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Insulation Co-ordination & Surge Arrester Selection

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About This Standard

This document explains the methods employed to ensure that equipment is not damaged by lightning.

It provides data on lightning characteristics and frequency, and on the impulse withstand levels of common insulating materials. It describes the various types of AC arresters in use.

It details the steps necessary to calculate the type of arrester needed to protect a given situation and provides an example calculation for this.

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1 Basic Insulation Level

The process of ensuring that equipment is not damaged by overvoltages - usually due to lightning on the ARTC system - is called Insulation Co-ordination.

The Basic Insulation Level (BIL) of equipment such as transformers, is defined as the peak voltage of a 1.2/50 μ s wave which does not cause insulation to fail; see AS 1824.1. This definition of a surge (1.2/50 μ s) indicates a surge which reaches its peak value in 1.2 μ s and decays to half the peak in 50 μ s.

Lightning is a **current** wave. Testing of equipment BIL is performed using voltage waves that have different rise times to what are now known to be typical lightning surges. These test voltages have been 'historically' used for testing but it is now recognised that this not a typical lightning representation. The waveform was originally derived from the response time of gapped Silicon Carbide (SiC) arresters.

Transformers are also subjected to a chopped - wave test where a 1.5 * BIL wave is chopped off after 3 μ s by a gap flashing over. This is to simulate the effect of a transmission line flashing over. The equipment covered by these values includes switchgear, transformers, cables, etc.

The ARTC specifies equipment BIL to AS 1824.1 as summarised in Table 1.

Nominal System Voltage	BIL (kV peak)	1 Minute, Dry, Power Frequency, Flashover voltage (kV RMS)
1500Vdc cable	60	
11kV	95 ^{Note 1}	28
33kV	200 ^{Note 2}	70
66kV	325	140
132kV	550	230

Table 1 BIL Levels

Note 1: If all 11kV feeders supplying the SS consist of at least 0.5 km of cable, and all equipment is indoor, a BIL of 75 kV is used.

Note 2: If all 33 kV feeders supplying the SS consist of at least 0.5 km of cable, and all equipment is indoors, a BIL of 170 kV is used.

Typical values of BIL for transmission lines can be estimated using the data in Table 2.

Material	BIL
Wood/Plastics (wet)	350 kV/m
Air (wet)	700 kV/m
11 kV pin insulator	100 kV
33 kV pin insulator	200 kV
Disk type - 1 insulator	125 kV
Disk type - 2 insulators	255 kV
Disk type - 3 insulators	345 kV
Disk type - 4 insulators	415 kV
Disk type - 5 insulators	495 kV
Disk type - 6 insulators	585 kV

Table 2 Typical BIL Values

The BIL of different types of materials when in series can be estimated as follows:

- The BIL of wood, plastic and fibreglass in series are added arithmetically.
- When combining series wood etc. and insulators, use $\sqrt{\sum \text{BIL}^2}$ as an approximation.

Using values from table 2, the BIL of some typical ARTC lines is as follows:-

Insulator BIL level	Steel or Concrete Poles or crossarms		Timber poles & crossarms (painted to existing standard) Wet	Unpainted timber poles & crossarms Wet
	$\phi - \phi$ kV	$\phi - E$ kV	$\phi - \phi$ kV	$\phi - \phi$ kV
11 kV pins	200	100	330	415
11 kV suspension	250	125	275	320
11 kV suspension through air	700	350	-	-
33 kV post type				
33 kV suspension	345	170	425	525
33 kV suspension through air	1000	500	-	-
66 kV suspension 4 insulators	760	380	800	900
66 kV suspension 5 insulators	990	490	1050	1100
66 kV suspension through air	1500	750	-	-

Table 3 Typical Construction BIL

Since these transmission line values are above the equipment values, surge arresters are required to protect the equipment.

2 Lightning

2.1 Typical Lightning Characteristics

Table 4 is derived from AS 1768 - Table A1, and shows the characteristics of lightning strokes.

	Minimum	Typical	Maximum
Peak current kA	-	10-20	110
Front rise time μs	0.1	2	30
Time to decay to half peak μs	10	40	250
Total duration sec	0.01	0.2	2
strokes per flash	1	3-4	26

Table 4 Typical Lightning Stroke Current

The stroke median peak current is 34 kA with a 2.5% chance of exceeding 100 kA.

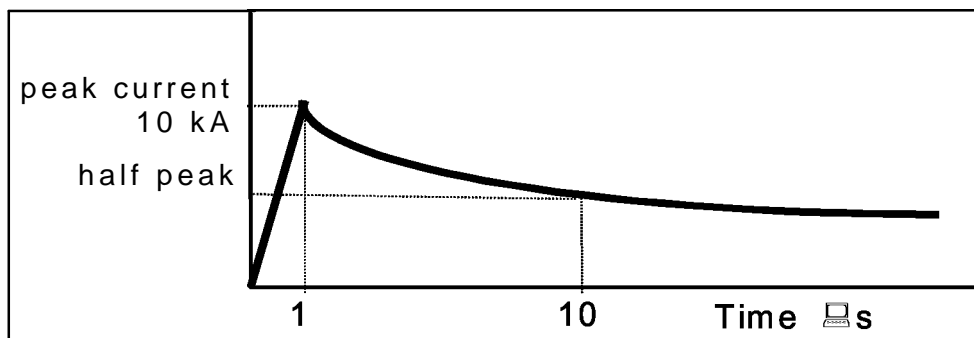


Diagram 1 Typical Lightning Current Waveform

17% of surges currents have a rise time less than 1 μs

40% of surges currents have a rise time less than 2 μs

57% of surges currents have a rise time less than 2.5 μs

80% of surges currents have a rise time less than 4 μs

AS 1768, Appendix C suggests that the following represents an "idealised lightning stroke current for design purposes" (Design of lightning protection systems - not surge arresters).

First stroke: 150 kA 4.6/40 μ s

Subsequent: 40 kA 0.2/20 μ s

A more realistic worst case surge arrester current for distribution systems is 20 kA with a 1/10 μ s shape with maybe 10 kA, 1/10 μ s as typical. See Diagram 1.

The standard AS 1307 calls for a 8/20 μ s current wave for testing equipment. This has been 'historically' used for testing but it is now recognised that this is not a typical representation. It was originally derived from the response time of gapped Silicon Carbide arresters.

2.2 Lightning & Surge Arrester Current

Table 4 shows the lightning **stroke** current. The current in an arrester is usually **much** less than this. When the lightning hits a conductor, the stroke current divides in two, with half the current going in each direction.

This current in the conductor causes a voltage to be generated. The approximate voltage is calculated by multiplying the line current by the line characteristic impedance which is around 500 - 600 ohms for ARTC transmission lines. From Table 3 it can be seen that the following stroke currents will almost certainly cause a flashover at the first crossarm:-

11 kV (say 400 kV) ⤵ 1.6 kA

33 kV (say 525 kV) ⤵ 2.1 kA

66 kV (say 900 kV) ⤵ 3.6 kA

These are very low values so it is almost certain that every lightning strike to an ARTC line will cause a flashover at the first pole.

When flashover occurs, the current divides into all the conductors. For a 3 phase line, one sixth of the current travels down each line in each direction. **ie One twelfth of the stroke current continues to flow down each conductor to be ultimately discharged to ground by an arrester.**

A typical 40 kA strike only requires a 3.6 kA rated arrester and even a major 150 kA strike means only 12.5 kA in an arrester.

Studies have shown that "Distribution arrester currents rarely exceed 40 kA because of T.L. flashovers" and these high values are therefore chopped waves.

2.3 Lightning Strike Rate

It is possible to estimate how often a transmission line will be struck by lightning.

The number of Thunder days (TD) per year is documented (see AS 1768). For the Sydney area it can be taken as an average 30 with the Blue Mountains being 40. The annual number of lightning strikes to ground can be approximated by $N_g = 0.07 * TD$ strokes/km²/year.

2.3.1 Direct Strikes

A tall structure, like a transmission line attracts lightning. A simple rule of thumb gives the width of the attractive area either side of a transmission line as $6*h$ where h is the height (of the highest conductor).

A line around 15m high attracts lightning for 90m on either side.

So a line of 1 km length and 15m high has a lightning 'attractive area' of around 0.18 km² and can expect $0.18*30*0.07 = 0.4$ strikes per year (0.5 in Blue Mountains and even more because lines are higher over valleys).

This attraction only applies for flat ground and other high structures around the line will reduce the value above by around a half.

Not all these strikes will cause a trip. The surge magnitude and wave shape affect whether a flashover will occur and also whether a power follow occurs. Lines with wood crossarms are able to extinguish the power follow arc without the protection operating. ie no outage.

The percentage of strikes which do cause a trip is approximately as follows:-

	φ-φ distance	Wood crossarms	Steel crossarms
11 kV	1.5 m	35%	85%
11 kV	2.1 m	30%	85%
33 kV	2.1 m	60%	85%
33 kV	2.7 m	50%	85%
66 kV	3.25 m	60%	85%

With this data it is possible to calculate the theoretical outage rate of a transmission line. See section [2.5.1](#)

2.3.2 Nearby Strokes to Ground

Nearby strikes to ground can induce currents into all 3 phase conductors. However the induced voltages rarely exceed 200 kV and so do not cause flashover, even at 11 kV, as long as wood crossarms are used.

2.4 Overhead Earth Wire Shielding

Overhead earth wires (OHEW) are installed on high voltage feeders to intercept lightning strikes before they hit phase conductors. OHEW are installed on ARTC lines as follows:

- On all new 33kV lines.
- On existing 33 kV and above transmission lines, for 800 m adjacent to substations, to protect substation equipment. Any direct lightning strikes to the phase conductors more than 800 m from the SS will have been attenuated to a level that the SS arresters can handle by the time they reach the SS.
- On 33 kV and above transmission lines for 800 m from a cable to aerial termination.
- OHEW are not used on ARTC 11 kV lines.

Conservative literature recommends a shielding angle as shown below depending on the height of the OHEW:

Height (m)	angle (deg)
20	35-40
30	25-30
40	15-20
50	5-10

2.5 Outage Rates

It is accepted industry practice that shielded transmission lines should give outage rates due to lightning, of around 0.01 outages/km/year and unshielded lines about 0.02 to 0.08 outages/km/year.

2.5.1 Example of Outage Rate Calculation

Data:

803 feeder from Lawson to Katoomba.

Length 13.2 km.

Average height is 20m (to allow for high valley crossings.) 40 thunderdays pa.

0.5 shielding by trees.

wood crossarms.

Calculations:

attraction width = $6 \times 20 \times 2 = 240\text{m}$ total = 0.24 km.

attraction area of line = $0.24 \times 13.2 = 3.168 \text{ km}^2$

ground flash rate = $40 \times .07 = 2.8 \text{ /km}^2\text{/year}$

line hit rate = $2.8 \times 3.168 \times .5 = 4.4$ per year

Therefore the outage rate = $4.4 \times .6 = 2.7$ trips/year

3 AC Surge Arrester Types

There are 3 common types of surge arrester in use:

- Silicon Carbide (SiC).

These have a series of air gaps to withstand normal system voltage and the SiC element has a negative resistance characteristic to clamp the voltage after the air gaps flashover.

- Gapless Metal Oxide (MOV).

Gapless MOV types have no air gaps. The MOV element is a constant voltage element with a set breakdown voltage. Because there are no gaps, some current flows in the MOV at all times and this can cause thermal runaway in some circumstances.

- Gapped Metal Oxide.

Gapped MOV types use the same MOV element (but less of them) in series with air gaps. The air gaps and MOV element share the system voltage normally, but once the gaps break down the MOV element limits the voltage (to a lower level than the gapless type).

Table 5 shows the advantages and disadvantages of each type.

Type of Arrester	Advantages	Disadvantages
SiC	No current flows normally.	High initial sparkover voltage needed to operate gaps. This is usually higher than the following voltage 'clamped' by the SiC. There is also some time delay before sparkover. Problems with moisture ingress to gaps (breathing)
Gapless MOV	No time delay to operate. Tightly controlled voltage during operation.	Because they are very voltage sensitive, overvoltages can cause deterioration of the MOV with resultant thermal runaway.
Gapped MOV	Lower voltage needed to operate gaps than SiC so it operates faster and at a lower voltage than the MOV clamping voltage. Clamp surges to lower levels than either SiC or gapless MOV.	Possible moisture ingress

Table 5 Types of Surge Arrester

4 Selection & Specification of Arresters

4.1 Parameters for Arrester selection

In order to correctly specify an arrester to protect given equipment, the following parameters must be considered.

a) Arrester waveform.

For determining the arrester residual voltage, a waveform with 1 μ s rise time & 10 kA peak is used. (This is the value given in AS 1307.2 Table 5.1 Cols 3 & 4 "Steep Current Impulse")

b) Leads Induced Voltage.

For determining the lead induced voltage, a waveform with 1 μ s rise time, 20 kA peak and a lead inductance of 1.25 μ H/m is used. This corresponds to a lead voltage drop of 25 kV/metre of lead. This wave has twice the rate of rise of the wave in a) to allow for worst cases.

c) Margin of Protection.

This value should be greater than 0.2 for shielded locations.

This value should be greater than 0.5 for unshielded locations.

$$\text{Margin of Protection (MOP)} = \frac{\text{BIL} - \text{arrester Volts}}{\text{arrester Volts}}$$

In this expression, the term "arrester Volts" includes lead voltage drop and if there is an open point in the system, voltage doubling can occur and so the "arrester voltage" used in the above equation must be doubled.

d) System Earthing Considerations.

System earthing determines the voltages on unfaulted during a phase to earth fault. Table 6 summarises the voltages for ARTC lines.

Col 1	Col 2	Col 3
Nominal System Volts	Maximum Continuous Volts applied to Arrester	Temporary System Overvoltage kV rms
11 kV solidly earthed	6.9 kV	8.6
11 kV non-effectively earthed	6.9 kV	11.9
33 kV non-effectively earthed	20.6 kV	35.7
66 kV non-effectively earthed	41.2 kV	71.3

Table 6 ARTC system continuous and overvoltage levels

As ARTC 33 kV and 66 kV systems mainly originate from resistance earthed supplies, these circuits must be considered to be "non-effectively" earthed. Thus during faults, the unfaulted phase arresters are subjected to phase to phase volts (for 2 seconds maximum.)

Most of the ARTC 11 kV system has solidly earthed neutrals and so in parts of the system that can only be fed from solidly earthed supplies, the unfaulted phases are subjected to only phase to earth volts.

However, on solidly earthed lines, some allowance must be made for earth resistance so the maximum arrester voltage is taken as 1.25 times phase-earth volts.

Note

The actual earth resistance of the arresters (as opposed to the system earth) has little effect on the efficiency of the arrester. However the earth resistance usually needs to be kept low for safety reasons. Keeping the H.V. & L.V. earths separate helps to stop L.V. surges damaging a transformer.

e) Temporary System Overvoltages.

As a worst case a maximum 8% overvoltage can be assumed to be provided by supply authorities.

If assuming an 8% overvoltage will not allow a suitable arrester to be sourced, then the actual overvoltage level that may be experienced may be obtained from the relevant Distributor.

4.2 Standard Arrester Ratings

As a result of applying the above procedure, most ARTC equipment is protected by 'standard' arresters as follows:

- 10 kA arresters are used:-
 - at major substations with aerial connections
 - on transformers 1 MVA and over
 - on all aerial to cable terminations
- 5 kA arresters are used at all other locations.

If the 'standard' arresters do not provide sufficient protection, then specific arresters can be chosen using the following procedure.

4.3 Procedure for Selecting Gapless MOV Arresters

To determine whether a given arrester will provide protection for equipment it is necessary to check the following:-

- a) That the normal Continuous overvoltage does not damage the arrester.
- b) That the voltage on unfaulted phases, before the protection operates, does not damage the arrester. The protection time can be taken as maximum 2 second in the ARTC system.
- c) That the arresters have a MCOV (max continuous overvoltage) greater than Col 2 in Table 6.

Temporary overvoltage (during faults) data for arresters is usually available but if not assume that typically arresters can handle a 25% overvoltage for 2 seconds.

eg. 33 kV system, non-effectively earthed.

- (i) max cont. ϕ -E = 21 kV

(ii) temporary ϕ -E = 36 kV (33 x 1.08)

from i) could choose an arrester with MCOV > 21 kV

but because of ii) need MCOV > 36 kV/1.25 = 29 kV

d) Then consult the data table for 20 kA current wave to determine maximum arrester voltage (around 130 kV for 33 kV).

e) Then add the lead voltage drop due to 20 kA/ μ s = 25 kV/m.

If the result exceeds 200 kV * (MOP+1), then that arrester does not provide suitable protection.

4.3.1 Example of Arrester Selection Procedure

A 33 kV arrester is required for a 33 kV/240V transformer on an unshielded 33 kV line.

Data:

BIL = 200 kV. MOP = 0.5. Non-effectively earthed line.

Lead Length = 2 m. Normal continuous overvolts = 8%.

Available Arresters' Characteristics are:-

	5 kA type	10 kA type L.D.	10 kA type H.D.
MCOV	29 kV	29 kV	29 kV
Rated Voltage	36 kV	36 kV	36 kV
Residual voltage @ 10 kA	130 kV	130 kV	125 kV

Calculations:

Max allowable residual voltage = $200/(1+MOP) = 133$ kV

Required max. cont. operating voltage MCOV > $\frac{33 * 1.08}{1.25} = 28.5$ kV

(The '1.25' is from the temporary overvolts characteristics, section 4.1 d)

Therefore, choose an arrester with 29 kV.

Lead voltage for 2 m length = $2 * 25 = 50$ kV

Conclusions:

Without the leads any of the arresters will protect the equipment since the residual voltage of 130 kV (125 kV) exceeds the required 133 kV.

With the 2 m leads, none of the surge arresters will protect the transformer.

5 References

AS 1824.1	Basic Principles, Standard Insulation Levels and Test Procedures.
AS 1824.2	Insulation Co-ordination-Application Guide.
AS 1307	Surge Arresters
AS 1768	Lightning Protection
AS 1429	Polymeric insulated cables up to 19/33 kV.
ESAA	Annual Lightning Strike Counter Figures
M Darveniza:	A Review of Modern Lightning Protection for Sub-transmission and Distribution Systems