High Voltage Engineering – 18EE56

Module-4

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Course Outline

Course Code	Course Title	Core/Elective	Prerequisite	Contact Hours			Total Hrs/ Sessions
				L	T	P	
18EE56	High Voltage	Core	-	3	-	-	40

Course Module Details

Module-4

Overvoltage Phenomenon and Insulation Coordination in Electric Power Systems: Natural Causes for Over voltages - Lightning Phenomenon, Overvoltage due to Switching Surges, System Faults and Other Abnormal, Principles of Insulation Coordination on High Voltage and Extra High Voltage Power Systems.

External Overvoltages

These overvoltages originate from atmospheric disturbances, mainly due to lightning. These overvoltages take the form of a unidirectional impulse (or surge) whose maximum possible amplitude has no direct relationship with the operating voltage of the system. They may be due to any of the following causes.

(i) Direct lightning strokes

(ii) Electromagnetically induced overvoltages due to lightning discharge taking place near the line (commonly known as 'side stroke')

(iii) Voltages induced due to changing atmospheric conditions, along the line length

(iv) Electrostatically induced overvoltages due to the presence of charge clouds nearby

(v) Electrostatically induced overvoltages due to the frictional effects of small particles such as dust or dry snow in the atmosphere or due to change in the altitude of the line

Internal Overvoltages

These overvoltages are caused by changes in the operating conditions of the network.

Internal overvoltages can further be divided into two groups as follows.

(i) Switching overvoltages (or transient overvoltages of high frequency)

(ii) Temporary overvoltages (or steady-state overvoltages of power frequency)

LIGHTNING PHENOMENON

Phenomenon of lightning is defined as the discharge between two clouds and between cloud and the earth through the air which acts as a dielectric medium.

Some facts relevant to lightning.

1. In this phenomenon, the height of the base of cloud is between 160 metres to 9500 metres.
2. The maximum potential of the cloud lies approximately within the range of 10 MV to 100 MV.
3. The energy in lightning stroke may be of the order of 250 kWh.
4. The maximum charge over the clouds may be of the order of 10 coulombs.
5. During the phenomenon, the rain drops elongate under the effect of electric field in the clouds. In this phenomenon, when a rain drop is broken by air currents, due to friction, rain drop is positively charged where as air is negatively charged.
6. When an ice-crystal available at extreme height collide with air currents, the ice-crystal is negatively charged where as, air is positively charged.

CHARGE-SEPARATION PROCESS IN LIGHTNING

Various theories explaining the charge-formation or charge separation process in a thunder cloud and the mechanism of lightning

Simpson's Theory

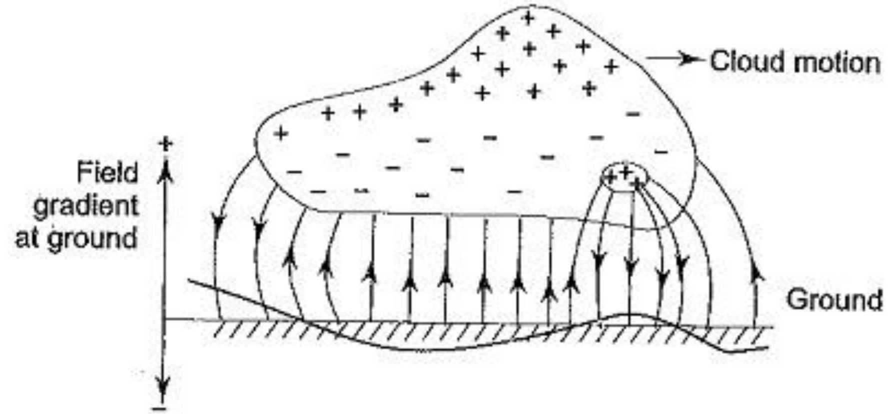


Fig. 8.1 *Probable field gradient near the ground corresponding to the probable charge distribution in a cloud*

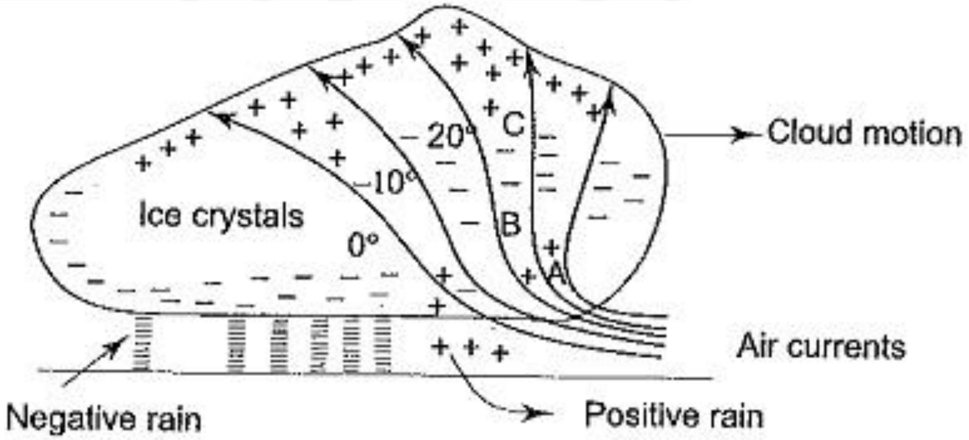


Fig. 8.2 *Cloud model according to Simpson's theory*

Reynolds and Mason Theory

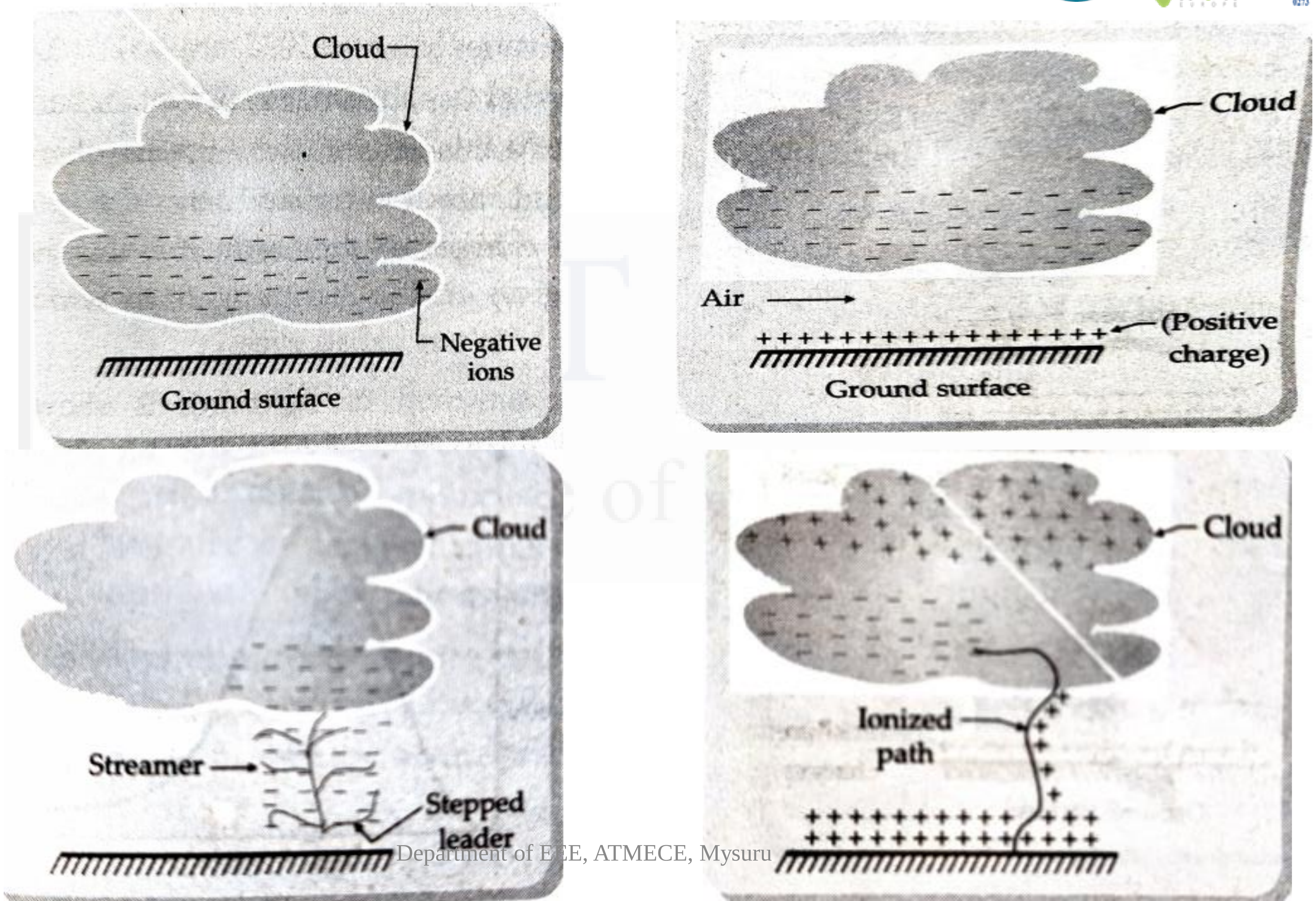
Reynolds and Mason proposed modification, according to which the thunder clouds are developed at heights **1 to 2 km above the ground level** and may extend up **to 12 to 14 km** above the ground.

1. For thunder clouds and charge formation air currents, moisture and specific temperature range are required.
2. The air currents controlled by the temperature gradient move upwards carrying moisture and water droplets. The temperature is **O^{0}C** at about 4 km from the ground

   and may reach - **5O^{0}C** at about 12 km height. But water droplets do not freeze as soon as the temperature is O^{0}C. They freeze below - 4O^{0}C only as solid particles on which crystalline ice patterns develop and grow.
3. The larger the number of solid sites or nuclei present, the higher is the temperature (> -4O0C) at which the ice crystals grow.
4. In clouds, the effective freezing temperature range is around - 330C to - 4O0C.

5. The water droplets in the thunder cloud are blown up by air currents and get super cooled over a range of heights and temperatures

Mechanism of Lightning Strokes



PROTECTION AGAINST OVER VOLTAGES

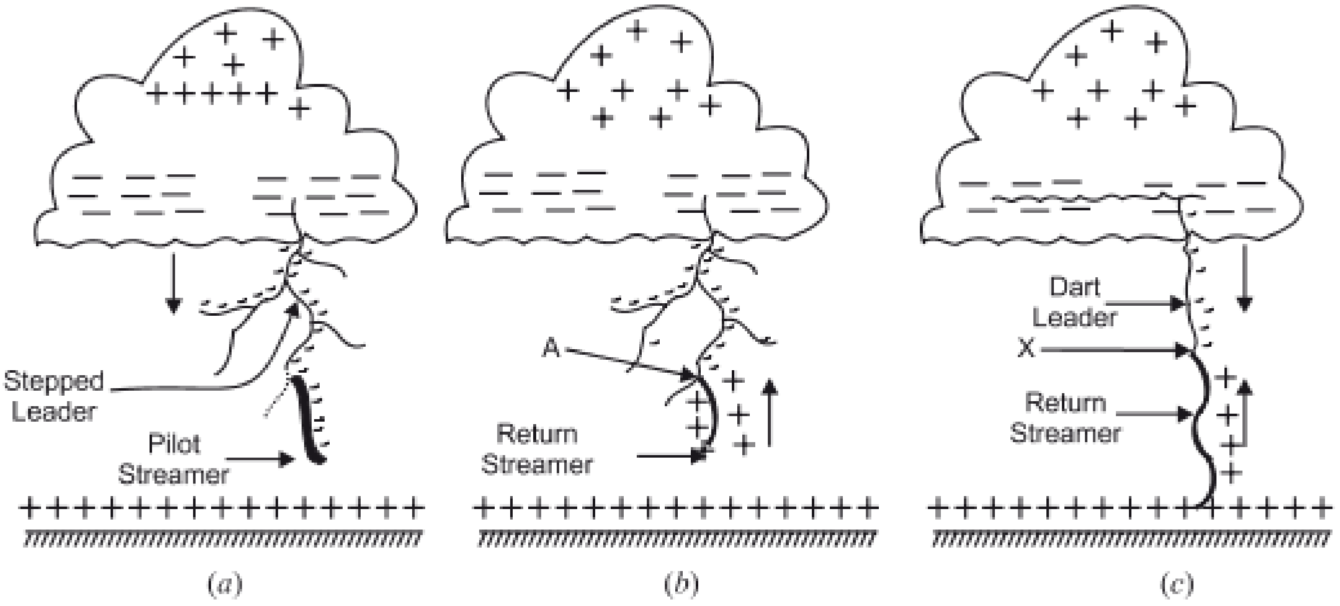


Fig. Phenomenon of lightning

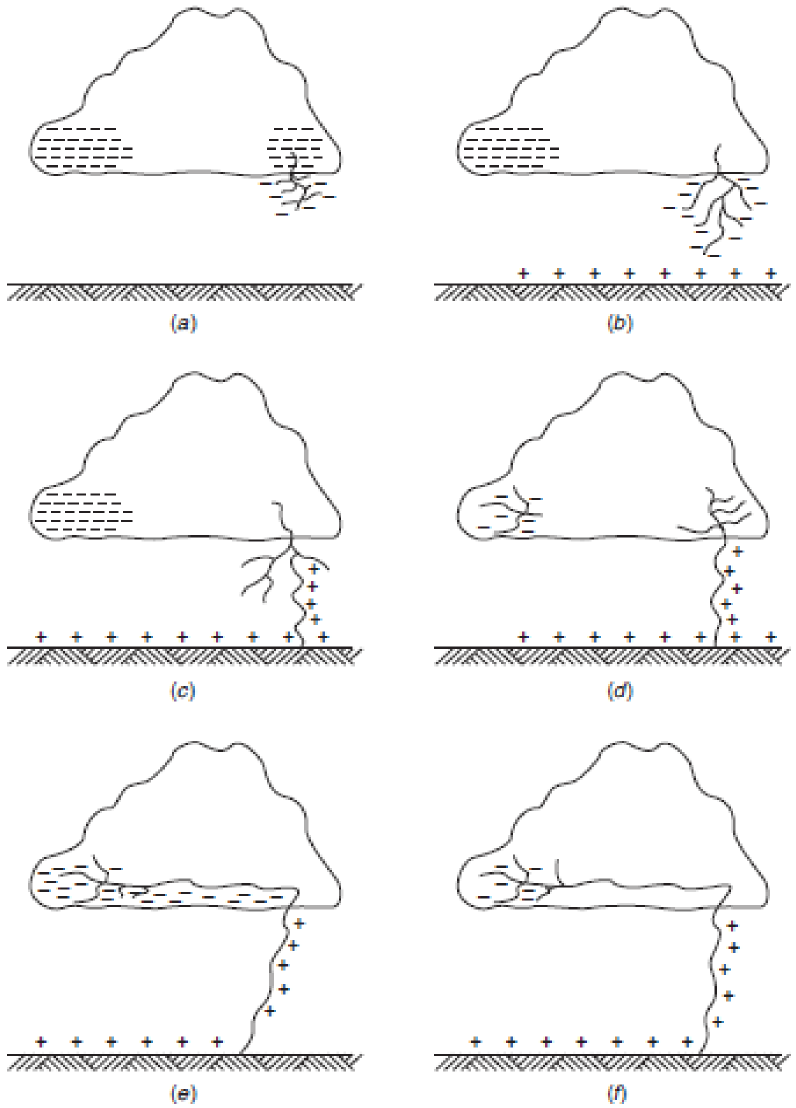


Fig. Lightning mechanism

Mechanism of Lightening Stroke

1. When the electric field intensity at some point in the charge concentrated cloud exceeds the breakdown value of the moist ionized air (>= 10 kV/cm), an electric streamer with plasma starts towards the ground with a velocity of about 1/10 times that of the light, but may progress only about 50 m or so before it comes to a halt emitting a bright flash of light.

2. The halt may be due to insufficient build-up of electric charge at its head and not sufficient to maintain the necessary field gradient for further progress of the streamer. But after a short interval of about 1OO μs, the streamer again starts out repeating its performance.

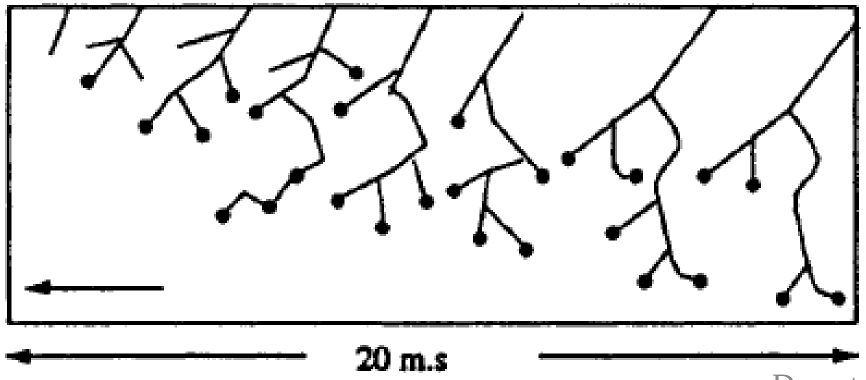
3. The total time required for such a **stepped leader** to reach the ground may be **20 ms**. The path may be quite lustrous, depending on the local conditions in air as well as the electric field gradients. Branches from the initial leader may also be formed. Since the progress of this leader stroke is by a series of jumps, it is referred as stepped leader. The picture of a typical leader stroke taken with a Boy's camera is shown in Fig. 4.3

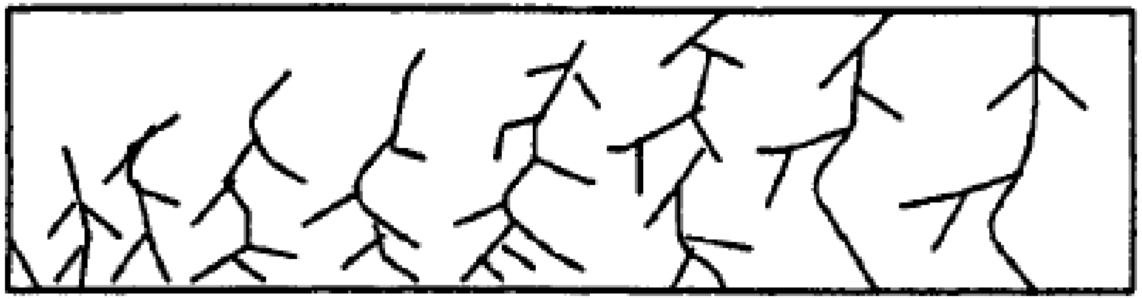
Mechanism of Lightening Stroke

4. After the leader touches the ground, the return stroke follows. As the leader moves towards the ground, positive charge is directly accumulated under the head of the stroke or canal.

5. By the time the stroke reaches the ground or comes sufficiently near the ground, the electrical field intensity on the ground side is sufficiently large to build up the path. Hence, the positive charge returns to the cloud neutralizing the negative charge, and hence a heavy current flows through the path.

6. The velocity of the return or main stroke ranges from 0.05 to 0.5 times the velocity of light, and currents will be of the order of 1000 to 250,000 A. The return strokes vanish before they reached the cloud, suggesting that the charge involved is that conferred to the stroke itself.



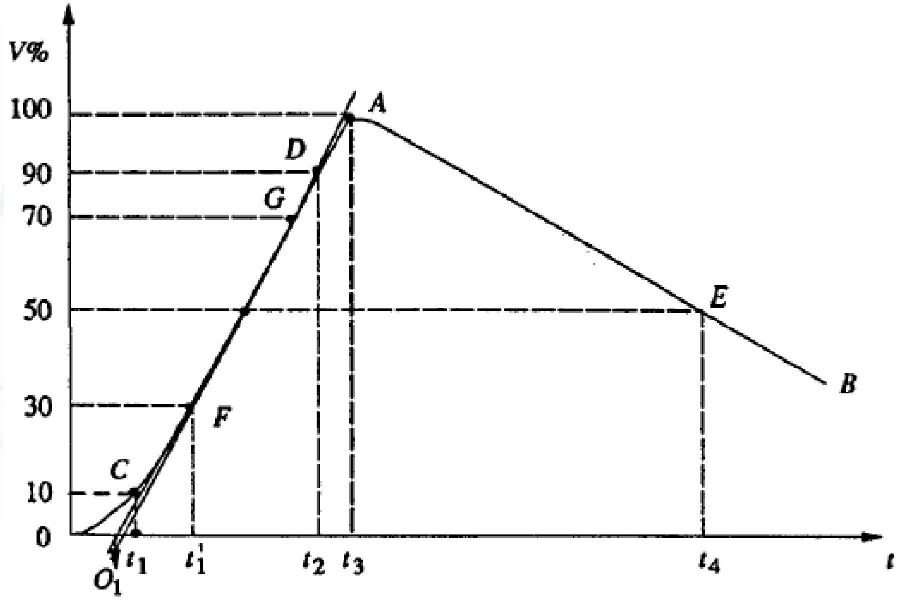


Development of the main or return stroke

IMPULSE LIGHTNING VOLTAGES

An impulse voltage is a unidirectional voltage which, without appreciable oscillations, rises rapidly to a maximum value and falls more or less rapidly to zero

A full impulse voltage is characterized by its peak value and its two time intervals, the wave front time and wave tail time intervals defined below



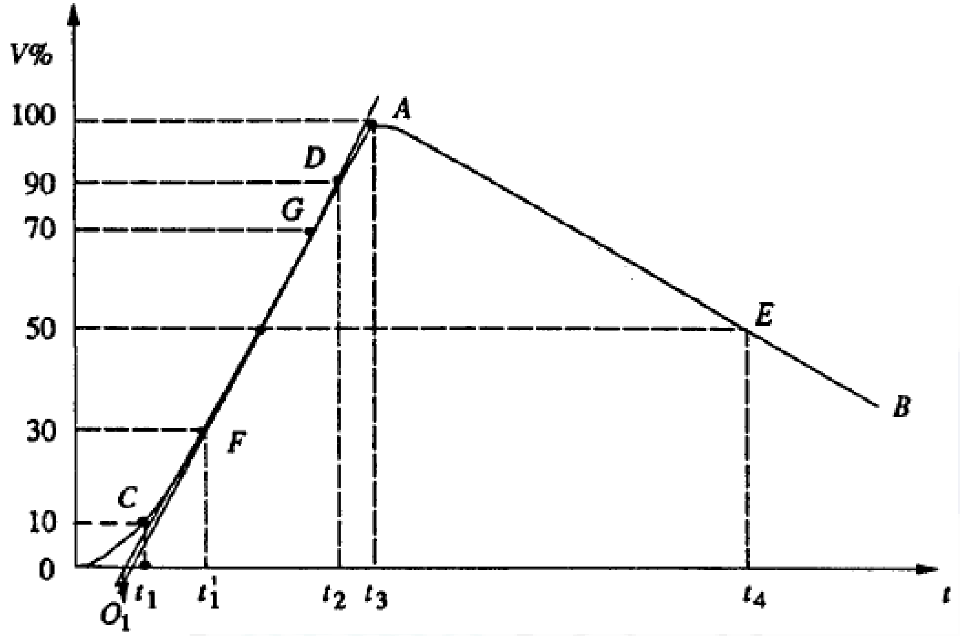
Standard Lightning Impulse

The **wave front time** of an impulse wave is the time taken by the wave to reach to its maximum value starting from zero value

The wave front time is specified as 1.25 times (t2 – t1), where t2 is the time for the wave to reach to its 90% of the peak value and t1 is the time to reach 10% of the peak value.

Since (t2 – t1) represents about 80% of the wave front time, it is multiplied by 1.25 to give total wave front time.

Standard Lightning Impulse



The standard wave shape specified in BSS is a 1/50 micro sec. wave i.e. a wave front of 1 micro sec. and a wave tail of 50 micro sec.

The standard wave shape specified in ISS is a 1.2/50 micro sec. wave i.e. a wave front of 1.2 micro sec. and a wave tail of 50 micro sec.

The Wave tail time is defined as time taken for the wave to reach 50% of its peak value over the tail position expressed as (t4 – O).

The point E is located on the wave tail corresponding to 50% of the peak value, and its projection on the time axis is t4. O*t4 is defined as the fall or tail time

It is shown that lightning overvoltage wave can be represented as double exponential waves defined by the equation $V = V_0 [\exp(-\alpha t) - \exp(-\beta t)]$

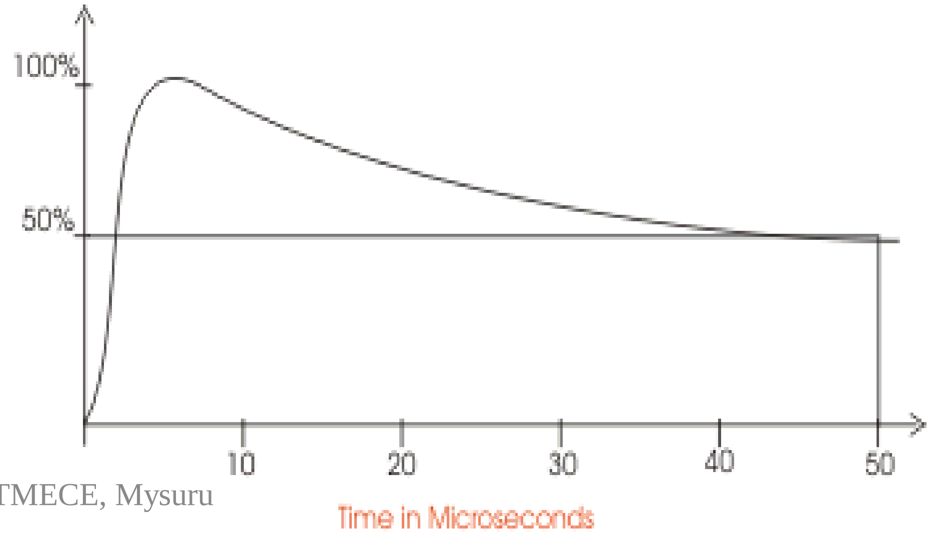
Where α and β are constants values

Impulse Voltage

As per Indian Standard this is 1.2/50 microsecond.

As per American Standard the impulse wave shape is 1.5/40 microsecond.

This representation of the wave has a special significance. Such as 1.2/50 microsecond impulse wave represents a unidirectional wave which rises to its peak value from zero in 1.2 microseconds and then falls to 50% of peak value in 50 microseconds. The represented wave shape is shown below,



OVERVOLTAGE DUE TO SWITCHING SURGES

Switching over voltages or Transient over voltages

Till the time when the transmission voltages were about **220 kV and below**, over voltages due to lightning were of very lower order and over voltages generated inside the system were not of much consequence. In later years, with increase in **transmission voltages, (400 kV and above)** the overvoltages generated inside the system reached the same order of magnitude as those of lightning over voltages, or higher

In insulation co-ordination, where the protective level of any particular kind of surge diverter is proportional to the maximum voltage, the insulation level and the cost of the equipment depends on the magnitudes of these overvoltages. **In the EHV range, it is the switching surge and other types of overvoltages that determine the insulation level of the lines and other equipment** and consequently, they also determine their dimensions and costs.

Origin of Switching Surges

- The making and breaking of electric circuits with switchgear may result in abnormal overvoltages in power systems having large inductances and capacitances.
- The overvoltages may go as high as six times the normal power frequency voltage.
- In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated restriking of the arc between the contacts of a circuit breaker, thereby causing destruction of the circuit breaker contacts.

Characteristics of Switching Surges

The wave shapes of switching surges are quite different and may have origin from any of the following sources.

(i) De-energizing of transmission lines, cables, shunt capacitor, banks, etc

(ii) Disconnection of unloaded transformers, reactors, etc.

(iii) Energization or reclosing of lines and reactive loads,

(iv) Sudden switching off of loads.

(v) Short circuits and fault clearances.

Switching Overvoltages In EHV and UHV Systems

- Switching overvoltages are of relatively higher magnitudes as compared to the lightning overvoltages for UHV systems.
- Overvoltages are generated in EHV systems when there is a sudden release of internal energy stored either in the electrostatic form (in the capacitance) or in the electromagnetic form (in the inductance).

Causes of Switching Over voltages in EHV and UHV Systems

- Interruption of low inductive currents (current chopping) by high speed circuit breakers. This occurs when the transformers or reactors are switched off
- Interruption of small capacitive currents, such as switching off of unloaded lines
- Energization of long EHV or UHV lines.
- Transient overvoltages in the above cases will have magnitudes of the order of 1200 kV to 2000 kV on 750 kV systems.

The measures taken to control or reduce the overvoltages are

(i) one step or multi-step energization of lines by pre insertion of resistors,

(ii) draining of trapped charges on long lines before the reclosing of the lines.

(iii) limiting the overvoltages by using surge diverters.

Overvoltages due to Switching Operations Under Different Conditions

Maximum value of the system line-to-ground voltage = 1.0 p.u.

Sl. no.		Type of operation	Overvoltage (p.u.)
1		Switching an open ended line with:	
	(a)	infinite bus as source with trapped charges on line	4.1
	(b)	infinite bus as source without trapped charges	2.6
	(c)	de-energising an unfaulted line with a restrike in the circuit breaker	2.7
	(d)	de-energising an unfaulted line with a line to ground fault (about 270 km in length)	1.3
2	(a)	switching a 500 kV line through an auto-transformer, 220 kV/500 from the L.V. side	2.0
	(b)	switching a transformer terminated line	2.2
	(c)	series capacitor compensated line with 50% compensation	2.2
	(d)	series capacitor compensated line with shunt reactor compensation	2.6
3		High speed reclosing of line after fault clearance	3.6

Temporary over voltages or steady state over voltages of Power Frequency in Power Systems

The power frequency overvoltages occur in large power in EHV systems, i.e. systems of 400 kV and above.

The main causes for power frequency and its harmonic overvoltages are

(a) sudden loss of loads

(b) disconnection of inductive loads or connection of capacitive loads

(c) Ferranti effect, unsymmetrical faults, and

(d) saturation in transformers, etc.

- The duration of the overvoltages may be from one to two cycles to a few seconds depending on the overvoltage protection employed

Sudden Load Rejection

Sudden load rejection on large power systems causes the speeding up of generator prime movers. The speed governors and automatic voltage regulators will intervene to restore normal conditions. But initially both the frequency and voltage increase.

The approximate voltage rise, neglecting losses, etc. may be taken as

$$v = \frac{f}{f_0} E' \left[\left(1 - \frac{f}{f_0} \right) \frac{x_s}{x_c} \right]$$

- Xs is the reactance of the generator (≈ the sum of the transient reactances of the generator and the transformer),
- Xc is the capacitive reactance of the line at open end at increased frequency,
- E′ the voltage generated before the over-speeding and load rejection,
- f is the instantaneous increased frequency, and fo is the normal frequency

- This increase in voltage may go to as high as 2.0 per unit (p.u.) value with 400 kV lines.
- Installation of Shunt reactors may reduce the voltage to 1.2 to 1.4 p.u.

Ferranti Effect

Long uncompensated transmission lines exhibit voltage rise at the receiving end.

The voltage rise at the receiving end V_2 is approximately given by

$$V_2 = \frac{V_1}{\cos \beta l}$$

V_1 = sending end voltage,

l = length of the line,

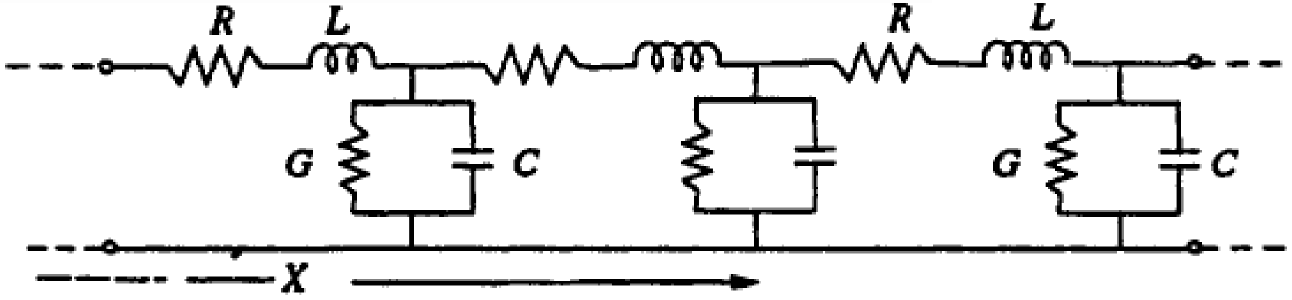
β = phase constant of the line

$$\approx \left[\frac{(R + j\,\omega L)\,(G + j\,\omega C)}{LC}\right]^{1/2}$$

≈ about 6° per 100 km line at 50 Hz frequency.

R, L, G, and C are as defined

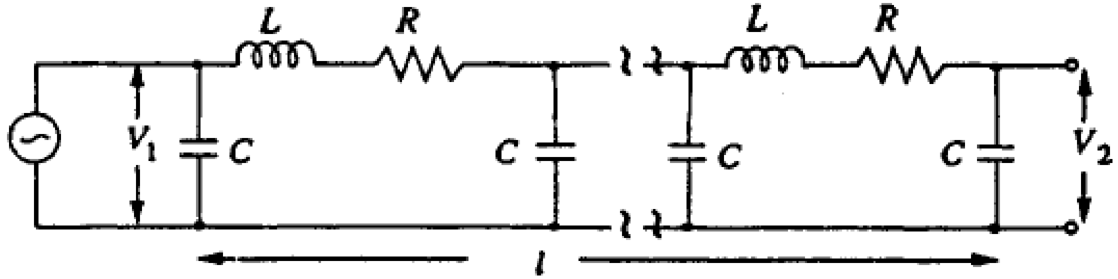
ω = angular frequency for a line shown in Fig.



Voltage: $e(t)$, Current $i(t)$

R — Resistance per unit length
L — Inductance per unit length
C — Capacitance per unit length
G — Leakage conductance per unit length

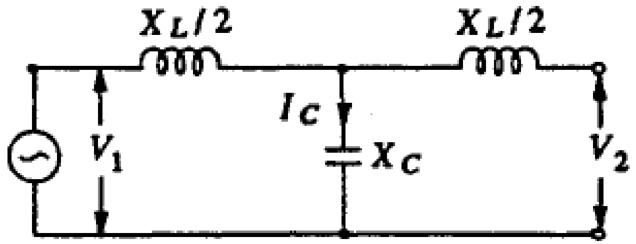
Fig. Distributed characteristic of a long transmission line



L, *R* and *C* — Inductance, resistance and capacitance per unit length of the line

l — Length of the line

Fig. Typical uncompensated long transmission line



Transmission line approximation for line in Fig.

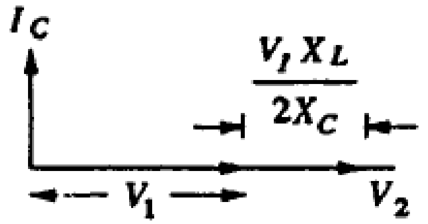


Fig. Vector (phase) diagram of an open circuited uncompensated line showing Ferranti effect

Considering that the line capacitance is concentrated at the middle of the line,

Under open circuit conditions at the receiving end, the line charging current, $I_C \approx j\omega CV_1 = \dfrac{V_1}{X_C}$

and the voltage $V_2 \approx V_1 \left[1 - \dfrac{X_L}{2X_C}\right]$

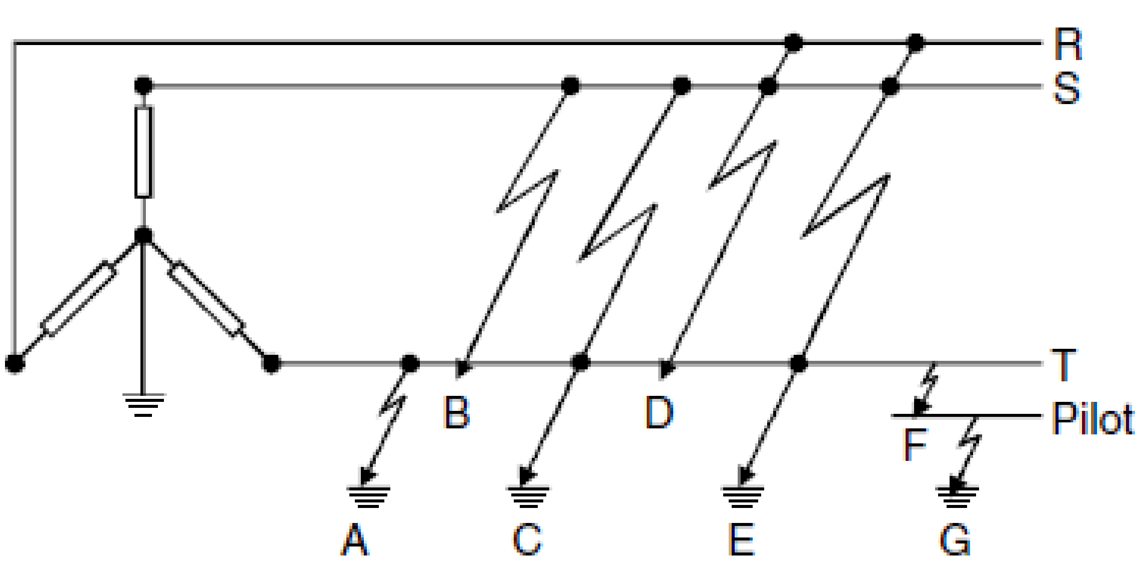
where, X_L = line inductive reactance, and

X_C = line capacitive reactance.

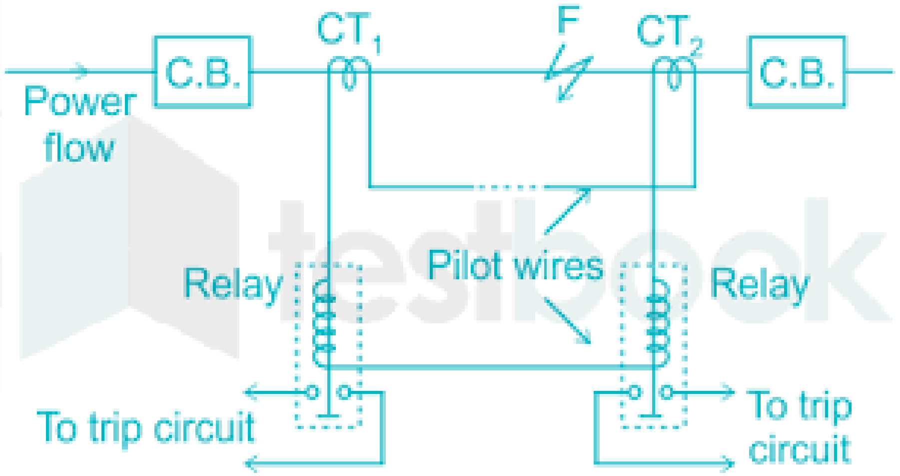
Types of faults on a three-phase system

Largely, the power distribution is globally a three-phase distribution especially from power sources. The types of faults that can occur on a three-phase AC system are shown in Figure

The pilot wire provides the path for the circulating current produce in an abnormal condition, which is sensed by the relay and therefore is tripped



Types of faults on a three-phase system: (A) Phase-to-earth fault; (B) Phase-to-phase fault; (C) Phase-to-phase-to-earth fault; (D) Three-phase fault; (E) Three-phase-to-earth fault; (F) Phase-to-pilot fault; (G) Pilot-to-earth fault**
**In underground mining applications only*



Symmetrical and asymmetrical faults

Symmetrical faults: Fault current is same in all the Three Phases and hence system remains balanced even after fault occurrence, Three Phase Short Circuit is generally treated as a standard fault to determine the system fault level

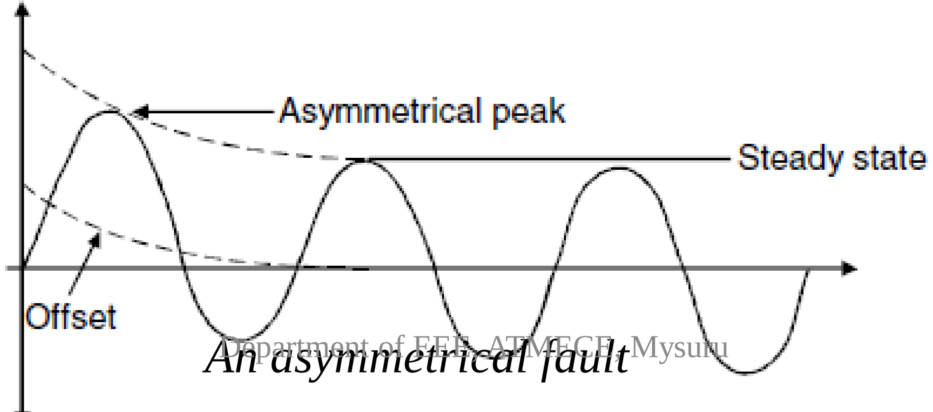
Unsymmetrical faults: Fault current is not same in all the Three Phases , System is no longer balanced; these faults are very common, but more difficult to analyze. Analyzed using symmetrical components

Symmetrical and asymmetrical Faults

	Types of fault	% of occurrence
asymmetrical faults	Single Line to ground faults	70%
	Double line faults	15%
	Double line to ground faults	10%
symmetrical faults	Triple line faults (Balanced three phase faults)	5%

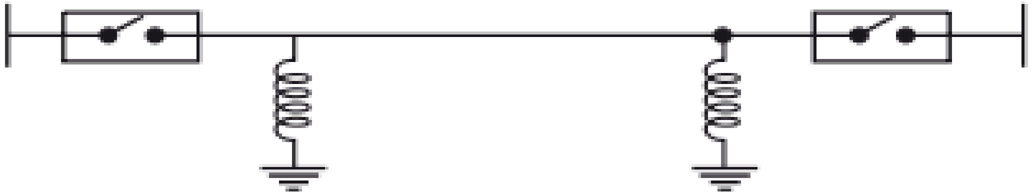
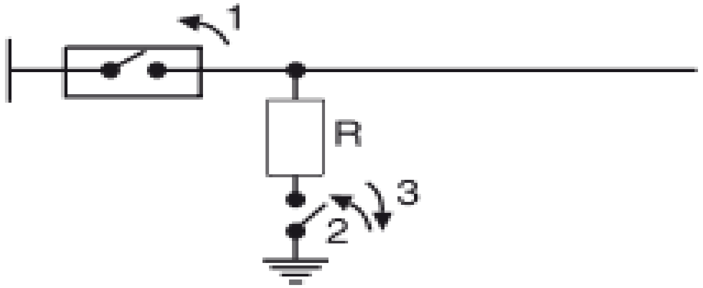
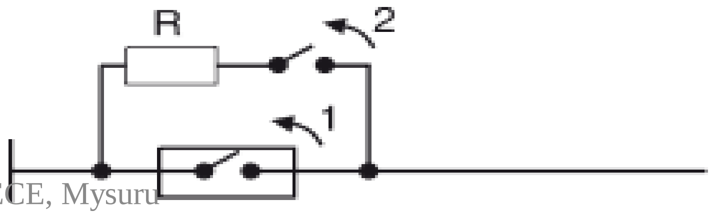
symmetrical fault is a balanced fault with the sinusoidal waves being equal about their axes, and represents a steady-state condition.

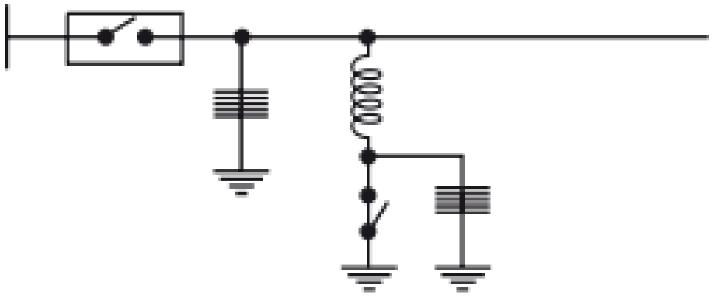
An asymmetrical fault displays a DC offset, transient in nature and decaying to the steady state of the symmetrical fault after a period of time, as shown in Figure



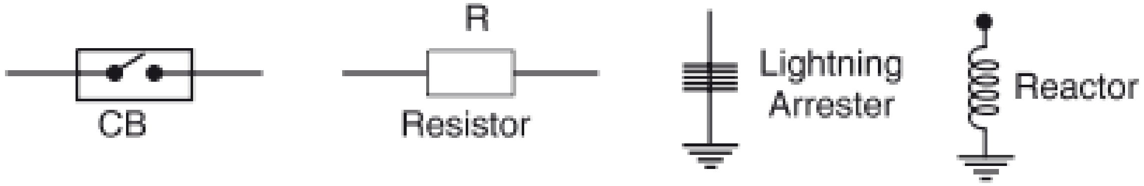
An asymmetrical fault

Table Methods of Reducing Switching Overvoltages

Condition of Switching	*Method of reducing switching overvoltage*
1. Energising an unchanged line.	High voltage shunt reactors connected to line to reduce power frequency-overvoltages. 
2. Elimination of trapped charge on the line.	Line shunting after opening. 
3. Reduction of current chopping.	Opening Resistors (Resistance Switching) 

Condition of Switching	*Method of reducing switching overvoltage*
Use of Surge arresters Modem Gapless Surge Arresters having high energy absorption capability and precise protective levels are useful against switching overvoltages.	While closing of line  While disconnecting reactor 

Symbol: 1, 2, 3 etc sequence of operation



Direct Lightening Stroke

Direct Stroke

(i) Effect on Overhead Line :

$$V_L = I_S \frac{Z_o}{2}$$

V_L = Voltage rise at the point of strike

I_s = Stroke current

Z_o = Surge impedance of the line.

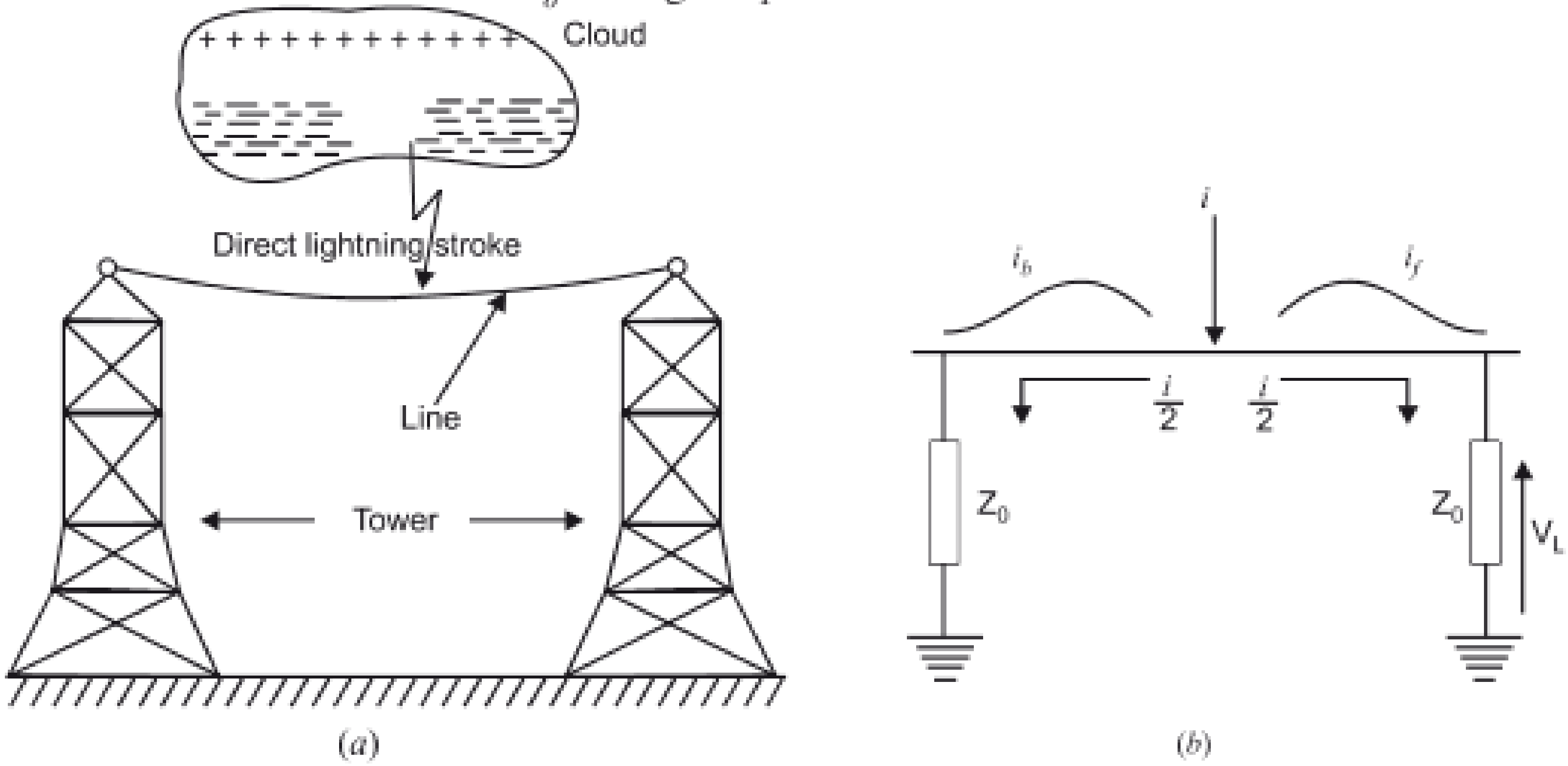


Fig. Development of lightning voltage

Indirect Lightening Stroke

The amplitudes of voltages induced on lines due to indirect lightning strokes on a tower, ground wires or nearby ground or object are much lesser than those caused by direct strokes.

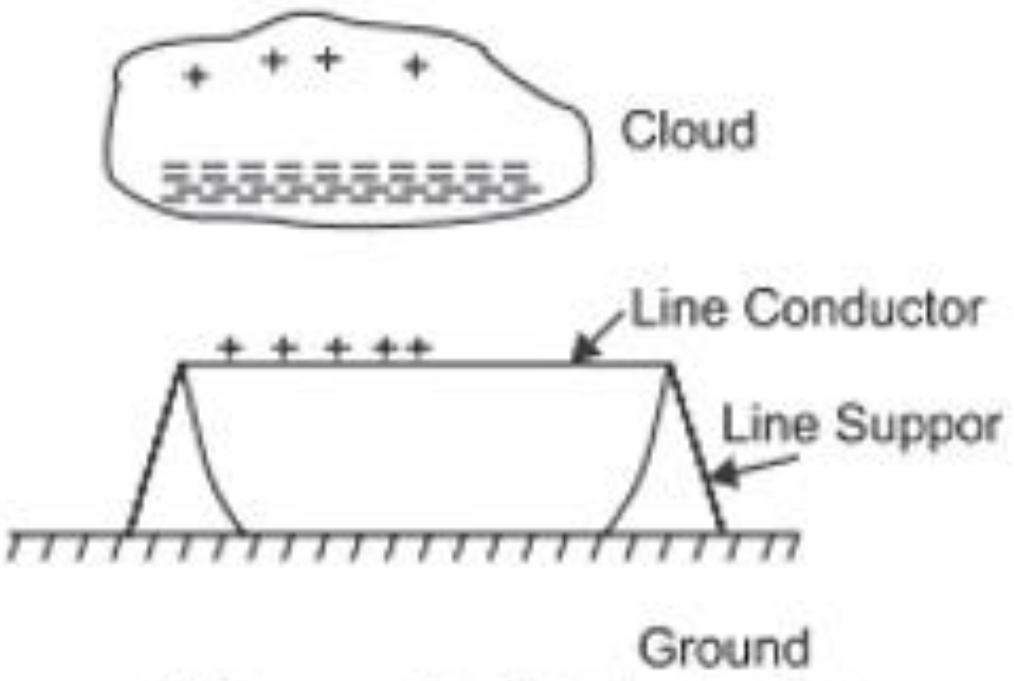
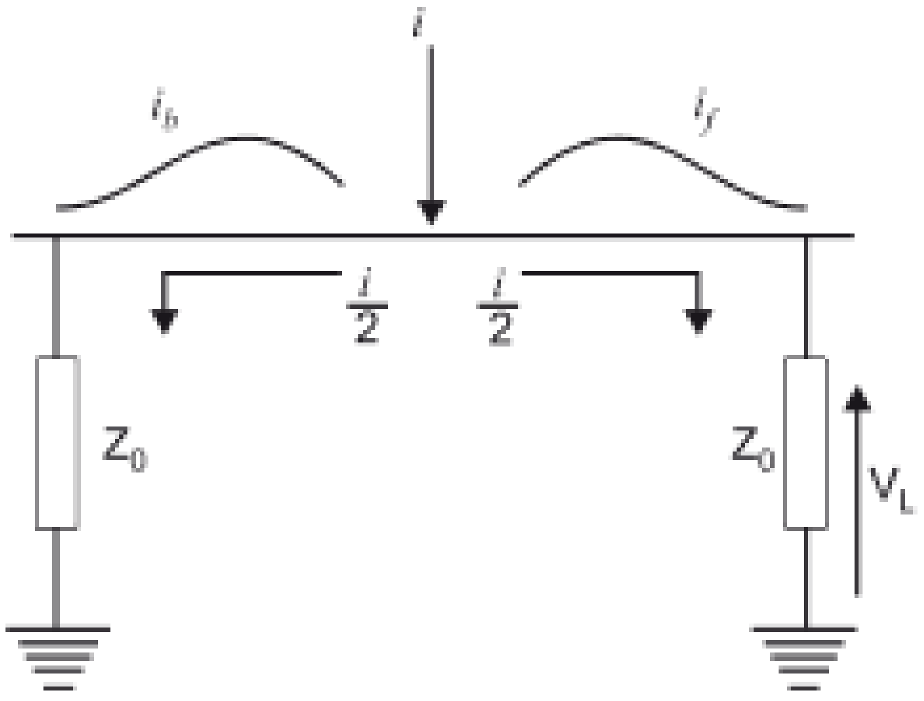


Fig. Indirect strokes



(b)

Surge diverters or lightning arresters

An ideal surge diverter should have the following characteristics:

i. It should not draw any current during normal operating conditions, i.e., its spark over voltage must be above the normal or abnormal power frequency that may occur in the system.

ii. Any abnormal transient voltage above the breakdown value must cause it to breakdown as quickly as possible so that it may provide a conducting path to ground.

iii. When the breakdown have taken place, it should be capable of carrying the resulting discharge current without getting damaged itself and without the voltage across it exceeding the breakdown value.

iv. The power frequency current following the breakdown must be interrupted as soon as the transient voltage has fallen below the breakdown value.

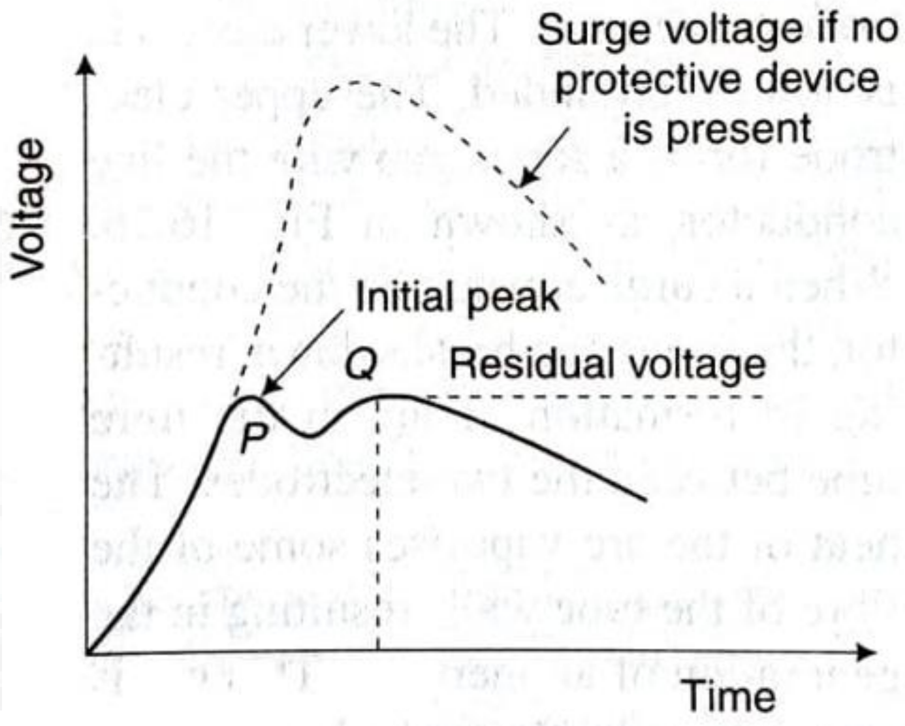


Fig. *Voltage characteristic of surge diverter*

The choice of lightning arrester depends upon the following factors:

(i) Voltage of the line.

(ii) Frequency of the lightning.

(iii) Cost

(iv) Weather conditions

(v) Reliability

Lightning Arresters

There are several types of lightning arresters in general use. They differ only in constructional details but operate on the same principle *viz*. providing low resistance path for the surges to the ground.

Types of lightning arresters :

1. Rod gap arrester

2. Horn gap arrester

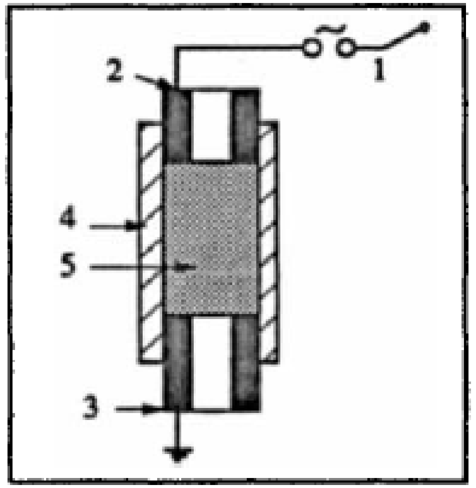
3. Multigap arrester

4. Expulsion type lightning arrester

5. Valve type lightning arrester

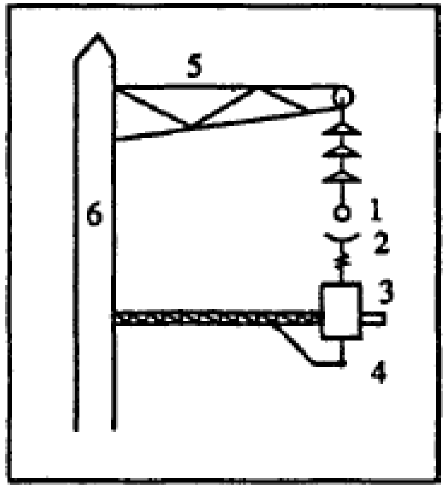
Expulsion type lightning arresters

In regions where lightning strokes are intensive or heavy, the overhead lines within these zones are fitted with shunt protected devices. On the line itself two devices known as expulsion gaps and protector tubes are used.



1. External series gap
2. Upper electrode
3. Ground electrode
4. Fibre tube
5. Hollow space

Fig. a Expulsion gap

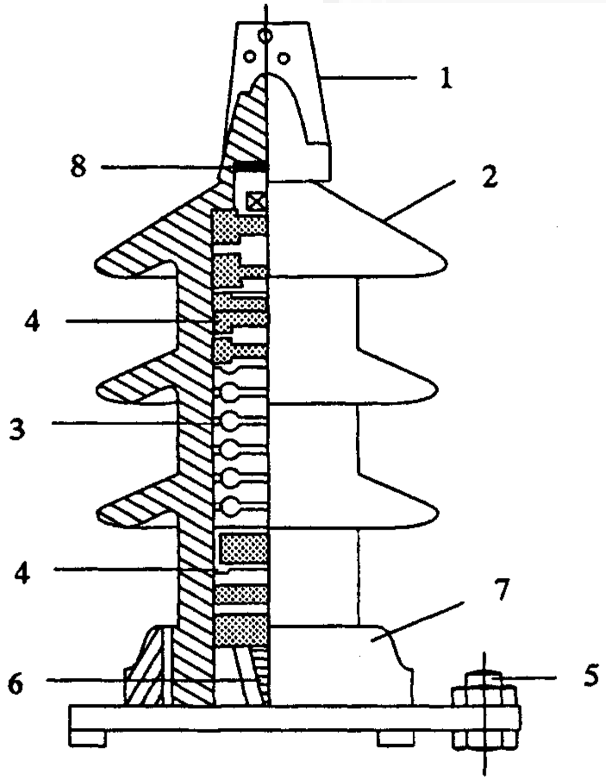


1. Line conductor on string insulator
2. Series gap
3. Protector tube
4. Ground connection
5. Cross arm
6. Tower body

Fig. b Protector tube mounting

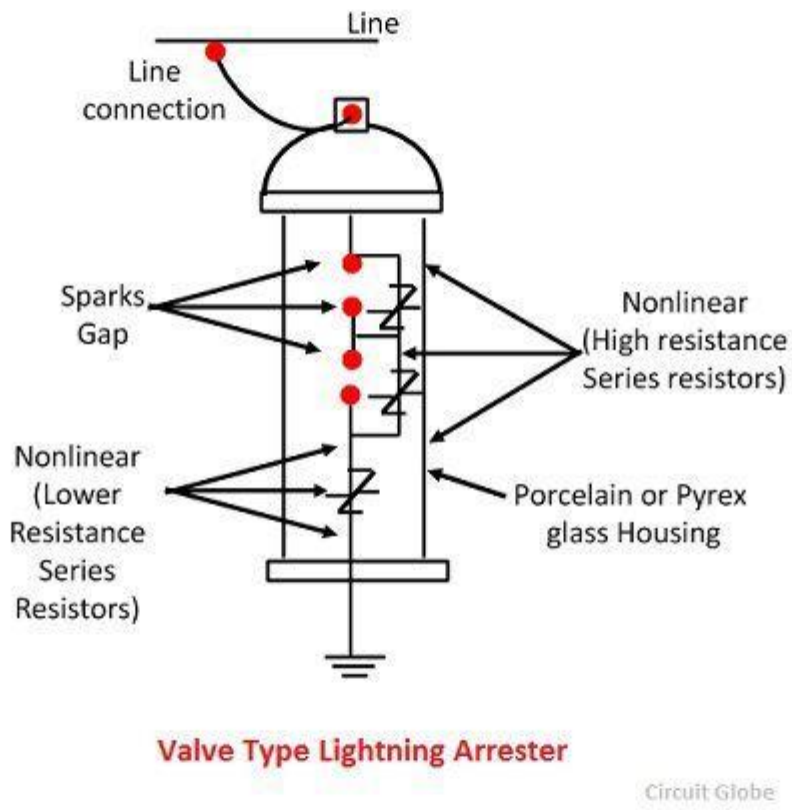
These are capable of discharging 10 to 20 kA of long duration surges (8/20µs) and 100 to 250 kA of the short duration surge currents (1/5µs).

Valve type arrester



1. Line end connector
2. Porcelain housing
3. Series gaps
4. Non-linear resistance element blocks
5. Ground connection
6. Spring
7. Base
8. Water tight sealing

Fig. 8.23 Non-linear element surge diverter



Metal Oxide Lightning Arrester

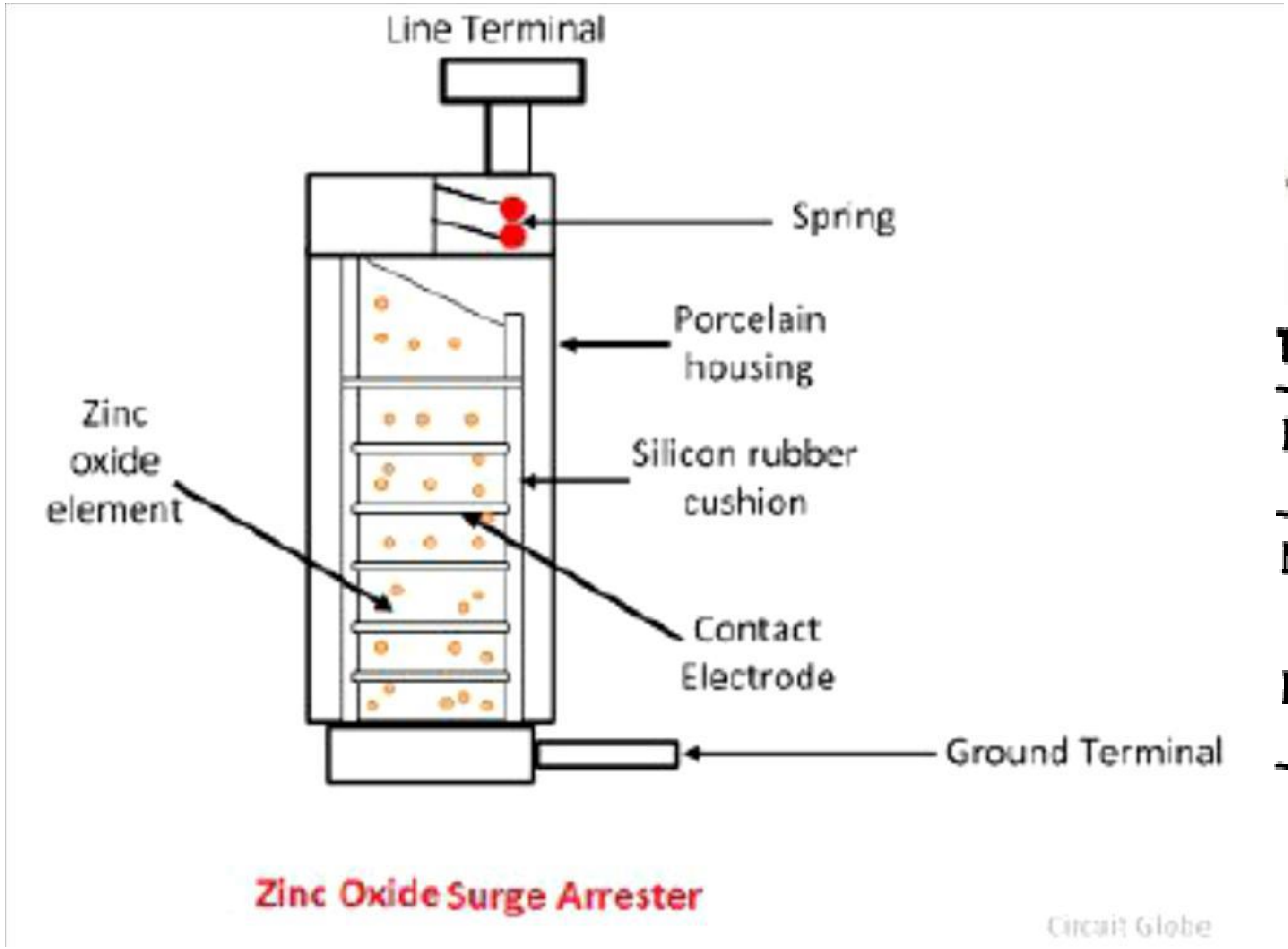
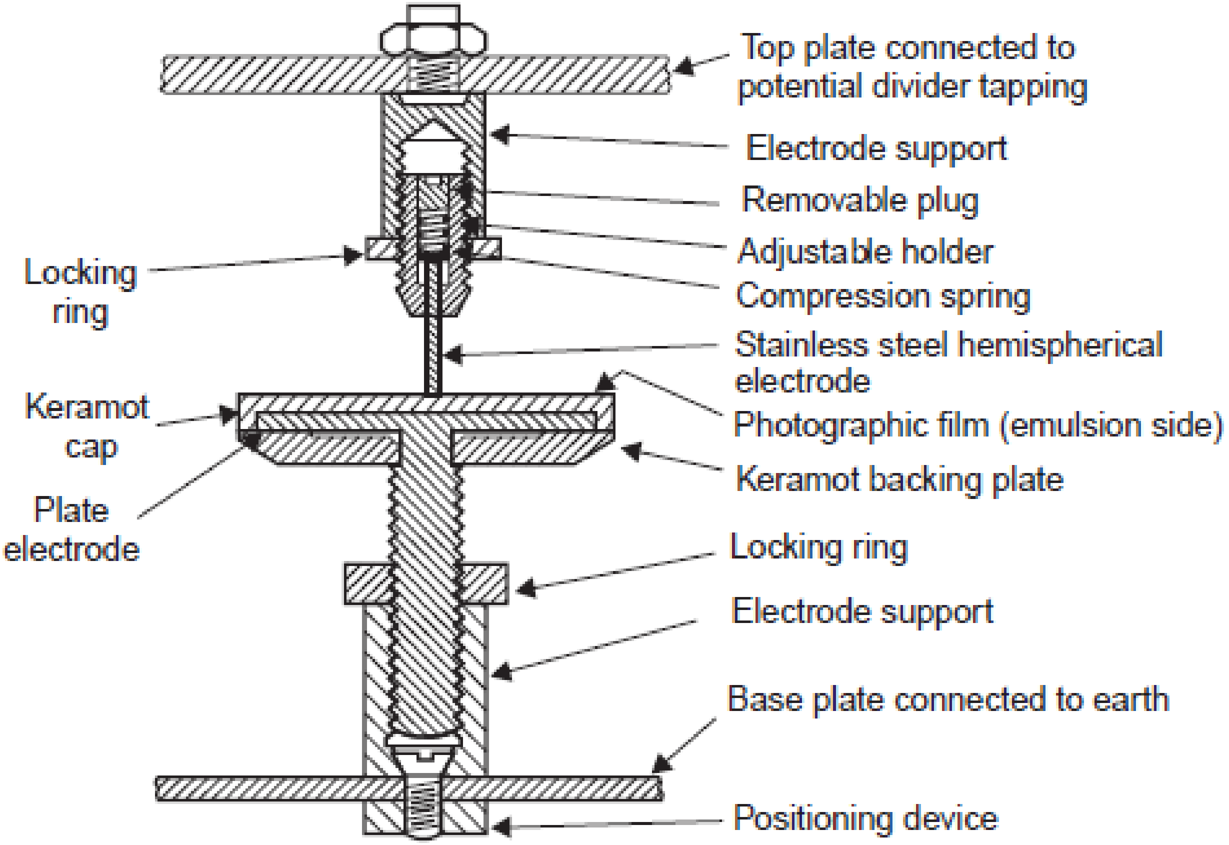
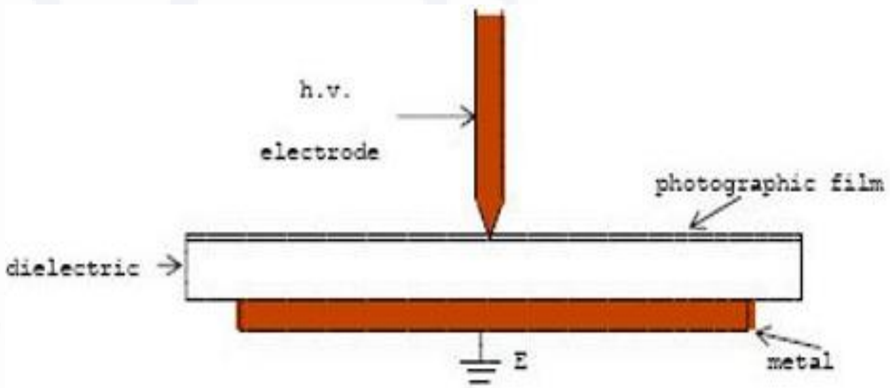


Table 8.5 Maximum Switching Surge Levels at Different Line Voltages

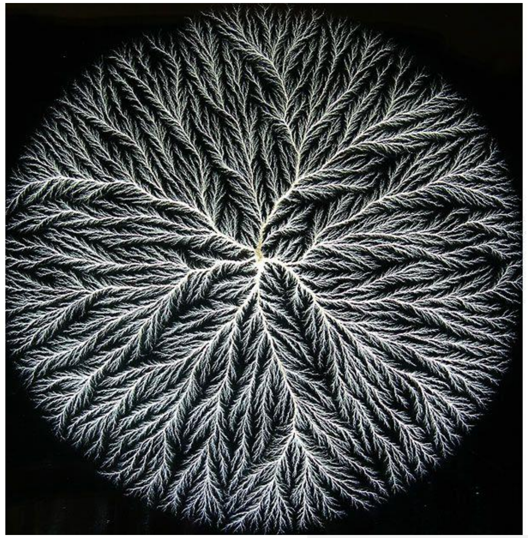
Highest system voltage (kV)	420	525	765	1150
Maximum switching surge level (kV) = Highest system voltage multiplied by	2.5	2.25	2.0	1.8 to 1.9

Klydonograph or Surge Recorder





Klydonograph or Surge Recorder



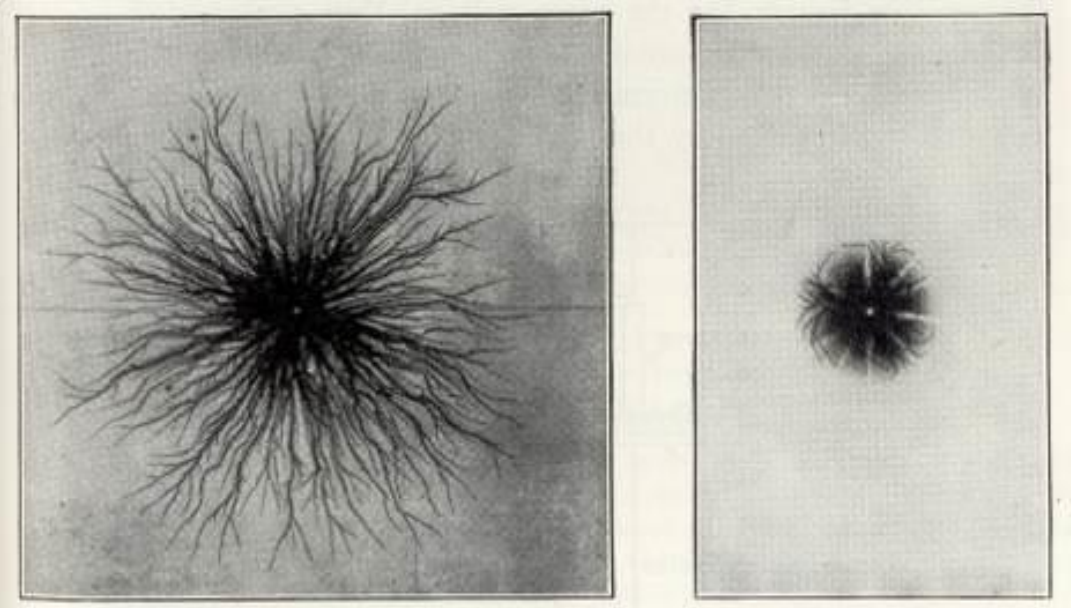


Fig. 3·2. Positive and negative photographic Lichtenberg figures produced by positive and negative surge voltages of same magnitude and wave shape.[9]

Insulation Coordination

It is the process of determining the proper insulation levels of various components in a power system.

It is determined from the known characteristics of voltage surges and the characteristics of surge arresters.

Some common terms that must be known when performing an Insulation Coordination Study.

1. Basic Impulse Insulation Level (BIL)

This is the reference insulation level expressed as an impulse crest (or peak) voltage with a standard wave not longer than a **1.2 / 50 microsecond** wave.

A **1.2 / 50 microsecond** wave means that the impulse takes 1.2 microseconds to reach the peak and then decays to 50% of the peak in 50 microseconds.

Basic Insulation Level

- When lightning impulse over voltage appears in the system, it is discharged through surge protecting devices before the equipments of the system gets damaged.
- Hence, the insulation of such equipment must be designed to withstand a certain minimum voltage before the lightning impulse over voltage gets discharged through surge protecting devices.
- Therefore, operating voltage level of surge protecting devices must be lower than the said minimum voltage withstanding level of the equipment.
- This minimum voltage rating is defined as BIL or basic insulation level of electrical equipment

2. Withstand Voltage

This is the BIL level that can repeatedly be applied to an equipment without flashover, disruptive charge or other electrical failure under test conditions.

3. Chopped Wave Insulation Level

This is determined by using impulse waves that are of the same shape as that of the BIL waveform, with the exception that the wave is chopped after 3 microseconds.

Generally, it is assumed that the Chopped Wave Level is 1.15 times the BIL level for oil filled equipment such as transformers. However, for dry type equipment, it is assumed that the the Chopped Wave Level is equal to the BIL level.

4. Critical Flashover Voltage

This is the peak voltage for a 50% probability of flashover or disruptive charge.

5. Impulses Ratio

This is normally used for Flashover or puncture of insulation. It is the ratio of the impulse peak voltage to the value of the 60 Hz voltage that causes flashover or puncture. Or, it is the ratio of breakdown voltage at surge frequency to breakdown voltage at normal system frequency (60 Hz).

Basic Insulation Level Table

Nominal System Voltage	Indian Standards BIL	British Standards BIL
11 KV	75 KV	-
33 KV	170 KV	200 KV
66 KV	325 KV	450 KV
132 KV	550/650 KV	650/750 KV
220 KV	900/1050 KV	900/1050 KV

THANK YOU