resistance (Ω)

c, is the velocity of light (300m/µS)

D.5 Maximum allowed arrester lead length and separation distance:

Figure D2 below uses the equations from the previous subsections and shows the surge arrester lead length vs separation distance from the protected equipment for the different system nominal voltages, network effectively or non-effectively earthed and equipment LIWL (shown in brackets).

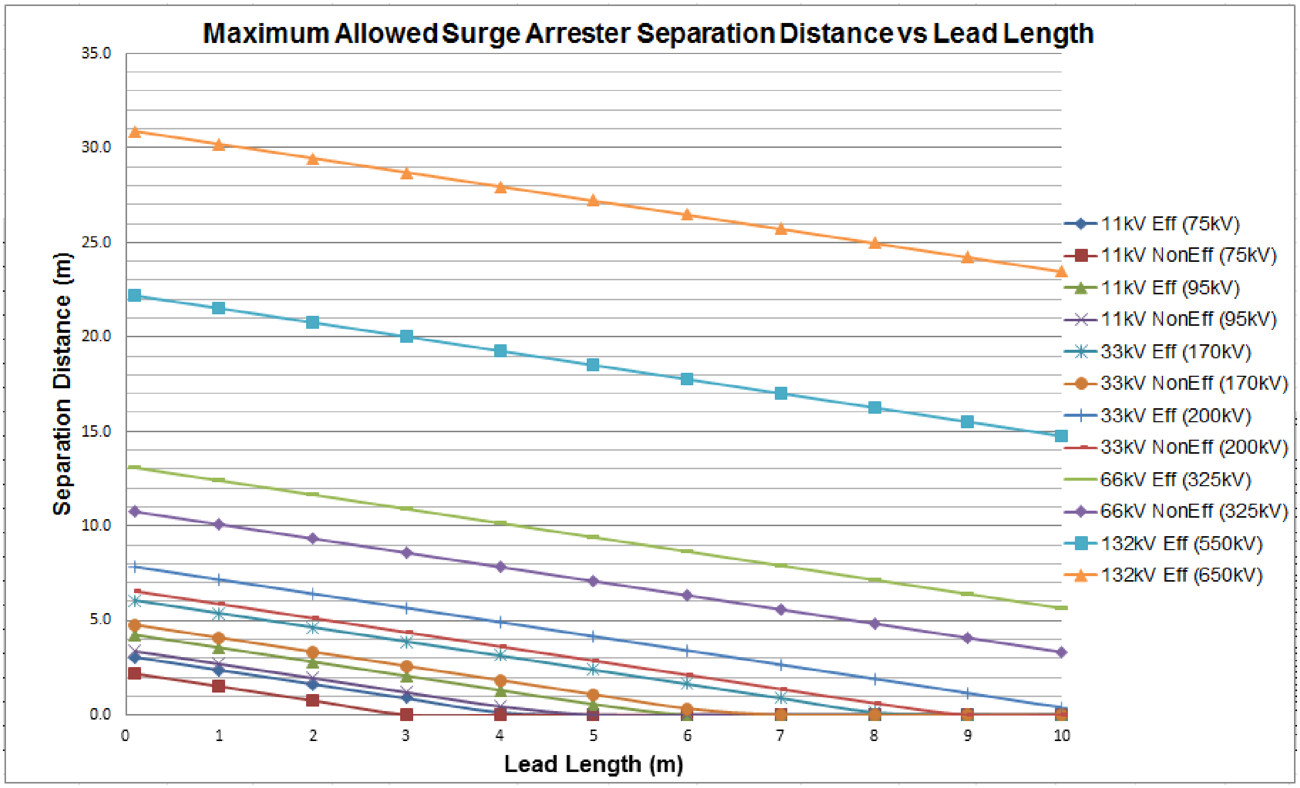


Figure D2: Arrester separation distance vs lead length – Overhead system

The following parameters in Table 11 have been used to calculate the curves in Figure D2:

Table 11: Arrester separation distance main parameters

Parameter	33kV	66kV	132kV
Calculated Surge Steepness	2200 kV/µS	1700 kV/µS	1500 kV/µS
Chosen MTBF	100 years	200 years	400 years
Calculated BFR	7.34 f/100km/yr	2.8 f/100km/yr	0.25 f/100km/yr
Calculated SFFOR	0.01 f/100km/yr	0.02 f/100km/yr	0.14 f/100km/yr
Calculated Critical Distance	186 m	253 m	739 m
Assumed nearby shielding	0.67	0.51	0.3
Ground flash density	4.3 f/1km^2/yr	4.3 f/1km^2/yr	4.3 f/1km^2/yr
Line insulator CFO	200 kV	350 kV	720 kV
Footing Resistance (low current measured)	30 Ω	20 Ω	10 Ω
Soil Resistivity	100 Ωm	100 Ωm	100 Ωm
Ausgrid Line Construction Drawing Number	514169 Sh01 Amd4	514159 Sh01 Amd4	514195 Sh01 Amd0
Estimated shielding angle	27°	27.8°	33°
Average Span Length	50 m	75 m	100 m
Avg Line Structure Height	15 m	17.5 m	20 m
Chosen corona damping constant Kc	405 kVkm/µS	405 kVkm/µS	1050kVkm/µS

Other assumptions:

- The arrester down lead is inductance is taken to be1.2µH/m
- Insulation safety factor of 1.15
- Open circuit at protected equipment (i.e. at transformer) and transformer capacitance neglected as per IEC 60071-2:1996 Annex F
- Surge arrester V-I curve

Annexure E – Switching surge energy discharge

(Informative only)

Conservative estimates for the switching surge energy discharge for a shunt capacitor bank and feeder are provided by IEEE Std C62.22-2009 Annex G.

E.1 Shunt capacitor bank:

$Arrester\ Energy\ (kJ) = 16.0 \times MVAr\ per\ phase$

Arrester energy requirements for typical Ausgrid shunt capacitor bank sizes are shown in Figure E1.

Application of Ausgrid standard arresters are generally not suitable for this task.

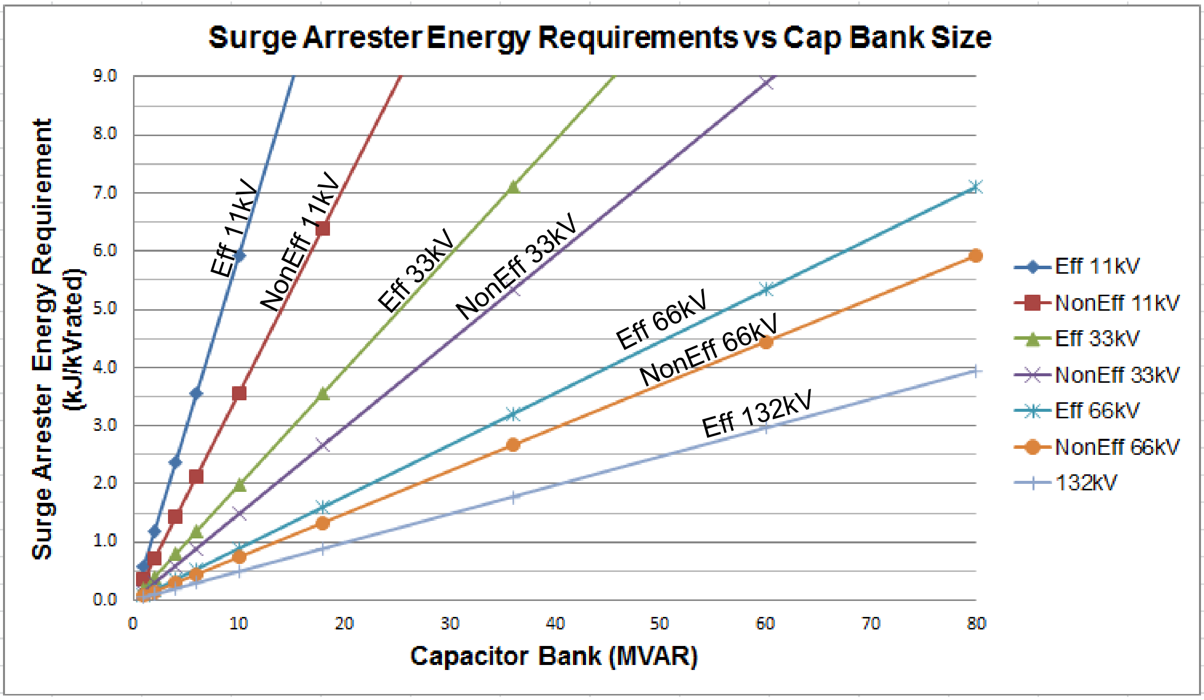


Figure E1: Surge arrester energy requirements for cap banks

E.2 Unloaded feeder:

$$W_{MCOV} = 0.021 \times V_{Max} \times \frac{L}{Z_{surge}}$$

Where:

W_{MCOV} is the energy discharge in to the arrester (kJ/kV of MCOV)

V_{Max} is the maximum line to ground voltage on the feeder (kVrms)

L is the length of the feeder (km)

Z_{surge} is the surge impedance of the feeder (Ω), Using 450Ω for lines and 30Ω for cables

Table E1 shows the maximum allowed feeder length for a 4.5kJ/kV of surge arrester rated voltage energy absorption.

Table E1: Max feeder allowed feeder length not impacting surge arresters

Nominal System Voltage	Cable max length (km)	Line max length (km)
132	96	1438
66	192	2876
33	383	5751
11	1083	16239

Note: Ausgrid surge arrester specification calls for a minimum 4.5kJ/kV of surge arrester rated voltage. For each nominal voltage the rated energy absorption of the surge arrester is converted to kJ/kV of MCOV (where MCOV is the IEEE equivalent to COV in IEC standards).