



Part of Energy Queensland

Substation Standard

Standard for Insulation Co-ordination

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Approver	Carmelo Noel General Manager Asset Standards
If RPEQ Sign-off required insert details below.	
Certified Person Name and Position Title	Registration Number
John Lansley Manager Substation Standards	RPEQ 6371

Abstract: The aim of this document is to establish guidelines for insulation co-ordination within Energy Queensland. This document describes the functional requirements for substation insulation co-ordination and the integration of insulation co-ordination systems into a substation. This is to ensure the safety of personnel, the general public and network assets.

Keywords: Insulation, co-ordination, overvoltage, low frequency, transient, lightning, switching surge, surge arrester, protection, standard.

CONTENTS

1	Overview	5
1.1	Purpose	5
1.2	Scope	5
2	References	5
2.1	Legislation, regulations, rules, and codes.....	5
2.2	Energy Queensland controlled documents.....	5
2.3	Other sources	6
3	Definitions and abbreviations	6
3.1	Definitions.....	6
3.2	Abbreviations	9
4	Performance and Ratings.....	10
4.1	Ranges for highest voltage for equipment.....	10
4.2	Origin and classification of voltage stresses.....	11
4.3	Insulation characteristics.....	13
4.3.1	General.....	13
4.3.2	Self-restoring insulation	13
4.3.3	Non-self-restoring insulation	13
4.3.4	Insulation behaviour at power frequency voltage and temporary overvoltages.....	14
4.3.5	Probability of disruptive discharge under impulse voltage.....	14
4.4	Acceptable failure rates.....	14
5	Overvoltage protective devices and their characteristics	14
5.1.1	Surge arresters.....	14
5.1.2	Application of surge arresters	15
5.1.3	Surge arrester earthing	16
5.1.4	Surge arrester separation distance.....	16
5.1.5	Safety factor	16
5.1.6	Additional considerations.....	16
5.1.7	Pole footing impedance	16
5.1.8	Reducing lightning surges.....	16
5.1.9	Insulator design for overhead lines	16
6	Insulation co-ordination	17
6.1	General.....	17
6.2	Insulation co-ordination objectives	17
6.3	Procedure for insulation co-ordination.....	18
6.3.1	Design data and parameters.....	18

Standard for Insulation Co-ordination

6.3.2	Design considerations	19
6.3.3	Design outputs.....	19
Annex A	.....	20
Types of overvoltages	.....	20
A.1	Continuous power-frequency voltages.....	20
A.2	Temporary overvoltage.....	20
A.3	Fault overvoltage.....	20
A.4	Load rejection overvoltages.....	20
A.5	Transformer energisation overvoltages	21
A.6	Longitudinal overvoltage during synchronisation	21
A.7	Slow front overvoltage	21
A.8	Line energisation and re-energisation overvoltages.....	21
A.9	Fault and fault clearing overvoltages	22
A.10	Switching of capacitive or inductive current overvoltages	22
A.11	Slow-front lightning overvoltage	23
A.12	Fast front overvoltage	23
A.13	Shielding failure	23
A.14	Backflash.....	23
A.15	Induced voltage	23
A.16	Lightning type overvoltages due to switching.....	24
Annex B	.....	25
Insulation co-ordination checklist – example	.....	25
Annex C	.....	26
Historical overview of standards.....		26
Annex D	.....	28
Revision History	.....	28

FIGURES

Figure 4-1 - Classes and shapes of overvoltages, standard voltage shapes and standard withstand voltages tests (IEC 60071.1, 2019)	11
Figure 4-2 - Overvoltage representation of magnitudes and durations.	12
Figure 6-1 Insulation Co-ordination Procedure (IEC 60071.1, 2019)	18

TABLES

Table 4-1 - Substation equipment insulation ratings as outlined in the Standard for HV Equipment Ratings - 26945507 (STNW3015)	10
Table 4-2 - System temporary overvoltage characteristics	12
Table 5-1 - Surge arrester locations	15

Standard for Insulation Co-ordination



EQUATIONS

Equation 1: p.u. reference value 12

1 Overview

1.1 Purpose

Insulation co-ordination is the arrangement of insulation levels of different components in the substation. This is required so that if an insulation failure occurs, it would be confined to the place on the system where it would result in the least damage, be the least expensive to repair and cause the least disturbance to the continuity of supply. In addition to the substation equipment normal operating voltage, it will be subjected to different types of overvoltages. It is required to select dielectric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available protective devices.

Ergon Energy and Energex have adopted a set of standards rated withstand voltages, minimum clearances, and a specified outage rate for direct lightning strike shielding. Therefore, insulation co-ordination studies are shortened to the task of reducing overvoltage stresses on equipment by providing adequate surge protection by selection and positioning of surge arresters.

1.2 Scope

This document provides an overview of insulation levels, voltage stresses and procedures for insulation co-ordination studies.

The aim is to minimise equipment damage and network outages due to overvoltages so far as reasonably practicable.

This document does not cover specific aspects of insulation co-ordination such as lightning strike shielding and selection of surge arresters. They are covered in other documents and application guides.

2 References

2.1 Legislation, regulations, rules, and codes

Document	Type
<i>Electricity Act 1994 (Qld)</i>	Legislation
Electricity Regulation 2006 (Qld)	Regulation
<i>Electrical Safety Act 2002 (Qld)</i>	Legislation
Electrical Safety Regulation 2013 (Qld)	Regulation
National Electricity Rules	Regulation
<i>Queensland WH&S Regulation 2011</i>	Legislation

2.2 Energy Queensland controlled documents

Document	Alternative Doc ID
Standard for Clearances in Air - 3054141	STNW3013

Standard for Insulation Co-ordination

Standard for Selection of Surge Arresters - 3055929	STNW3033
Standard for Substation Direct Lightning Strike Shielding - 20389422	STNW3032
Standard for HV Equipment Ratings - 26945507	STNW3015
Standard for Substation Earthing - 39342177	

2.3 Other sources

AS 60099.4:2022, (Standards Australia)

Surge arresters, Part 4: Metal-oxide surge arresters without gaps for a.c. systems, (Australian Standard)

AS 2067, 2016, (Standards Australia)

Substations and high voltage installations exceeding 1 kV a.c., (Australian Standard)

IEC 60071.1, 2019, (IEC)

Insulation co-ordination, Part 1: Definitions, principles and rules, (IEC Standard)

IEC 60071.2, 2023, (IEC)

Insulation co-ordination, Part 2: Application guidelines, (IEC Standard)

IEC TR 60071-4, 2004, (IEC)

Insulation co-ordination, Part 4: Computational guide to insulation co-ordination and modelling of electrical networks, (IEC Standard)

C62.82.2-2022 (IEEE)

IEEE Guide for the Application of Insulation Coordination, (IEEE Guide)

Juan A. Martinez-Velasco, Francisco González Molina, 2015, POWER SYSTEM TRANSIENTS – Temporary Overvoltages in Power Systems viewed August 2020, <http://www.eolss.net/Sample-Chapters/C05/E6-39-59-05.pdf>

3 Definitions and abbreviations

3.1 Definitions

For the purposes of this standard, the following definitions apply.

Continuous voltage	Considered having constant r.m.s value, continuously applied to any pair of terminals of an insulation [(IEC 60071.1, 2019), modified].
Earth fault factor (k)	At a given location of a three-phase system, and for a given system configuration, the ratio of the highest RMS phase-to-earth power-frequency voltage on a healthy phase during a fault to earth affecting one or more phases at any point on the system to the RMS phase-to-earth power-frequency voltage which would be obtained at the given location in the absence of any such fault (IEC 60071.1, 2019).
External insulation	The distances in atmospheric air, and the surfaces in contact with atmospheric air of solid insulation of the equipment which are subject to dielectric stresses

	and to the effects of atmospheric and other external conditions, such as pollution, humidity, vermin, etc. (IEC 60071.1, 2019).
Highest voltage for equipment (U_m)	The highest r.m.s. value of phase-to-phase voltage for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage [(IEC 60071.1, 2019), modified].
Highest voltage of a system (U_s)	The highest value of operating voltage which occurs under normal operating conditions at any time and at any point in the system [(IEC 60071.1, 2019), modified].
Impedance earthed (neutral) system	A system where the neutral point is connected through an impedance (resistor/reactor) to reduce the prospective earth fault current. For a line-ground fault, the unfaulted phases may rise above normal operating voltages. The ratio between the upstream positive and zero sequence impedance and the neutral impedance will affect the earth fault factor.
Insulation co-ordination	Selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices. The "dielectric strength" of the equipment is meant here as its rated insulation level or its standard insulation level (IEC 60071.1, 2019).
Insulation failure	Failure of insulation is the most common cause of problems in electrical equipment. The purpose of insulation is to prevent the flow of electric current between points of different potential in an electrical system.
Internal insulation	The internal solid, liquid, or gaseous parts of the insulation of equipment which are protected from the effects of atmospheric and other external conditions (IEC 60071.1, 2019).
Lightning impulse protection level (U_{pl})	Maximum permissible peak voltage value on the terminals of a protective device subjected to lightning impulses under specific conditions (IEC 60071.1, 2019).
Lightning impulse withstand voltage (LIWV) or basic insulation level (BIL)	The electrical strength of insulation expressed in crest value of a standard lightning impulse under standard atmospheric conditions. The standard lightning impulse is an impulse voltage having the front time 1.2 μ s and a time to half value of 50 μ s (1.2x50 μ s).
Nominal Voltage of a System (U_n)	A suitable approximate value of voltage used to designate the identity of a system (IEC 60071.1, 2019).
Non self-restoring insulation	Insulation which loses its insulating properties, or does not recover them completely, after a disruptive discharge (IEC 60071.1, 2019).
Overvoltages (OV)	Between one phase conductor and earth or across a longitudinal insulation having a peak value exceeding the peak of the highest voltage of the system divided by $\sqrt{3}$ or between phase conductors having a peak value exceeding the amplitude of the highest voltage of the system (IEC 60071.1, 2019).
Performance criterion	The basis on which the insulation is selected so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to equipment insulation or affect continuity of service.

	<p>This criterion is usually expressed in terms of an acceptable failure rate (number of failures per year, years between failures, risk of failure, etc.) of the insulation configuration. See Substation Direct Lightning Strike Shielding SS-1-8-2 for more information [(IEC 60071.1, 2019), modified].</p>
Rated insulation level	A set of standards withstand voltages which characterise the dielectric strength of the insulation.
Rated withstand voltage	<p>The value of the test voltage, applied in a standard withstand voltage test that proves that the insulation complies with one or more required withstand voltages.</p> <p>Note 1 to entry: It is a rated value of the insulation of the equipment.</p>
Representative overvoltages (U _{rp})	Overvoltage assumed to produce the same dielectric effect on the insulation as the overvoltage of a given class occurring in service due to various origins (IEC 60071.1, 2019).
Required withstand voltage (U _{rw})	The test voltage that the insulation must withstand in a standard withstand test to ensure that the insulation will meet the performance criterion when subjected to a given class of overvoltages in actual service conditions and for the whole service duration. The required withstand voltage has the shape of the co-ordination withstand voltage and is specified with reference to all the conditions of the standard withstand test selected to verify it (IEC 60071.1, 2019).
Self-restoring insulation	Insulation which completely recovers its insulating properties within a short time interval after a disruptive discharge (IEC 60071.1, 2019).
Service reliability	The ability of a power system to meet its supply function under stated conditions for a specified period of time.
Short-duration power frequency withstand voltage (PFWV) also referred to as ACWV	The electrical strength of insulation expressed in r.m.s value of a standard short-duration power frequency voltage under standard atmospheric conditions. The standard short-duration power frequency voltage is a sinusoidal voltage with frequency between 48 Hz and 62 Hz, and duration of 60 s.
Standard rated withstand voltage (U _w)	Standard value of the rated withstand voltage as specified in this document (IEC 60071.1, 2019).
Statistical LIWV/BIL (or SIWV/BSL)	The crest value of a standard lightning (or switching) impulse for which the insulation exhibits a 90% probability of withstand (or a 10% probability of failure) under specified conditions applicable to self-restoring insulation.
Surge arrester (SA)	A protective device for limiting surge voltages on equipment by diverting surge current and returning the device to its original status. It is capable of repeating these functions as specified.
Switching impulse protective level (U _{ps})	Maximum permissible peak voltage value on the terminals of a protective device subjected to switching impulses under specific conditions (IEC 60071.1, 2019).
Switching impulse withstand voltage (SIWV) or basic	The electrical strength of insulation expressed in crest value of a standard switching impulse.

switching impulse insulation level (BSL)	
Switching overvoltage	A transient OV in which a slow front, short duration, unidirectional or oscillatory, highly damped voltage is generated (usually by switching or faults). $T_1 = 20\text{-}5000 \mu\text{s}$, $T_2 < 20000 \mu\text{s}$.
The standard lightning impulse	An impulse voltage having a front time of $1.2 \mu\text{s}$ and a time to half value of $50 \mu\text{s}$.
The standard short duration power frequency voltage	A sinusoidal voltage having a frequency between 48 Hz and 62 Hz , and duration of 60 s .
The standard switching impulse	An impulse voltage having a time to peak of $250 \mu\text{s}$ and a time to half value of $2500 \mu\text{s}$.
Transient overvoltage	Short duration overvoltage of few milliseconds or less, oscillatory or non-oscillatory, usually highly damped (IEC 60071.1, 2019).
Withstand voltage	Value of the test voltage to be applied under specified conditions in a withstand voltage test, during which a specified number of disruptive discharges is tolerated [(IEC 60071.1, 2019), modified].

3.2 Abbreviations

This list does not include well-known unambiguous abbreviations, or abbreviations defined at their first occurrence within the text.

BIL	Basic Insulation Level
CFO	Critical Flashover
EQL	Energy Queensland Limited
FFO	Fast-front overvoltages
IEC	International Electrotechnical Commission
k	Earth fault factor
Kc	Co-ordination factor
Ks	Safety factor
Kt	Atmospheric correction factor
LIWV	Lightning Impulse Withstand Voltage also referred to as Basic Insulation Level (BIL)
OV	Overvoltage
p.u.	Power System Computer Aided Design / Electromagnetic Transients Program
PSCAD/EMTP	Power System Computer Aided Design / Electromagnetic Transients Program
SIWV	Switching impulse withstand voltage
SFO	Slow-front overvoltages
SM	Station class arrester – Medium duty type
TOV	Temporary power-frequency overvoltage

Standard for Insulation Co-ordination

Um	Highest equipment voltage
Un	Nominal voltage
Ur	Surge diverter rated voltage level
Urw	Required withstand voltage
Us	Highest voltage of a system
Uw	Standard rated withstand voltage
VFFO	Very-fast-front overvoltages

4 Performance and Ratings

4.1 Ranges for highest voltage for equipment

Two standards rated withstand voltages are sufficient to define the rated insulation levels of the equipment (IEC 60071.1, 2019):

- For equipment in range I: Above 1 kV to 245 kV:
 - the standard rated lightning impulse withstand voltage and,
 - the standard rated short-duration power-frequency withstand voltage.
- For equipment in range II: Above 245 kV:
 - the standard rated switching impulse withstand voltage, and
 - the standard rated lightning impulse withstand voltage.

Within substations, equipment insulation shall meet the required withstand voltages outlined in Table 4-1. These insulation levels have been predetermined and are discussed in the Standard for HV Equipment Ratings - 26945507 (STNW3015).

Table 4-1 - Substation equipment insulation ratings as outlined in the Standard for HV Equipment Ratings - 26945507 (STNW3015)

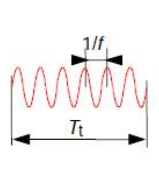
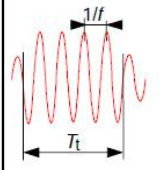
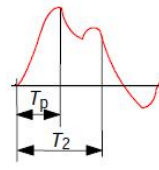
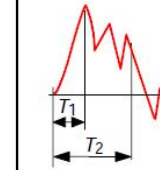
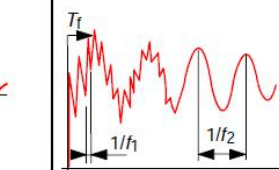
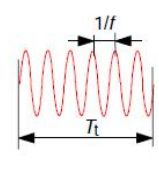
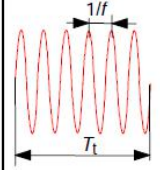
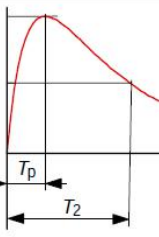
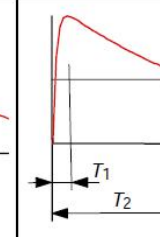
Nominal Voltage kV	Highest Voltage kV	Rated Short duration power frequency withstand voltage (PFWV) kV	Rated lightning impulse withstand voltage (LIWV) kVp
11	12	28	95 (75)
22	24	50	150 (125)
33	36	70	200 (170)
66	72.5	140	325
110	123	230	550
132	145	275 (230)	650 (550)

Standard for Insulation Co-ordination

Nominal Voltage kV	Highest Voltage kV	Rated Short duration power frequency withstand voltage (PFWV) kV	Rated lightning impulse withstand voltage (LIWV) kVp
220	245	460 (395)	1050 (950)
NOTE: 1. Values in brackets specify lower acceptable LIWV and PFWV ratings for cable connected equipment.			

4.2 Origin and classification of voltage stresses

The voltage stresses on insulation (IEC 60071.1, 2019) have been classified with reference to the shape of the voltage wave, which determines their effect on insulation and protective devices, without reference to the cause of overvoltages, as shown in Figure 4-1 below.

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	$f = 50 \text{ Hz or } 60 \text{ Hz}$ $T_t \geq 3 \text{ 600s}$	$10 \text{ Hz} < f < 500 \text{ Hz}$ $0,02 \text{ s} \leq T_t \leq 3 \text{ 600 s}$	$20 \mu\text{s} < T_p \leq 5 \text{ 000 } \mu\text{s}$ $T_2 \leq 20 \text{ ms}$	$0,1 \mu\text{s} < T_1 \leq 20 \mu\text{s}$ $T_2 \leq 300 \mu\text{s}$	$T_t \leq 100 \text{ ns}$ $0,3 \text{ MHz} < f_1 < 100 \text{ MHz}$ $30 \text{ kHz} < f_2 < 300 \text{ kHz}$
Standard voltage shapes	 $f = 50 \text{ Hz or } 60 \text{ Hz}$ T_t^a	 $48 \text{ Hz} \leq f \leq 62 \text{ Hz}$ $T_t = 60 \text{ s}$	 $T_p = 250 \mu\text{s}$ $T_2 = 2 \text{ 500 } \mu\text{s}$	 $T_1 = 1,2 \mu\text{s}$ $T_2 = 50 \mu\text{s}$	a
Standard withstand voltage test	a	Short-duration power frequency test	Switching impulse test	Lightning impulse test	a

^a To be specified by the relevant apparatus committees.

Figure 4-1 - Classes and shapes of overvoltages, standard voltage shapes and standard withstand voltages tests (IEC 60071.1, 2019)

It is conventional to express overvoltages as a ratio in terms of per unit (p.u.) of the peak value of overvoltages to the peak value of phase-to-earth of the highest voltage for system and or equipment.

$$\text{The p.u. reference value} = \sqrt{2} \times \frac{Um}{\sqrt{3}}$$

Equation 1: p.u. reference value

The relative magnitude and duration of overvoltages are illustrated in Figure 4-2

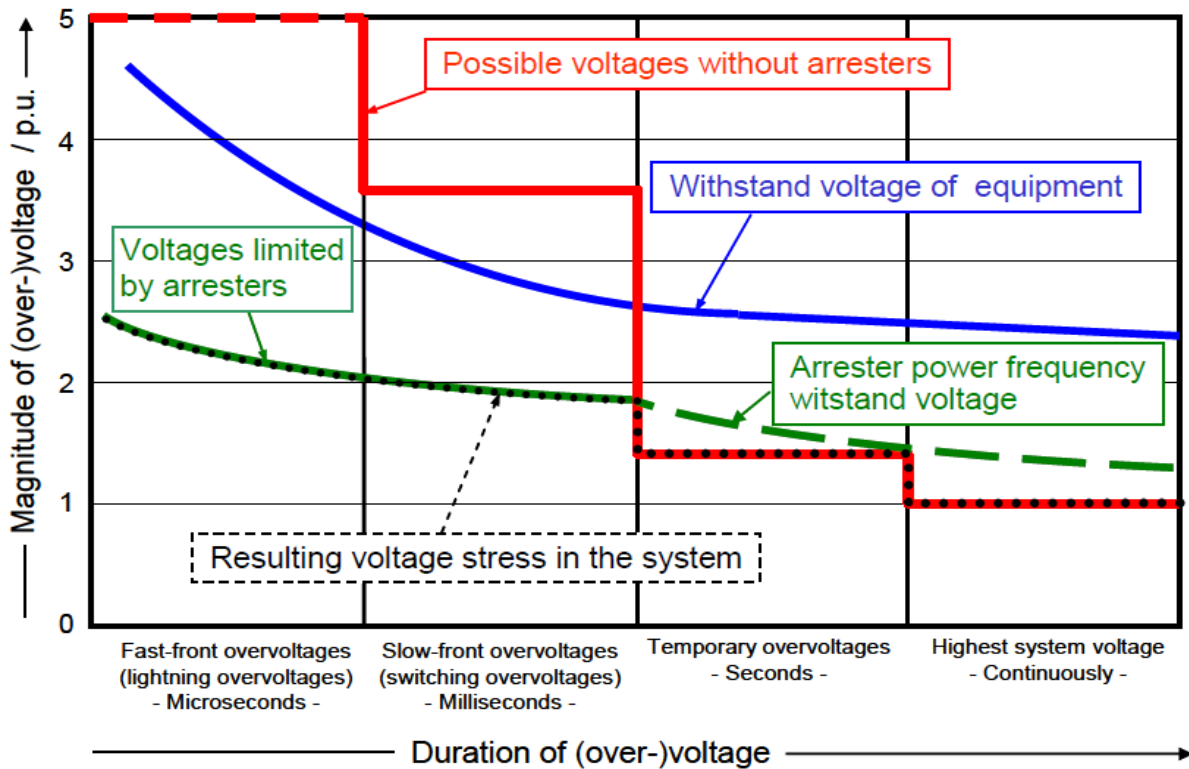


Figure 4-2 - Overvoltage representation of magnitudes and durations.

Table 4-2 - System temporary overvoltage characteristics below outlines the typical magnitudes of temporary overvoltages in p.u. and typical fault times.

Table 4-2 - System temporary overvoltage characteristics

Temporary Overvoltage Cause	Magnitude of Overvoltage (p.u.)	Fault time
Fault Overvoltage (Effectively earthed)	1.3	Less than 1 second
Fault Overvoltage (Impedance earthed)	1.3 - 1.73	Less than 3 seconds
Load Rejection (Moderately extended)	< 1.2	Up to 7 minutes
Load Rejection (Extended system)	1.5	A few seconds
Load Rejection (Resonance & Ferroresonance)	3	Until cleared
Transformer Energisation	1.5 to 2.0	May last for seconds
Longitudinal Overvoltage (synchronisation)	2.0	A few seconds to several minutes

Standard for Insulation Co-ordination

Temporary Overvoltage Cause	Magnitude of Overvoltage (p.u.)	Fault time
Slow Front Overvoltage (Line Energisation Ph-E)	2.8 to 3.0	-
Slow Front Overvoltage (Line Energisation Ph-Ph)	1.55 x Line Energisation Ph-E Fault level	-
Slow Front Overvoltage (Fault initiation max.)	2(k-1) k = earth fault factor	-
Slow Front Overvoltage (Fault clearing max.)	2.0	-
Slow Front Overvoltage (Switching of capacitive or inductive current)	< 2.0 (Ph-Ph) < 3.0 (Ph-E)	-
Switching (Lightning Type)	2.0 (Without restrike) 3.0 (With restrike)	-

4.3 Insulation characteristics

4.3.1 General

Several factors which influence the dielectric strength of insulation include:

- The magnitude, shape and polarity of the applied voltage
- The type of insulation (gaseous, liquid, impurity and local inhomogeneities)
- The physical state of the insulation medium (temperature, pressure and other ambient conditions, mechanical stresses)
- Prior duty on the insulation
- Chemical effects
- Conductor surface effects

Insulation may be classified as either self-restoring or non-self-restoring.

4.3.2 Self-restoring insulation

The breakdown of air is strongly dependent on the gap configuration, wave shape and polarity of the surge and on ambient conditions. For outdoor insulators, the effects of humidity, rain and pollution on the surface of the insulation also become important. For metal enclosed gas-insulated systems, the effect of the internal pressure, temperature, local inhomogeneities and impurity play an important role.

4.3.3 Non-self-restoring insulation

In liquid insulation, particle impurities, bubbles caused by chemical and physical effects or local discharges can drastically reduce the insulation strength. The amount of chemical degradation of the insulation may tend to increase with time. The same is valid for solid insulation. In this case, the mechanical stress may also affect the insulation strength.

4.3.4 Insulation behaviour at power frequency voltage and temporary overvoltages

Generally, discharge under power frequency voltage in normal operating conditions and under TOV will be caused by progressive deterioration of the insulating properties of the equipment or by exceptional reductions in insulation withstand due to severe ambient conditions.

Rain, fog, dew formation together with pollution can drastically reduce insulation strength.

4.3.5 Probability of disruptive discharge under impulse voltage

Non-self-restoring insulation

There are no methods presently available for determining the probability of a disruptive discharge of non-self-restoring insulation. Therefore, the probability of a withstand is assumed to be 100% at or below LIWV and SIWV. However, for stresses above the LIWV and SIWV level the probability of withstand is assumed to be zero.

Partial discharge in non-self-restoring insulation is not covered in this standard.

Self-restoring insulation

For self-restoring insulation, the probability of flashover may be described by an insulation strength characteristic curve. This curve has two basic parameters, the Critical Flashover (CFO), corresponding to the 50% probability of flashover for single impulse application, and a normalised standard deviation σ_t . σ_t may be taken as 0.03 p.u. for lightning impulse voltages and 0.06 p.u. for switching impulse voltages.

4.4 Acceptable failure rates

The performance of an insulation system is determined by the number of insulation failures while in service. This is based on the voltage stresses imposed on equipment which cause damage to equipment insulation or affect continuity of service. The Insulation Co-ordination Application Guidelines (IEC 60071.2, 2014) provides the following general guidance on acceptable failure rates:

- Substation equipment: 0.001/year to 0.004/year depending on repair times or (250 to 1000 years mean time between failure (MTBF)).
- Overhead lines 0.1 to 20 failures / 100km /year (depending on design of line, lightning protection online, tower footing resistance among other factors).
- Switching overvoltages: 0.01 to 0.001 per operation.

Minimum MTBF design targets to be used for the Ergon and Energex network are specified in Substation Direct Lightning Strike Shielding Standard - 20389422 (STNW3032).

5 Overvoltage protective devices and their characteristics

5.1.1 Surge arresters

Surge arresters are designed to limit the magnitude of overvoltage across their terminals to an acceptable voltage. Spark gaps shall not be used in EQL.

The main type of surge arrester currently employed within the EQL networks is the metal-oxide surge arresters without gaps, type SM or higher (IEC 60099-4, 2014), although gapped silicon-carbide arresters may still exist in older installations.

5.1.2 Application of surge arresters

Table 5-1 provides a guide to locations of where surge arresters are to be installed within a substation to ensure insulation co-ordination.

Table 5-1 - Surge arrester locations

Case / Equipment	Surge Arrester Requirement
Equipment connected to an overhead line	Location at feeder bay entrance/exit.
Overhead line to cable transition point	For distribution, sub-transmission and transmission high voltages.
Power transformer	<p>On all HV open bushings, located on separate structure no more than 5m from the bushings or located on bracket attached to the transformer.</p> <p>Arresters are not required:</p> <ul style="list-style-type: none"> • On transformer cable boxes • On plug-in connected bushings • Where the LIWV of the winding exceeds both the inductive transferred voltage and initial spike voltage • Connected directly to cables and completely shielded by an earthed enclosure, and the next transitions to overhead conductors are protected by surge arresters. • The neutral is directly earthed • Impedance-earthed neutral bushings on uniformly-insulated windings
Gas insulated switchgear (GIS) and MV switchboards	For switchgear with lower LIWV rating connected by mixed overhead/underground feeder, 2 x surge arresters to be installed at overhead transition pole and next pole back.
Capacitor bank and shunt reactor	At the line terminals, no more than 5m from terminals
Reclosers	Arresters at HV bushings to take account of lower LIWV (where applicable)
Underground cable sheaths (33kV cables and above)	<p>In addition to the primary insulation, protection of the outer cable jacket or oversheath may also be required. Sheath voltage limiters (SVL's) may be required to reduce transient and steady state voltages to acceptable levels on the cable screen/sheath to prevent puncture of the cable jacket/oversheath. In the absence of an insulation co-ordination study specific to the cable, the following SVLs shall be used:</p> <ul style="list-style-type: none"> • 33kV – 3kV • 66kV – 4.5kV • 110/132kV – 6.0kV

There are no surge arrester requirements for the following equipment:

- Outdoor equipment such as instrument transformers, disconnectors and circuit breakers should be adequately protected by the surge arresters installed on feeder line entry.
- Wave Traps. Phase-to-earth protection is not provided for this equipment since flashover would occur at the support insulators. Furthermore, manufacturers provide a protective device for low voltage components of the tuning pack.

5.1.3 Surge arrester earthing

To adequately protect substation equipment through the use of surge arresters, both the equipment being protected, and surge arresters shall be connected to the substation earth grid. Arrester footing resistance and downloads also have an impact on travelling waves from surges.

See (Substation Earthing - 39342177) for more information.

5.1.4 Surge arrester separation distance

The shorter the distance between the surge arrester and the equipment to be protected, the better is the protection against overvoltages.

5.1.5 Safety factor

The following safety factors (Ks) should be used as a minimum when using protective devices, such as metal-oxide surge arresters (IEC 60071.2, 2014).

- Internal insulation: $K_s = 1,15$
- External insulation: $K_s = 1,05$

5.1.6 Additional considerations

Other considerations for substation insulation co-ordination include:

- Pole footing impedance
- Reducing wavefront of incoming lightning surges
- Lightning surges under surge arrester discharge current

5.1.7 Pole footing impedance

Reducing the footing resistance of the overhead earth wire on towers or poles adjacent to the substation will lessen the incidence, steepness and magnitude of lightning surges entering the substation. Footing resistances shall be 10Ω and 5Ω within 2km of a substation before being connected to the OHEW.

5.1.8 Reducing lightning surges

The magnitude and wavefront rise time of any lightning surge entering a substation from a connecting feeder can be reduced by:

- Increasing the lightning shielded zone of feeders out from the substation.
- A lower surge impedance for HV underground cable reduces the impulse voltage transmitted into the substation, even for short lengths of cable. Transitions between overhead and underground cable will include a set of surge arresters as well.

5.1.9 Insulator design for overhead lines

Outage rates for overhead lines can be reduced by increasing the number of insulator discs. This also reduces back flashovers from strikes to the overhead earth wire. However, it also allows higher magnitude strikes to phase conductors to pass into the substation, which can adversely affect insulation co-ordination.

An additional disc is required at the where the overhead line landing span terminates at the substation landing structure.

6 Insulation co-ordination

6.1 General

Insulation co-ordination within substations is required to achieve acceptable service reliability by minimising the risk of insulation failure to major plant and equipment. This is achieved by a combination of the following:

- Determination of voltage stresses
- Minimum insulation levels for substation equipment
- Limitation of voltage stresses, through the use of protective devices, shield wires and improved earthing.

A new or review of an existing insulation co-ordination study is **NOT** required if:

- Surge arresters are installed at locations in accordance with Table 5-1 - Surge arrester locations.
- The selection of surge arresters and selection of pollution level has been in accordance with Selection of Surge Arresters - 3055929 (STNW3033). The response to power frequency of external insulation of equipment becomes important when contamination is present. The external insulation must be designed for contamination severity.
- Equipment LIWV values are selected in accordance with Table 4-1 - Substation equipment insulation ratings.
- Substation sites are protected from direct lightning strikes by adequate shielding in accordance with Substation Direct Lightning Strike Shielding Standard - 20389422 (STNW3032).
- Sites meet minimum overhead earth wire shielding distance of the overhead lines entering or leaving major substations. The OHEW shall be sized to carry expected earth fault currents without damage, including the effects of auto-reclose. In the absence of any other information, assume an arc resistance of 10 ohms for any studies. The first span of an OHEW from the substation shall carry 100% of the expected earth fault current, the first 2 km from the substation 80% and the remainder 50%.
- The associated structure footing resistances meet the requirements of Section 5.1.7

Equipment clearances shall maintain electrical safety and maintenance requirements. The minimum air clearance requirements shall be as per the Clearances in Air Standard (STNW3013).

6.2 Insulation co-ordination objectives

The objective of insulation co-ordination study is to minimise the risk of equipment failure and outages due to overvoltages as far as reasonably practical. This can be achieved by:

Defining the rated insulation level of the equipment. Lightning impulse and short duration power frequency withstand voltage for the range I voltages (U_m up to 245 kV) is required (IEC 60071.1).

Switching studies may be required at lower voltages in special applications (e.g., non-standard configurations) using the methods outlined in the Insulation Co-ordination Application Guidelines (IEC 60071.2) and/or simulation studies. PSCAD / EMTP software shall be used where computer modelling is required.

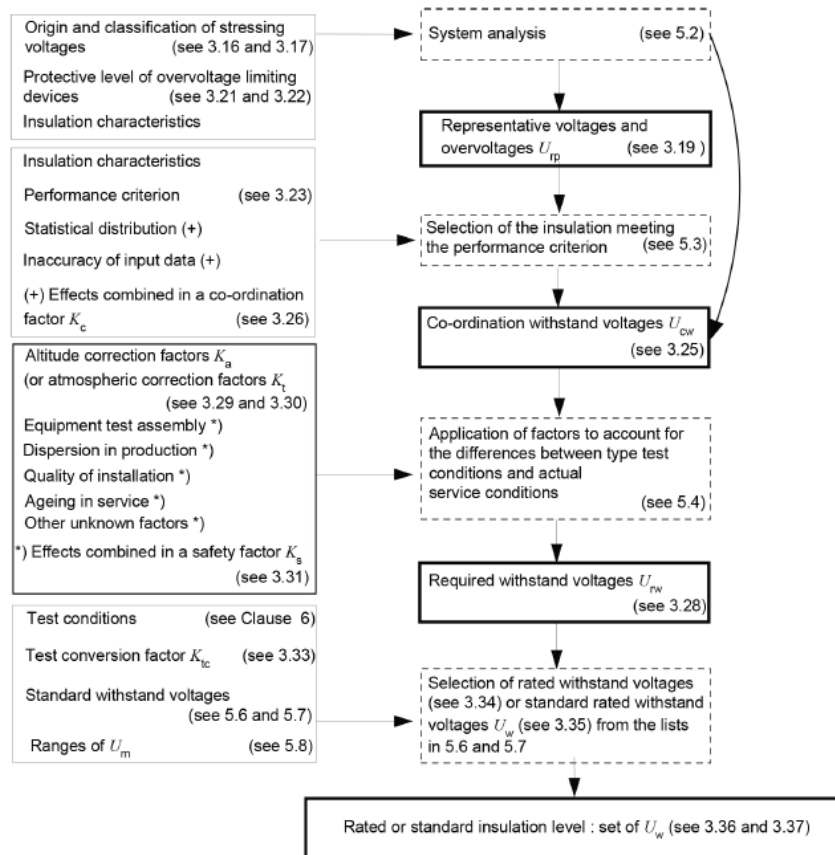
Substation sites should be protected from direct lightning strikes by adequate shielding in accordance with Substation Direct Lightning Strike Shielding Standard - 20389422 (STNW3032).

Equipment clearances shall maintain electrical safety and maintenance requirements as per the Clearances in Air standard (STNW3013).

6.3 Procedure for insulation co-ordination

The procedure for insulation co-ordination consists of the selection of the highest voltage for the equipment together with a corresponding set of standards rated withstand voltages which characterise the insulation of the equipment needed for the application.

The general procedure can be summarised by the following steps for insulation co-ordination:



NOTE In brackets the subclauses reporting the definition of the term or the description of the action.

- Sided boxes refer to required input
- Sided boxes refer to performed actions
- Sided boxes refer to obtained results

IEC

Figure 6-1 Insulation Co-ordination Procedure (IEC 60071.1, 2019)

The requirements for equipment insulation are already predetermined via a set of withstand voltages, as outlined in clause 4.1. The process of insulation co-ordination is reduced to the selection and suitable placement of adequate overvoltage protective devices to limit voltage stresses on equipment insulation.

6.3.1 Design data and parameters

The following items are design inputs for a substation insulation co-ordination study and design;

- Substation single line diagram
- Substation equipment insulation withstand levels
- System voltages, system impedance, system earthing, and pollution levels
- Characteristics of protective devices such as surge arresters
- Incoming/outgoing feeder configuration, e.g., underground or overhead feeder, overhead earth wire /cable sheath configuration details

6.3.2 Design considerations

The following overvoltages should be considered:

- Continuous and temporary over-voltages
- Slow front and
- Fast front over-voltages

The study should consider all operational scenarios that may cause system overvoltage including capacitor and reactor switching.

The detailed procedure for the calculation of overvoltages in 6.3.2 is outlined in Annex G of the Insulation Co-ordination Application Guidelines (IEC 60071.2). The Computational Guide to Insulation Co-Ordination and Modelling of Electric Networks (IEC 60071-4) gives examples of the insulation co-ordination procedure if using PSCAD / EMTP.

6.3.3 Design outputs

The following items are the design outputs to be produced to identify the major substation insulation co-ordination design and installation requirements and is to include, but not limited to, the following:

- Determination of locations and details of overvoltage protective devices shown on substation design drawings; (updated SLD if modification have been made)
- Calculations to determine surge arrester ratings and evaluation of protective ratios and margins (separation distances) using (STNW3033) Selection of Surge Arresters - 3055929
- Completed checklist for Insulation Co-ordination Report in Annex B

Annex A

Informative

Types of overvoltages

A.1 Continuous power-frequency voltages

The continuous power-frequency withstand voltage of the insulation can be defined as the highest equipment voltage, U_m .

A.2 Temporary overvoltage

Temporary overvoltages can be defined by an amplitude-duration characteristic. The four main types of temporary overvoltages are:

- Fault overvoltages
- Load rejection overvoltages
- Transformer energisation overvoltages
- Longitudinal overvoltage during synchronisation

A.3 Fault overvoltage

Earth faults produce temporary power-frequency phase-earth overvoltages on the healthy phases. The temporary overvoltage between phases or across longitudinal insulation normally does not occur.

The amplitude of the temporary overvoltages depends on system earthing. In effectively earthed systems, the TOV is about 1.3 p.u. and the duration, considering backup protection, is generally < 1 s.

In impedance earthed systems, the TOV is about 1.73 p.u. or greater the duration is generally less than 10 s with earth fault clearing or undefined in systems without fault clearing. The amplitude of fault overvoltages depends on the earth fault factor of the system. Calculation of earth fault factor is given in (STNW3033) Selection of Surge Arresters - 3055929.

A.4 Load rejection overvoltages

Temporary overvoltages caused by load rejection are a function of the load rejected, system topology after rejection and the characteristics of the sources. In a system with relatively short lines for full load rejection, the temporary overvoltage is < 1.2 p.u. and the duration of the overvoltage may be up to several minutes.

In a system with long lines, the temporary overvoltage may be 1.5 p.u. or more, the duration of the overvoltage may be in the order of a few seconds.

Resonance and ferroresonance should also be considered as part of load rejection overvoltages. Temporary overvoltages arise from the interaction between capacitive elements (lines, cables, capacitors) and inductive elements having non-linear magnetising characteristics (transformers, shunt reactors). These types of overvoltages can have a magnitude of 3.0 p.u. and last until the condition is cleared.

A.5 Transformer energisation overvoltages

The temporary overvoltages resulting from transformer energisation typically have a magnitude in the range of 1.5 to 2.0 p.u. and may last for seconds.

A.6 Longitudinal overvoltage during synchronisation

Longitudinal overvoltages may occur during synchronisation of generators to the network, due to phase opposition. (Martinez-Velasco & Molina, 2015) The magnitude of the overvoltage is 2 p.u. and may last from a few seconds to several minutes.

A.7 Slow front overvoltage

Slow-front overvoltages (SFO) typically have a duration of tens to thousands of microseconds and tail durations in the same order of magnitude, with an oscillatory nature. The representative voltage shape of the SFO is the standard switching impulse, 250/2500 μ s, as seen in Figure 4-1.

SFO generally arise from:

- Line energisation and re-energisation
- Faults and fault clearing
- Switching of capacitive or inductive current
- Load rejection
- Distance lightning strikes to conductors and overhead lines

A.8 Line energisation and re-energisation overvoltages

In the earlier defined ranges for U_m , in range I switching overvoltages generally do not constitute a serious problem and therefore insulation co-ordination is primarily based upon the lightning overvoltage in overhead line systems.

In range II, however, overvoltages due to closing and re-closing of single-phase or three-phase are of great importance in the selection of system insulation.

Line switching overvoltages may be reduced through the use of the following:

- Pre-insertion of resistors on the circuit breakers
- Controlled closing of the breaker
- Surge arresters

The typical phase-to-earth switching overvoltages at the end of a line have a magnitude of 2.8 to 3.0 p.u. when pre-insertion of resistors on the circuit breakers are not used. Where surge arresters are used at the end of the line the overvoltage is limited to the surge arrester SPL, typically 70% of the typical overvoltage magnitude.

Phase-to-phase switching overvoltages are typically 1.55 times the phase-to-earth switching overvoltages. The use of surge arresters will limit the overvoltage to approximately twice the SPL of the arrester.

Longitudinal switching overvoltages, in synchronised systems, have the same polarity as the operating voltage. Thus, longitudinal insulation is exposed to a lower overvoltage than the phase-to-earth overvoltages. In non-synchronous systems longitudinal insulation can be subject to opposing polarities at each end, with different overvoltage levels. One terminal will be subject to energisation overvoltages while the other terminal is subject to the peak of the operating voltage, with each terminal having opposite polarities (IEEE, 2022).

A.9 Fault and fault clearing overvoltages

Within the previously defined ranges in clause 4.1, range I and sometimes range II, high switching overvoltages can arise at the initiation of an earth fault or load rejection. Conservative estimates of maximum levels are:

- Fault initiation maximum is equal to $(2k-1)$ p.u.
- Fault clearing maximum is equal to 2.0 p.u.

Where k is the earth fault factor of the system.

A.10 Switching of capacitive or inductive current overvoltages

Where switching is concerned, the following operations should be considered:

- Interruption of motor starting current
- Interruption of transformer or reactor magnetising current
- Switching arc furnace and their transformers
- Switching of unloaded cables and capacitor banks
- Interruption of currents by high voltage fuses

In range I defined in clause 4.1, the switching of inductive or capacitive current can give rise to overvoltages, which may require attention, however, are generally not of great concern.

In range II, overvoltages due to restrikes or re-ignitions of the arc of a switching device during interruption of capacitive current such as unload of lines, cables or capacitor banks can produce extremely high overvoltages.

The energisation of capacitor banks produces overvoltages at the capacitor location, line terminations, transformer & remote capacitor banks and at the cables.

The phase-to-earth energisation transient at the switched capacitor location should be less than 2.0 p.u. while phase-to-phase should be less than 3.0 p.u. (Martinez-Velasco & Molina)

The phase-to-phase transient at the line terminations can be 4.0 p.u. or in some cases higher due to travelling wave reflection.

The higher phase-to-phase overvoltages are mostly associated with floating capacitor banks.

The chopping of inductive current produces high overvoltages due to the transformation of magnetic energy to capacitive energy and should therefore also be considered.

A.11 Slow-front lightning overvoltage

Slow-front lightning OV originate from lightning strike to a phase conductor of long lines (>100 km) when the lightning current is sufficiently small to cause flashover and sufficient distance from the considered location. As the time to half-value rarely exceeds 200 μ and amplitude is not critical for the insulation, slow-front lightning OV, therefore, are usually neglected.

A.12 Fast front overvoltage

Fast Front Overvoltages (FFO) have time to crest/peak typically within the range of 0.1 to 20 μ s. The standard voltage shape of the FFO is shown in Figure 4-1. This is represented as the standard lightning impulse 1.2/50 μ s.

FFOs as a result of the following:

- Shielding failure
- Backflash
- Induced voltage
- Switching

A.13 Shielding failure

Shielding failure is usually as a result of lightning strikes to the phase conductors. For shielding failures, the voltage on the struck phase is random.

A.14 Backflash

Backflash is due to lightning strikes to the line shielding system, such as an overhead earth wire which flashes over to the phase conductors. The incoming surges caused by the backflash are more severe than those caused by shielding failures.

Backflash usually occurs on a phase with power frequency voltage that is opposite in polarity to the surge voltage. The maximum longitudinal overvoltage is the difference between the lightning overvoltage on one terminal and the power frequency voltage of the opposite polarity on the other terminal of the switching device.

A.15 Induced voltage

Voltages are induced in overhead lines when lightning strikes to ground are in close proximity to a line, thus inducing an overvoltage in the phase conductors. For strikes close to the substations, lightning overvoltages between phases have approximately the same magnitude as those for phase-to-earth.

A.16 Lightning type overvoltages due to switching

Lightning type overvoltages, caused by switching, are a result of the connection or disconnection of nearby equipment. This produces voltage surges with similar wave shapes of shorter duration to the standard lightning surge, as seen in Figure 4-1. Generally, these short duration and fast-rising surges are oscillatory. Therefore, the insulation strength for this wave shape is closer to that of the standard lightning impulse than that of the standard switching impulse.

Maximum values of these overvoltages are approximately:

- 2.0 p.u. for switching without restrike
- 3.0 p.u. for switching with restrike

Annex B

Informative

Insulation co-ordination checklist – example

This Standard identifies the minimum insulation co-ordination requirements for the design and construction of major substations.

Item	Description	Completed/Actioned
	Insulation Co-ordination	
1.	Major substation lightning protection designed to the acceptable shielding level (STNW3032)	Yes/No/NA
2.	Down conductors and earthing requirements met (Substation Earthing - 39342177)	Yes/No/NA
3.	Equipment minimum insulation level requirements are met as per Table 4-1	Yes/No/NA
4.	Electrical clearance requirements are met (STNW3013)	Yes/No/NA
5.	Insulator pollution minimum creepage requirements are met (Pollution Class IV)	Yes/No/NA
6.	Surge arrester selection minimum requirements are met (STNW3033)	Yes/No/NA
7.	Surge arrester connection requirements are met	Yes/No/NA
8.	Surge arrester location requirements are met as per Table 5-1	Yes/No/NA
9.	Overhead earth wire requirements for incoming overhead lines are met (STNW3355)	Yes/No/NA
	If answered NO to any question 1-9:	
10.	Insulation co-ordination design inputs are documented	Yes/No/NA
11.	Insulation co-ordination designed complies with IEC 60071 all applicable parts.	Yes/No/NA
12.	Switching studies be required at lower voltages for special applications (e.g. non-standard configuration).	Yes/No/NA
13.	Insulation co-ordination design outputs are documented	Yes/No/NA

Where a detailed insulation co-ordination study is required, it is recommended that the insulation co-ordination report be structured as per the following:

- Input data and methodology
 - Discusses the input data used, the methodology adopted and the development of the PSCAD/EMTP model (if applicable) and for the studies.
- Results and discussion
 - Discuss the results from the fast front lightning studies. Could also include lightning incidence probability and stroke magnitude calculations in this section.
- Conclusions and recommendations

Summarise the case studies, draws conclusions and presents the main recommendations arising from the studies.

Annex C

Informative

Historical overview of standards

These standards have been revised, redesignated and withdrawn over the years to align with international standards. This Annex has been added to detail these changes.

Australian Standards

(AS 2067, 2016) Calls upon (AS 1824.1, 1995) (AS 1824.2, 1985).

Note AS1824, Parts 1 and 2 have been withdrawn due to age.

SECTION 3 INSULATION

3.1 GENERAL

As conventional (air-insulated) installations are normally not impulse tested, the installation requires minimum clearances between live parts and earth and between live parts of phases in order to avoid flashover below the impulse withstand level selected for the installation.

Insulation coordination shall be in accordance with AS 1824, Parts 1 and 2.

For minimum phase-to-phase and phase-to-earth clearances required refer to Tables 3.1 and 3.2.

NOTES:

- 1 AS 1824.1 relates values for the highest voltage for equipment U_m to rated lightning impulse withstand voltages as well as rated short-duration power-frequency withstand voltages or rated switching impulse withstand voltages.
- 2 Standard nominal voltages for traction systems are also given in AS 60038. Other relevant values for traction systems can be interpolated from those in Table 3.1 of this Standard.

Annex D

Revision History

Revision date	Version number	Author	Description of change/revision
01/01/2020	1	Tara-lee MacArthur	Revised to incorporate IEC 60071-1:2019 due to Australian Standards being withdrawn. Clause 5.1 IEEE and AS ranges for equipment and insulation level removed Table 5-3 Surge arrester locations added Determination of creepage distance removed as this section is covered in other standards and specifications. Clause 6.3 General procedure for insulation co-ordination revised to IEC 60071-2 Update to the documentation required and checklist for procedure included in Annex B.
June 2023	2	John Lansley	Update format ECM audit. Moved legislation to Section 2.
April 2026	3	John Lansley	Update references.