Assets Planning and Delivery Group
Engineering

DESIGN STANDARD DS 27

Lightning Protection and Insulation Coordination

VERSION 1
REVISION 0

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FOREWORD

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

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

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

Overview of Western Australia's Work Health and Safety (General) Regulations 2022 (dmirs.wa.gov.au)

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

Head of Engineering

This document is prepared without the assumption of a duty of care by the Water Corporation. The document is not intended to be nor should it be relied on as a substitute for professional engineering design expertise or any other professional advice.

Users should use and reference the current version of this document.

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Any interpretation of anything in the Standards/Specifications that deviates from specific Water Corporation Project requirements must be referred to, and resolved by, reference to and for determination by the Water Corporation's project manager and/or designer for that particular Project.

REVISION STATUS

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

REVISION STATUS						
SECT.	VER./ REV.	DATE	PAGES REVISED	REVISION DESCRIPTION (Section, Clause, Sub-Clause)	RVWD.	APRV.
1	1/0	06.03.25	All	New Version	NHJ	EDG
2	1/0	06.03.25	All	New Version	NHJ	EDG
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5	1/0	06.03.25	All	New Version	NHJ	EDG
6	1/0	06.03.25	All	New Version	NHJ	EDG
App A	1/0	06.03.25	All	New Version	NHJ	EDG
App B	1/0	06.03.25	All	New Version	NHJ	EDG
App C	1/0	06.03.25	All	New Version	NHJ	EDG
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App E	1/0	06.03.25	All	New Version	NHJ	EDG

DESIGN STANDARD DS 27

Lightning Protection and Insulation Coordination

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1 Introduction

1.1 Purpose

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

This design standard (i.e., Electrical Design Standard DS27) sets out design standards and engineering practice which shall be followed in respect to the design and specification of lightning protection systems being acquired by the Corporation. This design manual does not address all issues that will need to be considered by the Designer in respect to a particular Corporation asset.

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

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

1.2 Scope

The scope of this standard (i.e., Electrical Design Standard DS27) covers key aspects of lightning protection systems and associated insulation coordination for the electrical power design associated with major electrical assets within Corporation pump stations, treatment plants, desalination plants and large bore sites. Major electrical assets include the power supply substations, transformers, High Voltage switchboards, Low Voltage switchboards, switchboards controlling drives, main pump drives, main power circuits and other main power electrical equipment.

The standard also covers the key aspects of lightning protection systems for the protection of buildings and structures as appropriate.

For the purposes of this standard, major electrical assets are defined as electrical equipment within major pump stations, treatment plants, desalination plants, large bore sites and associated substations having individual drives rated in excess of 150 kW or an incoming supply rated in excess of 315 kVA. Major pump stations are as defined in DS21.

Generally, the key aspects of the lightning protection system design of auxiliary drives, small switchboards and auxiliary services are covered in Electrical Design Standard DS22 and associated standard drawings MN01. Any minor electrical design and installation work associated with a major electrical installation shall align with the requirements of DS22.

This standard does not address the lightning protection systems of solar energy systems as this is described in AS/NZS 5033 and to some extent within DS25 - Solar Energy Systems. Nor does this standard address lightning protection for SCADA, communication and battery bank systems.

1.3 Aim and Content

The reliability of electrical equipment, and thus of the Corporation asset, as judged by the frequency and duration of equipment outages, is very dependent on the effectiveness of its lightning protection system. Although there are many causes of electrical equipment failure, insulation breakdown is one of the most frequent.

It is possible to develop reasonably effective lightning protection methods, and in terms of system performance, it is possible to achieve acceptable lightning outage and minimal damage rates at reasonable cost.

In respect of interruptions to Corporation customers, the electrical power components most vulnerable to lightning are exposed transformers, High Voltage equipment (including H.V. switchboards, capacitor banks) followed by H.V. and L.V. drive systems (motors and/or VSCs).

The aim of this standard (i.e., DS27) is to provide the Designer with guidance and direction as to the policy and requirements for the design of safe, cost-efficient, technically effective, lightning protection and insulation coordination systems, by the Designer, for Corporation assets.

Furthermore, this standard provides an overview of lightning phenomena, lightning protection system design techniques/requirements, surge protection device characteristics/selection/testing/monitoring and insulation coordination design and report requirements. In order to assist the operations and maintenance of lightning protection systems, guidance has been provided in Section 6 relating to monitoring, protection device testing and audits.

1.4 References

Reference shall be made also to the following associated design standard manuals and drawings:

DS 20	Design Process for Electrical Works
DS 21	Major Pump Station - Electrical
DS 22	Ancillary Plant and Minor Pump Stations
DS 23	Pipeline AC Interference and Substation Earthing
DS 24	Electrical Drafting
DS 25	Solar Energy Systems
DS 26	Type Specifications – Electrical
DS 28	Water and Wastewater Treatment Plants - Electrical
MN00	Electrical Standard Switchboard Designs - Major Pump Stations (*under preparation*)
MN01	Electrical Standard Switchboard Designs - Small Pump Stations

1.5 Definitions

1.5.1 General

Asset Manager:	The Water Corporation officer responsible for the operation of the asset being acquired.
Corporation:	The Water Corporation (of Western Australia).
Designer:	The consulting engineer carrying out the electrical design.
Principal Engineer:	Senior Principal Engineer – Electrical Standards Section, Engineering.
Network Operator:	As defined in the WASIR.

1.5.2 Technical

Lightning Protection System (LPS)	Complete system, inclusive of air terminals, down conductors, earth network and equipotential bonding, used to reduce physical damage due to lightning flashes to a structure or its contents.
Insulation Coordination	The correlation of the insulation of electrical equipment and circuits with the characteristics of protective devices such that the insulation is protected from excessive overvoltage.
H.V. / L.V.	High Voltage / Low Voltage.

Note: Refer Appendix A for further detailed technical definitions.

1.6 National and International Standards

1.6.1 General

Electrical installations shall be designed in accordance with the latest edition of AS3000 and except where otherwise specified in this design manual, electrical design shall be carried out in accordance with the latest edition of all other relevant Australian Standards. In the absence of relevant Australian Standards, the latest edition of relevant international, other national or industry standards shall be followed.

Except where a concession is obtained from Energy Safety, electrical design shall be in accordance with the W.A. Electrical Requirements Manual (WAER) produced by the Energy Safety Division (EnergySafety) of the Department of Mines, Industry Regulation and Safety.

Except where a concession is obtained from the Network Operator, the electrical design of all installations to be connected to the Network Operator's system shall be designed in accordance with the Western Australian Service and Installation Requirements (WASIR) and the Technical Rules for the Southwest Interconnected Network published by Western Power/Horizon Power.

1.6.2 Technical Standards

Lightning protection systems and insulation coordination protection systems shall be designed, constructed and tested in accordance with the following AS/IEC standards as applicable/relevant to the particular type of asset:

AS 1307.2:2015 "Surge arresters - Metal oxide surge arresters without gaps for AC system"

AS 1768:2021 "Lightning Protection".

AS 2067:2016 "High Voltage Installations exceeding 1kV a.c."

AS 4436:1996 "Guide for the selection of insulators in respect of polluted conditions"

AS 60071.1:2024 "Insulation Co-Ordination, Part 1: Definitions, Principles and Rules (IEC 60071-1:2019 (ED. 9.0) MOD)"

AS 60071.2:2024 "Insulation Co-Ordination, Part 2: Application Guidelines (IEC 60071-2:2023 (ED. 5.0) MOD)"

AS 60099-4:2022 "Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems"

AS 60099-5:2018 "Surge arresters – Part 5: Selection and application recommendations"

IEC 60071-1:2019, "Insulation co-ordination – Part 1: Definitions, principles and rules"

IEC 60071-2:2023, "Insulation co-ordination – Part 2: Application guide"

IEC TR 60071-4:2004, "Insulation co-ordination – Part 4: Computational guide to insulation co-ordination and modelling of electrical networks"

IEC 60099-4:2014 "Surge arresters - Part 4: Metal-oxide surge arresters without gaps for a.c. systems"

IEC 60099-5:2018 "Surge arresters - Part 5: Selection and application recommendations"

IEC 60507:2013 "Artificial pollution tests on ceramic and glass insulators to be used on a.c. systems"

IEC/TS 60815-1:2008 "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – part 1: Definitions, information and general principles"

IEC 61643-11:2011, "Low-voltage surge protective devices - Part 11: Surge protective devices connected to low-voltage power systems - Requirements and test methods"

IEC 61643-12:2020, Low-voltage surge protective devices - Part 12: Surge protective devices connected to low-voltage power systems - Selection and application principles”

IEC 61643-21:2000: “Low voltage surge protective devices - Part 21: Surge protective devices connected to telecommunications and signalling networks - Performance requirements and testing methods”

IEC 61643-22:2015: “Low-voltage surge protective devices - Part 22: Surge protective devices connected to telecommunications and signalling networks - Selection and application principles”

IEC 62305-1:2010, “Protection against lightning – Part 1: General principles”

IEC 62305-2:2010, “Protection against lightning - Part 2: Risk management”

IEC 62305-3:2010: “Protection against lightning - Part 3: Physical damage to structures and life hazard”

IEC 62305-4:2010: “Protection against lightning - Part 4: Electrical and electronic systems within structures”

IEC 62561-1:2023: “Lightning protection system components (LPSC) - Part 1: Requirements for connection components”

IEC 62561-2:2018: “Lightning protection system components (LPSC) - Part 2: Requirements for conductors and earth electrodes”

IEC 62561-3:2023: “Lightning protection system components (LPSC) - Part 3: Requirements for isolating spark gaps (ISGs)”

IEC 62561-4:2023: “Lightning protection system components (LPSC) - Part 4: Requirements for conductor fasteners”

IEC 62561-5:2023: “Lightning protection system components (LPSC) - Part 5: Requirements for earth electrode inspection housings and earth electrode seals”

IEC 62561-6:2023: “Lightning protection system components (LPSC) - Part 6: Requirements for lightning strike counters (LSCs)”

IEC 62561-7:2024: “Lightning protection system components (LPSC) - Part 7: Requirements for earthing enhancing compounds”

IEC TS 62561-8:2018: “Lightning protection system components (LPSC) - Part 8: Requirements for components for isolated LPS”

IEEE Std 998:2012 ‘IEEE Guide for Direct Lightning Stroke Shielding of Substations’

Insulation Co-ordination in High-voltage Electric Power Systems, W. Diesendorf, 1974.

1.7 Use of Type Specifications

Type Specifications (Design Standard DS26) have been prepared in order to assist the Designer to prepare specifications for electrical work designed in accordance with this Design Standard DS27 and these Type Specifications shall be used for this purpose whenever practical. Where a relevant Type Specification does not exist, the Designer shall prepare an appropriate specification based on this design standard and in alignment with the intent and specification structure of Design Standard DS26. The Designer shall refer to DS26-01, Directions for Use, when preparing Type Specifications.

1.8 Electrical Safety

Electrical installations shall be designed to facilitate the safe operation and maintenance of the electrical assets.

In respect to High Voltage equipment (e.g., surge arresters), mechanically and/or key interlocked isolating switches, earthing switches and access doors shall be employed wherever practical to prevent access to live conductors. In instances where interlocking is not practical, High Voltage isolating and earthing switches and access doors shall be protected with Water Corporation EL1 keyed locking systems.

Access doors providing access to exposed live Low Voltage conductors or equipment (e.g., surge arresters), shall be protected with Water Corporation EL2 equivalent keyed locking systems (Bilock).

1.9 Mandatory Requirements

In general, the requirements of this manual are mandatory. If there are special circumstances which would justify deviation from the requirements of this manual, the matter shall be referred to the Principal Engineer for his consideration. No deviation from the requirements of this manual shall be made without the written approval of the Principal Engineer. Such dispensation, if granted, applies only to the case in question based on the merits of the argument presented and documented, and does not set a precedent.

1.10 Quality Assurance

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

1.10.1 Equipment Suppliers

Suppliers of major electrical equipment (such as surge arresters, etc.) shall only supply equipment from a Manufacturer that has in place a Quality Management System certified by an accredited third party to AS/NZS ISO 9001 or an approved equivalent.

1.10.2 Installers

Installers of electrical equipment shall have in place a Quality Management System certified by an accredited third party to AS/NZS ISO 9001 or an approved equivalent.

1.10.3 Acceptance Tests

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

a) it can be verified that sufficient funds have been allowed to carry out such testing satisfactorily, and,

b) it is clear that works tests and site tests are separate critical deliverables.

2 Lightning Protection System (LPS)

2.1 General

Lightning presents a significant risk to personnel safety, structural integrity, and increasingly to the internal systems of structures due to the prevalent use and dependence on electrical and electronic equipment.

The lightning protection standard for Australia is AS 1768. This standard, AS 1768, refers throughout to, and aligns closely with, the international standard IEC 62305 parts 1 to 4.

IEC 62305 is a comprehensive and detailed standard and is a valuable resource for the design and implementation of lightning protection systems. The Designer shall comply with the requirements of AS 1768 and, where possible and practical, the requirements of IEC 62305.

2.2 Function of a Lightning Protection System

The function of a LPS is to protect structures and equipment from fire or mechanical/electrical damage and persons within buildings, or within the vicinity, from injury or death due to lightning induced touch and step voltages.

2.3 Objective of a Lightning Protection System

All equipment, structures, buildings, and personnel within sites susceptible to direct lightning strikes shall be protected in accordance with the requirements of AS1768. This protection is implemented by installing a Lightning Protection System (LPS), which consists of both external and internal components.

2.3.1 External

An external system shall provide:

a) An air termination system to intercept direct lightning strikes.
b) A down conductor system to safely conduct the lightning current to earth.
c) An earth termination system to distribute the lightning current in the ground.

2.3.2 Internal

An internal system, to prevent hazardous sparking inside the building/structure, shall provide:

a) A separation distance between the components of a LPS and other electrically conductive elements within the structure/building
b) The establishment of equipotential bonding of all metallic components within the structure/building. Equipotential bonding includes the application of surge protective devices (SPDs).

Note: Such bonding reduces the potential difference between isolated conductive parts of the installation directly by means of conductors or surge protective devices (SPDs).

2.4 General Principles of Lightning Protection.

Thunderstorms are natural phenomena and there are no proven devices or methods capable of preventing lightning flashes. Direct and indirect cloud-to-ground lightning discharges can be hazardous to power lines, substations, electrical equipment, structures (substations, buildings, water towers/tanks, etc.) and people within or near them. Therefore, careful consideration must be given to the application of lightning protection measures.

The Australian Standard AS 1768 - Lightning Protection approach is that of probabilistic risk management, which integrates the determination of the need for protection with the selection of adequate protection measures to reduce the risk of lightning outages and damage to

tolerable levels. This selection considers both the effectiveness of the measures and the cost of their provision. In the risk management approach, the lightning threats that create overvoltage risks are identified, the frequencies of such risk events are estimated, the consequences of the risk events are determined, and if these are above a tolerable level of risk, protection measures are applied to reduce the risk to below the tolerable level. This involves a choice from a range of protection measures for protection against direct strikes to aerial connected substations and structures, and for protection against surges induced indirectly by nearby strikes, particularly the measures for protecting distribution and High/Low Voltage systems and electronic equipment against indirect lightning overvoltage.

The lightning protection measures for structures (substations, buildings, water towers/tanks, etc.) shall include a lightning protection system (LPS). The lightning protection measures for High/Low Voltage electrical equipment (switchboards, transformers, motors, etc.) shall include transient protection systems to protect against the lightning electro-magnetic pulse (LEMP) caused by direct and nearby strikes.

The LPS for the structures comprise air terminals to intercept the lightning strike, a down-conductor

system to conduct the discharge current safely to earth, an earth termination system to dissipate the current into the earth, as mentioned in clause 2.3, the installation of properly selected and located surge arresters and adequate insulation to withstand the remaining lightning overvoltage.

The transient protection system includes several measures to protect HV equipment and sensitive LV and electronic equipment such as the use of multiple down-conductors (buildings) to minimise the internal magnetic field, equipotential earth bonding and the installation and coordination of surge protective devices (SPDs).

Furthermore, power system equipment requires insulation to withstand normal operating system voltage, temporary power frequency overvoltage (sags, surges, etc.) and, for transmission voltage substations (rare for the Corporation), switching over voltages. In some cases, consideration may be given to provide additional insulation to raise the lightning impulse insulation strength to the level required for acceptable lightning performance.

Comprehensive lightning protection can only be achieved through a coordinated design approach.

2.5 Lightning Transient Waveforms

The most common waveform representations for lightning are the 8/20 µs (for an indirect strike) and 10/350 µs (for direct strike) current waveform and the 1.2/50 µs voltage waveform. These types of lightning current waveforms are used to define tests on SPDs (IEC standard 61643-11), design of LPSs and equipment immunity to lightning currents.

Even though the rise time of the current in subsequent return strokes is less than 1 µs, the 8/20 µs current waveform and the 1.2/50 µs voltage waveforms are intended to approximate the direct effects of a lightning first return stroke.

Current Waveform	**Duration of rising edge T_1** *(Refer Figure 2.1)*	**Duration of tail T_2** *(Refer Figure 2.1)*	**I (peak current)**
10/350 µs	10 µs	350 µs	I_{imp}
8/20 µs	8 µs	20 µs	I_n or I_{max}

Table 2.1 Lightning Transient Waveforms

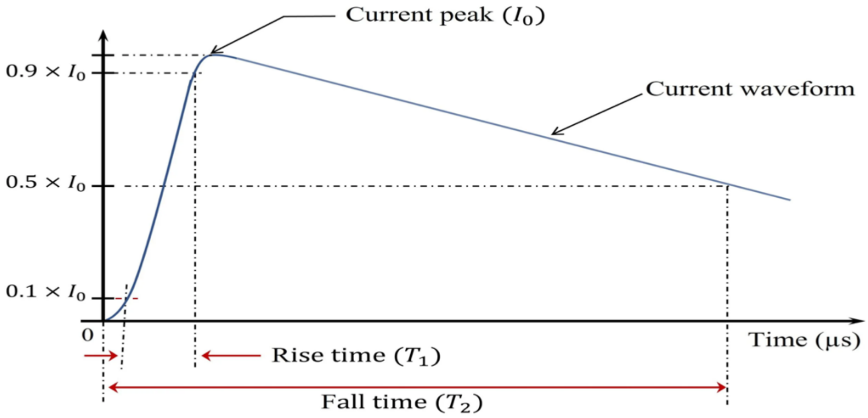


Figure 2.1 Waveform Definition

Note: It should be noted that a lightning stroke event consists of an initial stroke of high amplitude followed by subsequent smaller amplitude strokes. That is, the first lightning stroke is characterised by a current peak higher than that of subsequent lightning strokes (refer clause 6.6 for detail).

2.5.1 Direct Lightning Strike

Lightning currents that can occur during a direct lightning strike can be simulated with the surge current of waveform 10/350µs. The lightning test current imitates both the fast rise and the high energy content of natural lightning. SPDs and external lightning protection components are tested using this pulse waveform characteristic.

2.5.2 Remote Lightning Strike

The surge currents created by remote lightning strikes and switching operations are simulated with test impulse 8/20µs. The energy content of this impulse significantly lower than the lightning test current of surge current wave 10/350µs. SPDs are tested with this impulse waveform characteristic.

The area under the current-time curve for surge currents represents the amount of energy. The energy of the lightning test current with a 10/350µs waveform is approximately equivalent to 20 times the energy of a surge current with an 8/20µs waveform of the same amplitude.

Mathematically, the Energy $\approx \int_0^T I^2 dt$.

2.5.3 Voltage waveform

Lightning impulse overvoltage, which takes the form of a double exponential wave shape having a front time of 1.2µs and a time to decay to half magnitude on the tail of 50µs.

This type of voltage wave is used to verify equipment's withstand to an overvoltage of atmospheric origin (impulse voltage as per IEC 61000-4-5).

2.6 Lightning Protection System Components

2.6.1 Air Termination System

Conventional air terminations may consist of vertical rods (minimum 10 mm diameter), a single horizontal conductor along a roof ridge (minimum 25 x 3 mm copper strip), a horizontal conductor network for roof protection or an overhead shield conductor supported on poles independent of the building to be protected. These are applied where there are no natural suitably sized conductive structural parts that can form an air termination.

Suitable natural air terminations are metallic roofs or handrails around the roof perimeter. A metallic roof (minimum 4 mm thick) and/or handrail on the roof of a Water Corporation concrete tank for example will serve as an excellent air termination. Where available such natural air terminations shall be used. It should be noted that additional vertical rods installed on metallic roofs are ineffective and shall not be deployed.

Note: With agreement with the Asset Manager, the metal thickness of the tank roof may be less than 4 mm, provided that it is understood that regular inspections and repairs to the roof may be required after lightning activity.

Non-conventional air termination systems on the market claim to have enhanced lightning intercept performance. It is somewhat questionable whether these intercept systems, at considerably more cost, provide superior protection to those of the conventional passive type. At this stage the non-conventional air termination products are not recommended.

The location of air terminals shall be determined by the LPS design via the rolling sphere method as described in the Australian and international standards and determined by the Class of LPS (I, II, III, IV). Air terminations shall not be mounted on substation equipment such as transformers, etc.

Class of Lightning Protection Level (LPL)	Sphere Radius (m)	Interception Current (kA)	Interception Efficiency	Sizing Efficiency	LPS Efficiency
I	20 (40) *	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

Table 2.2 Lightning Protection Level (LPL) Class

* *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.*

Outdoor (aerial) Corporation substations LPS shall be designed using the Rolling Sphere Method (RSM) to an LPL Class I as defined in AS 1768 and the table 2.2 above. Hence the rolling sphere radius to be used for the substations LPS design is 20m.

It is common to consider that LPL III using a sphere radius of 45 m provides “standard” protection. LPL I and II with sphere radius of 20 m and 30 m provide higher degrees of protection and therefore these protection levels will require a considerably greater number of air terminals.

Protection level III ensures that for striking distances of 45 m or more, the shortest distance to the structure is an air terminal. Such striking distances correspond with peak currents of 10.1 kA or greater, which has an interception efficiency of 91 %, meaning about 9 % of all possible strikes will have a lower current which would potentially not be intercepted.

The designer of the LPS shall utilise the rolling sphere method to optimise the locations and configurations of lightning masts and shield wires in order to prevent direct lightning strikes to energised conductors, busbars, electrical equipment, support structures and buildings.

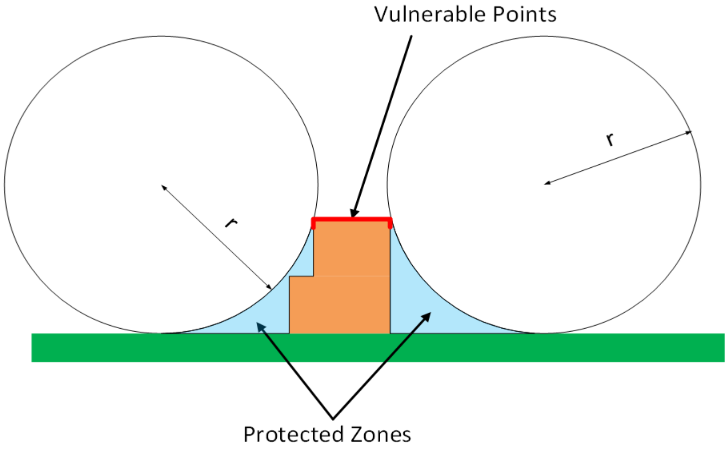


Figure 2.2 Rolling Sphere Method for Protection Zone

There are another two methods for determining the position of air termination systems.

a) The protective angle method and,
b) The mesh method.

The protective angle method is a mathematical simplification of the rolling sphere method. The protective angle (α) is the angle created between the tip (A) of the vertical rod and a line projected down to the surface on which the rod sits (see Figure 2.3 below). The protective angle afforded by an air rod is a three-dimensional concept whereby the rod is assigned as a cone of protection by sweeping the line from A at the angle of protection a full 360^{o} around the air rod.

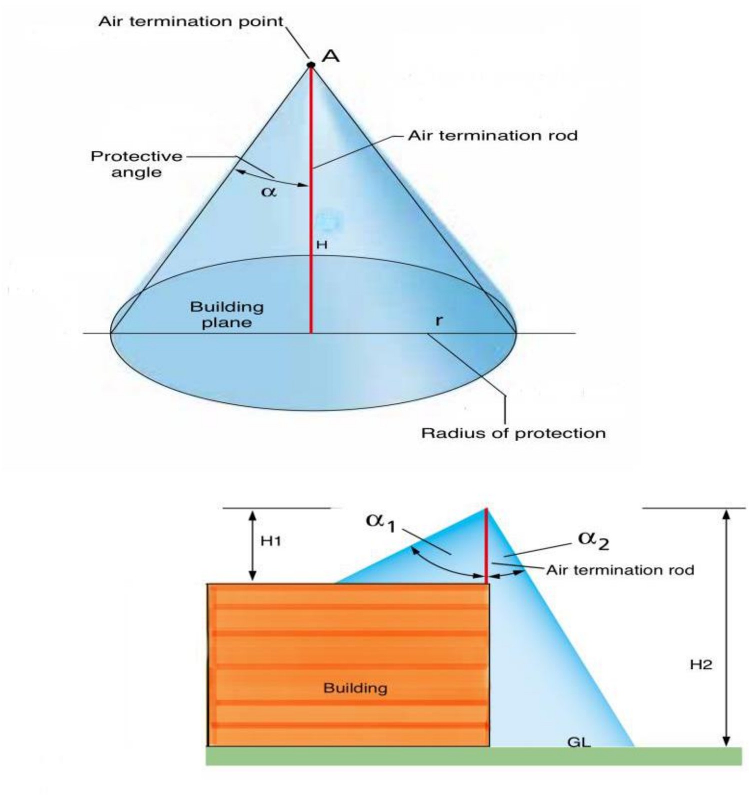


Figure 2.3 Air Termination Protection Angle

The protective angle differs with varying height of the air rod and class of LPS.

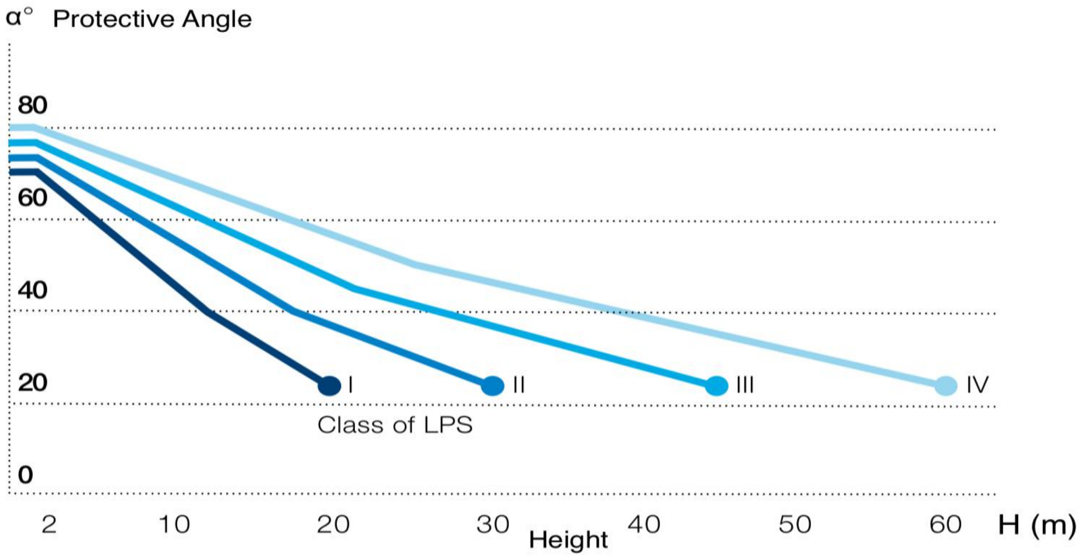


Figure 2.4 Protective Angle versus Height and Class of LPS

The protective angle method is best suited for simple shaped buildings and only valid up to the height equal to the rolling sphere radius of the appropriate LPL.

The mesh method is suitable where plain surfaces require protection if the following conditions are met:

- Air termination conductors must be positioned at roof edges, on roof overhangs and on the ridges of roof with a pitch in excess of 1 in 10.
- No metal installation protrudes above the air termination system.

IEC 62305 lists four different air termination mesh sizes that are defined and correspond to the relevant class of LPS. These are: LPS Class I (5 x 5 m), LPS Class II (10 x 10 m), LPS Class II (15 x 15 m) and LPS Class IV (20 x 20 m).

The edges and corners of roofs are most susceptible to lightning damage, so all structures with flat roofs, perimeter conductors shall be installed as close to the outer edges of the roof as practicable.

2.6.2 Down Conductor System

The down conductor system, from the air termination to the earth termination system, shall be mounted to ensure several parallel paths exist, the length of each down conductor is as short and straight/vertical as possible with no loops, and connections to conductive parts of the structure made whenever required. The surge impedance shall be as low as possible.

The down conductors shall be arranged to ensure that they are distributed uniformly around the perimeter of the structure. Generally, the separation distance between the various down conductors shall be 10 metres (can be 15m and 20 m for LPS class III and IV respectively) starting at the corner of the structure if appropriate. The minimum number of down conductors shall be two.

The minimum down conductor size shall be 70 mm^2 stranded copper.

In special cases (occupied Water Corporation structures), High Voltage insulated down conductors may be necessary to prevent hazardous flashover between the LPS and conductive parts within the structure (e.g. electrical equipment, pipes, air duct systems, etc.) in situations where it is impractical to maintain the required separation distance (Refer clause 2.6.4).

Subject to the structural engineer's approval, if reinforcing bars or structural steel frames are intended to be used as down conductors, it is essential to ensure electrical continuity from the air termination system to the earthing system. These should ideally be bonded into the reinforcing network of the structures at the top and bottom of the structure. If there is doubt as to the route and continuity of the reinforcing bars within existing structures, or approval is not granted by the structural engineer, then an external down conductor system shall be installed.

2.6.3 Earth Termination System

The earth termination system shall be designed in accordance with the requirements of Design Standard DS23.

The earth electrode system shall be designed to ensure safe touch and step voltages around the structure while safely dissipating the lightning energy into the earth. Furthermore, the earthing design shall provide integrity for primary (e.g. transformers, etc.) and secondary (e.g. protection systems, SCADA, etc.) electrical equipment, buildings and external services (e.g. communications, pipes, etc.).

CDEGS modelling/simulation software package, from SES Canada, shall be used for analysis and design of the lightning protection earthing system as it provides for consistency of approach, consistency of output, high levels of confidence and accurate modelling resulting in minimal installation costs.

Note:

1) *Because of ionisation and arcing in the soil during a lightning discharge, the effective resistance for high impulse currents is often very much lower (after a critical breakdown field 'E' is reached), hence the importance of CDEGS modelling. For example, single rod in soil of 100 Ω-m (or 1000 Ω-m) has 'low current' resistance of 30 ohms (300 ohms) compared to 11.3 ohms (54 ohms) for 'high current'.*

2) *Furthermore, in power system earthing design the main parameter is that safe touch voltage must be satisfied and hence step voltages are usually a lot smaller. However, currents due to lightning are often much larger hence step voltages are of significant concern.*

Soil resistivity tests shall be performed for all lightning protection earth termination systems and performed by the CDEGS specialist consultant from the Corporation's Specialist Earthing Panel (Refer DS20).

In general, an earth electrode system impedance (depends upon waveshape, front time and frequency effects) shall be less than 10 ohms (measured with a low frequency meter) but actual earth system impedance will be determined by the CDEGS modelling.

Note: A low impedance reduces surface voltage gradients, the risk of side flashing within structures and the risk of equipment insulation breakdown.

Particular attention shall be made to corrosion resistance of materials and connections within the earth termination system.

Earth electrode arrangements may consist of vertical or horizontal electrodes, ring electrodes, foundation electrodes or a combination as determined by the designer to meet performance requirements.

2.6.4 Separation Distances

The risk of uncontrolled side flash from the external LPS to metallic parts and electrical equipment within the building/structure is considerable if the distance between the LPS (air termination and down conductor) and the metallic parts and electrical equipment is insufficient. Separation can be achieved by air clearance or insulating materials.
Metallic component within the building (e.g. water, air conditioning, cable services, etc.) form induction loops where impulse voltages are induced due to the rapidly changing magnetic field of the lightning.
To reduce the probability of the risk of side flash effects the lightning study shall calculate the required separation distance.
AS 1768 equation 3.6.3 suggests:

$$S = (k_i \times k_c \times L) / k_m$$

Where:

S	is the separation distance
k_i	depends on the class of LPS selected (induction factor or LPS factor)
k_c	depends on the geometric arrangement (down conductor factor)
k_m	depends on the material used in the point of proximity (material factor)
L	is the length along the air termination system and the down conductor from the point where the separation distance is to be determined to the next equipotential bonding or earthing termination point.

The simplified k factors are provided in AS 1768.

2.6.5 Lightning Equipotential Bonding

Often referred to as Internal LPS, equipotential bonding is to reduce the risk of sparkover and potential difference from external lightning affected conductive parts over to the internal metallic parts of the installation.

Equipotential bonding shall be provided for all electrical equipment and metallic parts within the building (extraneous parts) to prevent hazardous potential differences (touch voltages) due to uncontrolled lightning discharges.

Connection of all extraneous conductive parts to the main earth busbar shall include:

a) Main power system earth electrodes.
b) Lightning protection earth electrodes.
c) Protective bonding conductors.
d) Metallic pipes for all services (e.g. water, gas, drainage, HVAC systems, etc.).
e) Antenna and telecommunications equipment.
f) Metal sheaths of power cables.
g) Conductive parts of the building (e.g. ducts, handrails, floors, walls, steel frame, etc.).
h) Metal reinforcements in building structures made from reinforced concrete.

Equipotential bonding for a LV power supply system represents an extension of the protective equipotential bonding system above. That is, the connection to the equipotential bonding system is only possible via adequate surge protective devices. Furthermore, bonding can also be accomplished using surge protective devices (SPDs) where the direct connection with bonding conductors is not suitable (e.g. cathodic protection isolation).

A typical equipotential bonding arrangement is shown in Figure 2.5 below for guidance purposes.

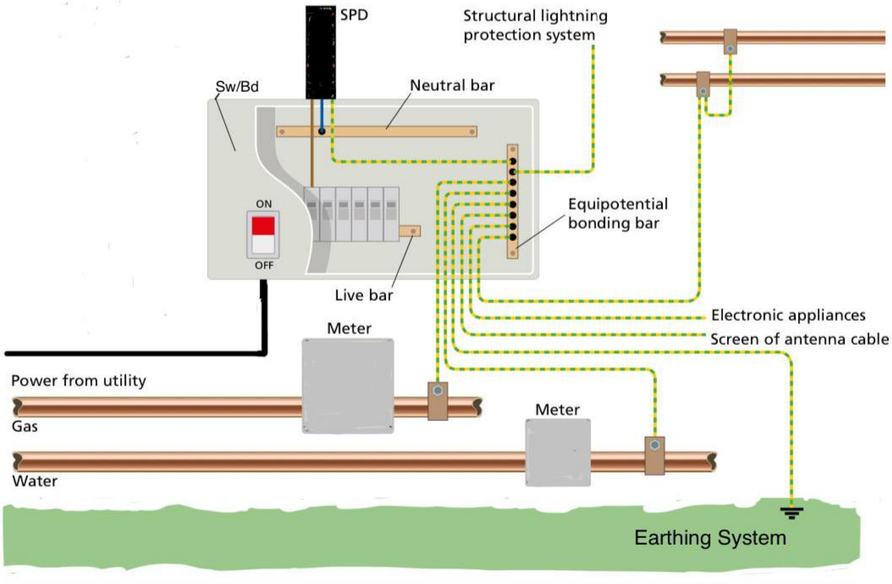


Figure 2.5 Typical Equipotential Bonding Concept

2.6.6 Lightning Protection Zone

The Lightning Protection Zone (LPZ) concept is based on the principle of gradually reducing the surge to a safe level prior to reaching the terminal devices. Hence, a building's entire network is divided into lightning protection zones (LPZ 0A, LPZ 0B, LPZ 1, LPZ 2 and LPZ 3). In general, the higher the zone number the lower are the electromagnetic effects experienced.

A zone is an area or building section in which all equipment requires the same level of protection.

Equipotential bonding is created at each transition from one zone to another. Metal parts shall be connected directly to the equipotential bonding system, while surge protection devices, corresponding to the relevant requirements class (Class 1, 2 or 3 to IEC 61643-11 – refer clause 2.6.6.1 below), shall be installed between the active conductors and the earth. All cables shall be kept as short as possible, without cable loops and with copper conductors sized in accordance with the standards to ensure a low impedance.

Successive zones use a combination of bonding, shielding and coordinated SPDs to achieve a significant reduction in LEMP severity, from conducted surge currents and transient overvoltages, as well as radiated magnetic field effects. Designers shall coordinate these levels so that the more sensitive equipment is sited within the more protected zones. Protection levels within a zone shall be coordinated with the immunity characteristics of the equipment to be protected (Refer clause 2.6.6.2).

Appropriate SPDs shall be fitted wherever services cross from one LPZ to another.

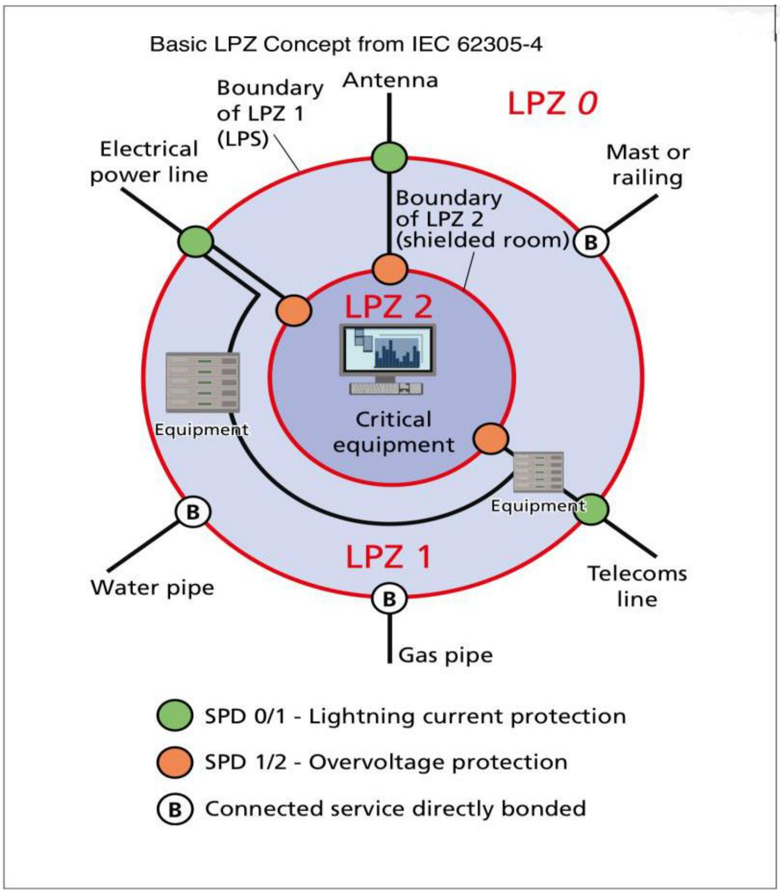


Figure 2.6 Lightning Protection Zone Concept Diagrammatic

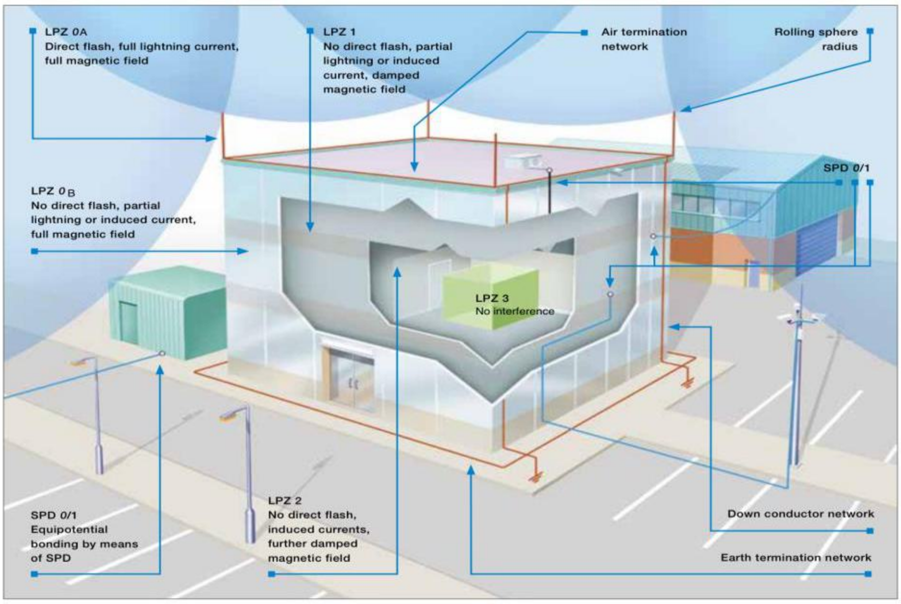


Figure 2.7 Lighting Protection Zones Example

LPZ 0A: Unprotected zone outside a building. Direct lightning strike, no shielding against lightning electromagnetic interference pulses (LEMP).

LPZ 0B: Zone protected by external lightning protection system. No shielding against LEMP.

LPZ 1: Zone inside the building. Low partial energy possible.

LPZ 2: Zone inside the building. Low level surges possible.

LPZ 3: Zone inside the building. No interference pulses via LEMP or surges.

2.6.6.1 SPD Class

As part of the lightning protection zone concept SPDs are classified into three types, namely Class 1, 2 and 3, according to the requirements and stress on the places of installation and tested to IEC 61643-11.

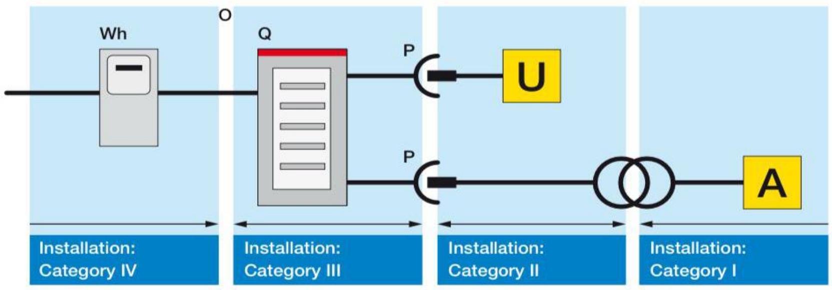
a) Class 1 SPDs are installed at the boundary/service entrance (LPZ 0A to LPZ 1 and higher). Highest discharge capacity capable of carrying lightning currents of up to 100 kA and a 10/350 μs wave form. Their function is to prevent destructive partial lightning currents entering the electrical installation. That is, they allow a small portion of the impulse current into the downstream system.
b) Class 2 SPDs are installed primarily in submain circuits near equipment to be protected (LPZ 0B to LPZ 1 and higher or LPZ 1 to LPZ 2 and higher). A lower discharge capacity capable of carrying surge currents of approximately 10 kA with an 8/20 μs wave form.
c) Class 3 SPDs are located at sensitive terminal devices (transition from LPZ 2 to LPZ 3). The prime function of the SPD is overvoltage protection arising from switching voltages.

IEC 62305 part 4 is specifically dedicated to the protection of electrical and electronic systems within structures and shall be referred to by the designer. Zone 0/1 SPDs only provide protection against common mode surges (between live conductors and earth). IEC 62305 and AS 1768 promote the use of enhanced SPDs (both common mode and differential mode (between live conductors)), for the downstream zones, that further reduce the risk of damage and malfunction to critical equipment where continuous operation is required.

2.6.6.2 Equipment Impulse Withstand Category

The tolerance of equipment to overvoltage surges is classified according to 4 categories, pursuant to IEC 60364-4-44, IEC 60664-1 and IEC 60730-1.

The figure below outlines the four categories.



O = origin of the installation; Wh = electricity meter; Q = main electrical switchboard;
P = electric socket; U = end-user electrical equipment; A = electronic equipment

Category	U_n				Examples
	120-220 V	230-400 V	400-690 V	1 000 V	
I	800 V	1 500 V	2 500 V	4 000 V	Equipment containing particularly sensitive electronic circuits: – Servers, computers, TVs, HiFis, videos, alarms etc. – Household appliances with electronic programs etc.
II	1 500 V	2 500 V	4 000 V	6 000 V	Non-electronic household appliances, devices etc.
III	2 500 V	4 000 V	6 000 V	8 000 V	Distribution switchboards, switching devices (switches and circuit breakers, sockets, insulators etc.), conduits and accessories (wires, bars, junction boxes etc.)
IV	4 000 V	6 000 V	8 000 V	12 000 V	Industrial equipment and equipment such as, for example, fixed motors connected permanently to fixed systems, electricity meters, transformers etc.

Figure 2.8 Equipment Impulse Withstand Categories

Voltage protection levels or let-through voltages of installed SPDs shall be coordinated with the insulation withstand voltage of the parts of the installation and the immunity withstand voltage of electronic equipment.

Refer Appendix C for further information/ guidance relating to zones, SPD types and waveforms.

2.6.7 Step and Touch Voltage

Touch and step voltages outside a building or structure in the vicinity of down conductors can potentially present a safety hazard and hence must be considered during lightning system protection design.

In power system earthing design, touch voltage is the main safety parameter that must be addressed (design for safe touch and usually safe step voltage is satisfied). However, the currents associated with lightning are often much larger resulting in a high risk of step voltage hazards.

$V_{st} = (K + \rho)/\sqrt{t}$

ρ = soil resistivity, ohm-metres.

K = constant (165 – 250).

t = Strike duration.

For LPSs, both touch voltage and step voltage calculations shall be performed.

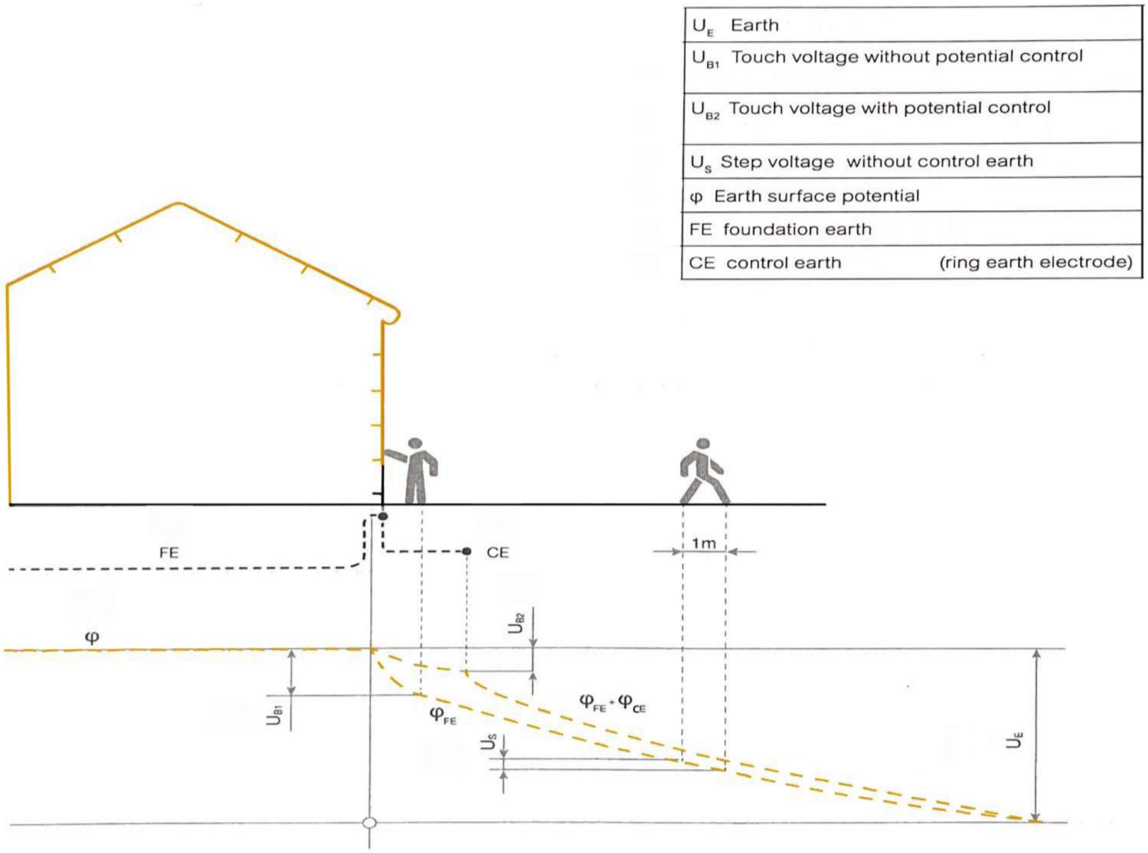


Figure 2.9 Step and Touch Voltage versus Erath Surface Potential

2.7 Materials and Components

Materials and components for lightning protection systems shall be designed and tested for electrical, mechanical and corrosion stress expected during use (operation and maintenance).

IEC 62561 series require manufacturers to undertake thorough testing and performance measurement of their components in order to gain compliance. By specifying lightning protection components conforming to the IEC 62561 series, the designer ensures the products are durable, fit for purpose for the life of the asset and in compliance with IEC 62305.

In this regard, the Designer shall ensure, where possible and practical, compliance with the IEC 62561 series (parts 1 to 8) of standards as documented in clause 1.6.2.

2.8 Process – Risk Assessment & Lightning Protection Selection

AS 1768 (Section 2 and Figure 2.1) outlines the process to be followed for both risk assessment of a site and the selection of appropriate lightning protection surge protection measures (SPM).

The Designer shall comply with this process for all operation buildings, substations, major pump station sites, treatment plant sites, desalination plant sites and small pump station sites considered vulnerable.

The Designer shall document the results of the risk assessment in a report to be submitted to the Corporation for acceptance. The report (hard copy and electronic) shall be submitted during the Engineering Design stage of the project and, as a minimum, consist of:

a) Drawing showing the plan of the installation and the appropriate zones ($LPZ0_{A/B}$, LPZ1, LPZ2, etc.) relevant to the installation.
b) All assumptions applicable to the preparation of the risk analysis.
c) Results of the risk analysis spreadsheet calculation both in hard copy and electronic format.
d) Recommendations relating to external (air terminal, down conductor, earth system) and internal (separation, bonding including SPDs) LPSs.
e) Clear statement as to the tolerable risk adopted for the four risk categories (Loss – refer clause 2.9). Note that the loss of economic value will need determination as it is not stated in AS 1768 and may need to be discussed with the Corporation prior to evaluation.

2.9 Risk Analysis

The first stage of the risk assessment is to identify which of the four types of loss (as identified in AS 1768, clause 2.4 Table 2.1) the structure and its contents can incur. The ultimate aim of the risk assessment is to quantify and if necessary, reduce the relevant primary risks i.e.:

a) R1, risk of loss of human life (including permanent injury)
b) R2, risk of loss of service to the public
c) R3, risk of loss of cultural heritage
d) R4, risk of loss of economic value

For each of the first three primary risks, a tolerable risk (R_T) is set.

It is this iterative process as shown in Figure 2.1 of AS 1768 that decides the choice or indeed the Lightning Protection Level (LPL) of Lightning Protection System (LPS) and Surge Protective Measures (SPM) to counter Lightning Electromagnetic impulse (LEMP).

2.10 Design – Lightning Protection System

The Designer shall carry out an Engineering Design of the lightning protection system based on the findings/calculations in clauses 2.8 and 2.9 above.

Integrate the design and results into the Design Summary Drawings (as referred to in DS20). Conduct a third-party review of the Design Summary Drawings.

As a minimum, the design shall detail the following in the Design Summary drawings:

a) Substation/building equipment layout detail (e.g. plan and section views indicating building heights).
b) The Protection Level (PL) to provide sufficient protection to the substation/building against direct lightning strikes identified.
c) Earthing layout drawings showing placement and height of lightning spires, any lightning protection elements, and all connections to the earth grid.

d) Earthing design detailing the results of calculations that demonstrate the LPS compliance with the relevant rolling sphere radius, protective angle method or mesh method.
e) All details of internal building bonding and protection systems.

3 Application of High Voltage Surge Arresters

3.1 Introduction

Overvoltage in a power supply system result from the effects of lightning incidents and switching actions which can endanger electrical equipment as electrical insulation cannot be designed to withstand all possible overvoltage stresses.

Overvoltage protection can be achieved in basically two ways:

a) Avoid lightning overvoltage through shield wires to intercept prior to, for example, a substation and,
b) Limit overvoltage at the electrical equipment via surge arresters in the vicinity of such equipment.

Both methods of protection are common in High Voltage transmission/distribution systems however shield wire protection of overhead lines in distribution systems is generally not applied.

The most effective protection against overvoltage surges, especially in distribution systems, is the application of surge arresters in the vicinity of electrical power equipment. Surge arresters act as insurance against insulation breakdown/damage and limit expensive repair costs and lost production costs.

The Designer shall base all design, selection and application of metal oxide surge arresters, for Corporation installations, on AS/IEC 60099 parts 4 and 5.

Note: As defined in the WASIR and the Technical Rules, the Distribution System refers to high voltages of < 66kV and the Transmission System refers to high voltages 66kV and above. Hence, IEC term "High Voltage" equates to Transmission Voltage and IEC term "Medium Voltage" equates to Distribution Voltage.

3.2 Technology

3.2.1 General

The principal types of impulsive overvoltage shunt connected protective device in common use are discussed in Appendix B for general information. Information specifically related to metal oxide surge arresters, to be deployed at Corporation High Voltage assets, is discussed below.

3.2.2 Gapless Metal Oxide Surge Arresters

Most arresters employed in transmission and distribution systems are gapless metal-oxide (ZnO) surge arresters with a synthetic housing.

The reliability of modern metal oxide (MO) surge arresters, enclosed within polymeric material housing, is very high. Generally, the probability of High Voltage MO arresters breaking down is approximately 0.1 percent throughout the world, however, regional differences can vary this probability. These MO arresters do not suffer from the weaker sealing system issues (humidity ingress over years of service) common with porcelain housings.

3.2.3 Materials

A metal-oxide (MO) surge arrester is made up of two parts, namely, the active part, consisting of multiple MO resistors, and an insulating housing, which guarantees both the insulation and the mechanical strength.

Fundamentally, there are many different materials for housing construction, however a polymeric material (such as silicone, also known as silicone rubber) directly moulded on to the MO resistors, with the MO resistors held together with glass fibre straps, provides one of the best sealing measures where inner partial discharges are effectively eliminated.

Silicone rubber (usually simply referred to as "silicone") is an excellent insulating material for high-voltage insulators under all climate conditions (high temperature stability, very low combustibility (silicone is a self-extinguishing material), high dielectric strength, negligible risk of hazardous shattering and a high hydrophobic quality).

The polymer insulation is moulded directly onto the reinforced metal oxide blocks. This construction method is intended to eliminate the risk of seal failure and moisture entry into the surge arrester housing.

Surge arresters for use in Corporation assets shall be MO with silicone housing type.

Note: Silicon Carbide (SiC) surge arrester technology is outdated and shall not be used for Corporation assets. Furthermore, it is recommended that SiC surge arresters less than 25 years old be closely monitored and those greater than 25 years old be considered for replacement.

3.2.4 Metal-Oxide Resistors

MO resistors are made of different metal-oxides in powder form, which are compressed and sintered in the form of round blocks.

The diameter of the MO resistors determines the current, the height of the MO resistors (or resistor stack) determines the continuous operational voltage, and the volume of the blocks determines the energy handling capability and charge transfer capability.

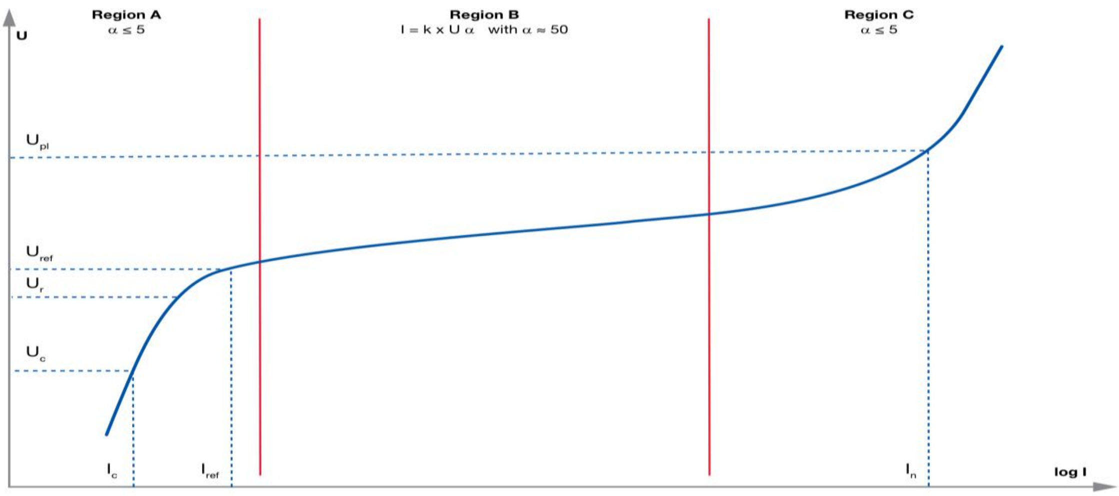
MO resistors have a very non-linear voltage-current characteristic, which is described generally as:

$I = k \times U^{\alpha}$

where,

α	=	variable between $\alpha \leq 5$ and $\alpha \approx 50$.
k	=	is a material factor.
U	=	voltage
I	=	current

Figure 3.1 below refers.



Region A: relevant to power frequency voltage. Region B: highest non-linearity. Region C: protection characteristic.

Figure 3.1 Non-Linear VI Characteristics of a MO Resistor

Region A: The part of the U-I characteristic curve relevant to the power frequency voltage and considered to be the pre-breakdown or low-current region. The current flowing through the MO surge arrester is the "leakage" current I_C (about 1 mA), which is almost purely capacitive. Generally, the power losses at U_C can be neglected as the resistive component of I_C is very small, assuming standard ambient conditions (this region has a negative temperature coefficient where a strong increase in power losses can result), and correct selection of the arrester.

Region B: The breakdown region. It is the part of the U-I curve in which even minimal voltage increases lead to a significant rise in the current. Only transient events in the time range of milli to micro-seconds (switching overvoltage) can be handled by the arrester. A continuous application of power frequency voltage in this area of the characteristic could destroy the arrester within a short time (seconds).

Region C: This, high current region, describes the protective characteristic of the MO surge arrester. The most important parameter is the lightning impulse protective level U_{pl}, the maximum permissible peak voltage on the terminals of an arrester subjected to the nominal discharge current I_n.

The amplitude of the nominal discharge current I_n, with a wave shape of 8/20 µs, together with the arrester class prescribe the test parameters. This region has a positive temperature coefficient however, the influence of the temperature on the residual voltage of the MO resistors is minimal (few percent) and can be neglected in normal applications.

The relevant characteristics of gapless surge arresters shall be in accordance with IEC 60099.4 Surge arresters - Part 4: Metal-oxide surge arresters without gaps for a.c systems.

The voltage-current (V-I) characteristic illustrates how a surge arrester's resistance varies with voltage, whilst also providing insights into its operation. The highly non-linear V-I characteristics of the metal oxide varistor makes it suitable for surge protection application. The varistor's resistance depends inversely on the applied voltage i.e., the greater the voltage, the lower the resistance.

Metal-oxide surge arresters without gaps shall be used for equipment protection and insulation coordination.

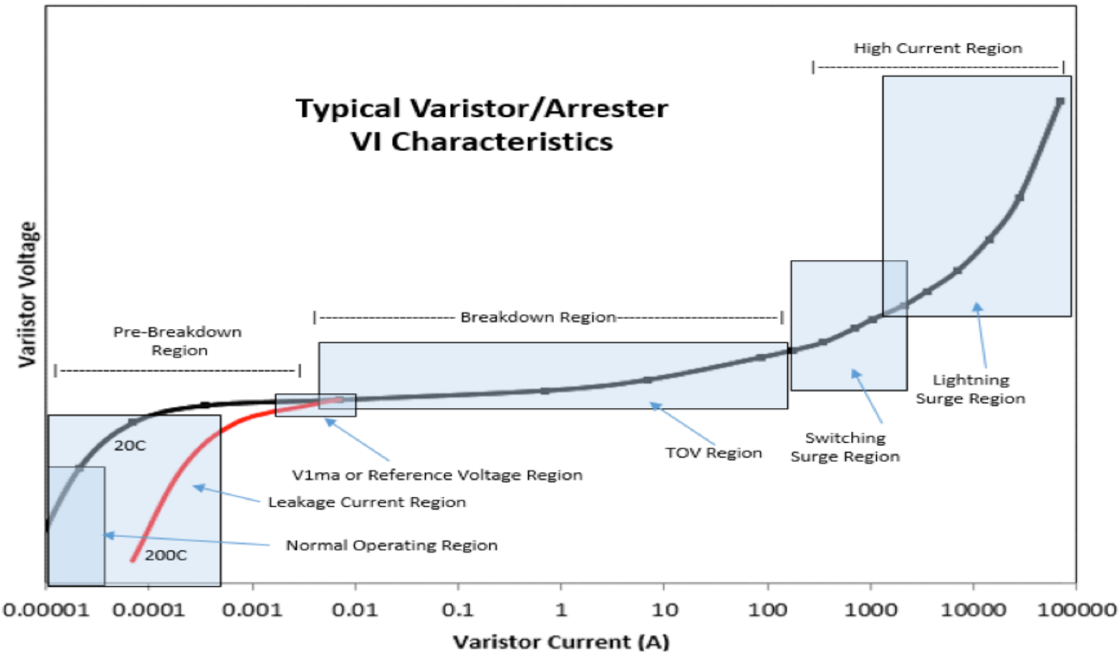


Figure 3.2 Operating Regions of the MO Arrester VI Characteristic

3.2.5 Special High-field MO Resistors

The field strength (voltage per unit height of the MO resistor) is generally in the range of 2 kV/cm at a given current in the breakdown range, considered to be the "normal" field strength. By reducing the size of grains in a MO resistor (increase in the number of boundary layers) the field strength can be increased up to 4 kV/cm. The advantage presented is a significantly thinner resistor block resulting in a reduced volume stack with reduced power losses.

In arrester designs with SF_6 gas, as an insulating medium (GIS arresters), the use of high-field MO resistors can facilitate a reduction in the MO resistor stack (up to 50 percent) resulting in size reduction for the GIS vessel. This also reduces the volume and amount of SF_6 gas needed.

Hence, high-field MO resistors shall be specified wherever possible for SF_6 gas insulation applications.

It should be noted that the use of high-field MO resistors in standard applications, e.g. air-insulated MO surge arresters (AIS), brings little or no benefit, because the height of a surge arrester is given by the external flashover withstand capability of the housing.

Note: Doubling the field strength means doubling the energy under a given current impulse and consequently increasing the temperature rise (energy absorption capability and thermal stability is decreased). Industry has addressed this disadvantage either by increasing the diameter of the MO resistors or using heat sinks in an arrester design.

3.3 Function and Performance

MO surge arresters are devices that protect electrical equipment and installations by limiting surge voltages and diverting surge currents to earth.

MO surge arresters shall comply with AS 60099.4 Surge arresters Part 4: Metal-oxide surge arresters without gaps for a.c. systems (IEC 60099-4:2014 (ED. 3.0) MOD).

The terms and definitions for MO arresters are defined in section 3 of the above standards (AS and IEC), however, one of the most critical terms for equipment protection and insulation coordination is lightning impulse protection level Upl or LIPL. It is defined as the maximum voltage between the terminals of the surge arrester during the flow of nominal discharge current In.

The protection level Upl of an MO surge arrester must be well below the LIWV of the equipment to be protected. On the other hand, the MO surge arrester must withstand all stresses from the system. Therefore, the continuous operating voltage Uc must be well above the maximum power frequency voltage of the system Us (or UTOV).

3.3.1 Charge Transfer and Energy Absorption Capability

With the release of Ed.3.0 of IEC 60099-4, a new concept of arrester classification and energy withstand testing was introduced. The line discharge classification was replaced with a classification based on repetitive charge transfer rating (Qrs), as well as on thermal energy rating (Wth) for station class and thermal charge transfer rating (Qth) for distribution class arresters.

Station and distribution class arresters are classified as indicated in the table below.

In distribution voltage systems, distribution class arresters are mainly used. However, for specific applications, where higher energy requirements apply, such as protection of cables, rotating machines or capacitor banks, station class arresters may be required for the distribution voltage systems.

For definitions of Qrs, Qth and Wth refer to AS 60099-4.

Arrester class	Station			Distribution		
Designation	SH	SM	SL	DH	DM	DL
Nominal discharge current [kA]	20	10	10	10	5	2.5
Switching impulse discharge current [kA]	2	1	0.5	-	-	-
Q_{rs} [C]	≥ 2.4	≥ 1.6	≥ 1.0	≥ 0.4	≥ 0.2	≥ 0.1
W_{th} [kJ/kV]	≥ 10	≥ 7	≥ 4	-	-	-
Q_{th} [C]	-	-	-	≥ 1.1	≥ 0.7	≥ 0.45
Corresponding previous discharge class according to IEC 60099-4: (2009) (Old classification)	4/5	3	2	1	-	-

Designation letters "H", "M" and "L" mean "high", "medium" and "low" duty, respectively.

Table 3.1 Classification of surge arresters according to their energy and charge absorption capacity in accordance with AS/IEC60099-5.

Note: IEC 60099.5:2022 stipulates the following:

"For surge arresters protecting high-voltage substation equipment typically arresters with designation SL, SM or SH are used. In medium voltage systems, mainly arresters with designation DL, DM or DH are used." (Refer note at clause 3.1)

3.3.2 Protective Characteristics

The protective characteristic of an arrester is defined by the maximum voltage Ures at the terminals of an arrester during a current surge In. Generally, a lightning impulse protective level of Upl ≤ 4 pu (where 1 pu = Us x √2/√3, Us is system voltage) is considered acceptable. This is a value that is generally accepted for the insulation coordination. Furthermore, the smaller the Upl/Uc ratio, the better the protection.

The residual voltages at steep current impulse and at switching current impulse are also important. The residual voltage increases slightly with these currents, as can be seen from the data sheets of each arrester, and from the voltage-current characteristic. Depending on the application, the residual voltage at the steep current impulse and at switching current impulse must also be considered.

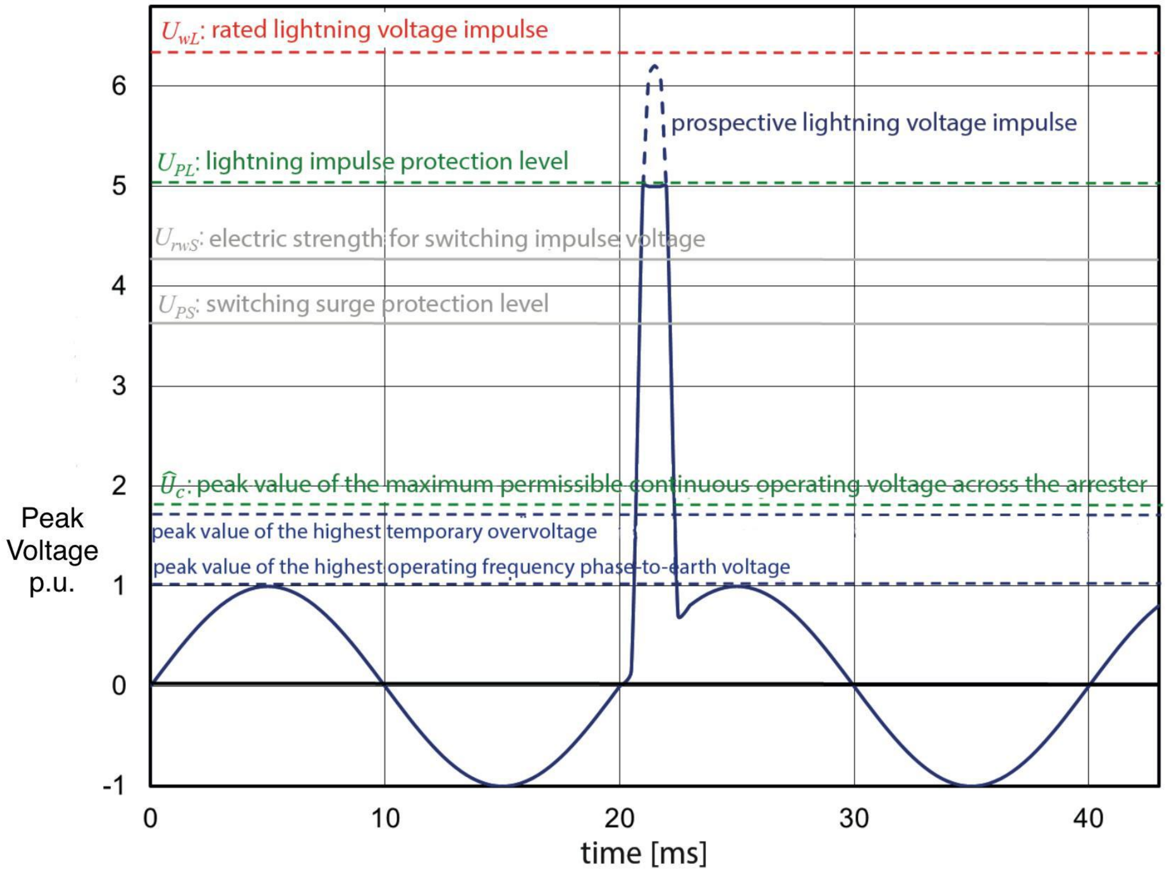


Figure 3.3 Lightning Voltage Impulse and Arrester Limitation Concept Example

The figure above provides an example of the voltage curve for one phase during the limitation of a lightning impulse voltage by a surge arrester to the corresponding residual voltage at a lightning impulse of 8/20µs, 10 kA.

Technical data	8kV	12kV	17kV	19,5kV	22kV	24kV	34kV
Rated voltage (U_r)	10 kV	15 kV	21 kV	24 kV	27 kV	30 kV	42 kV
Maximum continuous operating voltage (U_c)	8.0 kV	12.7 kV	17.0 kV	19.5 kV	22.0 kV	24.4 kV	34.0 kV
Residual voltage (IEC 60099-4) with:							
Steep current impulse (1/T, T< 20 µs)	28.3 kV	42.5 kV	59.5 kV	68.0 kV	76.5 kV	85.0 kV	119.0 kV
Lightning current impulse 8/20 µs:							
5 kA	24.8 kV	37.2 kV	52.1 kV	59.6 kV	67.0 kV	74.4 kV	104.0 kV
10 kA	26.9 kV	40.3 kV	56.4 kV	64.4 kV	72.5 kV	80.5 kV	112.8 kV
20 kA	29.3 kV	44.0 kV	61.6 kV	70.4 kV	79.2 kV	88.0 kV	123.2 kV

Manufacturer specification of the arrester data

Table 3.2 Typical Protection Characteristics of HV Surge Arresters

3.3.3 Temporary Overvoltage

Temporary overvoltages (U_{TOV}) are power frequency overvoltages of short time duration and can result from switching operations or earth faults within the system. The magnitude depends on the power system configuration and treatment of the star point.

MO surge arresters can withstand an increased operating voltage for a temporary period. The factor of resistance (T) of an arrester is defined as $T = U_{TOV}/U_c$

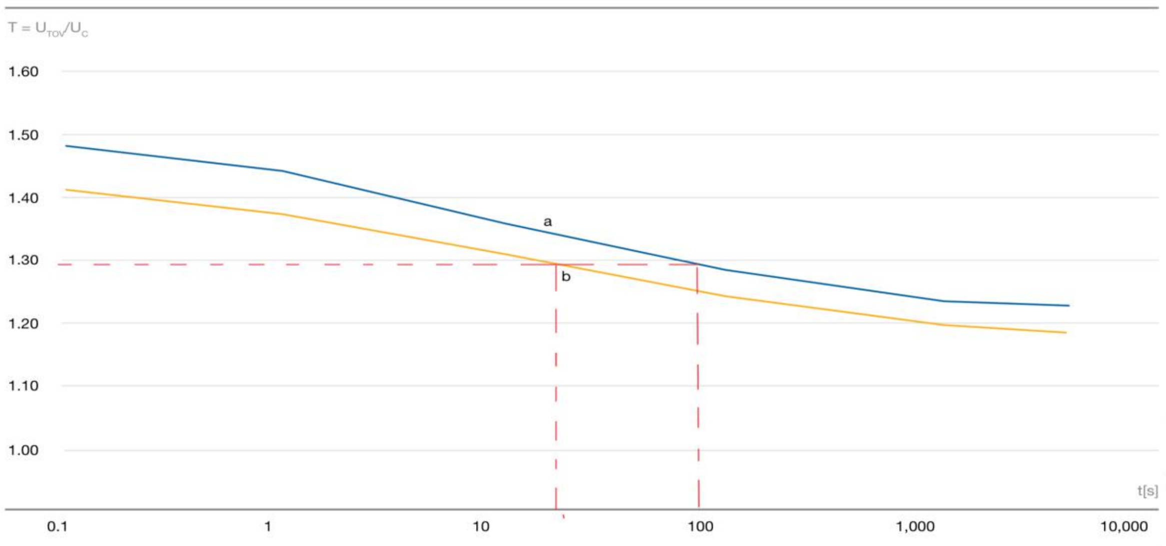
Example of the application of TOV curves:

With reference to the Figure 3.4 below, an arrester with U_C = 24 kV is operated at U_C as normal for an unlimited period. At time t = 0 the arrester is stressed with an energy of W_{th}. Immediately afterwards, a temporary overvoltage U_{TOV} = 31 kV occurs. This, for example, could be due to an earth fault where the calculation of the earth fault factor determines the magnitude of the temporary voltage.

Therefore,

$T = U_{TOV}/U_C$ = 31 kV/24 kV = 1.29. T = 1.29 results in a time of t = 20 secs according to curve "b" (i.e. the arrester can withstand an increased voltage of 31 kV for 20 s without becoming thermally unstable).

If the arrester is not subjected to the energy W_{th} before the appearance of the temporary overvoltage, it is curve "a" that counts, and the arrester can withstand U_{TOV} for approximately 100 secs.



Curve 'a' is valid for an arrester (typical) without energy pre-stress, curve 'b' with a pre-stress of the guaranteed energy W_{th}, and 't' is the time duration of the overvoltage at power frequency.

Figure 3.4 Arrester Temporary Power Frequency Withstand Curves

With regards to the TOV performance of the arrester, the designer shall base calculations on the assumption of a pre-stressed arrester of the designated thermal energy rating W_{th} for the class of arrester to be specified.

3.3.4 Nominal Discharge Current I_n

The nominal discharge current shall correspond to the current impulse at the maximum expected lightning overvoltage at the input to the substation.

The maximum current amplitude I_{max}, which the arrester must conduct to earth, can be calculated from the flashover voltage U_{fo} of the incoming overhead line insulators, the lightning protection level U_{pl} of the arresters and the characteristic impedance Z_s of the overhead line.

$I_{max} = (2 \cdot U_{f0} - U_{pl}) / Z_s$

Where:

U_{fo} = Flashover voltage of the overhead line insulation.

U_{pl} = Protection level during a lightning impulse.

Z_s = Surge impedance of the line.

3.3.5 Neutral Earthing – Consideration of Uc

The earthing method of the star point of a transformer has a direct influence on the choice of the continuous operating voltage U_C of all MO surge arresters to be installed in the system.

Attention shall be paid to potential temporary overvoltage U_{TOV} (and the fault clearance time), that occur during earth faults, associated with the treatment of the transformer star point.

Such star point arrangements are:

a) Direct (solidly earthed) star point earthing. The EFF is not greater than 1.4.
b) Low ohmic star point earthing. The EFF can be greater than 1.4.
c) High ohmic star point earthing. The EFF can approach 1.9.
d) Insulated star point. The EFF can approach 1.9.

However, most Corporation applications employ direct earthing of the neutral star point of the transformer.

Generally, the determination of the continuous operating voltage is:

$U_C \geq K \times U_S / (\sqrt{3} \times T)$

where:

K = Earth Fault Factor (EFF).

U_S = System voltage - highest voltage of a system.

T = the factor given in the TOV curves, supplied by the manufacturer.

Example of a distribution voltage:

K = 1.4

t = 3 seconds (say for a worst-case situation)

$U_S/\sqrt{3}$ = Phase to earth system voltage

T = 1.343

Thus, $U_C \geq 1.05 \times U_S / \sqrt{3}$ for arresters of phase to earth.

3.4 Service Conditions

MO surge arresters must perform reliable under normal and special (abnormal) service conditions.

3.4.1 Normal Conditions

The service life of a MO arrester is approximately 30 years or more under normal operating conditions and if it is correctly chosen according to the system voltages and the expected electrical and mechanical loads. The normal service conditions for an arrester are listed in IEC/AS 60099-4 as:

- Ambient air temperature within the range of -40 °C to +40 °C
- Solar radiation of 1.1 kW/m^2
- An altitude not exceeding 1,000 m above sea level
- Frequency of AC voltage between 48 Hz and 62 Hz
- A power frequency voltage at the arrester terminals not higher than the continuous operating voltage Uc of the arrester

- Wind speed ≤ 34 m/s
- Vertically installed, not suspended

3.4.2 Abnormal Service Conditions

Abnormal service conditions (listed in Annex A of AS 60099-4) that may require special consideration in application of surge arresters shall be discussed with the manufacturer.

3.4.3 Special Considerations

3.4.3.1 Overstress

In the case of an overstress, the MO resistors either spark-over or break down and tend to create a permanent short-circuit which is cleared by the upstream protection. The MO arrester will fulfil its protective function during a breakdown as the short circuit ensures the voltage decreases towards zero thus protecting the equipment from extreme surge voltages.

Surge arresters with directly moulded silicone housings do not face the risk of explosion or violent shattering in the case of an overload. There is no air space between the active part of the arrester and its silicone insulation hence, there is no space for the pressure to build up.

Surge arresters with directly moulded silicone housings shall be specified in the design. Porcelain surge arresters shall not be used.

Note: MO surge arresters, direct sealed with silicone, can suffer overstress only by a limited number of events such as, extreme lightning strokes in the line directly at the arrester or high-power frequency long duration overvoltages and ferromagnetic resonance.

3.4.3.2 Elevated Ambient Temperature

If the ambient temperature exceeds 40 °C, U_C must be increased by 2 percent for every 5 °C of temperature elevation. This correction is possible up to maximum ambient temperature as specified by the manufacturer.
If it is not acceptable to increase the continuous operating voltage U_C, and consequently the protection level U_{pl}, in an application, then a reduction of the thermal energy rating has to be considered.

3.4.3.3 Pollution

Silicone is the best insulating material in high pollution areas and is water repellent (hydrophobic). Consequently, this renders the material a more advantageous choice compared to porcelain-housed arresters or other polymeric insulation materials such as EPDM.

3.4.3.4 Mechanical

The manufacturer shall be consulted regarding mounting and support requirements of surge arresters during design.

3.4.3.5 Altitude Adjustment

Though generally not applicable to Corporation sites within Western Australia, the following should be considered in any applicable situations.

At higher altitudes, the air density reduces and subsequently the withstand voltage of the arrester housing (external flashover) may no longer be sufficient. The MO resisters within the arrester still have the same performance in relation to U_{pl}. In such a case, the MO resisters may require an extended housing with a longer flashover distance.

However, the flashover distances of surge arresters for lower voltage levels are relatively large, exceeding the minimum requirements of the withstand voltage. In any case it should be checked whether the normal housing possesses sufficient withstand voltage for application at higher altitudes.

3.5 Tests

Tests (Type and Routine) demonstrate that an MO surge arrester can survive the rigors of reasonable environmental conditions and system phenomena, while protecting equipment and/or the system from damaging overvoltage caused by lightning, switching, and other system disturbances.

Arresters shall be of a Type Tested design and Routine Tested in accordance with the current IEC and Australian Standards, IEC /AS 60099-4, for the MO surge arresters with polymer housings and GIS arresters as applicable.

3.5.1 Type Tests

If the MO surge arrester being offered is not of an identical design that has been type tested in accordance with IEC/AS 60099-4, then the MO surge arrester shall undergo type tests in accordance with IEC/AS 60099-4.

Test requirements on polymer-housed surge arresters refer clause 10 of IEC/AS 60099-4.

Test requirements on gas-insulated metal enclosed arresters (GIS-arresters) refer clause 11 of IEC/AS 60099-4.

Certified test certificates including the actual type test results recorded shall be provided to the Principal either at the time of enquiry or directly after any additional type tests performed.

3.5.2 Routine Tests

MO surge arresters shall undergo routine tests in accordance with clause 9 of IEC/AS 60099-4 with the additional requirements of clause 10.9 for polymer housed arresters and of clause 11.9 and 11.10 for GIS arresters.

Apart from the routine tests, considered as the minimum requirement by the IEC, an additional routine test on the MO arresters shall be measurement of the total leakage current on each arrester at U_C.

All MO surge arresters shall be subjected to Routine Tests at the manufacturer’s works.

Certified test certificates including the actual routine test results recorded shall be provided to the Principal upon delivery.

3.5.3 Commissioning and On-Site Tests

No on-site or commissioning test is necessary nor recommended.

On-site insulation tests on cables or gas-insulated substations (GIS), cannot be correctly performed if MO surge arresters are connected to the system under test. This is because MO surge arresters will carry a current in the mA range and will limit the test voltage. In the worst case, the MO surge arresters can be destroyed by the application of AC withstand voltage for a prolonged time. Hence, MO surge arresters must be disconnected when on-site tests are performed.

3.6 Protective Distance

The following discussion and figures are supplementary to clause 4.3.1 “Effect of Cable Length”.

The location of the surge arrester relative to the equipment to be protected is critical. To provide the best protection the surge arrester shall be located as close as possible to the equipment under consideration.

Furthermore, inductive voltage drop (U = LCI x di/dt), where LCI is cabling inductance) along the connections from the line to the surge arrester terminal and the earth conductor shall be considered when selecting the location of the arrester. For example, an inductive voltage of Ui = 1.25 kV per metre results from a cable of inductance L = 1µH per metre and a lightning current of 10 kA peak and 8/20 µs wave shape.

In addition, any difference in earth potential between the equipment earth and the arrester earth also adds to the voltage impressed across the equipment insulation.

That is, U = Ures + Ucabling + UEarth difference

As dictated by travelling wave theory, a change of surge impedance $Z = \sqrt{(L/C)}$ (e.g. line to transformer, line to cable, line to open circuit, etc.) part of the voltage wave reflected and part is transmitted resulting in voltage increases/decreases. Hence significant overvoltages will appear at transformer terminals or open circuits.

At the time the surge arrester conducts the current to earth and limits the voltage, the condition can be considered as a short circuit to earth (very low ohmic value). Consequentially the travelling voltage wave is reflected back and forth between the high impedance (positive reflection) and a short circuit (negative reflection). Furthermore, at the moment the surge arrester limits the voltage, all overvoltage is reflected negatively, hence the surge arrester protects equipment in both directions.

To illustrate this protective distance, the diagram (Figure 3.5) below outlines the protective surge voltage of the arrester in relation to the LIWV of the equipment.

The MO surge arresters installed in position XA1 will not protect the transformer, because the voltage at the transformer will be higher than the withstand voltage (LIWV) of the transformer insulation. If the arrester is installed at position XA2, the voltage at the transformer is well below the LIWV and provides very good protection. As shown, there is protection at a distance L both upstream and downstream of the surge arrester.

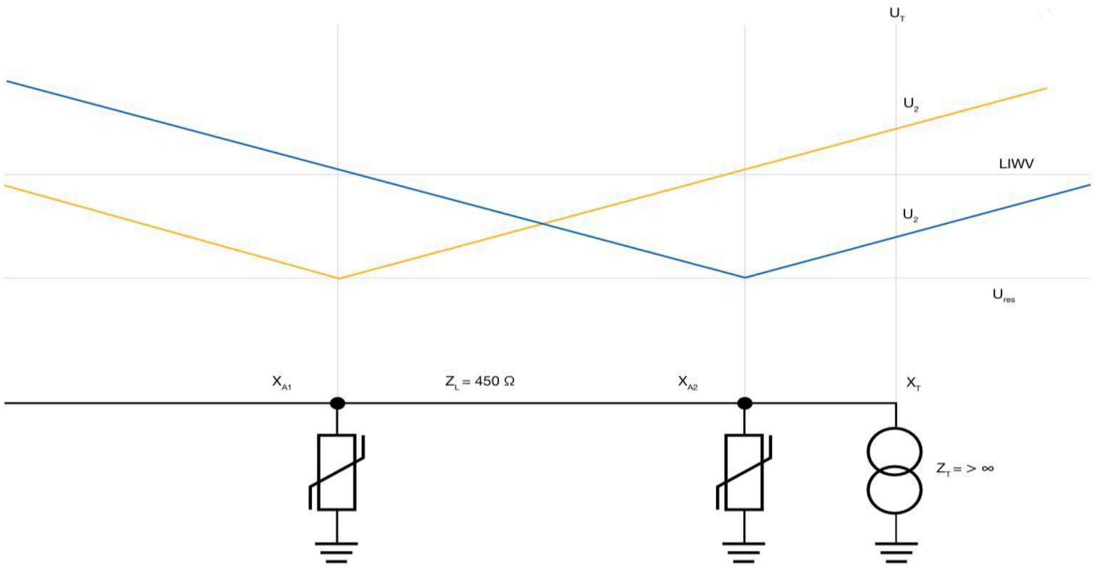


Figure 3.5 Protective Surge Voltage of the Arrester in Relation to the LIWV of the Equipment (Separation Distance Dependant)

With reference to the following diagram (Figure 3.6), the relationship for the voltage at E (equipment) is:

UE = Ures + (2 x du/dt x L)/V up to a maximum of 2Ures

where:

L = a + b,

V = the velocity of the wave

du/dt = the rate of rise of the wave front.

To take into consideration aging of the equipment insulation and statistical uncertainties in defining the LIWV of the equipment, a safety protection factor shall be applied such that the LIWV = KS x UE.

For Corporation equipment the factor KS shall be 1.25 (Note: IEC 60071-2 recommends 1.15 as a minimum).

The protection distance can be defined in the following relationship:

L = V/2S x (V/2S - Ures)

where S = du/dt slope or rate of rise of the voltage wave.

The steepness S (du/dt) of the incoming overvoltage (U_E) wave must be known to determine the protective distance or the voltage at the equipment. A general value for the steepness S cannot be given as it depends on various parameters and statistics. Values between 100 kV/µs and 1000 kV/ µs are expected in medium voltage systems.

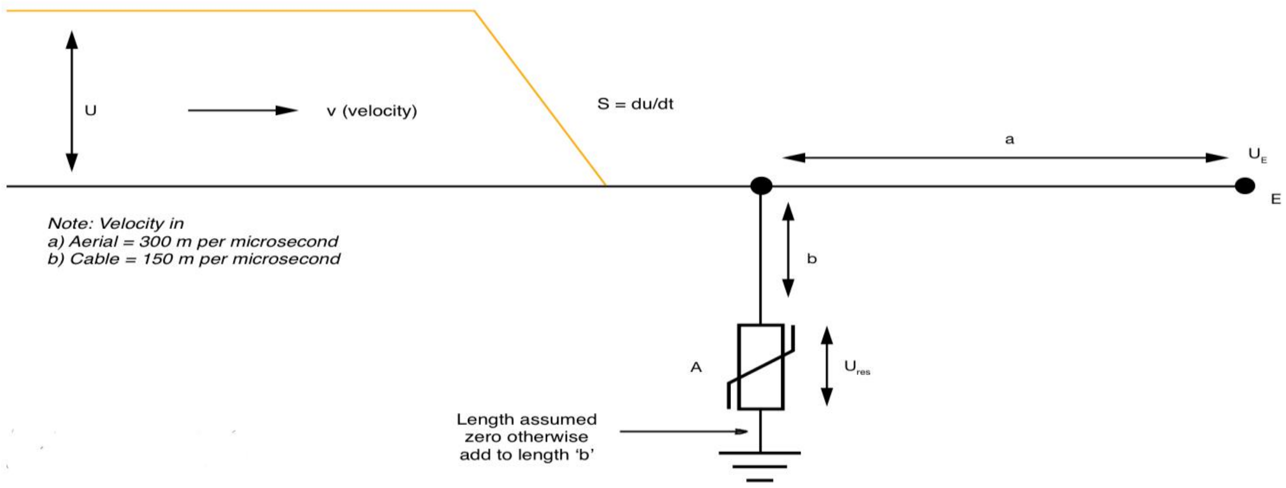


Figure 3.6 Voltage Relationship at the Equipment (E)

3.7 MO Surge Arresters in Parallel Connection

There are two main reasons to connect arresters in parallel, namely, to increase the energy handling capability (energy ratings) and reduce the residual voltage (lower protection level).

3.7.1 MO Arresters in Close Parallelism

Two or more MO surge arresters may be connected in parallel to increase the energy handling capability if the application dictates that the energy cannot be handled by a single MO surge arrester. The requirement for equal current sharing, and consequently even energy sharing, between the arresters is that the arresters must have almost identical voltage current characteristics. In view of the extreme non-linearity of MO resistors, small differences can lead to significant current sharing differences. Therefore, it is important to perform a current sharing measurement on all MO surge arresters that are proposed to operate in parallel. The Designer shall inform the manufacturer if the Designer intends to connect two or more MO surge arresters in parallel.

Surge arresters should be installed in close proximity to each other and connected with short, low inductance cables. Failure to do so may result in uneven current distribution and potential stress on one arrester.

However, it is always better to use a MO surge arrester with a larger MO resistor diameter than to connect more MO surge arresters in parallel with smaller MO resistor diameters.

The Designer shall consider these issues for the application.

3.7.2 MO Arresters in Separated Parallelism

In some applications, it may be necessary or advantageous to use two arresters in an installation separated from one another by distance, but electrically parallel on the same cable. For example, one set of arresters is installed at the entrance of the substation and another arrester set is placed directly at the transformer terminal some distance from the entrance. In such a case, two arresters of the same type and with the same continuous voltage may be used.

In case of an incoming voltage surge, both arresters will discharge a part of the current to earth and will provide very good overvoltage protection. However, it is not to be assumed that the surge energy will be uniformly shared.

For example, an arrester installed on the pole at the junction of the overhead line to the cable (riser pole or UGOH pole) must have a higher energy absorption capability and a lower residual voltage characteristic than the arrester within the station at the transformer. The means that the larger portion of the surge energy is absorbed by the arrester on the pole and the arrester within the substation absorbs the smaller portion of the surge energy while providing protection of the transformer.

3.8 Flow Chart for MO Surge Arrester Selection

The selection of MO surge arresters must be a step-by-step process in accordance with the flow chart below.

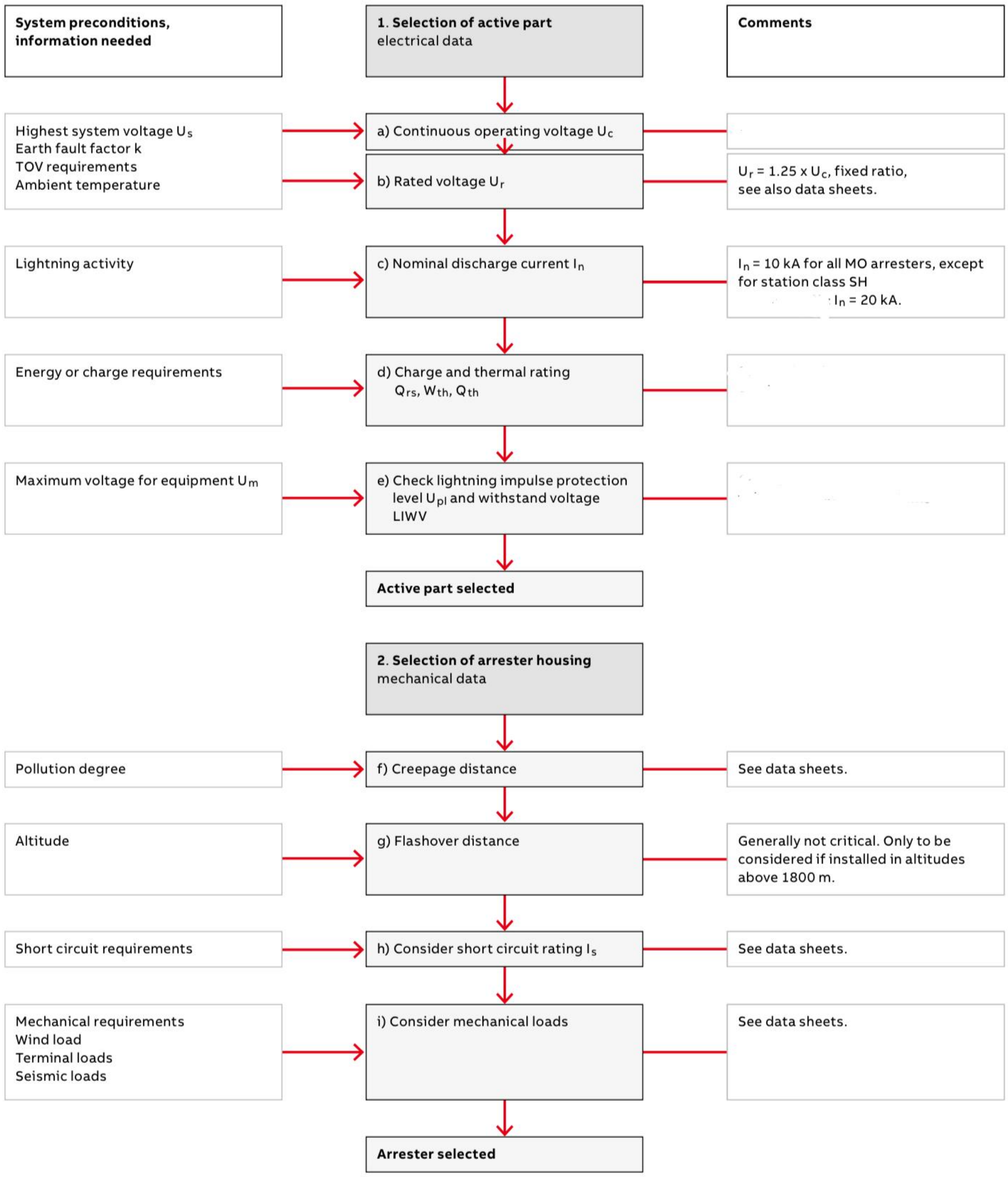


Figure 3.7 Flow Chart for Arrester Selection Process

3.8.1 Selection of Arrester Active Part

3.8.1.1 Selection of U_C.

The calculation of the continuous operating voltage U_C depends on the maximum system voltage U_S and the earthing conditions.

For solidly grounded systems, the MCOV shall be greater than the line-to-neutral voltage. For a resistance grounded or ungrounded system, it should be greater than the line-to-line voltage.

3.8.1.2 Selection of arrester class.

The class is given by the nominal discharge current I_n, the repetitive charge transfer rating Q_{rs}, the thermal charge transfer rating Q_{th} for distribution class arresters or the thermal energy rating W_{th} for station class arresters. Table 3.1 refers.

3.8.1.3 Nominal discharge current I_n

The choice according to IEC 60099-4, Ed. 3.0 is between I_n = 2.5 kA, 5 kA, 10 kA and 20 kA. However, this is usually reduced to either 10 kA or 20 kA depending upon whether the arrester application is distribution or station class (e.g. SH-20 kA).

3.8.1.4 Repetitive charge transfer rating Q_{rs}

Q_{rs} is defined as the maximum charge transfer capability in the form of a single current impulse or group of current impulses that may be transferred through the arrester without causing mechanical damage or unacceptable electrical changes. This rating is verified on single MO resistors and therefore, is a MO resistor-related material test.

3.8.1.5 Thermal charge transfer rating Q_{th} and thermal energy rating W_{th}

Q_{th} and W_{th} are the maximum thermal charge transfer rating and maximum thermal energy rating, respectively, that may be injected in a MO surge arrester without causing thermal runaway. These tests are thermal stability tests.

3.8.1.6 Ambient temperature.

If the required ambient temperature is higher than the standard value of 40°C, then the continuous operating voltage must be increased accordingly, or the MO arrester (thermal rating W_{th} or Q_{th}) derated.

3.8.1.7 Altitude.

For an installation located at an altitude above 1,800 m the flashover distance may have to be increased.

3.8.1.8 Residual voltage.

Ensure the residual voltage U_{Pl} is well below the required LIWV of the equipment.

3.8.2 Selection of Arrester Housing

The housing of MO surge arresters must fulfill two requirements, the creepage distance (which depends on the pollution class) and the flashover distance (which depends on the required external withstand voltage of the insulation).

The pollution classes and the corresponding reference unified specific creepage distances (RUSCD) are specified in IEC 60507 and IEC/TS 60815-1, see Table 3.3 below.

The flashover distance of the external insulation is generally not critical for MO surge arresters for application in distribution systems. The required values of the designs are verified during the insulation withstand tests under dry and wet conditions.

Pollution class	Minimum recommended specific creepage distance in mm/kV*	Possible reduction of the creepage distance with silicone insulation
a – Very light	22.0	30%
b – Light	27.8	30%
c – Medium	34.7	20%
d – Heavy	43.3	No reduction recommended
e – Very heavy	53.7	No reduction

* the shortest specific creepage distance for insulators between phase and earth.

Table: 3.3 Pollution Class versus Recommended Minimum Creepage Distances

3.9 Pressure Relief and Explosion Resistance

Power frequency over voltages in excess of the minimum power frequency residual voltage, long time surge current impulses and direct lightning strokes can all cause a surge arrester short circuit.

IEC 60099-4 defines Design A gapless surge arresters as those units having an enclosed volume of gas more than 50% of the volume of the enclosed volume of the arrester housing. These surge arresters typically have enclosures made of porcelain or similarly brittle polymer material.

Gap type arresters also have a significant volume of enclosed gas.

If a short circuit occurs in a gap type surge arrester or in a Design A gapless surge arrester the resulting internal arc and associated increased internal gas pressure will result in violent shattering of the arrester housing unless the design of the enclosure includes some means of pressure relief. The risk being surge arrester housing explosions can cause extensive secondary damage as they are usually located near other electrical equipment.

Some such surge arresters are provided with specific pressure relief devices while others have enclosures with prefabricated weak spots to limit the extent of shattering of the enclosure.

Gap type surge arresters and Design A surge arresters shall be permitted only if fitted with specific pressure relief devices.

IEC 60099-4 defines Design B gapless surge arresters as those units having an enclosed volume of gas less than 50% of the volume of the enclosed volume of the arrester housing. Typically Design B gapless surge arresters have no enclosed volume of gas and have enclosures made of shatter resistant material, thus avoiding the possibility of violent shattering.

Therefore, Design B gapless surge arresters shall be installed.

4 Insulation Coordination

4.1 General

4.1.1 Background

Insulation coordination is the correlation of the insulation of electrical equipment with the characteristics of protective surge arresters such that the insulation is protected from excessive voltages. Thus, in a substation, the insulation of transformers, circuit breakers, busbar supports, capacitors, etc. shall have insulation strength in excess of the voltage levels that can be provided by protective equipment such as surge arresters.

Surge arresters are designed to fulfill two basic tasks:

a) To limit the transient overvoltage to a value that is not damaging to the electrical equipment and,
b) to ensure a safe and reliable electrical power system.

The principle of insulation coordination for an electrical system is detailed in AS/IEC 60071.1 Insulation Co-ordination - Part 1: Definitions, Principles and Rules and AS/IEC 60071.2 Insulation Co-ordination - Part 2: Application Guidelines. AS 60071.1:2024 and AS 60071.2:2024 adopt and modify IEC 60071-1:2019 and IEC 60071-2:2023 respectively.

The Designer shall base all design for Corporation installations on these AS/IEC standards, this standard DS27 and relevant good practice nationally and internationally.

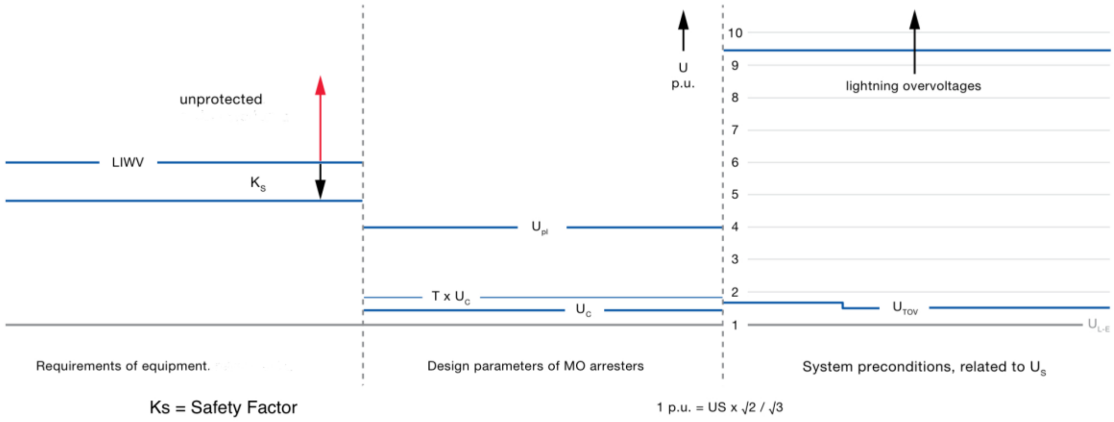


Figure 4.1 Basic Principle of Insulation Coordination

4.1.2 Insulation Coordination Study

A detailed insulation co-ordination investigation and design shall be carried out to ensure that the risks of insulation failure due to lightning and switching surges is minimised. Such design shall match surge protection levels and insulation impulse withstand levels including adequate safety margins and shall consider the connection and positioning of earthing conductors. Reference shall be made to IEC 60071.1 Insulation Co-ordination - Part 1: Definitions, Principles and Rules and IEC 60071.2 Insulation Co-ordination - Part 2: Application Guidelines.

The level of excessive impulse/surge voltages is unknown for all sites, so in order to protect substation equipment, surge arresters shall be installed at all substations (aerial, indoor, padmount type, etc.). The insulation coordination study determines the most suitable rating and location of surge arresters to ensure the insulation of substation equipment is protected during severe impulses/surges. It is a reasonably complex area of electrical engineering where surge arrester residual voltage characteristics, connection arrangement, location, cable length, characteristic impedance changes (especially at the worst case of transformer terminals) and earth fault factor play a critical role in the appropriate selection of surge arresters.

Soil resistivity tests and modelling/simulation, utilising the CDEGS modelling/simulation software package (from SES Canada), shall be performed for insulation coordination earth termination systems and performed by the CDEGS specialist consultant from the Corporation's Specialist Earthing Panel (Refer DS20).

4.1.3 Insulation Coordination Study Process

Insulation coordination studies are essential for maintaining the integrity, reliability, and safety of electrical power systems. By carefully selecting and coordinating insulation levels, the risk of insulation failures and associated consequences can be minimised, leading to improved system performance and reduced downtime.

In general, and as outlined in IEC 60071-2, the process steps required are:

4.1.3.1 Transient Overvoltage Analysis

Assess, and understand, the potential transient overvoltage type and magnitude (i.e. lightning strikes, switching operations, or other transient events) that can occur in the power system. That is, identify the peak overvoltage that the system might experience, including temporary overvoltage (TOV), slow front overvoltage (SFO), fast front overvoltage (FFO), and very fast front overvoltage (VFFO),

4.1.3.2 Selection of Insulation Levels

Determine the suitable insulation withstand levels (rated continuous voltage and impulse withstand levels) for each component of the power system based on AS/IEC 60071. This includes transformers, circuit breakers, cables, capacitors, and other equipment.

4.1.3.3 Coordination of Insulation Levels

Ensure that the insulation levels are appropriately coordinated to avoid insulation failures and flashovers. This involves evaluating the voltage withstand capabilities of the equipment in relation to potential overvoltage, applying surge arresters, conducting earthing analysis, making altitude corrections, and ensuring the required safety margin.

4.1.3.4 Validation

Apply simulation software to model the system and test the proposed mitigation measures under various scenarios. Check compliance with industry standards and regulations.
Third party review of the insulation coordination design.

4.1.3.5 Design

Integrate the design and results into the Design Summary Drawings (as referred to in DS20). Conduct a third-party review of the Design Summary Drawings.

4.1.3.6 Implementation

Procurement, installation, commissioning, documentation and training as per the requirements of DS20 process.

4.1.3.7 Post-Implementation Review

Although not directly involved in the design process beyond providing constructive feedback, it is advisable to implement monitoring to ensure that measures are performing as intended. Additionally, scheduled maintenance checks should be conducted to maintain optimal performance, and operational staff should be encouraged to provide feedback to assist in system performance reviews.

The Designer shall provide recommendations in this regard at the conclusion of the project.

4.1.4 Self-Restoring and Non-Self-Restoring Insulation

Electrical insulation is categorised as self-restoring and non-self-restoring insulation.

Self-restoring insulation is defined as the type of insulation that reverts to its original insulating characteristics once the arc following electrical breakdown is extinguished. Aerial insulators normally fail in this mode and generally are considered self-restoring.

Self-restoring insulation is generally external insulation (e.g. air gaps, insulators, wood, fibre glass) which recovers the integrity of its insulating properties after disruptive discharges. The LIWV characteristics of external self-restoring insulation are universally tested and verified under dry conditions. The SIWV of external self-restoring insulation is universally tested under wet conditions because this withstand characteristic depends on an insulator's creepage distance when wet.

Non-self-restoring insulation, on the other hand, is permanently damaged and degraded by overvoltage failure. Non-self-restoring insulation (e.g. oil-paper, polymer, etc.) is usually internal insulation comprising solid, liquid or gaseous elements of equipment insulation protected from atmospheric influences. Motor and transformer winding insulations are examples of non-self-restoring insulation.

Overvoltage protection for electrical equipment shall be designed so that over-voltages do not exceed the ratings of non-self-restoring insulation. Conversely, self-restoring insulation may be allowed to fail under certain conditions, provided that protective devices are configured to interrupt the resulting fault current.

Note: Arc quenching.

Lightning flashovers generally cause power-follow fault currents and hence outages, but this is not always the case. For flashovers involving wood, this is known as impulse arc quenching. For flashovers through air or over insulators, the probability of a power arc following a lightning flashover is on average 0.85. However, wood always contains some moisture and so is capable of far superior arc quenching because a relatively high minimum arc voltage is required to maintain conduction after lightning flashover.

This probability is controlled by the power frequency voltage gradient across the wood after flashover, and with sufficient wood length in the flashover path, it is possible to achieve values of probability in the range 0.4 to 0.7.

4.1.5 Types of Overvoltage

Overvoltage is classified into three types, each characterised by an internationally agreed set of parameters defining the waveform, as follows: -

a) Power frequency overvoltage, which takes the form of a sinusoidal wave at 50 Hz.

b) Switching impulse overvoltage, which takes the form of a double exponential wave shape, having a front time of 250µs and a time to decay to half magnitude on the tail of 2500µs.

c) Lightning impulse overvoltage, which takes the form of a double exponential wave shape having a front time of 1.2µs and a time to decay to half magnitude on the tail of 50µs.

As illustrated in the Figure 4.2 below, surge arresters play a critical role by keeping the voltage (lightning and switching overvoltage) at a level that is below the withstand voltage of the equipment, by an adequate safety (protective) margin. However, surge arresters are ineffective to limit oscillatory power frequency temporary overvoltage (TOV) and must be designed/selected to withstand such temporary overvoltage, together with the maximum operating voltage of the system, without sustaining damage.

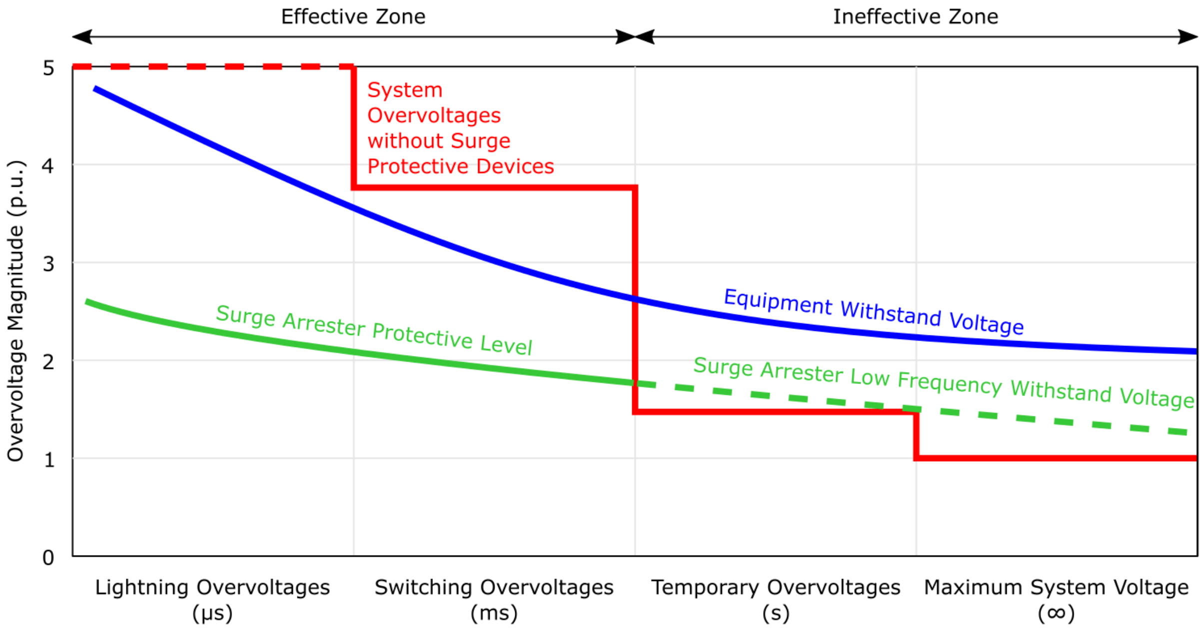


Figure 4.2 Types of Overvoltage vs Arrester Effectiveness

The insulation used in motor windings is, however, less able to withstand impulsive overvoltage and the provision of protection against switching surges needs to be considered for motors, particularly where vacuum contactor switching is employed.

It should be recognised that all surge arresters have a voltage-time characteristic, and to provide complete protection against lightning impulses, the voltage-time characteristic of the surge arrester must lie below the associated insulation withstand voltage-time characteristic.

4.2 Surge Impedance

4.2.1 Definition

Surge impedance is defined as the square root of the conductor per unit series inductance divided by the conductor per unit shunt capacitance,

i.e. $\mathbf{Z_0 = (L_C/C_C)^{0.5}}$ **ohms**

4.2.2 Cable Surge Impedance

The surge impedance of a cable is typically 50 ohms.

4.2.3 Line Surge Impedance

An overhead line has characteristic surge impedance, depending on its inherent series inductance, and shunt capacitance.

The surge impedance $\mathbf{Z_O = 138 \text{ Log } [2h\,(ar)^{-1/2}]}$ **ohms**

Where: h = height of conductor above ground, m

r = radius of each phase conductor, m

a = intra-phase conductor separation, m

(= r, if single conductor per phase)

The above expression assumes a long line and consequently can only be applied where end effects will be negligible, i.e., line lengths of greater than 100 metres, say 1 km.

The surge impedance of an overhead line is typical 500 ohms.

4.2.4 Transformer Surge Impedance

The surge impedance of a transformer winding is typically 5000 ohms.

4.3 Application of Surge Arresters

4.3.1 Effect of Cable Length

When a lightning surge travels along an overhead line and reaches a cable, the cable acts primarily as a capacitor, reducing the steepness of the original surge due to its lower surge impedance. However, because the transformer has a high surge impedance, the surge will be reflected at the transformer terminals, increasing the voltage to ground. This reflection process repeats when the return surge reaches the overhead line, continuing the cycle.

Note: Further discussion provided at clause 3.6. "Protective Distance".

The Designer shall carry out design calculations to determine if the surge arresters will limit the surge voltage at the end of a cable to no more than 80% of the rated lightning impulse withstand voltage (LIWV) of the connected equipment including the cable terminations (i.e., a 25% safety margin – refer clause 4.3.3 below). If the cable length is too long to make these practical, additional surge arresters shall be installed at the equipment end of the cable.

Note: In any case, all transformers shall be fitted with surge arresters as discussed in clause 7.14.7 and 3.10 of DS21.

4.3.2 Selection of Surge Arrester Power Frequency Voltage Rating

The maximum power frequency voltage that can be developed at a surge arrester during an earth fault depends on the ratio of system positive and zero sequence impedances.

IEC 60099.5 Annex A details the method for determining power frequency over voltages due to earth faults. It should be noted that the system neutral earthing resistance has a major effect, and care should be taken that realistic values are used in such calculations. Care must also be taken to ensure that the scale factors derived from IEC 60099.5 Annex A are applied to the maximum system voltage, not the nominal system voltage.

Power frequency over voltages can be caused by sudden load shedding as described IEC 60099.5 clause 2.2.1. On extended systems the system phase to earth overvoltage may be as high as 1.5 per unit.

For a rural 33 kV effectively earthed system, surge arresters installed at pump stations shall be specified to have a maximum continuous operating voltage rating of 30 kV, unless detailed calculations have been made to indicate that a lower figure would be adequate.

For a similar 22kV system, an arrester maximum continuous operating voltage rating of 20 kV would be appropriate, unless detailed calculations have been made to indicate that a lower figure would be adequate.

For pump station 6.6kV systems, surge arresters shall be specified to have a maximum continuous operating voltage rating of 7.2kV.

Note: Further discussion provided at clauses 3.3.3 and 3.3.5.

4.3.3 Selection of Equipment LIWV Rating-Margin of Protection

The lightning impulse withstand voltage (LIWV) rating of protected equipment shall be not less than 1.25 ET kV (a 25% safety margin), where ET is the equipment terminal maximum surge voltage, kV. Clause 4.3.1 above refers.

As outlined in clause 4.4 below, achieving a balance between an adequate protection margin and operating voltage may necessitate a compromise. In situations where a 25% margin cannot be attained, the Designer must obtain approval from the Principal Engineer for an exemption.

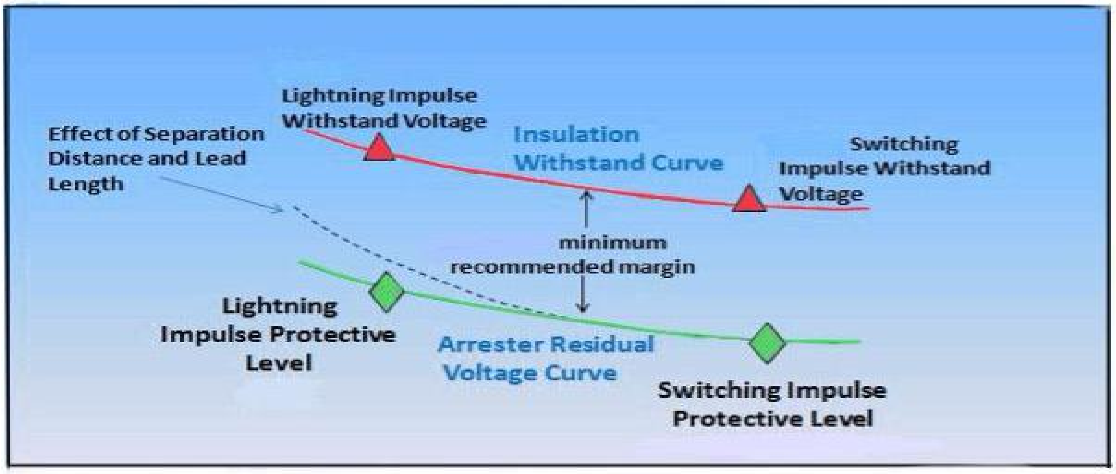


Figure 4.3 Margin of Protection for Non-self-restoring Insulation (voltage vs pulse duration)

Note: Due to the simplification or omission of many critical parameters, incorporating a substantial safety margin in the design process is necessary. Most organisations select a margin of 20% or 25%.

4.3.4 Network Operator Feeder

Surge arresters shall be installed at all HV cable to overhead line cable terminations.

When an overhead line operated by the Network Operator is connected to an underground cable also owned by the Network Operator, which then feeds into the Corporation's incoming High Voltage (HV) equipment, the protective properties of the Network Operator's surge arresters shall not be relied upon for the purpose of insulation coordination. Therefore, Corporation surge arresters shall be installed in the incoming section of the Corporation's high-voltage switchgear.

4.3.5 Nominal Discharge Current Rating

Surge arresters fitted to 33 kV, or 22 kV systems shall be rated for a discharge current of 10 kA.

4.4 Selection and Configuration of Surge Arresters

The general philosophy when selecting surge arresters for any system, entails matching the electrical and mechanical characteristics of the arrester with the system's electrical demands and mechanical requirements. The simplified flow chart presented at Figure 4.4 illustrates the general methodology and procedural steps for configuring a metal oxide arrester. Further details can be found in IEC 60071.1 and clause 3.8.

The requirements for optimal and satisfactory selection of surge arresters dictate that surge arresters should provide an adequate protection margin and that they should also be suitable for stable continuous operation. An 'adequate protection margin' means that the device overvoltages are always below its withstand voltage, with a sufficient safety factor (safety margin). Whereas 'stable continuous operation' refers to the surge arrester's ability to handle all long-term, temporary, or transient stresses (which can be caused by system operation), whilst remaining electrically and thermally stable throughout its useful working life.

Regrettably, it is not possible to independently satisfy both the adequate protection margin and stable continuous operation. Reducing the arrester's protective level to enhance the protective margin inevitably induces higher electrical stresses during continuous use. Similarly, increasing the rated voltage of the arrester cannot be achieved arbitrarily without raising its protective level, which in turn diminishes the protective margin. Consequently, a balanced compromise must be made, ensuring that both requirements are optimally addressed. Refer clause 4.3.3.

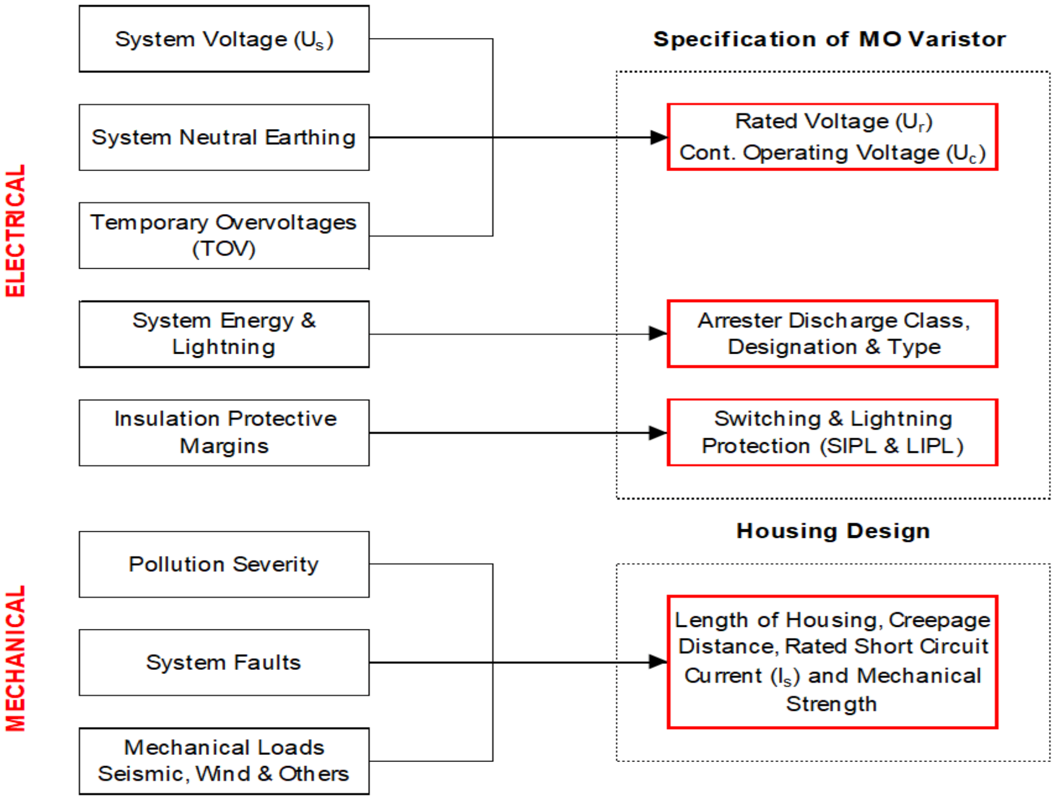


Figure 4.4 Flow Chart – Arrester Selection

4.5 Insulation Coordination Report

The Designer shall prepare a comprehensive 'Insulation Coordination Report' addressing the essential criteria of protection, surge arrester selection and surge arrester location.

The report shall address, as a minimum, the following items:

a) The calculated lightning impulse level at the transformer terminals and how this compares to the LIWV of the transformer.

b) The calculated lightning impulse level at the other HV equipment terminals and how this compares to the LIWV of the equipment.

c) Where applicable, the calculated switching impulse level at the transformer and other HV equipment terminals and how this compares to the SIWV of the equipment.

d) A statement regarding the safety margin achieved.

e) The calculated earth fault factor at the installation.

f) The calculated AC voltage rating of the surge arresters. (Based on the earth fault factor, EFF).

g) Drawing showing location of surge arresters.

h) Surge arrester type/model selected and its associated performance parameters such as:

   i. Maximum system voltage U_S

   ii. Maximum continuous operating voltage, MCOV, U_C

   iii. Rated voltage (temporary over voltage) U_r for 10 seconds.

iv. Peak residual voltage at a discharge current peak of 10 kA (or higher as justified) 8/20 µs wave.

v. Creepage distances.

vi. The maximum energy absorbed by the surge arrester(s) compared to the thermal energy rating of the selected surge arrester.

vii. Mechanical details.

viii. Other relevant electrical characteristics.

i) All assumptions (e.g. lightning stokes direct/indirect, powerline shielding, backflash, switching scenarios, temporary transient scenarios, etc.).

j) Modelling of the Network Operator's network, aerial and/or cable feeders to the substation, upstream surge arresters and the Corporation substation.

k) Modelling results for the computational insulation coordination study for the various overvoltage scenarios applicable, e.g. Lightning impulse transients, switching transients and temporary transients.

l) Third Party review of the modelling results above along with the TPR report.

m) Provision of a summary table for the primary and secondary high voltage systems showing the overvoltage identified in the study, along with their associated equipment withstand ratings. It shall be shown that the maximum representative overvoltage is all well within the proposed equipment voltage withstand ratings.

n) Detailed discussion regarding the simulation/study outcome, design and any special considerations.

o) Discussion of any non-compliance issues.

The report and drawings (Design Summary Drawings) shall be prepared and completed at the Engineering Design stage of the project. Revisions and modifications during the detail design phase shall comply with the requirements specified in DS20.

4.6 Equipment Protection

4.6.1 General

To achieve appropriate overvoltage protection in High Voltage systems, it is necessary to balance technical/economic considerations (compromise between the costs and the benefits of the protection devices to be used).

Well-designed surge protection systems ensure reduction in:

- Outages of substations
- Interruptions of critical manufacturing processes that demand high voltage stability
- Costs due to interruptions in the energy supply
- Costs for the replacement and repair of electrical equipment
- Ageing of the insulation (e.g. cables, etc.)
- Maintenance work

Therefore, the costs for a set of surge arresters are not the primarily consideration, but rather the costs that may arise in the long-term if adequate surge protection is not deployed.

The following equipment shall be protected against voltage surges:

- Transformers
- Cables and cable sheaths
- Capacitors and capacitor banks
- Overhead lines
- Rotating machines (motors and generators)

- Power electronics

4.6.2 General Considerations

4.6.2.1 Continuous Operating Voltage

The continuous operating voltage U_C is to be chosen in such that the arrester can withstand all power frequency voltages and temporary over voltages without being overloaded.

$T \times U_C > U_{TOV}$

In consideration of U_C, and as previously discussed, it is important that the protection level of the surge arrester is below the LIWV of the equipment to be protected, allowing for the safety factor K_S.

Ferro-resonance is the exception here. This is difficult to take into consideration due to the magnitude and long duration. Therefore, design shall consider measures to avoid Ferro-resonance.

4.6.2.2 Protection Level

The protection level selection is of fundamental importance and must be balanced with the selection of the continuous operating voltage.

In this context, the selection of a high continuous operating voltage means that the residual voltage of a surge arrester lies significantly higher than desired, which would result in an unfavourably high protection level. Clause 4.4 refers.

The protection level shall be as low as possible to ensure optimal protection of equipment insulation.

4.6.2.3 Nominal Discharge Current

Further to clause 4.3.5, the nominal discharge current can be chosen according to the thunderstorm activity in a region or the expected threat of lightning to a substation. In this way, the requirements for the arresters can be clearly specified together with the repetitive charge transfer rating Q_{rs} and the thermal charge transfer rating Q_{th} or the thermal energy rating W_{th}. MO surge arresters with I_n = 10 kA and classification DH are generally used in distribution system applications.

Higher nominal discharge currents (In = 20 kA) and higher classifications like SL, SM and SH are chosen in special cases in distribution systems, such as:

a) Regions with extreme thunderstorm activities and the risk of direct lightning strikes
b) Overhead lines at concrete poles or wooden poles and cross arms that are not earthed
c) Capacitors and capacitor banks
d) Rotating machines
e) Very long cables

4.6.2.4 Arrester Housing

Silicone or EPDM are almost exclusively used in industry as housing material for MO arresters. Silicone is preferred due to its excellent behaviour, especially in regard to pollution. The flashover distance and the creepage distance of the arrester housing shall be considered during design.

Note: Refer clause 3.2.3 and 3.8.2 for further detail.

The minimum flashover distance is determined by the required withstand values of the test voltages which must be applied in the relevant withstand tests, the lightning voltage impulse test and the AC withstand test with power frequency for one minute. Generally, the withstand values of the manufacturer's housing are much higher than the IEC requirements.

The creepage distance for a MO surge arrester is sometimes specified in relation to the continuous operating voltage U_C. Therefore, it is important to carefully consider the voltage to which the creepage requirements are related.

4.6.2.5 Selection of Surge Arresters

Metal oxide surge arresters shall be selected in accordance with the flow chart in clause 3.8.

4.7 Overvoltage Protection of High Voltage Cables

4.7.1 Introduction

Even though cables have a relatively high self-capacitance it is not correct to assume that a cable can protect itself against overvoltage. Cables subject to repeated overvoltage stress can have a detrimental effect on the aging behaviour of the cable insulation.

Cables shall be protected against overvoltage like other electrical equipment.

4.7.2 Overvoltage in Cables

An overhead powerline lightning overvoltage is generally limited to the sparkover voltage of the line insulators, assuming a few insulators between the point of strike and the cable bushing. It can be assumed that the peak value of the overvoltage wave travelling in the direction of the cable is equal to the sparkover voltage of the line insulator. Assuming a flashover distance of 500 mm of a line insulator (e. g. in a 24 kV-system and poles with earthed cross arms) a flashover voltage of approximately 300 kV can be expected at least, depending on the steepness of the incoming overvoltage.

A switching overvoltage is a slow front overvoltage and occurs as a transient phenomenon during a change in the supply system conditions. If a current circuit is opened or closed the transition takes place in form of an oscillation with a frequency and duration dependent on the system parameters. Typically, the transient voltage rise time is of a few 100 µs with a time to half peak value of milliseconds. Insulation withstand tests (switching impulse withstand test) are conducted using a voltage waveshape of 250/2500 µs. However, switching operations of vacuum breakers can produce a very steep overvoltage.

Overvoltage waves in cables is dealt with by travelling wave theory and the difference in surge impedance between cables, powerlines, transformers and open circuits (e.g. open circuit breaker within a substation) as discussed in clause 4.11. For example, a disturbance voltage that travels along an overhead line at a velocity of 300 m/µs in the direction of a cable will travel within the cable at a velocity of 150 m/µs. At the transition point (overhead line/cable), voltage reflections and transmissions occur due to the change in the surge impedances. A part of the incoming wave is transmitted into the cable, the larger part is reflected.

In the case of a cable installed in line with an overhead line (e.g. an underground section of a powerline), the maximum value of the surge voltage will be approaching that as the incoming voltage.

If the cable is terminated with an open circuit breaker or a transformer the voltage will approach a maximum of two times the incoming voltage.

4.7.3 Protection of Cables

Reflection of the transient voltage wave at the end of the cable represents a high risk and can cause flashovers at the bushings with subsequent damage to the cable insulation. This risk can be mitigated by the application of surge arresters at the cable end. Hence, cables shall be treated like substation equipment with respect to insulation coordination.

A cable that connects an overhead line (subjected to lightning) with a substation shall have surge arresters installed at the junction between the overhead line and the cable. The arresters shall be connected directly to the cable termination, with connection leads as short and straight as possible and the earth connection of the arresters connected directly to the cable sheath.

Furthermore, surge arresters shall be provided at the following points in a cable system:

a) at all switchgear bays that are open during system operation and,
b) at the end points of the network (i.e., at the cable end of open rings).

The protection of the cable termination points and substations against overvoltage can be improved by applying shield wires along the last 3 to 4 spans of the overhead line. For a better protection of the overhead line, low footing impedance for the last poles at the cable terminations are recommended. Detailed discussion with the Network Operator will be required to implement such additional remedies.

Cables have the capacity to store a significant amount of energy, which, in the event of an overvoltage, can be discharged into the surge arrester. For this reason, metal oxide surge arresters with a high energy handling capability shall be used. Metal oxide surge arresters, with higher energy handling capability, provide a better protection level due to the lower residual voltage of the arrester at the same continuous operating voltage.

Long cable sections require arrester protection at both ends whereas short cable sections, protection on one side is usually sufficient. This is possible because the protection range of an arrester at one end of the cable may offer sufficient protection at the other end.

4.7.4 Protection of Cable Sheath

The cable sheath of a single-conductor High voltage cable is usually earthed on one end only to avoid circulating currents and hence increased thermal effects leading to cable derating. If the cable sheath is open at one end, the sheath can experience up to 50 percent of the transient overvoltage on the inner conductor at the non-earthed end. The sheath insulation may not be able to cope with this overvoltage stress, hence a breakdown between the sheath and the earth may occur resulting in damage to the external insulation of the sheath.

Therefore, the Designer shall investigate whether it is necessary to protect the cable sheath against overvoltages on the unearthed end of the cable sheath with a suitable surge arrester.

4.8 Overvoltage Protection of Transformers

All transformers shall be equipped with surge arresters between phase and earth. Suitably selected surge arresters shall be located at the transformer primary HV terminals with the total cabling less than 1 metre in length if possible and the earth side connected to the transformer tank.

The continuous operating voltage U_C of the MO surge arresters, which are required to protect the transformer insulation and neutral, shall be chosen to be equal to or greater than the calculated values. Furthermore, all MO surge arresters have a limited protective distance (clause 3.6) which must be considered when choosing the location of surge arresters.

Surge arresters shall be located very close to the transformer and, where possible, the earth terminal of the arrester and transformer, shall be bonded with a very short straight conductor. Figure 4.5 below highlights the good and poor practice connection principles.

One essential requirement is the earth point shall be common for the transformer and the surge arrester earth, and the earth resistance shall be as low as possible.

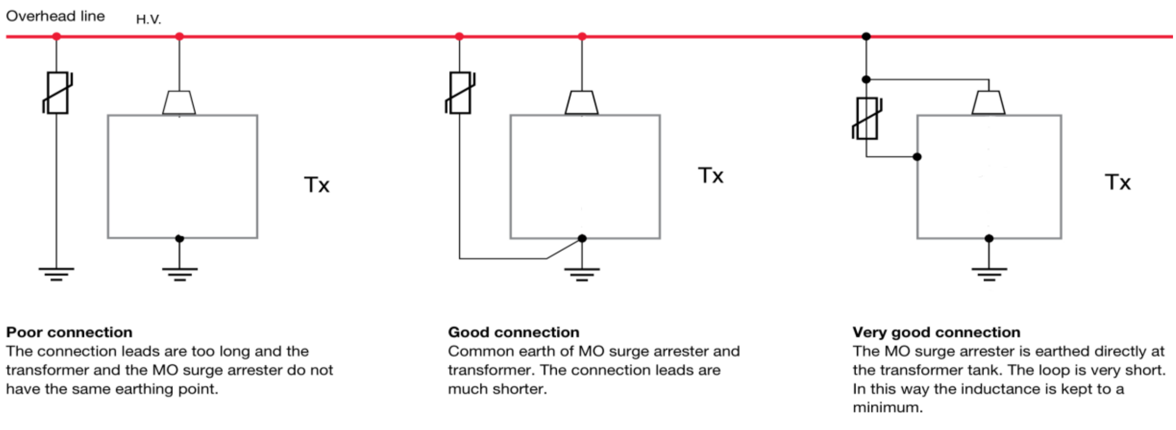


Figure 4.5 Arrester Connection Practice Principles

In principle it is advisable to install surge arresters on both sides of the transformer, particularly in regions with high thunderstorm activity.

Transient overvoltages can be capacitively coupled from the primary (transmission/distribution) to the secondary (distribution/low voltage) side of a transformer by as much as 40%. Refer Figure 4.6.

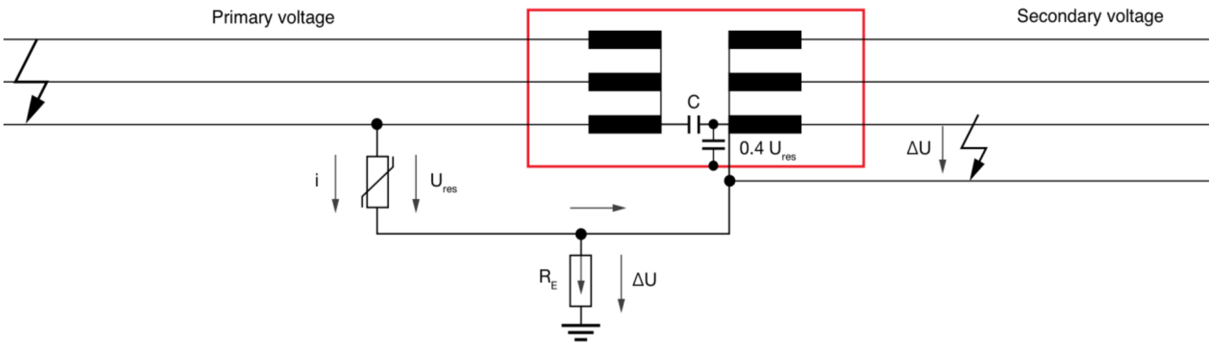


Figure 4.6 Capacitively Coupled Transient Overvoltage

4.9 Surge Protection for Rotating Machines

4.9.1 Introduction

The insulation on the windings of rotating AC machines, such as motors and generators, is held to a minimum because of limited space and no ability to be immersed in insulating oil. Even though modern solid insulation material is improving, special measures may still be necessary to protect such equipment when it is connected to a system subject to lightning surge voltages or switching surge voltages.

The stress on the insulation of any machine is determined by the magnitude of the surge voltage to ground, whereas the stress on the turn-to-turn insulation is more a function of the rate of rise of surge voltage as the surge penetrates the winding. Hence protection of a rotating machine requires limiting the surge voltage magnitude at the machine terminals and slowing the rate of rise of the wave front of the incoming surge.

To provide a level of mitigation, a special surge arrester (one with low residual voltage) is required at the machine terminals to limit the magnitude of the voltage impressed on the windings. The reduction in the rate of rise of the surge can be accomplished using a capacitor in parallel with the surge arrester and both connected to earth (Refer clause 4.9.3). Furthermore, an inductance can be added in series with the surge arrester/capacitor circuit, but this is usually unnecessary for motors connected via transformers.

Machines connected to overhead power lines through transformers are generally less prone to damage from lightning surges provided suitable surge arresters are connected to the primary side of the transformer. However, surges emanating from the incoming power line (Primary side of the transformer) may produce potentially damaging surges on the secondary side of the transformer as the surge is transmitted through the transformer by electrostatic and electromagnetic coupling. Thus, surge arresters shall be connected to the secondary side of the transformer usually at the switchboard.

Note: The electrostatic coupling depends upon the capacitances between windings and to earth and is independent of transformer reactance and turns ratio. Electromagnetic coupling, on the other hand, is dependent upon the turns ratio, reactance, transformer size and winding configuration (e.g. star-delta, star-star etc.).

4.9.2 Generator Protection Connected to a Distribution Voltage System

Generators are critical and sensitive equipment that require special attention regarding surge protection at the design stage. Consideration of the arrester protection characteristics, continuous voltage rating and location are essential.

If a loaded generator is suddenly disconnected from the system (load rejection), its terminal voltage increases until the voltage regulator readjusts the generator voltage after a few seconds. The ratio of the temporary overvoltage and the normal operating voltage is called the load rejection factor F_R and can reach a value of up to 1.5. hence, the surge arrester could experience a temporary overvoltage of $U_{TOV} = F_R$ x U_S, which must be considered when choosing U_C.

That is,

$U_C \geq F_R \times U_S / T$

The duration ‘t’ of U_{TOV} determines T (U_{TOV}/U_C) and lies in a range of 3 to 10 seconds. The high operational safety requirements for generators make it advisable to use arresters with low residual voltage U_{res} and high energy handling capability W.

For example:

$U_S = 24$ kV,

Load rejection factor, $F_R = 1.5$

t = 10 s

T = 1.291 derived from U_{TOV}/U_C =31 kV/24 kV

$U_C \geq 1.5 \times 24$ kV/1.291 = 27.8 kV

4.9.3 Motor Protection Connected to a Distribution Voltage System

High Voltage motor insulation can be voltage stressed due to vacuum switching (current chopping) or via a lightning impulse. To protect the motor insulation, surge arresters will be required close to the stator terminals or near the circuit breaker within the MCC switchboard.

If vacuum contactors are used, then surge arresters with appropriate capacitors shall be fitted to the motor circuit. Refer to the Figure 4.7 below.

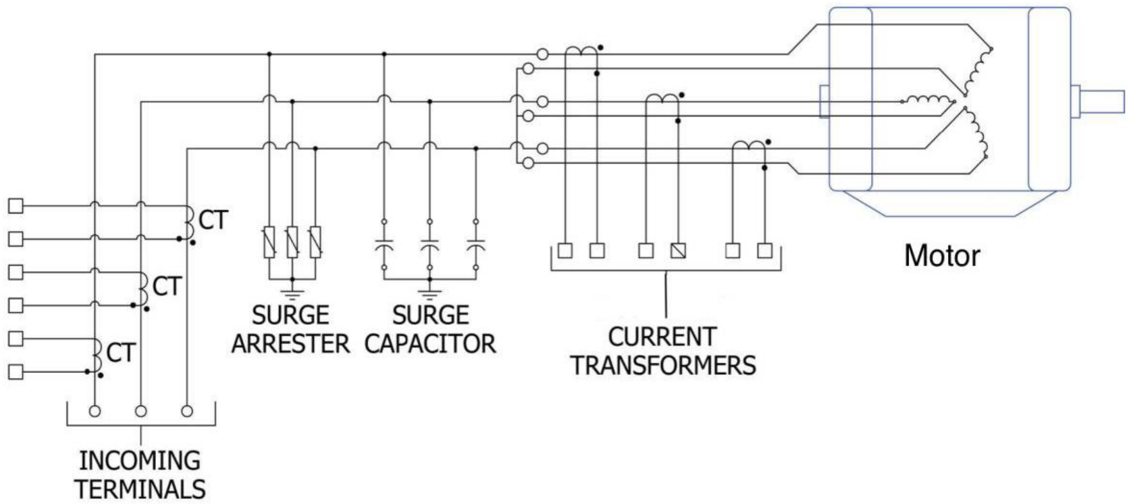


Figure 4.7 Motor Circuit Surge Protection Arrangement

Note:

1) *Surge Capacitors to be hermetically sealed low-loss, low-inductance.*
2) *Surge Arresters to be distribution class, silicone rubber housed MOV arresters.*

Due to the sensitive nature of motor insulation, especially as it ages with time and heat, it is critical to use an arrester with a residual voltage U_{res} as low as possible. Generally, a low residual voltage is achieved by selecting the lowest continuous voltage U_C available, however, U_C shall not be less than $U_S/\sqrt{3}$.

4.10 Surge Arresters in Parallel with a Capacitor Bank

Switching shunt capacitor banks creates excessive transient overvoltages (overvoltage at the capacitor between the phase and earth can reach up to 3 or 4 PU) during energisation and de-energisation, especially if restrike occurs. This can damage the capacitor bank and nearby equipment like power cables, circuit breakers, and transformers. Therefore, careful evaluation and selection of the thermal energy rating and U_C is essential during the design process.

All circuit breakers have an inherent probability of restrike during operation. The restrike performance of a circuit breaker is classified into C1 or C2 categories. Class C1 corresponds to a maximum expected probability of restrike per 3-phase operation of 0.02, while class C2 corresponds to a probability of 0.002 (as referenced in AS 62271.1).

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

If the circuit breaker operating the shunt capacitor bank corresponds to class C1, then it is necessary for the Designer to consider overvoltage limitation. Surge arresters installed in this context may be subjected to high energy absorption duties due to the significant energy stored in the capacitor bank. Therefore, as mentioned above, the energy absorption requirements for surge arresters protecting shunt capacitor banks must be thoroughly evaluated.

An additional technique to mitigate capacitive switching overvoltages is point-on-wave switching. When point-on-wave circuit breakers are employed, surge arresters are not necessary for overvoltage protection.

The Designer is responsible for ensuring that surge arresters are installed in parallel with capacitor banks. However, if a comprehensive evaluation provides well-documented evidence that surge arresters are unnecessary, they may be omitted subject to principal Engineer approval.

4.11 Overvoltage Protection of High Voltage Substations

4.11.1 Substation Insulation Coordination for Lightning Surges

Equipment installed within a substation that is directly connected to an overhead line is susceptible to direct, indirect and induced lightning overvoltages.

In the case of air-insulated substations, if lightning strikes the incoming power line within the a few spans of the incoming towers/poles from the substation, a surge is likely to enter the station along the conductors. A well shielded transmission/distribution line can allow a lightning surge to enter the substation if there is a backflash to the conductor during a lightning event.

Note: The key principle, for insulation coordination within a substation, is to ensure the substation and power line ends are well-shielded to prevent lightning from striking phase conductors near the substation. Effective protection also includes the correct design of insulators to prevent backflash.

Note: Owing to the high insulation withstand on systems above 245 kV, such back-flashovers are much less probable than on systems below this voltage level.

Lightning surges on an incoming conductor have a high probability of flashing over insulation in the substation if there are no arresters. The amplitude of these incoming surges will be equal to the flashover level of the insulator subjected to back flash. If the only mitigation tool is a surge arrester at the transformer, it will protect the transformer if properly coordinated with the transformer insulation. The arrester may even protect equipment on the surge side to some extent, but this may not be the case.

Hence, as previously discussed, Corporation owned surge arresters shall be installed at the entrance to the Corporation substation as well as at the transformers. This provides for greater assurance and redundancy (e.g. in case of entrance surge arrestor failure) and is considered good engineering practice.

4.11.1.1 Open Circuit breakers

Another important part of this coordination scenario is the state of the circuit breaker. If the breaker is in the open position, it will become an end point on the circuit. Because endpoints represent a significant change in characteristic impedance, voltage will be reflected and cause a doubling effect at the breaker. This voltage doubling effect (i.e. traveling wave theory) will likely cause the breaker insulator to flashover.

The voltage doubling effect can also occur if the breaker is open during operation to break the power frequency fault back at the tower. Since lightning seldom occurs as only a single stroke, another stroke along the original path can send a second fast rising surge down the same line. Due to these two potential open breaker scenarios, it is advisable to apply surge arresters at the line entrance of the substation to eliminate the voltage doubling at the breaker and an almost certain flashover of its insulation.

Yet another variable to consider in substation coordination for lightning is the number of incoming lines to the station. Fortunately, more lines make it harder to flashover insulators at the substation but, at the same time, increase the likelihood of an incoming surge. Both factors therefore must be considered in the formulas used to determine proper coordination.

4.11.1.2 Separation Distance

Separation distance is critical consideration when it comes to insulation coordination protection of substations (Clause 3.6 refers). Arresters will clamp a fast-rising surge according to their own V/I characteristics immediately in their vicinity. However, as protected insulation is located further from the arrester, it is increasingly less protected from fast rising surges. *Note: There is no separation distance issues for slow rising surges from switching sources.*

This reduced protection is again due to the effects of traveling waves and reflections. For this reason, the location of and distance between critical insulation points in the substation must be known before a proper insulation coordination study can be completed. Of course, the non-self-restoring insulation of the transformer is generally of highest consideration when it comes to separation distance issues. The formula for determining the farthest possible distance between an arrester and the transformer it protects is found in IEC 60099-5. *Note: The higher the system voltage, the shorter the separation distance becomes because the ratio of transformer withstand voltage to system voltage is reduced.*

4.11.2 Substation Insulation Coordination for Switching Surges

4.11.2.1 General

Switching surges are a concern for High Voltage systems, their importance and impact grow with the system voltage, making them a critical consideration in systems above 220 kV.

Switching surges can occur in systems below 220 kV, but their magnitudes are generally lower compared to higher voltage systems. The magnitudes for systems below 220 kV do not generally exceed 1.5 per unit (pu) of the system phase-to-ground voltage primarily due to the following reasons:

a) System Characteristics: Lower voltage systems (below 220 kV) typically have shorter transmission lines and fewer complex network configurations, which result in lower inductance and capacitance. This leads to smaller switching surge magnitudes.
b) Typical Magnitudes: In many cases, the switching surge magnitudes in these lower voltage systems do not exceed 1.5 pu of the system phase-to-ground voltage. This is due to the reduced energy levels involved in the switching operations of such systems.
c) Protective Measures: These systems often have effective protective measures, such as circuit breakers with controlled closing resistors, which help in reducing the switching surge magnitudes.

The primary reasons for magnitudes remaining below 1.5 pu are generally attributed to the following factors:

a) Controlled Switching: Controlled switching techniques are often employed to minimise the creation of switching surges.
b) Effective Grounding: Proper grounding reduces the potential difference during switching events, thus controlling the surge magnitudes.
c) Energy Dissipation: The relatively lower energy associated with switching operations in systems below 220 kV means that the system can dissipate these surges more effectively without significant overvoltages.

While this generalisation holds true for many practical situations, it's important to note that specific conditions and configurations can sometimes lead to higher switching surge magnitudes. Therefore, each system shall be evaluated based on its unique characteristics.

4.11.2.2 Methodology

There are two methods used in the practice of insulation coordination for the switching scenario, namely:

a) The deterministic method is used exclusively when applied to non-self-restoring insulation. Here the absolute maximum and minimum values are coordinated. For example, the maximum residual voltage of an arrester for a slow front surge (during switching) is coordinated and compared to the minimum withstand level of transformer switching impulse.
b) When coordinating self-restoring insulation, statistical (probabilistic) methods are generally used. When using the statistical method in determining the flashover rate of the self-restoring post insulators in the substation, the probability of flashover occurrence and magnitude of the surge are used in the calculation. The results are a probability distribution representing the overall switching surge flashover rate.

4.11.2.3 Switching Surge Examples

I. The following is a simplified example of switching surge calculations for insulation coordination with a transformer (non-self-restoring insulation):

System Parameters:

System Voltage: 132 kV

Transformer switching impulse withstand level (SIWV): 550 kV

Switching Surge Impulse (Slow Front): 1.5 pu

Steps:

1. Determine the Maximum Switching Surge Voltage:

- Maximum switching surge voltage = System Voltage × Switching Surge Impulse

- Maximum switching surge voltage = 132 kV × 1.5 = 198 kV

2. Compare with Transformer SIWV:
   a) Transformer SIWV = 550 kV
   b) Since the maximum switching surge voltage (198 kV) is significantly lower than the transformer BIL (550 kV), the transformer insulation is adequate to withstand the switching surges.
3. Select Surge Arrester:

   Choose a surge arrester with a Continuous Operating Voltage (MCOV) slightly above the system voltage (e.g., 150 kV) and an energy rating suitable for the expected surge energy.

4. Verify Insulation Coordination:
   a) Ensure that the surge arrester's residual voltage during a switching surge is lower than the transformer's minimum withstand voltage.
   b) For example, if the surge arrester's residual voltage is 120 kV, it is lower than the transformer's minimum withstand voltage, ensuring proper coordination.

In this example, the transformer's insulation is adequately coordinated with the switching surges, as the maximum switching surge voltage is well below the transformer's SIWV.

II. An example of insulation coordination for self-restoring insulation, such as a substation's overhead line insulation, using the statistical (probabilistic) method follows:

System Parameters:

- System Voltage: 132 kV

- Switching Surge Impulse: 1.5 pu

- Insulator Flashover Voltage (FOV): 500 kV (with a certain probability of failure)

- Probability of Flashover: 2% for a given switching surge magnitude

Steps:

1. Determine the Maximum Switching Surge Voltage:

a) Maximum switching surge voltage = System Voltage × Switching Surge Impulse
b) Maximum switching surge voltage = 132 kV × 1.5 = 198 kV

2. Probability Distribution:

a) Use the statistical method to calculate the probability distribution of the switching surge voltages.
b) The distribution will show the likelihood of various surge voltages occurring.

3. Calculate Probability of Flashover:

Determine the cumulative probability of the maximum switching surge voltage exceeding the insulator's flashover voltage.

a) Given FOV = 500 kV and the maximum switching surge voltage = 198 kV, calculate the probability of flashover.

Assume the probability distribution of switching surge voltages shows that 98% of the surges are below 500 kV (2% probability of flashover).

4. Compare with Design Criteria:

a) Design criteria typically aim to keep the flashover probability below a certain threshold (e.g., 2%).

5. Conclusion:

a) Flashover Probability: The calculated probability of flashover is 2%, which meets the design criteria.
b) Coordination: The self-restoring insulation is considered adequately coordinated if the probability of flashover remains within acceptable limits.

This basic example illustrates how the statistical method is used to coordinate self-restoring insulation by evaluating the probability distribution of surge voltages and comparing them to the flashover voltage of the insulators.

Note:

The 2% probability is an illustrative example to show how the statistical method works in insulation coordination. In a real-world scenario, the probability of flashover would be determined based on the specific system conditions and historical data.

Determining the Probability of Flashover:

1. System and Environmental Data: Collect data on the system's voltage levels, switching operations, and environmental factors that can influence overvoltages.

2. Historical Surge Data: Analyse historical data on switching surges, including their magnitudes and frequencies.

3. Insulator Flashover Characteristics: Obtain the flashover characteristics of the insulators, including the voltage levels at which flashovers occur, and the probabilities associated with these levels.

4. Statistical Analysis: Use statistical tools to analyse the data and calculate the probability distribution of surge voltages.

5. Calculate Flashover Probability: Determine the cumulative probability of the surge voltages exceeding the insulator's flashover voltage.

In practice, detailed simulations and statistical analyses are used to estimate these probabilities. The 2% flashover probability in the above example represents a typical threshold used in design criteria to ensure a balance between reliability and cost.

4.11.3 Arrester Characteristics for Substation Insulation Coordination

Arresters are primarily to protect the non-self-restoring insulation of power transformers and the like. The coordination of non-self-restoring insulation is accomplished using the deterministic method because there are no acceptable test methods that can determine the probability of disruptive discharge in non-self-restoring insulation systems. Therefore, the only option is a deterministic approach as discussed in clause 4.11.2.2.

Arresters, pertaining to insulation coordination, within substations are characterised by three voltages, namely, the arrester operating voltage, the lightning impulse protective level and the switching impulse protective level. After the insulation and surge arrester characteristics are determined, they shall be coordinated to ensure there is ample safety margin (margin of protection) between them.

By raising the operating voltage of the arrester, the clamping voltage is also increased and the margin between the transformer’s withstand curve and the arrester’s clamping curve is decreased. The designer shall consider the operating voltage of the arrester in relation to this margin and the earth fault factor (during system earth faults) implications on ratings.

Another factor that can have a major impact on insulation coordination on power systems is the lead lengths on arresters. Long leads can effectively render an arrester unable to protect non-self-restoring insulation on distribution equipment. As previously discussed, lead lengths must be kept to a minimum and included in the margin calculation for insulation coordination protection.

Note: While several variables can be involved in the engineering of insulation coordination and which can make this task quite complex, optimisation of arrester application can result in significant savings on insulation system costs.

4.11.4 Environmental Effects

Flashover voltages for air gaps depend on the moisture content and density of air such that insulation strength increases with absolute humidity up to the point where condensation forms on the insulator surface. Because insulation strength decreases with decreasing air density, longer strike distance is required to attain the same flashover voltage at say 2000m elevation compared to 100m above sea level. When determining the co-ordination withstand voltage, it should be kept in mind that most adverse conditions from the strength point of view (i.e. low absolute humidity, low air pressure and high temperature) do not usually occur simultaneously. In addition, at any given site the corrections applicable for humidity and ambient temperature variations basically cancel each other. Therefore, the estimation of strength can usually be based on the average ambient conditions at the location.

When contamination from salt or industrial pollution is present, the response of external insulation to power-frequency voltages becomes important and may dictate longer creepage distances. Flashover of insulation generally occurs when the surface is contaminated and becomes wet due to light rain, dew or fog. Such design considerations must be addressed by the designer.

4.12 MV Converter Drives

All AC converters for variable speed applications shall be equipped with appropriately rated surge arresters.

Given the sensitivity of converter drive components to lightning-induced voltage surges and switching surges, it is essential that the input to the AC converter is fitted with appropriately selected surge arresters. This measure will ensure adequate insulation coordination within the electrical system, thereby enhancing system reliability, safety, and efficiency in a cost-effective manner.

5 Protection of Buildings and Structures

5.1 Protection of buildings/indoor substations

All substation buildings and occupied buildings, where it has been determined a risk of direct lightning strikes, shall be protected with air terminals unless the building is designed to intercept lightning strikes.

Protection for non-metallic buildings is 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 have metal roofing or cladding, it may be feasible to eliminate some or all air terminals if the supporting roof steelwork is directly connected to the 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 (e.g. 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. When steel reinforcing is used as the down conductor system, and approved by a structural engineer, multiple effective electrical connections shall be established from the air terminal network to the steel reinforcing at the top of the building. These connections should be made at a minimum of one at each corner and spaced no less than 20 meters apart.

5.2 Protection of Aerial Substations

The following pertains to the additional requirements for High Voltage substations (both indoor and outdoor) as previously mentioned in clause 4.11.

The protection of substations against overvoltage can be enhanced by installing shield wires along the final 3 to 4 spans of the overhead line and ensuring low tower impedance to earth near the substation. In cases where the Network Operator provides limited or no line-end shielding, consideration of additional measures will be required, by the designer, to offer sufficient protection for substation equipment. Critical reliance will be placed on lightning interception masts, substation shield wires, earthing systems, higher insulation levels and surge arresters (e.g. special low protective level, high energy capability and a larger protection margin).

Note: Overhead earth wires (OHEW) mitigate overvoltage to sufficiently low levels, enabling safe discharge through the surge arresters positioned at the major substation entry. This principle also extends to cable-connected indoor switchgear, which are typically safeguarded by a set of surge arresters located at the UGOH end of the cable.

For substations exposed to close-in direct strikes, the protective and protection zone methods described in section 2 shall be considered.

Some design practice excludes surge arresters for GIS equipment due to cost considerations, space constraints, alternative protection methods, and specific risk assessments. While surge arresters provide essential protection against overvoltage, these designs tend to prioritise simplicity and reliability, avoiding additional components requiring maintenance. However, it's important to evaluate the specific needs and risks of each substation to ensure adequate protection against overvoltage.

In practice, surge arresters are frequently employed for the protection of GIS equipment due to their effectiveness in mitigating overvoltage. Therefore, the design of GIS-type substations for Corporation assets shall include provisions for surge arresters.

5.3 Protection of Water Tanks

Earthing, bonding and the provision of lightning air terminals at water tanks shall be designed in accordance with the requirements of AS/NZS 1768 and sections 2 and 5 of this standard. Lightning protection design of power and instrumentation equipment shall be in accordance with the requirements of the DS20 and DS40 series of design standards.

With respect to the tank, the philosophy is not to protect the tank from a direct strike but rather guide

the lightning surge safely to ground. In this regard, it is important to establish a connection from the air termination to a lightning earthing system with a combined resistance to earth of less than 10 ohms. As shown in IEC 62305-3 Table 3 a steel roof of 4 mm thickness will usually prevent puncture, hot spot or ignition from a direct lightning strike. Those with a roof of less thickness may sustain some damage which usually can be repaired after regular inspection.

Depending upon the type of tank construction this will involve either three down conductors from the air termination or simply a connection (minimum 3 points) from the metallic tank base to the earthing system. Furthermore, the connection to the earthing system shall be via suitably rated DC De-couplers (e.g., Dairyland Electrical Industries DEI SSD Solid State De-coupler) to provide corrosion/cathodic protection isolation.

For this section 5.3, the air termination is defined as the metallic roof and/or the protective railing of the tank and the down conductor is defined as an insulated copper conductor (minimum of 70 mm^2) from the air termination to the earthing system. The lightning earthing system is defined as a bare copper conductor (either 35mm^2 bare hard drawn copper or 70mm^2 bare soft drawn copper) buried encircling the tank (grading ring), spaced one metre from the tank wall and connected to three equally spaced earth electrodes along the circumference of the grading ring.

Additional requirements relating to the basic lightning system requirements outlined above is provided below (clause 5.3.1, 5.3.2 and 5.3.3) for various types of tank construction:

5.3.1 Ground Mounted Tanks

5.3.1.1 Steel roof of ground level concrete tank

Three down conductors originating from the steel roof shall be terminated into the earthing system.

5.3.1.2 Steel roof of ground level steel tank

Three connection points from the base of the tank to the earthing system shall be provided via suitably rated DC De-couplers. (Note: The steel tank may be insulated from the ground for cathodic protection purposes, hence the need for DC isolation).

Down conductors from the roof are not required as there is usually a solid electrical connection between the roof and tank wall. Should the roof be insulated from the tank wall then three equally spaced 70 mm2 insulated copper bonding cable connections shall be provided from the roof to the wall.

5.3.1.3 Concrete roof of ground level concrete tank

There are no earthing requirements for the tank. However, any metallic structure, such as ladders or stairs, shall be connected to the earthing system via two separate earth cables. In order to achieve 10 ohms earth resistance, either drilled electrodes and/or a grading ring can be provided in this case.

5.3.2 Elevated Tanks

5.3.2.1 Concrete roof of elevated concrete tank supported on concrete columns or shaft

Earthing and bonding of any internal metallic structure shall be provided.

5.3.2.2 Steel roof of elevated concrete tank supported on concrete columns or shaft

Three down conductors terminated into the earthing system shall be provided. Earthing and bonding of any internal metallic structure shall be provided.

5.3.2.3 Steel roof of elevated steel tank supported on concrete columns

Three down conductors terminated into the earthing system shall be provided. Any internal metallic structures shall be bonded and earthed.

5.3.2.4 Steel roof of elevated steel tank supported on steel frame

Three connection points from the base of the tank to the earthing system shall be provided. Any internal metallic structures shall be earth bonded.

5.3.3 Tanks on Tank Stands

5.3.3.1 Steel Tank on a steel frame

Three bonding straps from the tank to the steel frame shall be provided. The steel frame is considered the down conductor hence no additional down conductors are required.
The steel frame of the tank, embedded in the ground, may be used as the earthing system provided the total earth resistance is not greater than 10 ohms.

5.3.3.2 Steel tank on an insulated frame (wood)

Three down conductors from the steel tank terminated into the earthing system shall be provided.

5.3.3.3 Steel Tank on a steel frame but tank base insulated

If the steel tank is placed on an insulated base (e.g., wood, etc.), all supported on a steel frame, then a minimum of 3 bonding straps (70 mm^2 insulated copper cable) shall be installed from the tank to the steel frame (bond across the insulated base).

The steel frame is considered the down conductor hence no additional down conductors are required.

The steel frame of the tank, embedded in the ground, may be used as the earthing system provided the total earth resistance is not greater than 10 ohms.

5.4 Intake Towers

Intake towers for dams are usually concrete structures with a metal roof.

The lightning protection system shall consist of four equally spaced down conductors of bare flat copper bar (minimum 70 mm^2) construction, connected from the metal roof (air termination) to the earthing system.

The earthing system shall consist of radial bare copper cable arrangement (six equally spaced buried strip electrodes of bare 70 mm^2 copper) all connected to a bare copper ring (70 mm^2 minimum) at the base of the tower and connected to the four down conductors.

5.5 Lightning masts, metallic poles and air terminals

The location of air terminals shall be as determined by the LPS design following the risk analysis process in AS 1768. An air terminal may consist of a vertical rod, a single horizontal conductor, 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. Lightning air terminals shall not be mounted directly on substation equipment.

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. If the design does not specify the required clearance, a minimum clearance of five meters shall be maintained.

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

All metallic poles (e.g. light poles, communication poles, and lightning poles) 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 to the LPS earth system.

5.6 Overhead Line Design

AS 7000 offers guidelines for overhead line design, focusing on lightning protection. It covers lightning performance, insulation design, electrical clearances, conductor and insulator requirements, and coordination with substations to ensure compatibility and reliability.

As a general practice, the Corporation does not typically own overhead power line systems; hence, this standard does not include additional details regarding them.

6 Accessories, Condition Monitoring and Field Testing

6.1 General

Surge protective devices, such as arresters, reduce the impact of events that could cause outages. Monitoring these devices has become an important aspect of asset management focused on assessing the condition of key components. Over most of its service life, an arrester behaves much like an insulator, with low leakage current over its insulating surface and very low levels through the internal zinc oxide disks. Maintaining a low leakage current is required to ensure the arrester maintains its expected design life of up to 30 years.

Several assessment methods and indicators have traditionally been utilised to reveal signs of deterioration and provide clues to impending arrester failure. These range from fault indicators and disconnectors (which indicate complete failure) to instruments that can measure small changes in the resistive leakage current or power loss in the case of gapless type metal-oxide arresters.

Condition based assessment comes with a cost and is therefore most often performed only at critical asset locations where failure could have serious ramifications (i.e. an outage and loss of production/revenue). The goal in such cases, via testing, is to predict imminent failure and have the arrester removed before it does indeed fail.

6.2 Accessories

The Designer shall consult with the Corporation as to whether any of the following accessories are required for an installation.

6.2.1 Indicators

Indicators are devices that clearly indicate an overstressed (short-circuited) arrester. Such devices are installed either on the line side or on the earth side directly at the arrester.

6.2.2 Disconnectors

All forms of surge arresters are likely to fail in the event of extreme overload, such as continuous flow of network fault current, or exposure to lightning / network transients beyond the designed duty.

Polymer insulated metal oxide arresters, are often designed without the need for overpressure vents, but there can be an internal material breakdown that produces gaseous plasma. Pressure from these gases can then lead to elastic expansion of the polymer housing and the universal design criterion is that the housing will ultimately burst to release excessive pressure.

Disconnectors are designed to automatically disconnect a surge arrester that has been overstressed. These disconnectors are placed on the earth side directly under the arrester with a flexible earth connection that has sufficient distance beneath the arrester, so that the disconnected earth connection can hang freely and the applied operating voltage at the foot of the arrester does not lead to a spark-over.

The aim of a disconnector is to prevent overstressed arresters causing tripping and isolation of the electrical load or system, thus improving reliability and availability. The disadvantage is there is no overvoltage protection while the arrester is disconnected. Hence it is important to replace arresters as quickly as possible.

Care needs to be taken to ensure the upstream protection does not operate at the same time as the disconnector operation.

6.2.3 Spark Prevention Unit

The spark prevention unit (SPU) is a device to avoid wildfire hazards caused by thermally overloaded surge arresters. The SPU is installed in the earth connection of a distribution voltage arrester. These are generally not applied to substation installations but rather to high voltage aerial distribution lines of which the Corporation only has a few.

6.3 Monitoring

Assuming correct application, the performance of MO surge arresters does not usually change under normal system conditions over their lifetime.

Monitoring of events, like surges due to lightning and/or switching, or monitoring of MO surge arrester operational performance gives valuable information about activities/events within substations and possible impending failure of arresters.

IEC 60099-5 (Annex D) includes an overview of methods used for diagnosing High Voltage surge arresters.

6.3.1 Surge Counters

Surge counters can be installed to monitor and document the frequency of discharges occurring within an arrester in the system. These surge counters count all discharges above the threshold value of the surge counter. Very short discharges (impulses), such as multi-stroke flash events, may not register. Some products classify the current surges according to their magnitude.

Besides monitoring the MO surge arresters, the number and magnitude of counted surges gives valuable information about events in a substation. It can also provide useful statistics for the performance, potential malfunction and stresses seen by the system. Repetitive surges should not in themselves lead to degradation as the arrester is designed to withstand thousands of surges within its operating specification.

Ideally, the surge counter should be installed in a location that allows it to be read from ground level while the arrester is in service. *Note: ensure that the earth connection is neither extended nor its cross-section reduced.*

Most surge counters are equipped with digital monitoring capabilities, allowing them to record and transmit data about surge events in real-time. Some devices offer wireless cloud access to recorded data, which can be viewed via an app or web browser. This enables real-time remote monitoring and analysis of surge events, leakage currents, and other relevant parameters.

It is not uncommon for surge counters to be permanently installed on GIS arresters.

The inclusion of surge counters shall be considered during the design stage.

6.3.2 Leakage Current Measurement

Trend measurement of the continuous leakage current (combination of the capacitive current and the resistive current) that flows through an arrester can be an important indicator of arrester health and a possible predictor of impending failure. The momentary value cannot provide enough information about the condition of an arrester. Therefore, it is important to make the first measurement directly after the arrester installation and to record the conditions during the measurement (voltage, ambient temperature, pollution of the arrester housing, etc.) then follow up with periodic measurements.

If necessary, a milli-ampere meter may be permanently installed to monitor leakage current however due to the reliability of MO arresters a periodic performance measurement based on comparison with past measurements would suffice.

It is not uncommon for milli-ampere meters to be permanently installed on GIS arresters. Such meters should be considered during the Design stage for such applications.

A Leakage Current Monitor instrument performs non-invasive diagnostics of varistor-type surge arresters (with metal-oxide blocks) during operation. This type of instrument measures the quality of the metal oxide blocks to help manage the risk of failure. Specifically, it uses IEC60099-5 method B2, analysing the leakage current's 3rd harmonic with harmonics compensation in the grid voltage.

According to the IEC standard, this is the most reliable method of diagnosing high-voltage surge arresters during operation.

Note: Because metal oxide disks are more like insulators than conductors during steady state, they conduct very little resistive current but can carry from 2 to 10 mA of capacitive current. Such a high level of current offers little useful data about the actual condition of an arrester. Unfortunately, a 5 mA or higher total current (90% being capacitive) can shroud the resistive current and prevent any real detection of the arrester's condition.

6.3.3 Third Harmonic Current Monitoring

These surge counters can sense third harmonic current offering significantly more information on the condition of the arrester. Surge amplitude and time are recorded along with leakage current data which can be downloaded or available for continuous online monitoring. Based on total current, the device calculates the third harmonic content of the current (a value that is a very close representation of resistive current) and uses it as the fundamental means of assessment.

Note: Any change, modification, deterioration, or damage to a surge arrester will result in an increase in the third harmonic leakage current, making it a reliable indicator of the condition of the surge arrester.

6.3.4 Partial Discharge Detection

During the life of a gapless arrester, its internal components will continually be exposed to stresses that can lead to partial discharges. Arresters with some internal air volume (porcelain-housed and hollow core composite tube designs) will typically experience some partial discharge activity during rain, fog or damp conditions and this is an acceptable condition in arrester designs. However, these types of arresters should not experience partial discharge under dry conditions.

Because internal partial discharge (PD) in an arrester is an undesirable condition that can eventually lead to failure of its insulating materials, detection systems have been developed to detect PD and give users the opportunity to rectify the problem early. There is a wide array of on-line and field-oriented PD detection equipment that can be applied to arresters.

When arresters are manufactured, they are required to be tested for internal PD to IEC standards demanding no more than 10 pico-coulombs (pC) discharge. Therefore, 10pC can represent a baseline for arrester assessment and any arrester exhibiting more than this warrants closer inspection. The real task in PD detection is filtering out background noise, hence measurement devices able to filter out noise is required and are available.

However, polymer insulated housings for metal oxide surge arresters are generally less of a concern due to improved sealing hydrophobic properties, resistance to pollution, less prone to mechanical damage and reduced risk of cracking.

6.3.5 Thermal Imaging

Thermal vision cameras can be used to detect the temperature of MO surge arresters. Here again, the absolute temperature is not so important, but rather differences in temperature of arresters within the substation, or a steady increasing temperature of the arrester over time.

This form of arrester condition assessment is both fast and effective on the basis that any arrester in long-term failure mode, and nearing the end of its life, is likely to be significantly hot. Since all arresters should be from the same manufacturer and of the same design, they should all be at a similar temperature. Any difference detected should come only after a surge or temporary overvoltage event.

It is quite typical for arresters to run up to 5°C above ambient, but temperature deviations above that level should be considered a potential problem. Rarely is an arrester more than 20°C hotter than ambient other than in a laboratory setting. A 10°C difference between two arresters of the same design and vintage should be considered as a clear indication of maintenance action required. In this regard, the arrester should ideally be removed from the energised circuit.

Any arrester between 5 and 10°C from ambient should be monitored closely. An arrester that is 15°C different from other similar units should be de-energised as soon as possible to avoid an outage. Moreover, if the arrester is porcelain-housed, then personnel should not approach until it is deenergised.

Many infrared cameras available on the market are capable of detecting and visualizing very small temperature differences. These devices are highly sensitive and accurate, producing sharp images on screen.

Combining the results of the infrared camera measurement with the measurement of arrester leakage current, a very clear condition assessment of the surge arrester can be established.

6.3.6 Offline Arrester Testing

Offline testing is required if an arrester has been removed from its service location or if it is still in the circuit but has been de-energised for some time. The methods and ease of testing arresters to determine if they are worthy of re-installation are typically much more demanding than simple online condition monitoring. As such, if possible, arresters should ideally be assessed while online.

The main problem with offline testing is that to effectively assess an arrester's condition it must be energised near or above its operating voltage. For arresters, it is too difficult to easily generate the necessary voltages. For this reason, if it is decided to test an arrester, which in turn could be cost prohibitive, then it should be returned to the manufacturer for testing.

Generally, Corporation arresters should not adopt this approach of offline testing.

6.4 Arrester Failure

If an arrester breaks down in a phase and it is replaced, the other two arresters in the other phases shall also be replaced. It is recommended that all three arresters be sent to the manufacturer for examination.

6.5 Arrester System Audits

Audits of surge arresters within the Corporation are determined by the operations and maintenance guidelines and not covered by this standard.

6.6 Replacement of SiC Porcelain Arresters

As discussed in note for clause 3.2.3, it is recommended that SiC porcelain surge arresters less than 25 years old be closely monitored and those greater than 25 years old be considered for replacement.

As previously mentioned, the first lightning stroke is followed by multiple smaller strikes in 80% of cases. The number of strokes can range from 2 to 20 surges (average of 3 or 4) with inter-stroke time intervals of 15 to 150 ms (average 30 to 40). Studies (Darveniza, Queensland University) over the past 30 years have revealed that multi-stroke lightning is responsible for the high failure rate of SiC porcelain surge arresters, due primarily to the poorer insulation between the SiC blocks and the porcelain insulation, compared to the metal oxide polymer insulated surge arresters. The principal recommendation from these studies was that all gapped SiC surge arresters with 13 years' service or more should be replaced with polymer housed metal oxide arresters.

Hence, serious consideration should be given to the replacement of such surge arresters (SiC).

APPENDIX A - Characteristics of Lightning Ground Flash

The following information, relating to the characteristics of lightning ground flash, is provided as a short summary of the phenomenon to assist with the understanding of the origin of lightning surges that influence lightning protection and insulation coordination systems discussed in this standard.

Lightning comprises one or more short-duration high-current discharges with path lengths of several kilometres. The total duration of a multiple discharge lightning is usually less than one second and the whole event is known as a lightning flash. Only lightning ground flashes pose a threat to power system equipment. The hazard is particularly severe if the lightning strikes the object directly but may still be significant if the flash terminates on the ground near the object.

The following summarises the main features of a ground flash, with a concentration on those of relevance to lightning protection. The four categories of ground flash are:

a) Negative downward flash (cloud to earth)
b) Positive downward flash (cloud to earth)
c) Negative downward flash (earth to cloud)
d) Positive downward flash (earth to cloud)

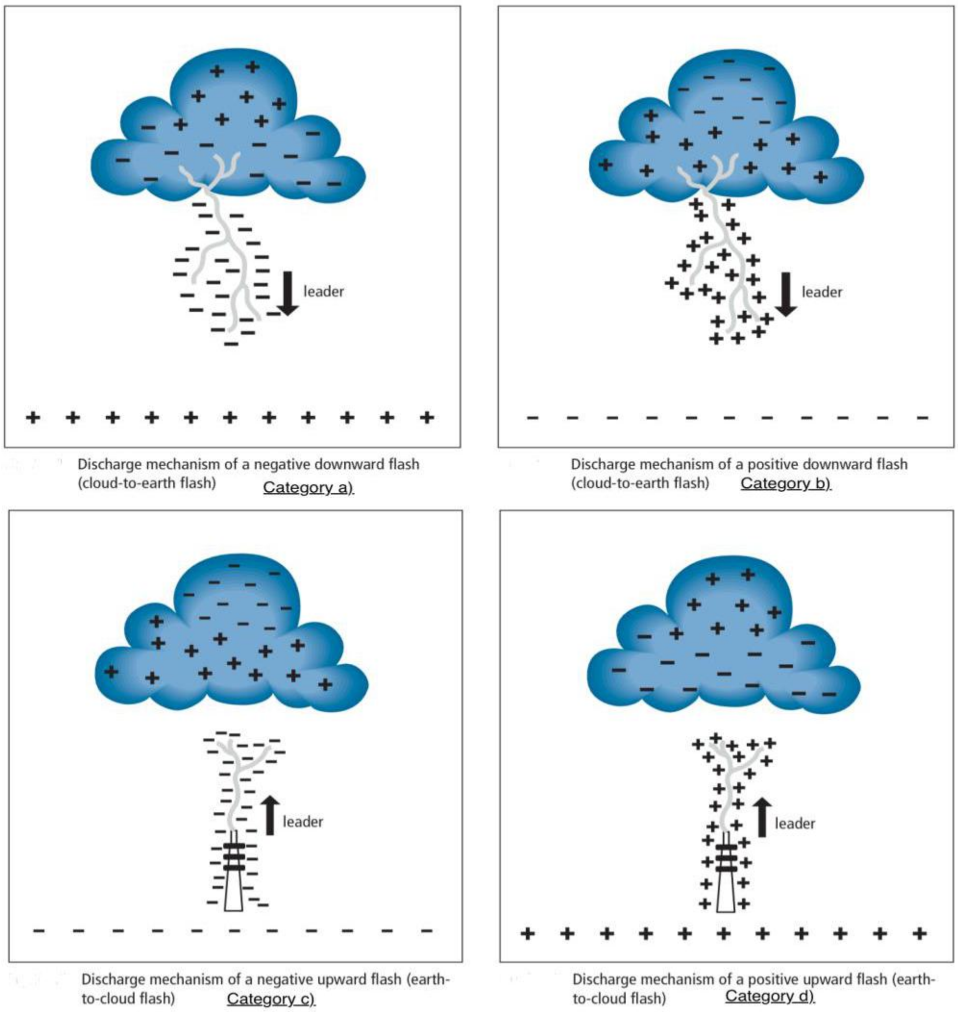


Figure A.1 Characteristics of Lightning Ground Flash

The last (namely, Cat c and d) above are mostly launched from tall objects such as mountain tops, tall man-made structures or from the rockets trailing wires used to trigger lightning.

Most lightning strikes to objects of height less than 100m above reasonably level ground are of the negative downwards leader category. For lightning protection purposes, it is commonly assumed that 90% of downwards flashes to ground are negative and 10% are positive but this ratio depends upon the geographical location.

For example, for summer thunderstorms, particularly in tropical and sub-tropical areas, positive downwards lightning flashes are rare (less than 5 percent). However, for the special circumstance of winter thunderstorms in mountainous regions located in temperate areas such as Japan and Norway, the majority are positive flashes.

Therefore, for lightning protection in tropical and sub-tropical areas, it is usually sufficient to concentrate on the negative downwards leader category.

After the thunderstorm cloud has been electrified by charge separation (positive charge at the top, negative charge below, with a pocket of positive charge at the base), the occurrence of pre-discharges near the cloud base is followed by the appearance of the downwards leader. The observable feature of the leader is that it proceeds towards ground by a stepped and branched process in which negative charge is lowered. The steps are typically several tens of metres in length. The physical processes that give rise to the short-duration steps (of about 1 μs) and the longer duration pauses between steps (about 50 μs) are not that well understood.

The average downward velocity of the leader tip is about 2 x 10^5 ms^{-1} whereas the velocity of individual steps is greater (by at least a factor of 10). The electric field at the ground increases as the leader tip approaches (its potential to ground is believed to be more than 10^4 kV), and in due course, upwards streamers and then leaders develop from protuberances on the ground. Contact between one of these upwards leaders and one of the tips of the downwards moving leader constitutes the last step in the leader's attachment process; the length of the last step is often called the striking distance (d_s). The leader channel is then discharged by the first return stroke which propagates upwards at about 1 to 1.5 x 10^7 ms^{-1}. The (first) return stroke injects current into the stricken object, typically rising to a peak of about 30kA in a few μs and falling to half value in about 30 to 50 μs. The high temperature (>3 x 10^4 °K) column expands rapidly, generating the high-pressure shock waves that cause thunder.

When the return stroke current has ceased, the flash may end completely, hence a single-stroke flash. But it is much more likely (approximately 70 to 80 %) that the flash processes will continue, leading to a multi-stroke flash (on average, there are three or four strokes per flash, with inter-stroke time intervals of 20 to 80 ms). Again, after some preliminary discharges which connect the upper end of the first return stroke channel to other charge regions in the cloud, a dart leader progresses downwards to ground along the same channel, and this initiates a second return stroke. Further subsequent strokes may follow. The dart leaders are not usually branched, and so the subsequent strokes mostly follow the original channel. Subsequent return stroke currents are smaller but have shorter rise-times than the first- stroke currents. On some occasions, a continuing current of about 100A (range 10 to 300A) and tens of msec duration flows in the channel after a return stroke. This is often called the 'hot' component of lightning current, because it is associated with lightning damage from thermal effects, such as melting of small diameter conductors and puncture of thin sheet metal, and the occurrence of lightning-initiated fires. Continuing currents can be of long duration, typically greater than 40 ms and even up to 500 ms. Some observers note that a continuing current component might be present in about 40 percent of all ground flashes.

On a significant number of occasions (30 to 50%), a subsequent leader may depart from the preceding stroke channel and may occasionally start from the cloud base. When this happens, it takes on the branched character of a ‘first leader’, and the resulting subsequent stroke current resembles that of a first stroke. This type of multi-stroke flash can terminate on two (sometimes three or four) objects, and these may be separated by hundreds of metres and even up to a few kilometres.

The much less frequent downwards positive discharge is very different in character. The leader progresses downwards from the upper positive charge regions of the thundercloud, usually in a continuously progressing channel but occasionally in a stepped but un-branched channel. Positive ground flashes are nearly always single stroke events and are of significant practical interest because their peak currents can be much larger (200 to 300 kA) than negative flashes (which rarely exceed

100kA). The associated charge transfer is also much larger, due in part to the presence of relatively large and long-duration continuing current. These large positive lightning flashes are sometimes called “super bolts”, and even though their rise times are relatively long (many tens of μs), they can be hazardous to objects susceptible to damage from high energy discharges.

An understanding of the process by which a downwards lightning leader terminates on an object on the ground is crucial to the design of interception systems. Intercepting air terminals such as vertical rods and overhead wires provide good shielding for objects that must be protected against direct strikes.

Modelling of interception systems, lightning overvoltage (induced, direct strike, backflash), down conductors and earthing for the safe dissipation of lightning energy is critical for protection of personnel, buildings and equipment.

Numerous texts provide information on the nature and phenomenon of lightning and ground flash along with an understanding of the various modes by which lightning can cause overvoltage. The reader is directed, as a minimum, to such documents as AS 1768 and IEC publications in this regard.

APPENDIX B - Types of Overvoltage Protective Devices

The principal types of impulsive overvoltage shunt connected protective device in common use are discussed hereunder.

Rod Gaps

Rod gaps are the simplest and cheapest form of surge arrester. However, such devices have several shortcomings, as discussed hereunder.

a) Rod gaps generally do not provide protection against lightning impulses with rise times less than 2μs.

b) Rod gaps are not self-quenching so that if long term outages are to be avoided, rod gaps must be used in conjunction with automatically reclosing circuit breakers.

c) The flashover characteristic for rod gaps is dependent on atmospheric conditions and is different for positive and negative going waves. Rod gap voltage-time characteristics are thus quite broad band.

Rod gaps shall not be deployed on Corporation assets.

Gap Type Surge Arresters

Gap type surge arresters are self-quenching and do not require to be used in conjunction with automatically reclosing circuit breakers. Gap type surge arresters respond faster and limit the residual voltage to lower values than do rod gaps.

Gapped silicon carbide (SiC) arresters have been replaced by Gapless metal-oxide arresters since the early 1980s and therefore gap type arresters shall not be used for Corporation assets. Refer Annex J of IEC 60099-5 for further information.

Gapless Surge Arresters

A surge arrester having several non-linear metal-oxide (ZnO) varistors with highly non-linear voltage-current characteristics, connected in series, but having no integrated series or parallel spark gaps.

Gapless surge arresters are self-quenching and do not require to be used in conjunction with reclosing circuit breakers.

Gapless surge arresters respond faster and limit fast front discharge voltages to lower values, than do either rod gaps or gap type surge arresters. However, gapless surge arresters are more sensitive to ambient temperature than are gap type surge arresters.

Some High Voltage gapless surge arresters can be fitted with disconnectors. Care shall be taken with equipment arrangements to ensure that operation of disconnectors is not inhibited and will not give rise to other faults.

Note: Section 3 provides further details of characteristics.

Special Purpose Surge Arresters

The Siemens type 3EJ0 (3EFI replacement) metal oxide surge arrester is designed to protect rotating machines (motors and generators at 3.6 to 12 kV), cable sheaths, capacitor banks and converters for drives. Such devices have a relatively low discharge current rating and are intended for suppression of switching surges and not for the suppression of lightning surges.

These surge arresters limit switching surge residual voltage levels to slightly lower values than other types of surge arresters and have the added advantage of being less sensitive to ambient temperature effects. However, their relatively low discharge current rating means that hybrid surge arresters must be protected from lightning surges.

The 3EF1 surge arrester (Hybrid combination air gap and metal oxide varistor), previously used within the Corporation, is now superseded. The 3EJ0 metal oxide surge arrester is fully compatible to the previous 3EF1 arrester used on existing Corporation assets.

APPENDIX C – Protection Zones

The table below illustrates the relationship between lightning strike penetration (10/350µs direct and 8/20µs indirect waveforms) and the protection zones, along with SPD type.

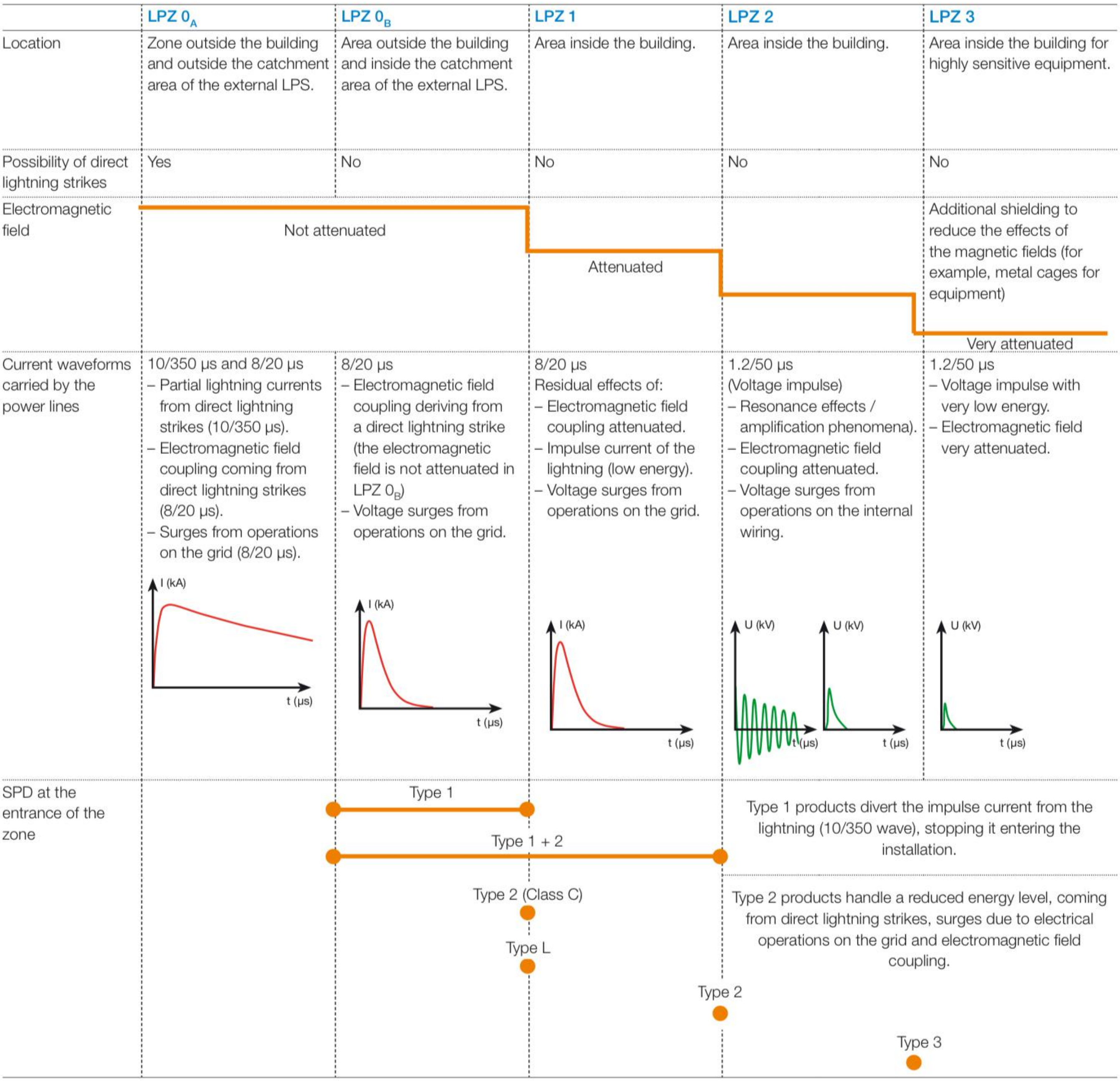


Figure C.1 Lightning Penetration into Zones, Waveforms and SPD Type

APPENDIX D - Technical Definitions

Terms (Primary)

I_n

Nominal discharge current of an arrester, i.e. the peak value of lightning current impulse which is used to classify an arrester.

k

Earth fault factor, $\mathbf{k \times U_s / \sqrt{3}}$ is the maximum voltage between phase and earth in case of an earth fault.

Lightning current impulse

8/20 µs current impulse with rise time of 8 µs and time to half-value of 20 µs.

LIWV

Standard rated lightning impulse withstand voltage of equipment or insulation configuration (kV_{Peak}).

SIWV

Standard rated switching impulse withstand voltage of equipment or insulation configuration (kV_{Peak}).

pu

Per unit, $\mathbf{1\ pu = \sqrt{2} \times Us / \sqrt{3}}$.

U_{TOV}

Temporary overvoltage (power frequency) of limited time duration.

U_c

Continuous operating voltage of an arrester, i.e. the designated permissible r.m.s. value of power-frequency voltage that may be applied continuously between the arrester terminals. Also known as the maximum continuous operating voltage (MCOV).

U_m

Highest voltage for equipment, i.e. highest value of the phase-to-phase voltage (r.m.s. value) for which the equipment is designed in respect of its insulation.

U_n

Nominal voltage of a system, i.e. a suitable approximate value of voltage used to identify a system.

U_{pl}

Arrester lightning impulse protective level (LIPL), i.e. the maximum residual voltage of the arrester at the nominal discharge current I_n.

U_{ps}

Arrester switching protective level SIPL, i.e. the maximum residual voltage of the arrester for the switching impulse discharge current specified for its class.

U_r

Rated voltage of an arrester, i.e. maximum permissible r.m.s. value of power-frequency voltage between its terminals at which it is designed to operate correctly under TOV conditions (**t = 10 s**).

U_{ref}

Reference voltage of an arrester, i.e. the peak value of power-frequency voltage divided by √2 which is obtained when the reference current flows through the arrester.

U_{res}

Residual voltage of an arrester, i.e. the peak value of voltage that appears between the terminals of an arrester during the passage of discharge current.

U_s

Highest voltage of a system, i.e. highest value of the phase-to-phase operating voltage (r.m.s. value) that occurs under normal operating conditions in the system.

Terms (Secondary)

Air terminal

A vertical or horizontal conductor of a lightning protection system (LPS), positioned to intercept a lightning discharge, which establishes a zone of protection.

Back Flashover

Back flashover occurs when lightning strikes a shield wire or tower and the resultant voltage across the insulator is large enough to cause a flashover from the tower to the line conductors.

Corona

Corona occurs when the local electric field near the surface of the conductor is high enough to ionise the gas molecules surrounding the conductor.

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.

Earth Grid

Interconnected uninsulated conductors installed in contact with the earth intended for the dissipation of current and or for the provision of a uniform voltage reference. One part of the earthing system.

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 and parallel earthing conductors.

Effectively earthed network

Earthed through a sufficiently low impedance so that the earth fault factor is approximately < 1.4.

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.

Flashover Distance

Flash over distance is the shortest distance between a conductor and the earth that an electrical discharge can travel through the air, surrounding an insulator. It's the distance an arc can travel through free air at a given voltage and environmental conditions.

GIS

Gas insulated switchgear or substation.

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.

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 ground/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.

Lightning Protection System (LPS)

Complete system used to reduce the risk of physical damage and injury due to direct flashes to the structure.

Substation

Aerial and indoor switching and transformer sites at both distribution and transmission voltage levels.

Metal-oxide surge arrester without gaps

An arrester having non-linear metal-oxide resistors connected in series without any integrated spark gaps.

Non-self-restoring insulation

Insulation which loses its insulating properties, or does not recover them completely, after a disruptive discharge. For example, solid insulators, transformer insulation, cable insulation etc.

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 e.g. 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 maxima (sizing criteria) and minimum (interception criteria) lightning current parameters is fixed, together with the corresponding rolling sphere radius.

Rolling Sphere Method (RSM)

A simplified technique for applying the electro-geometric theory to the shielding of structures (substations, buildings, etc.). 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 lifetime and those in the standard withstand test voltage.

Self-restoring insulation

Insulation which completely recovers its insulating properties after a disruptive discharge. For example, porcelain insulators for bus support in outdoor substation, air gaps, GIS, oil immersed insulators etc.

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 can repeat these functions as specified.

UGOH

Underground to overhead transition point in a feeder.

APPENDIX E – Example Calculations

1. High Voltage Arrester Selection Example for a 22 kV System

1. Determine Maximum Continuous Operating Voltage (MCOV)

For a 22 kV system with an earth fault factor (EFF) of 1.4:

$$MCOV = Line\ Voltage \times \frac{Earth\ Fault\ Factor}{\sqrt{3}}$$

Given:

- **Line Voltage** = 22 kV
- **Earth Fault Factor** = 1.4

$$MCOV = 22\ kV \times \frac{1.4}{\sqrt{3}}$$

$$MCOV \approx 22\ kV \times 0.81$$

$$MCOV \approx 17.82\ kV$$

2. Select Nominal Discharge Current (In)

Assume a nominal discharge current (In) of 10 kA, which is common for high-voltage arresters.

3. Calculate Energy Dissipation

Assume the energy rating is 2.5 kJ/kV of MCOV.

$$Energy = MCOV \times Energy\ Rating$$

$$Energy = 17.82\ kV \times 2.5\ kJ/kV$$

$$Energy \approx 44.55\ kJ$$

4. Determine Residual Voltage

Using the residual voltage curve from the manufacturer (assumed values for a 22 kV system):

- For 5 kA: 50 kV
- For 10 kA: 55 kV
- For 20 kA: 60 kV

For a nominal discharge current of 10 kA:

$$Residual\ Voltage\ (U_r) = 55\ kV$$

5. Compare Residual Voltage to Transformer LIWV

Assume the LIWV for a 22 kV transformer is 150 kV.

Calculation:

$$U_r < LIWV$$

$$55\ kV < 150\ kV$$

The residual voltage of 55 kV is well below the transformer LIWV of 150 kV.

6. Margin Calculation with Reflected Residual Voltage

If the residual voltage is reflected at the transformer terminals at nearly 2 times:

$$Reflected\ Residual\ Voltage = 2 \times U_r$$

$$Reflected\ Residual\ Voltage = 2 \times 55\ kV$$

$$Reflected\ Residual\ Voltage = 110\ kV$$

Margin:

$$Margin = LIWV - Reflected\ Residual\ Voltage$$

$$Margin = 150\ kV - 110\ kV$$

$$Margin = 40\ kV$$

Margin as a Percentage:

$$Margin\ Percentage = \left(\frac{Margin}{LIWV}\right) \times 100$$

$$Margin\ Percentage = \left(\frac{40\ kV}{150\ kV}\right) \times 100$$

$$Margin\ Percentage \approx 26.67$$

Conclusion:

- **Numerical Margin**: 40 kV
- **Percentage Margin**: 26.67%

The difference between the transformer's Lightning Impulse Withstand Voltage (LIWV) and the reflected residual voltage is 40 kV, which corresponds to approximately 26.7%. This demonstrates an adequate safety margin, exceeding the required 25%.

Effect of location of Surge Arresters from Transformer

Given Data:

- **System Voltage**: 22 kV
- **MCOV**: 17.82 kV (calculated previously)
- **Nominal Discharge Current (In)**: 10 kA
- **Residual Voltage at 10 kA**: 55 kV
- **Transformer LIWV**: 150 kV
- **Line Inductance**: Assume 1 μH/m (a typical value for overhead lines)

Example Calculation:

1. **Calculate Voltage Drop Due to Line Inductance**:
   For a surge traveling along a line with inductance, the voltage drop across the inductance can be estimated using:

$$V_L = L \times \frac{dI}{dt}$$

For a distance (d):

$$V_L(d) = 1\mu H/m \times 1.25 \times 10^9 \ A/s \times d$$

2. **Calculate Voltage Drop for Different Distances**:

Let's calculate for distances of 50 m and 100 m:

For 50 m:

$$V_L(50) = 1\mu H/m \times 1.25 \times 10^9 \ A/s \times 50 \ m$$

$$V_L(50) = 62.5 \ kV$$

For 100 m:

$$V_L(100) = 1\mu H/m \times 1.25 \times 10^9 \ A/s \times 100 \ m$$

$$V_L(100) = 125 \ kV$$

3. **Total Voltage at Transformer Terminals**:

The total voltage at the transformer terminals is the sum of the residual voltage and the voltage drop due to the line inductance.

For 50 m:

$$V_{total}(50) = Residual \ Voltage + V_L(50)$$

$$V_{total}(50) = 55\ kV + 62.5\ kV$$

$$V_{total}(50) = 117.5\ kV$$

For 100 m:

$$V_{total}(100) = Residual\ Voltage + V_L(100)$$

$$V_{total}(100) = 55\ kV + 125\ kV$$

$$V_{total}(100) = 180\ kV$$

4 **Compare with Transformer LIWV**:

- **For 50 m**: The voltage at the transformer terminals (117.5 kV) is below the LIWV (150 kV), providing adequate protection.
- **For 100 m**: The voltage at the transformer terminals (180 kV) exceeds the LIWV (150 kV), indicating insufficient protection and potential risk to the transformer.

Conclusion:

- **For a Distance of 50 m**: The arrester provides adequate protection as the voltage at the transformer terminals is within the LIWV. Margin 22%
- **For a Distance of 100 m**: The arrester does not provide adequate protection as the voltage at the transformer terminals exceeds the LIWV.

This demonstrates the importance of locating surge arresters as close as possible to the equipment they are protecting to ensure effective surge protection.

2. High Voltage Arrester Selection Example for a 132 kV System

1. Determine Maximum Continuous Operating Voltage (MCOV)

For a 132 kV system with an earth fault factor (EFF) of 1.4:

$$MCOV = Line\ Voltage \times \frac{Earth\ Fault\ Factor}{\sqrt{3}}$$

Given:

- **Line Voltage** = 132 kV
- **Earth Fault Factor** = 1.4

$$MCOV = 132\ kV \times \frac{1.4}{\sqrt{3}}$$

$$MCOV \approx 132\ kV \times 0.81$$

$$MCOV \approx 106.35\ kV$$

2. Select Nominal Discharge Current (In)

Assume a nominal discharge current (In) of 10 kA, which is common for high-voltage arresters.

3. Calculate Energy Dissipation

Using the updated energy rating of 4 kJ/kV of MCOV:

$$Energy = MCOV \times Energy\ Rating$$

$$Energy = 106.35\ kV \times 4\ kJ/kV$$

$$Energy \approx 425.4\ kJ$$

4. Determine Residual Voltage

Using the residual voltage curve from the manufacturer (assumed values for a 132 kV system):

- For 5 kA: 275 kV
- For 10 kA: 296 kV
- For 20 kA: 315 kV

For a nominal discharge current of 10 kA:

$$Residual\ Voltage\ (U_r) = 296\ kV$$

5. Compare Residual Voltage to Transformer LIWV

Assume the LIWV for a 132 kV transformer is 650 kV.

Calculation:

$$U_r < LIWV$$

$$296\ kV < 650\ kV$$

The residual voltage of 296 kV is well below the transformer LIWV of 650 kV.

6. Margin Calculation with Reflected Residual Voltage

If the residual voltage is reflected at the transformer terminals at nearly 2 times:

$$Reflected\ Residual\ Voltage = 2 \times U_r$$

$$Reflected\ Residual\ Voltage = 2 \times 296\ kV$$

$$Reflected\ Residual\ Voltage = 592\ kV$$

Margin:

$$Margin = LIWV - Reflected\ Residual\ Voltage$$

$$Margin = 650\ kV - 592\ kV$$

$$Margin = 58\ kV$$

Margin as a Percentage:

$$Margin\ Percentage = \left(\frac{Margin}{LIWV}\right) \times 100$$

$$Margin\ Percentage = \left(\frac{58\ kV}{650\ kV}\right) \times 100$$

$$Margin\ Percentage \approx 8.92$$

Conclusion:

- **Numerical Margin**: 58 kV
- **Percentage Margin**: 8.92%

The calculation indicates that the margin between a transformer's LIWV and the reflected residual voltage is 58 kV, or approximately 8.9%. This falls below the standard safety margin requirement of 25%.

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