10

Insulation Co-ordination

10.0 Insulation Co-ordination

The term Insulation Co-ordination was originally introduced to arrange the insulation levels of the several components in the transmission system in such a manner that an insulation failure, if it did occur, 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 the supply. The present usage of the term is broader. Insulation co-ordination now comprises the selection of the electric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended. The overall aim is to reduce to an economically and operationally acceptable level the cost and disturbance caused by insulation failure and resulting system outages.

To keep interruptions to a minimum, the insulation of the various parts of the system must be so graded that flashovers only occur at intended points. With increasing system voltage, the need to reduce the amount of insulation in the system, by proper co-ordination of the insulating levels become more critical.

10.1 Terminology

Nominal System Voltage: It is the r.m.s. phase-to-phase voltage by which a system is designated

Maximum System Voltage: It is the maximum rise of the r.m.s. phase-to-phase system voltage

For the nominal system voltages used in Sri Lanka, the international maximum system voltages are shown in table 10.1.

Nominal System Voltage (kV)	11	33	66	132	220
Maximum System Voltage (kV)	12	36	72.5	145	245

Table 10.1

Factor of Earthing: This is the ratio of the highest r.m.s. phase-to-earth power frequency voltage on a sound phase during an earth fault to the r.m.s. phase-to-phase power frequency voltage which would be obtained at the selected location without the fault.
This ratio characterises, in general terms, the earthing conditions of a system as viewed from the selected fault location.

Effectively Earthed System : A system is said to be effectively earthed if the factor of earthing does not exceed 80%, and non-effectively earthed if it does.

[Note: Factor of earthing is 100% for an isolated neutral system, while it is 57.7% (corresponding to 1/%3) for a solidly earthed system. In practice, the effectively earthed condition is obtained when the ratio $x_0/x_1 < 3$ and the ratio $r_0/x_1 < 1$.

Insulation Level: For equipment rated at less than 300 kV, it is a statement of the Lightning impulse withstand voltage and the short duration power frequency withstand voltage.

For equipment rated at greater than 300 kV, it is a statement of the Switching impulse withstand voltage and the power frequency withstand voltage.

Conventional Impulse Withstand Voltages: This is the peak value of the switching or lightning impulse test voltage at which an insulation shall not show any disruptive discharge when subjected to a specified number of applications of this impulse under specified conditions.

Conventional Maximum Impulse Voltage: This is the peak value of the switching or lightning overvoltage which is adopted as the maximum overvoltage in the conventional procedure of insulation co-ordination.

Statistical Impulse Withstand Voltage: This is the peak value of a switching or lightning impulse test voltage at which insulation exhibits, under the specified conditions, a 90% probability of withstand. In practice, there is no 100% probability of withstand voltage. Thus the value chosen is that which has a 10% probability of breakdown.

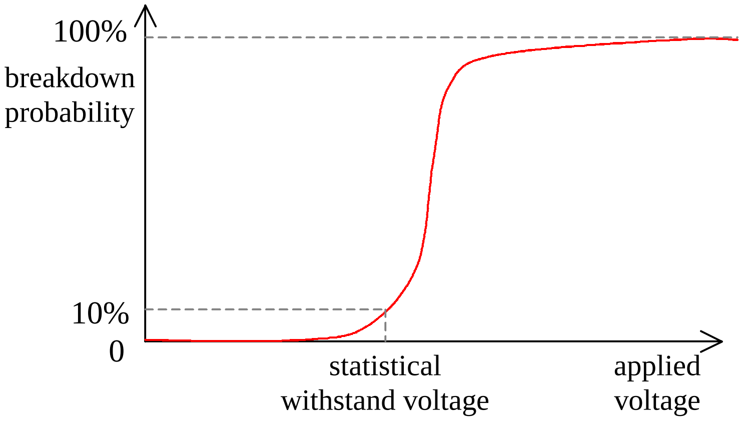


Figure 10.1 - Statistical Impulse Withstand Voltage

Statistical Impulse Voltage: This is the switching or lightning overvoltage applied to equipment as a result of an event of one specific type on the system (line energising, reclosing, fault occurrence, lightning discharge, etc), the peak value of which has a 2% probability of being exceeded.

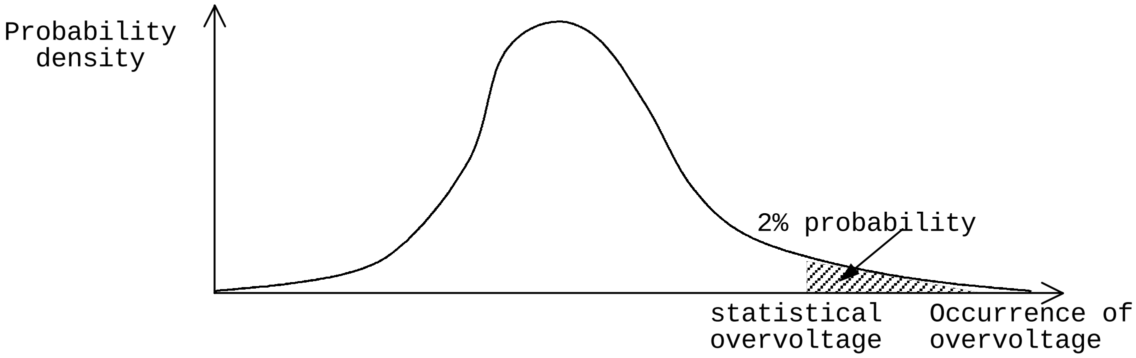


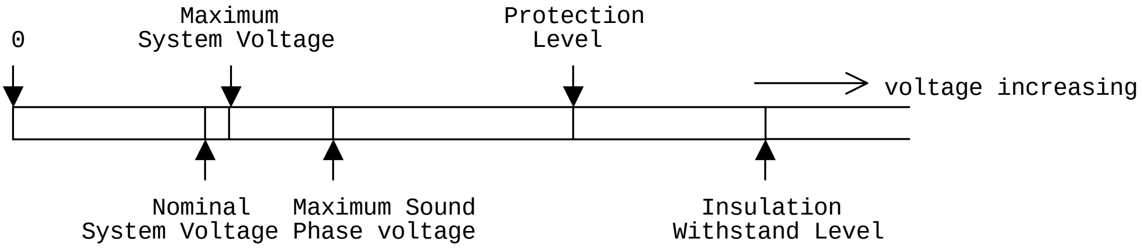
Figure 10.2 - Statistical Impulse Voltage

Rated Short Duration Power Frequency Withstand Voltage: This is the prescribed r.m.s. value of sinusoidal power frequency voltage that the equipment shall withstand during tests made under specified conditions and for a specific time, usually not exceeding one minute.

Protective Level of Protective Device: These are the highest peak voltage value which should not be exceeded at the terminals of a protective device when switching impulses and lightning impulses of standard shape and rate values are applied under specific conditions.

10.2 Conventional method of insulation co-ordination

In order to avoid insulation failure, the insulation level of different types of equipment connected to the system has to be higher than the magnitude of transient overvoltages that appear on the system. The magnitude of transient over-voltages are usually limited to a protective level by protective devices. Thus the insulation level has to be above the protective level by a safe margin. Normally the impulse insulation level is established at a value 15-25% above the protective level.



Consider the typical co-ordination of a 132 kV transmission line between the transformer insulation, a line gap (across an insulator string) and a co-ordinating gap (across the transformer bushing).

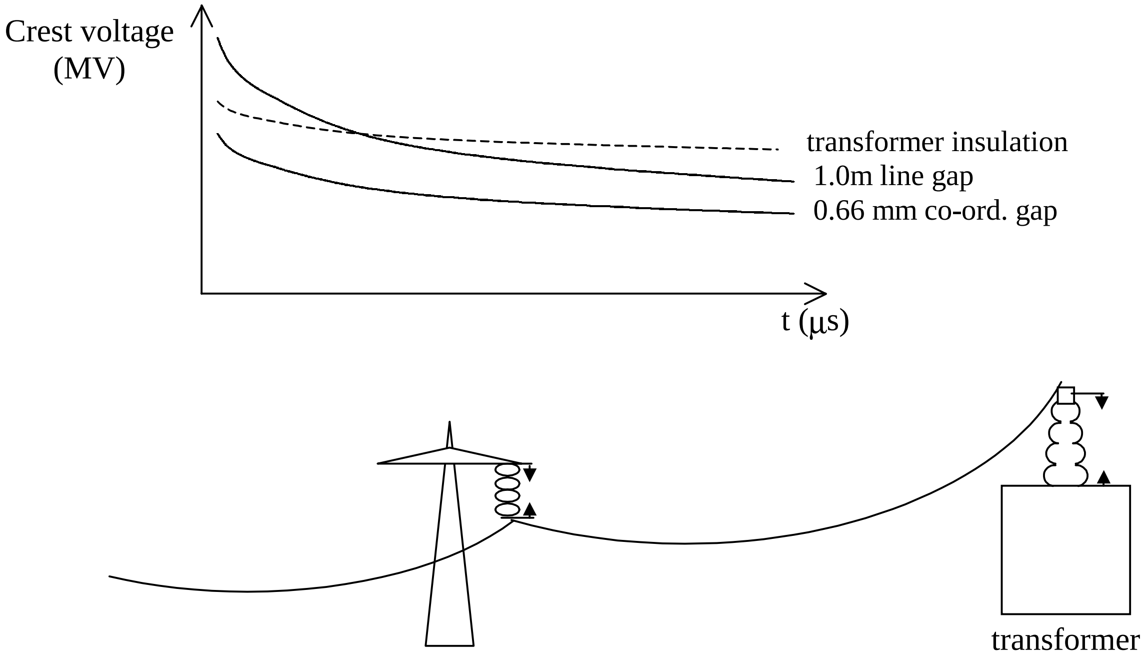


Figure 10.3 - Co-ordination using gaps

[Note: In a rural distribution transformer, a lightning arrester may not be used on account of the high cost and a co-ordinating gap mounted on the transformer bushing may be the main surge limiting device]

In co-ordinating the system under consideration, we have to ensure that the equipment used are protected, and that inadvertent interruptions are kept to a minimum. The co-ordinating gap must be chosen so as to provide protection of the transformer under all conditions. However, the line gaps protecting the line insulation can be set to a higher characteristic to reduce unnecessary interruptions.

A typical set of characteristics for insulation co-ordination by conventional methods, in which lightning impulse voltages are the main source of insulation failure, is shown in the figure 1.3.

For the higher system voltages, the simple approach used above is inadequate. Also, economic considerations dictate that insulation co-ordination be placed on a more scientific basis.

10.3 Statistical Method of Insulation Co-ordination

At the higher transmission voltages, the length of insulator strings and the clearances in air do not increase linearly with voltage but approximately to $V^{1.6}$ The required number of suspension units for different overvoltage factors is shown.

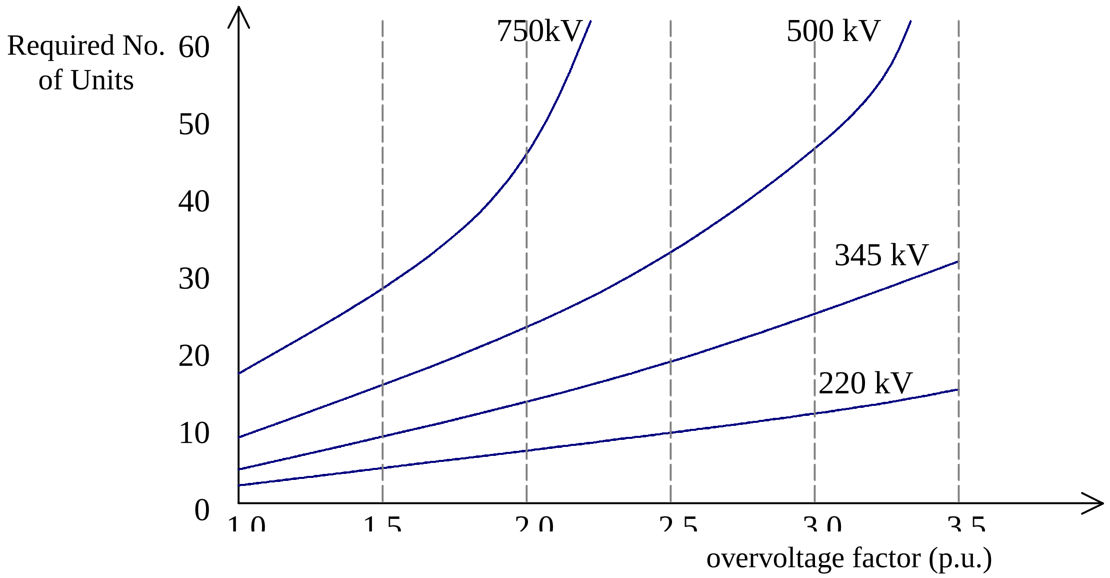


Figure 10.4 - Requirement of number of units for different voltages

It is seen that the increase in the number of disc units is only slight for the 220 kV system, with the increase in the overvoltage factor from 2.0 to 3.5, but that there is a rapid increase in the 750 kV system. Thus, while it may be economically feasible to protect the lower voltage lines up to an overvoltage factor of 3.5 (say), it is definitely not economically feasible to have an overvoltage factor of more than about 2.0 or 2.5 on the higher voltage lines. In the higher voltage systems, it is the switching overvoltages that is predominant. However, these may be controlled by proper design of switching devices.

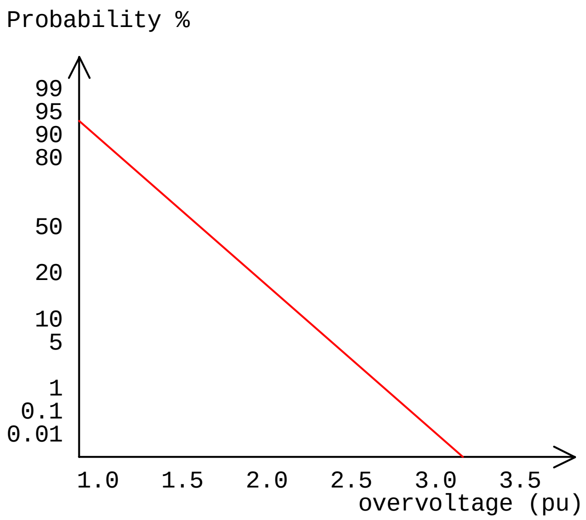


Figure 10.5 Probability of overvoltage exceeding abscissae

In a statistical study, what has to be known is not the highest overvoltage possible, but the statistical distribution of overvoltages. The switching overvoltage probability in typical line is shown. It is seen that probability of overvoltage decreases very rapidly. Thus it is not economic to provide insulation above a certain overvoltage value. In practice, the overvoltage distribution characteristic is modified by the use of switching resistors which damp out the switching overvoltages or by the use of surge diverters set to operate on the higher switching overvoltages. In such cases, the failure probability would be extremely low.

10.3.1 Evaluation of Risk Factor

The aim of statistical methods is to quantify the risk of failure of insulation through numerical analysis of the statistical nature of the overvoltage magnitudes and of electrical withstand strength of insulation.

The risk of failure of the insulation is dependant on the integral of the product of the overvoltage density function $f_0(V)$ and the probability of insulation failure P(V). Thus the risk of flashover per switching operation is equal to the area under the curve $\int f_0(V)*P(V)*dV$.

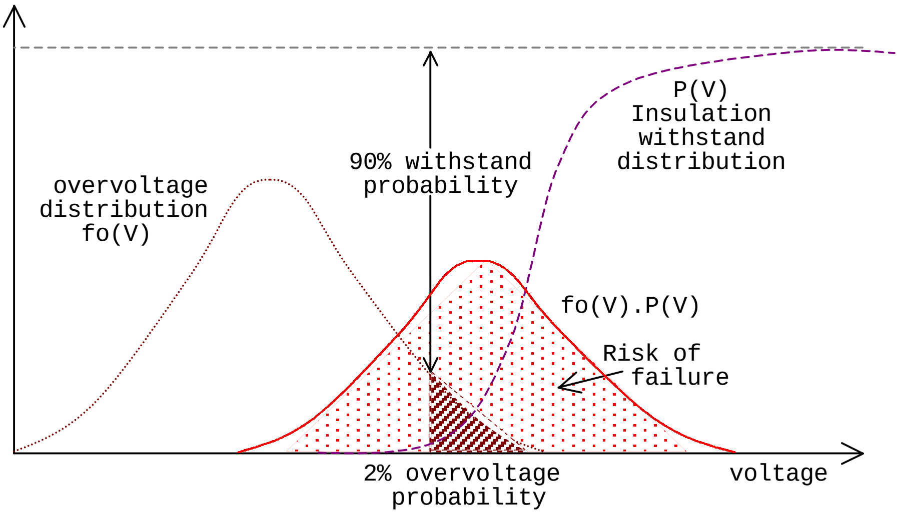


Figure 10.6 - Evaluation of risk factor

Since we cannot find suitable insulation such that the withstand distribution does not overlap with the overvoltage distribution, in the statistical method of analysis, the insulation is selected such that the 2% overvoltage probability coincides with the 90% withstand probability as shown.

10.4 Length of Overhead Shielding Wire

For reasons of economics, the same degree of protection is not provided throughout a transmission line. Generally, it is found sufficient to provide complete protection against direct strikes only on a short length of line prior to the substation. This can be calculated as follows.

Consider a surge **e** approaching the terminal equipment. When the surge magnitude exceeds the critical voltage $\mathbf{e_0}$, corona would occur, distorting the surge wavefront, as it travels. The minimum length of earth wire should be chosen such that in traversing that length, all voltage above the maximum surge that can arrive att the terminal has been distorted by corona. [The maximum permissible surge corresponds to the incident voltage that would cause insulation failure at the terminal equipment.]

10.4.1 Modification of Waveshape by Corona

When a surge voltage wave travelling on an overhead line causes an electric field around it exceeding the critical stress of air, corona will be formed. This corona formation obviously extracts the energy required from the surge. Since the power associated with corona increases as the square of the excess voltage, the attenuation of the waveform will not be uniform so that the waveform gets distorted. Further, corona increases the effective radius of the conductor giving rise to a greater capacitance for the outer layers. Since the line inductance remains virtually a constant, the surge associated with the outer layers of corona would have a lower wave velocity than in the conductor itself. These effects in practice give rise to a wavefront distortion and not a wavetail distortion, as shown in figure 10.7.

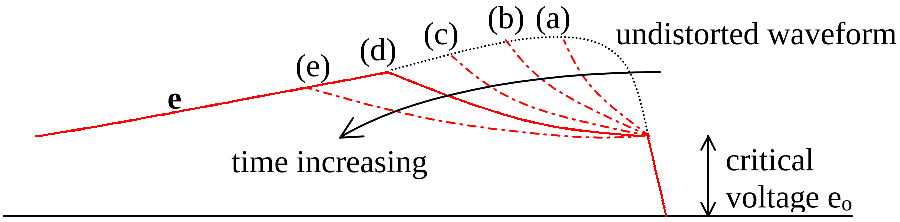


Figure 10.7 - Modification of waveshape due to corona

Corona thus reduces the steepness of the wavefront above the critical voltage, as the surge travels down the line. This means that energy is lost to the atmosphere.

Now consider the mathematical derivation.

Energy associated with a surge waveform = $\frac{1}{2} C\, e^2 + \frac{1}{2} L\, i^2$

But the surge voltage **e** is related to the surge current **i** by the equation

$$i = \frac{e}{Z_0} = e\sqrt{\frac{C}{L}}, \quad i.e. \quad \tfrac{1}{2} L\, i^2 = \tfrac{1}{2} C\, e^2$$

So that the total wave energy $= C\, e^2$

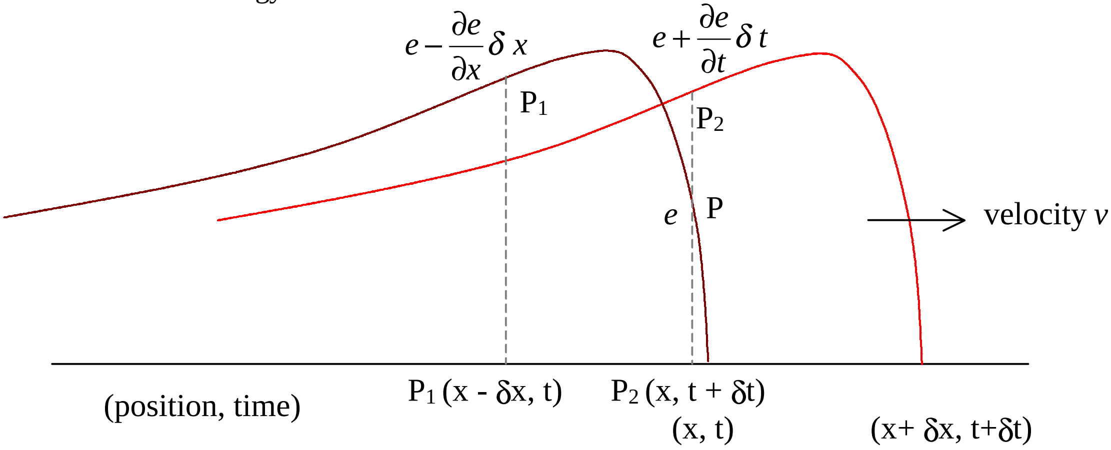


Figure 10.8 - Propagation of Surge

Consider the figure 10.8. Let the voltage at a point P at position **x** be **e** at time **t**.

Then voltage at point P_1 just behind P would be $e - \frac{\partial e}{\partial x}\delta x$ at time t, or $e - \frac{\partial e}{\partial x}.v.\delta t$.

If the voltage is above corona inception, it would not remain at this value but would attain a value $e + \frac{\partial e}{\partial t}\delta t$ at P at time t+Δt , when the surge at P_1 moves forward to P_2.

[Note: $\frac{\partial e}{\partial x}, \frac{\partial e}{\partial t}$ would in fact be negative quantities on the wavefront.]

Thus corona causes a depression in the voltage from $(e - v\frac{\partial e}{\partial x}\delta t)$ to $(e + \frac{\partial e}{\partial t}\delta t)$, with a corresponding loss of energy of $C\left[(e - v\frac{\partial e}{\partial x}\delta t)^2 - (e + \frac{\partial e}{\partial t}\delta t)^2\right]$ or $-2Ce\left[v\frac{\partial e}{\partial x} + \frac{\partial e}{\partial t}\right]\delta t$.

The energy to create a corona field is proportional to the square of the excess voltage. i.e. $k(e - e_0)^2$.

Thus the energy required to change the voltage from e to $(e + \frac{\partial e}{\partial t}\delta t)$ is given by

$$k\left[(e + \frac{\partial e}{\partial t}\delta t - e_0)^2 - (e - e_0)^2\right] \text{ or } 2k(e - e_0)\frac{\partial e}{\partial t}\delta t .$$

The loss of energy causing distortion must be equal to the change in energy required. Thus

$$-2Ce\left[v\frac{\partial e}{\partial x} + \frac{\partial e}{\partial t}\right]\delta t = 2k(e - e_0)\frac{\partial e}{\partial t}.\delta t$$

Rearranging and simplifying gives the equation

$$v\frac{\partial e}{\partial x} = -\left[1 + \frac{k}{C}.\frac{(e - e_0)}{e}\right]\frac{\partial e}{\partial t}$$

Wave propagation under ideal conditions is written in the form

$$v\frac{\partial e}{\partial x} = -\frac{\partial e}{\partial t}$$

Thus we see that the wave velocity has decreased below the normal propagation velocity, and that the wave velocity of an increment of voltage at **e** has a magnitude given by

$$v_e = \frac{v}{1 + \frac{k}{c}\left(\frac{e - e_0}{e}\right)}$$

Thus the time of travel for an element at **e** when it travels a distance **x** is given by

$$t = \frac{x}{v_e} = \frac{x}{v}\left[1 + \frac{k}{C}\left[\frac{e - e_o}{e}\right]\right]$$

$$\text{i.e.} \quad \left[\frac{x}{v_e} - \frac{x}{v}\right] = \frac{x}{v}.\frac{k}{C}\left[\frac{e - e_o}{e}\right]$$

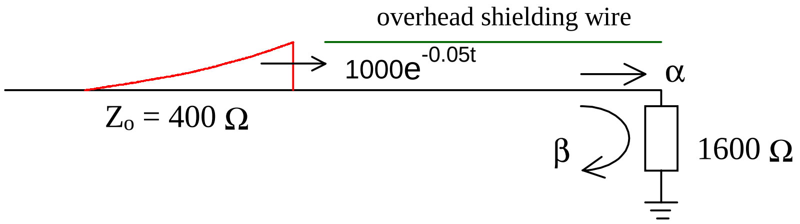
$\left(\frac{x}{v_e} - \frac{x}{v}\right)$ is the time lag Δt corresponding to the voltage element at **e**. Thus

$$\frac{\Delta t}{x} = \frac{k}{v.C}\left[1 - \frac{e_0}{e}\right]$$

Example 10.1

A transformer has an impulse insulation level of 1050 kV and is to be operated with an insulation margin of 15% under lightning impulse conditions. The transformer has a surge impedance of 1600 S and is connected to a transmission line having a surge impedance of 400 S. A short length of overhead earth wire is to be used for shielding the line near the transformer from direct strikes. Beyond the shielded length, direct strokes on the phase conductor can give rise to voltage waves of the form 1000 $e^{-0.05t}$ kV (where t is expressed in μs).

If the corona distortion in the line is represented by the expression $\frac{\Delta t}{x} = \frac{1}{B}\left[1 - \frac{e_0}{e}\right]\ \mu s/m$, where B = 110 m/μs and e_0 = 200 kV, determine the minimum length of shielding wire necessary in order that the transformer insulation will not fail due to lightning surges.



Transmission coefficient $\alpha = \dfrac{2 \times 1600}{1600 + 400} = 1.6$

For a B.I.L of 1050 kV, and an insulation margin of 15%,
Maximum permissible voltage = 1050 x 85/100 = 892.5 kV.

Since the voltage is increased by the transmission coefficient 1.6 at the terminal equipment, the maximum permissible incident voltage must be decreased by this factor.
Thus maximum permissible incident surge = 892.5/ 1.6 = 557.8 kV
Thus for the transformer insulation to be protected by the shielding wire, the distortion caused must reduce the surge to a magnitude of 557.8 kV.

Therefore, $1000\ e^{-0.05\ t_1} = 557.8$. This gives the delay time $t_1 = \Delta t = 11.6\ \mu s$.

Substitution in the equation gives $11.67/x = 1/100\ .\ (1 - 200/557.8)$

Solution gives x = 2002 m = 2.0 km.
Thus the minimum length of shielding wire required is 2 km.

10.5 Surge Protection

An overhead earth wire provides considerable protection against direct strikes. They also reduce induced overvoltages. However, they do not provide protection against surges that may still reach the terminal equipment. Such protection may either be done by diverting the major part of the energy of the surge to earth (surge diverters), or by modifying the waveform to make it less harmful (surge modifiers). The insertion of a short length of cable between an overhead line and a terminal equipment is the commonest form of surge modifier.

10.5.1 Spark gaps for surge protection

The simplest and cheapest form of protection is the spark gap. The selected gap spacing should no only be capable of withstanding the highest normal power frequency voltage but should flash-over when overvoltages occur, protecting the equipment.

However, this is not always possible due to the voltage-time characteristics gaps and equipment having different shapes. Also, once a gap flashes over under a surge voltage, the ionised gap allows a power frequency follow through current, leading to a system outage. Thus rod gaps are generally used as a form of back up protection rather than the main form of protection.

Typical values of gap settings for transmission and distribution voltages are as in the following table 10.3.

Nominal System Voltage (kV)	66	132	275	400
Gap setting (mm)	380	660	1240	1650

Table 10.3

One of the most extensively used protective spark gaps in distribution systems is the **duplex** rod gap, which makes use of 2 rod gaps in series. Typical settings for these gaps are as given in the table.

Nominal System Voltage (kV)	11	33
Gap setting (mm)	2 x 31	2 x 63

Table 10.4

When spark over occurs across a simple rod gap, the voltage suddenly collapses giving rise to a chopped wave. This chopped wave may sometimes be more onerous to a transformer than the original wave itself.

Expulsion Tube Lightning Arrestor

An expulsion tube arrestor consists essentially of a spark gap arranged in a fibre tube, and another series external rod gap. A typical arrangement for a 33 kV expulsion tube, with the external gap of the order of 50 mm and the internal gap of about 180 mm is shown in figure 10.9.

The purpose of the external gap is to isolate the fibre tube from normal voltages thus preventing unnecessary deterioration. When an overvoltage occurs, spark over takes place between the electrodes and the follow current arc is constrained within the small volume of the tube. The high temperature of the arc rapidly vaporises the organic materials of the wall of the tube and causes a high gas pressure (up to 7000 p.s.i.) to be built up. The high pressure and the turbulence of the gas extinguishes the arc at a natural current zero, and the hot gasses are expelled through the vent in the earthed electrode. The power frequency follow current is interrupted within one or two half cycles so that protective relays would not operate causing unnecessary interruptions.

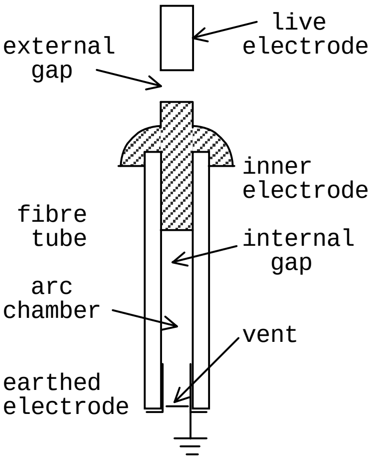


Figure 10.9 - Expulsion Tube

The expulsion gaps, which are comparatively cheap, are suitable for the protection of transmission line insulators and for the protection of rural distribution transformers, where other arrestors may be too expensive and rod gaps inadequate. However, they are unsuitable for the protection of expensive terminal equipment on account of their poor voltage-time characteristics.

10.5.2 Surge Diverters

Surge diverters (or lightning arrestors) generally consist of one or more spark gaps in series, together with one or more non-linear resistors in series. Silicon Carbide (SiC) was the material most often used in these non-linear resistor surge diverters. However, Zinc Oxide (ZnO) is being used in most modern day surge diverters on account of its superior volt-ampere characteristic. In fact the ZnO arrestor is often used gapless, as its normal follow current is negligibly small. The volt-ampere characteristics of SiC and of ZnO non-linear elements are shown for comparison with that of a linear resistor in figure 10.10.

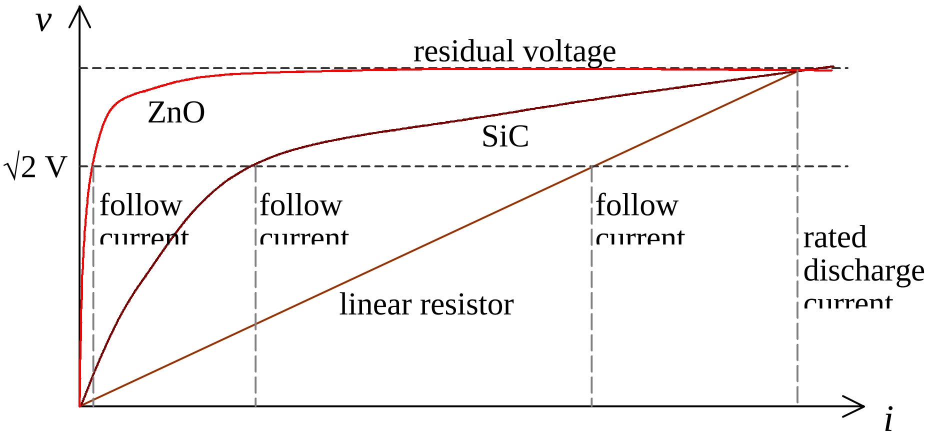


Figure 10.10 - Volt-Ampere characteristics of non-linear elements

It is seen that while a large current is drawn under overvoltage condition in all three cases, the follow current is fairly large in the linear resistor, small in the SiC resistor, and negligibly small in the ZnO resistor. Their characteristics may be mathematically expressed as follows.

$v = k_1\, i$ for a linear resistor
$v = k_2\, i^{0.2}$ for a Silicon Carbide resistor
$v = k_3\, i^{0.03}$ for a Zinc Oxide resistor

If the current were to increase a 100 times, the corresponding increase in voltage would be 100 times for the linear resistor, 2.5 times for the SiC resistor, but only 1.15 times for the ZnO resistor. This means that for the same residual voltage and the same discharge current, the follow current would be (in the absence of a series gap) of the **kA** for a linear resistor, **A** for a SiC resistor and just **mA** for a ZnO resistor.

When a series spark gap is required for eliminating the follow current, it is preferable to have a number of small spark gaps in series rather than having a single spark gap having an equivalent breakdown spacing. This is because the rate of rise of the recovery strength of a number of series gaps is faster than that of the single gap. However, when spark gaps are connected in series, it is difficult to ensure an even voltage distribution among them due to leakage paths (Figure 10.11)

The problem is generally overcome by having high equal resistances shunting the series gaps, ensuring a uniform distribution.

When a surge appears at a surge diverter terminal, within a short time the breakdown voltage of the series gap is reached, and the arrestor discharges. Unlike in the rod gap, the voltage does not collapse to zero instantly due to the voltage across the non-linear resistor. When the surge voltage increases, there is a corresponding but rapid decrease of the resistance discharging the surge energy to earth. Once the surge passes through, the power frequency voltage remaining is insufficient to maintain a sufficient current for the arc to continue. Thus the arcs extinguish and the gaps reseal. In the case of the ZnO arrestor, due to the negligible continuous power frequency current even in the absence of a series gap, the series gap is sometimes eliminated simplifying construction.

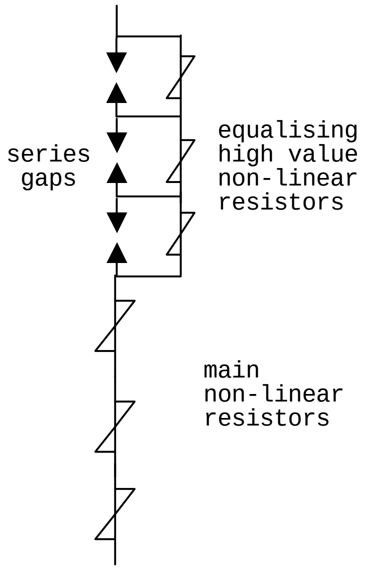


Figure 10.11 - Non-linear Arrestor

10.5.3 Selection of Surge Diverters

Surge diverters for a particular purpose are selected as follows.

(a) Rated Voltage

The designated maximum permissible r.m.s. value of power frequency voltage between line and earth terminals.

This is generally selected corresponding to 80% of the system phase-to-phase voltage for effectively earthed systems and corresponding to 100% of the system phase-to-phase voltage for non-effectively earthed systems. [Note: A surge diverter of a higher rating may sometimes have to be chosen if some of the other required criteria are not satisfied by this diverter].

(b) Discharge Current

The surge current that flows through the surge diverter after spark over.

Nominal discharge current: This is the discharge current having a designated crest value and waveshape, which is used to classify a surge diverter with respect to durability and protective characteristics.

The standard waveform for the discharge current is taken as 8/20 μs).

The nominal value of discharge current is selected from the standard values 10 kA (station type), 5 kA (intermediate line type), 2.5 kA (distribution type) and 1.5 kA (secondary type), depending on the application. The highest ratings are used for the protection of major power stations, while the lowest ratings are used in rural distribution systems. The above nominal discharge currents are chosen based on statistical investigations which have shown that surge diverter currents at the station has the following characteristic.

99 % of discharge currents are less than 10 kA
95 % of discharge currents are less than 5 kA
90 % of discharge currents are less than 3 kA
70 % of discharge currents are less than 1 kA
50 % of discharge currents are less than 0.5 kA

(c) Discharge Voltage (or Residual voltage)

The Discharge voltage is the voltage that appears between the line and earth terminals of the surge diverter during the passage of discharge currents.

The discharge voltage of the selected arrestor should be below the BIL of the protected equipment by a suitable margin (generally selected between 15% and 25%).

The discharge voltage of an arrestor at nominal discharge current is not a constant, but also depends on the rate of rise of the current and the waveshape. Typically, an increase of the rate of rise from 1 kA/μs to 5 kA/μs would increase the discharge voltage by only about 35 %.

The dependence of the discharge voltage on the discharge current is also small. Typically, an increase of discharge current from 5 kA to 10 kA would increase the discharge voltage by about 15% for Silicon Carbide arrestors and by about 2% for Zinc Oxide arrestors. {The discharge voltage is more often referred to as the residual discharge voltage].

(d) Power frequency spark over voltage

The power frequency spark over voltage is the r.m.s. value of the lowest power frequency voltage, applied between the line and earth terminals of a surge diverter, which causes spark-over of all the series gaps.
The power frequency spark over voltage should generally be greater than about 1.5 times the rated voltage of the arrestor, to prevent unnecessary sparkover during normal switching operations.

(e) Impulse spark over voltage

The impulse spark over voltage is the highest value of voltage attained during an impulse of a given waveshape and polarity, applied between the line and earth terminals of a surge diverter prior to the flow of discharge current.

The impulse spark over voltage is not a constant but is dependant on the duration of application. Thus it is common to define a wavefront impulse sparkover voltage in addition to the impulse spark-over voltage.

Arrestor Rating kV rms	Minimum Power frequency withstand	Maximum Impulse Spark-over voltage (1.2/50 μs) kV crest	Maximum Residual Voltage kV crest	Maximum Wavefront Sparkover Voltage kV crest
36	1.5 times rated voltage	130	133	150
50		180	184	207
60		216	221	250
75		270	276	310

Table 10.6

Good designs aim to keep (i) the peak discharge residual voltage, (ii) the maximum impulse sparkover voltage and (iii) the maximum wavefront impulse sparkover voltage reasonably close to each other. Table 10.6 gives a typical comparison.

Example 10.2

A lightning arrestor is required to protect a 5 MVA, 66/11 kV transformer which is effectively earthed in the system. The transformer is connected to a 66 kV, 3 phase system which has a BIL of 350 kV. Select a suitable lightning arrestor.

For 66 kV, maximum value of system rms voltage = 72.5 kV
Therefore, voltage rating for effectively earthed system = 72.5 x 0.8 = 58 kV

The selected voltage rating is usually higher by a margin of about 5%.
Selected voltage rating = 1.05 x 58 = 60.9 = 60 kV

Protective level of selected arrestor (highest of 216, 221 and 250 from table) = 250 kV
Margin of protection (crest value) = 350 - 250 = 100 kV
which is more than the required margin of 15 to 25%.
= 100/250 x 100 % = 40%
Check the power frequency breakdown voltage.
Power frequency breakdown voltage of arrestor = 60 x 15 = 90 kV

Assuming the dynamic power frequency overvoltage to be limited to 25% above maximum voltage at arrestor location,

Dynamic phase-to-neutral voltage = 1.25 x 72.5 x 0.8 = 72.5 kV

This voltage is less than the withstand voltage of the arrestor. In fact the factor of 1.5 automatically ensures that this requirement is satisfied.

Thus the chosen arrestor is satisfactory.

10.5.4 Separation limit for lightning arrestors

Best protection is obtained for terminal equipment by placing the arrestor as near as possible to that equipment. However, it is not feasible to locate an arrestor adjacent to each piece of equipment. Thus it is usually located adjacent to the transformer. However, where the BIL of the transformer permits, the arrestor may be located at a distance from the transformer to include other substation equipment within the protected zone. Thus it may be worthwhile installing them on the busbars themselves when permissible.

When arrestors must be separated from the protected equipment, additional voltage components are introduced, which add instant by instant to the discharge voltage. The maximum voltage at the terminal of a line as a result of the first reflection of a travelling wave may be expressed mathematically as

$$E_t = E_a + \beta \frac{de}{dt} x \frac{2l}{300}$$

up to a maximum of 2 β E_a. The factor 2 arises from the return length from arrestor to transformer, and the factor 300 is based on a travelling wave velocity of 300 m/μs in the overhead line. l is the separation between the arrestor and the transformer location, β the reflection coefficient at the transformer location, E_a is the discharge voltage at the arrestor, and de/dt is the rate of rise of the wavefront. When the value of \$ is not known, it may generally be assumed as equal to 1 without much loss of accuracy. Figure 10.12 shows how the voltage at the terminal increases with separation for typical rates of rise.

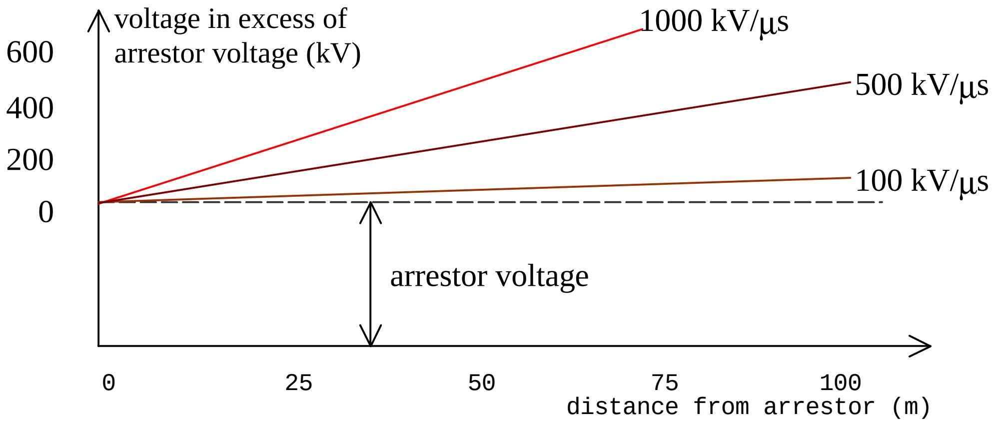


Figure 10.12 - Lightning arrestor separation

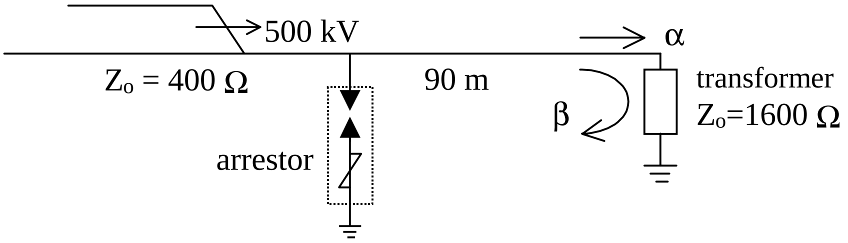
Example 10.3

A 500 kV steep fronted wave (rate of rise 1000 kV/μs) reaches a transformer of surge impedance 1600 Ω through a line of surge impedance 400 Ω and protected by a lightning arrestor with a protective spark-over level of 650 kV, 90 m from the transformer. Sketch the voltage waveforms at the arrestor location and at the transformer location. Sketch also the waveforms if the separation is reduced to 30 m.

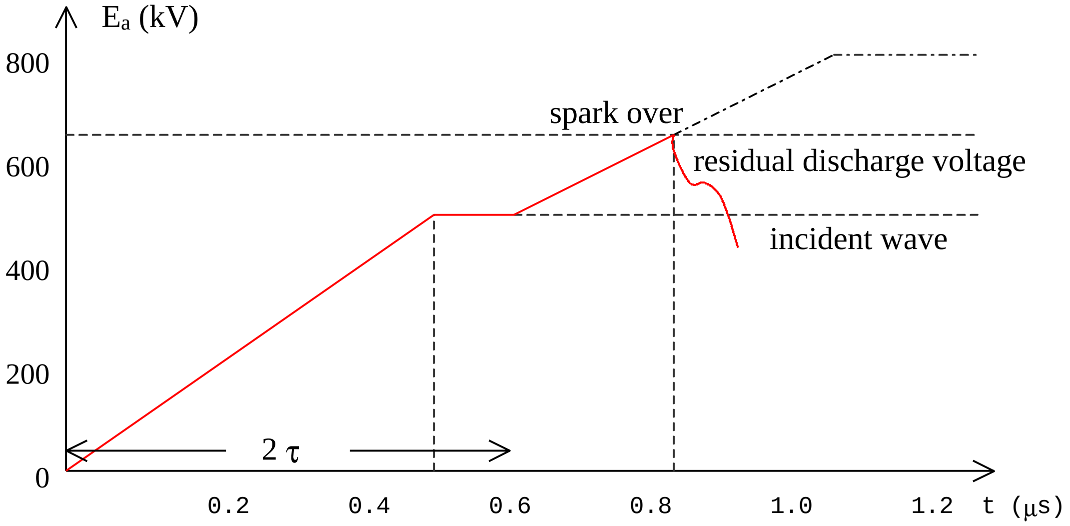
If the separation is 90 m, travel time of line τ = 90/300 = 0.3 μs

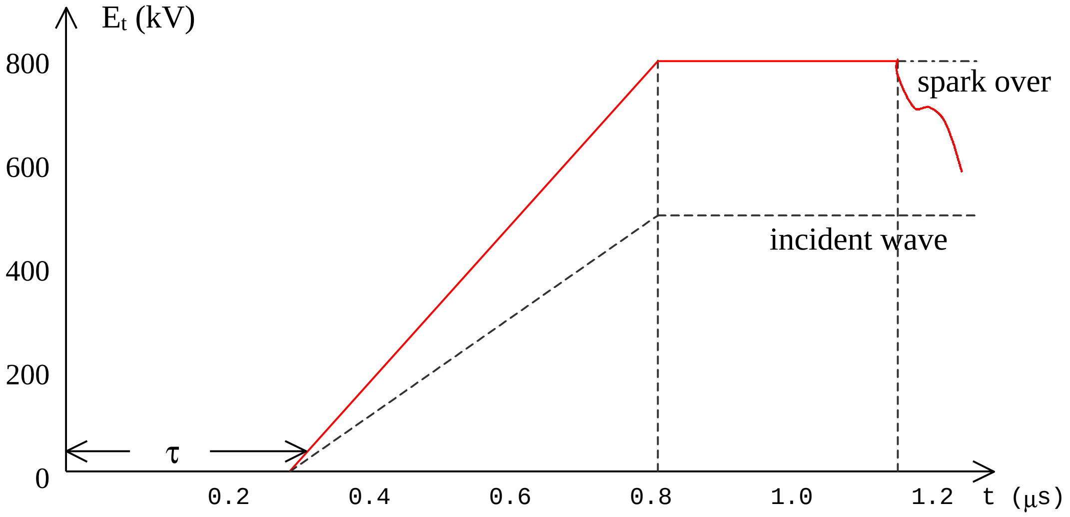
$$\text{Transmission coefficient } \alpha = \frac{2\,.\,1600}{1600+400} = 1.6$$

Reflection coefficient β = 1.6 - 1 = 0.6



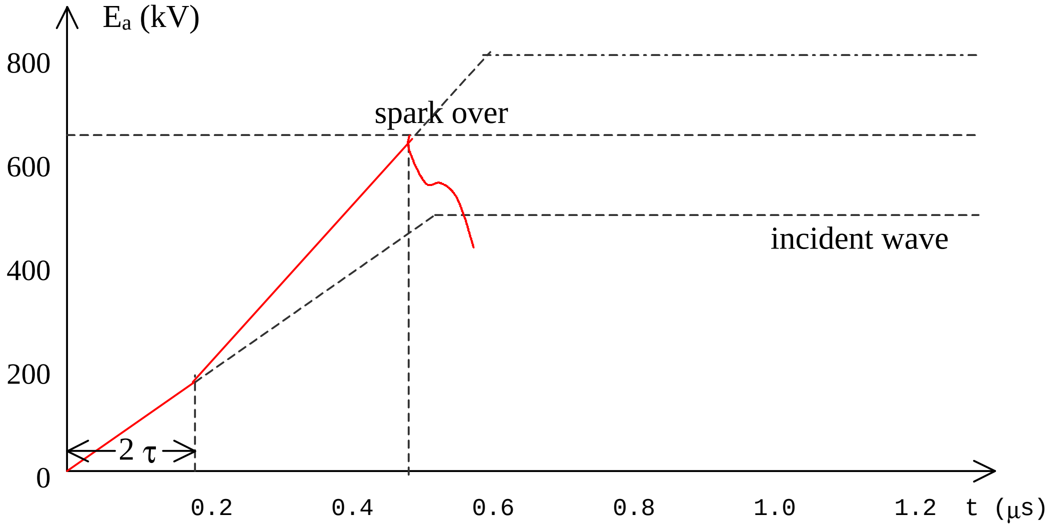
The voltage waveforms at the arrestor location and at the transformer location can be sketched as follows.

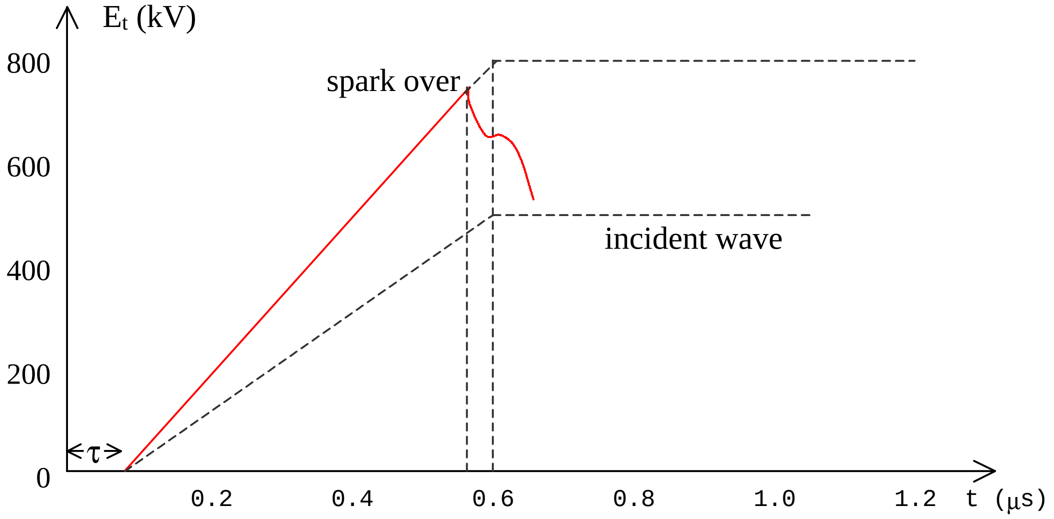




If the separation is 30 m, travel time of line τ = 30/300 = 0.1 μs

In this case the voltage waveforms at the arrestor and the transformer location are as follows.





The maximum value of the voltage E_t at the terminal for each case can be determined from $E_t = E_a + 0.6 \frac{de}{dt} x \frac{2l}{300}$ up to a maximum of 0.6 E_a.

For 90 m, maximum E_t -> 650 + 0.6 x 1000 x 90 x 2 / 300 = 1010 kV > 1.6 x 500

Therefore maximum E_t = 800 kV

For 30 m, maximum E_t -> 650 + 0.6 x 1000 x 30 x 2 / 300 = 770 kV < 1.6 x 500

Therefore maximum E_t = 770 kV

What would have been the maximum separation permissible between the transformer and the lightning arrestor, if the BIL of the transformer was 900 kV and a protective margin of 25 % is required, for the above example ?
For a protective margin of 25 %, maximum permissible surge at transformer = 900/1.25 = 720 kV

Therefore 720 = 650 + 0.6 x 1000 x 2 L / 300
This gives the maximum permissible length L = 17.5 m.

If the maximum rate of rise was taken as 500 kV/μs, the maximum length would have worked out at 35 m.

Characteristics of lightning arrestors and separation limits

Table 10.7 gives the characteristics for station type lightning arrestors and separation distances permissible between arrestor location and power transformer. For line type arrestors, the discharge voltages are about 10 to 20% higher and the corresponding separation distances are roughly half. When multiple lines meet at a busbar, the voltages transmitted are lower (corresponding to 2V/n for n identical lines). It has been suggested that in the presence of multiple lines, the separation distances may be exceeded by about 9% for one additional line, 21 % for two addition lines and 39% for three additional lines for the same degree of protection.

Nominal System Voltage kV	Transformer BIL kV (peak)	Line Construction	Line Insulation kV	Arrestor Rating kV	Discharge Voltage (kV) at			Separation distance m
					5 kA	10 kA	20 kA	
23	150	wood	500	20	58	65	76	23
				25	71	81	94	15
34.5	200	wood	600	30	88	101	117	27
				37	105	121	140	18
69	350	wood	1020	60	176	201	232	41
				73	210	241	279	23
		steel	600	60	176	201	232	47
				73	210	241	279	29
138	550	steel	930	109	316	350	418	52
	550			121	351	401	466	35
	650			145	420	481	558	47
230	825	steel	1440	182	528	605	700	44
	900			195	568	651	756	55
	1050			242	700	800	930	58

Table 10.7

A typical co-ordination of insulation in station equipment for some system voltages is given in table 10.8 together with the corresponding line insulation.

Rated System Voltage (kV)	Impulse Withstand Voltage (kV) peak						
	Transformer	Circuit Breakers CTs,CVTs	Switch & Post Insulation	Bus Insulation		Line Insulation	
				Suspension	Tension	Steel	Wood
22	150	150	225	255	255	-	500
33	200	250	250	320	320	-	600
66	350	350	380	400	470	600	1020
132	550	650	750	700	775	930	-
220	900	1050	1050	1140	1210	1440	-

Table 10.8

Example 10.4

A lightning arrestor is to be located on the main 132 kV busbar, 30 m away from a 132/33 kV transformer. If the BIL of the transformer on the 132 kV side is 650 kV, and the transformer is effectively earthed, select a suitable lightning arrestor to protect the transformer from a surge rising at 1000 kV/μs on the 132 kV side originating beyond the busbar on a line of surge impedance 375 Ω. (Use the tables given in the text for any required additional data).

No. of discs	Dry f.o.v. kV_{rms}	Wet f.o.v. kV_{rms}	Impulse f.o.v. kV_{crest}
1	80	50	150
2	155	90	255
3	215	130	355
4	270	170	440
5	325	215	525
6	380	255	610
7	435	295	695
8	485	335	780
9	540	375	860
10	590	415	945
11	640	455	1025
12	690	490	1105
13	735	525	1185
14	785	565	1265
16	875	630	1425
18	965	690	1585
20	1055	750	1745
25	1280	900	2145
30	1505	1050	2550

Table 10.9

Maximum system voltage for 132 kV = 138 kV
Nominal rating of surge diverter = 138 x 0.8 = 110.4 kV
If this amount is increased by a tolerance of 5%
Nominal rating = 110.4 x 1.05 = 115.9 kV

From these two figures, we can see that either the 109 kV or the 121 kV rated arrestor may be used. Let us consider the 109 kV arrestor.

Line insulation for 138 kV corresponds to 930 kV. Thus this would be the maximum surge that can be transmitted by the line. Assuming doubling of voltage at the transformer, and an arrestor residual discharge voltage of E_a, the surge current and hence the arrestor discharge current would be given by

$$I_a = \frac{2\,E - E_a}{Z_0} = \frac{2 \text{ x } 930 - E_a}{375}$$

For the 109 kV arrestor, E_a range from 316 kV to 418 kV. For this I_a has the range 4.12 kA to 3.85 kA. Thus the 5 kA rated arrestor is suitable. For this E_a = 315 kV.

Peak value to which the transformer potential would rise on a surge rising at 1000 kV/μs is given by

$$E_t = E_a + \beta \frac{de}{dt} x \frac{2l}{300}, \text{ assuming } \beta = 1$$

Thus $E_t = 315 + 2 \text{ x } 1000 \text{ x } 30 / 300 = 515$ kV

This gives a protective margin, for the BIL of 650 kV, of = 100 x (650 - 515)/515 = 26.2%

Thus the arrestor to be selected is the 109 kV, 5 kA one which is found to be completely satisfactory.

Flashover voltages of standard discs (254 x 146 mm) is given in the table 10.9.

In selecting the number of units, it is common practice to allow one or two more units to allow for a unit becoming defective. Thus for lines up to 220 kV, one additional unit; and for 400 kV, 2 unit may be used.

Rated System Voltage kV_{rms}	Tension Insulators		Suspension Insulators	
	Impulse f.o.v. kV	No. of discs	Impulse f.o.v. kV	No. of discs
33	320	3	320	3
66	470	5	400	4
132	775	9	700	8
220	1210	15	1140	14

Table 10.10

Also tension insulator units have their axis more or less horizontal and are more affected by rain. Also a failure of tension insulators are more sever than of suspension insulators. Thus one additional disc is used on tension insulators.

Table 10.10 shows the number of disc units (254 x 146 mm) used in Busbar Insulation in a typical substation, for both tension as well as suspension insulators.

Further, for the 132 kV and 220 kV systems, if the lines are provided with proper shielding and low tower footing resistances (say less than 7 S), the number of disc units may be reduced based on a switching surge flashover voltage of 6.5 × (rated phase to neutral system voltage) and a power frequency flash-over voltage of 3 × (rated phase to neutral system voltage).

On this basis, 7 units are recommended for the 132 kV system and 11 units for the 220 kV system.