High Voltage Engineering & Power System Protection – 21EE71

Module- 5b

Prepared By,

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Course Module Details

Module-5

- **Circuit Breakers:** Introduction, Arc Voltage, Arc Interruption, Restriking Voltage and Recovery Voltage, Current Chopping. Air Circuit Breakers, SF6 Circuit Breakers, Vacuum Circuit Breakers, Rating of Circuit Breakers,
- Testing of Circuit Breakers.
- **Protection against Overvoltage**: Causes of Overvoltage, Lightning phenomena, Klydonograph and Magnetic Link, Protection of power stations and Substations, Insulation Coordination.

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

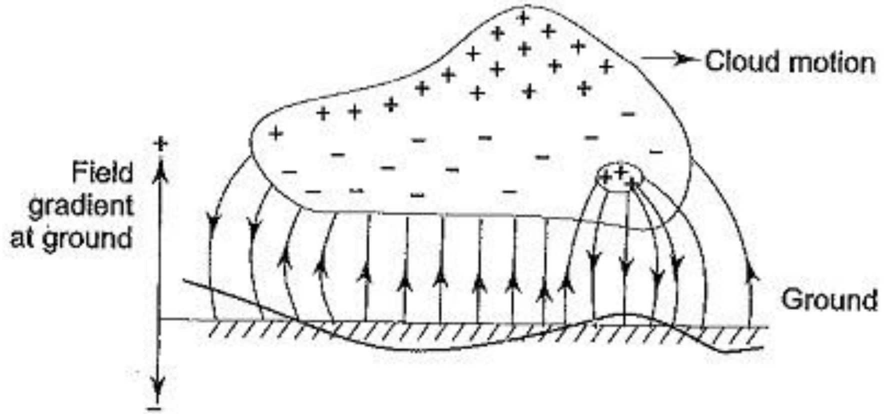


Fig. 8.1 *Probable field gradient near the ground corresponding to the probable charge distribution in a cloud*

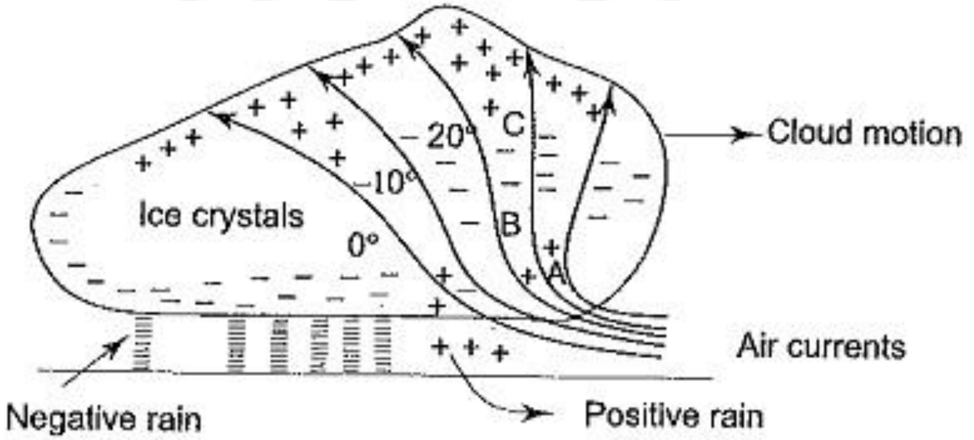


Fig. 8.2 *Cloud model according to Simpson's theory*

Reynolds and Mason Theory

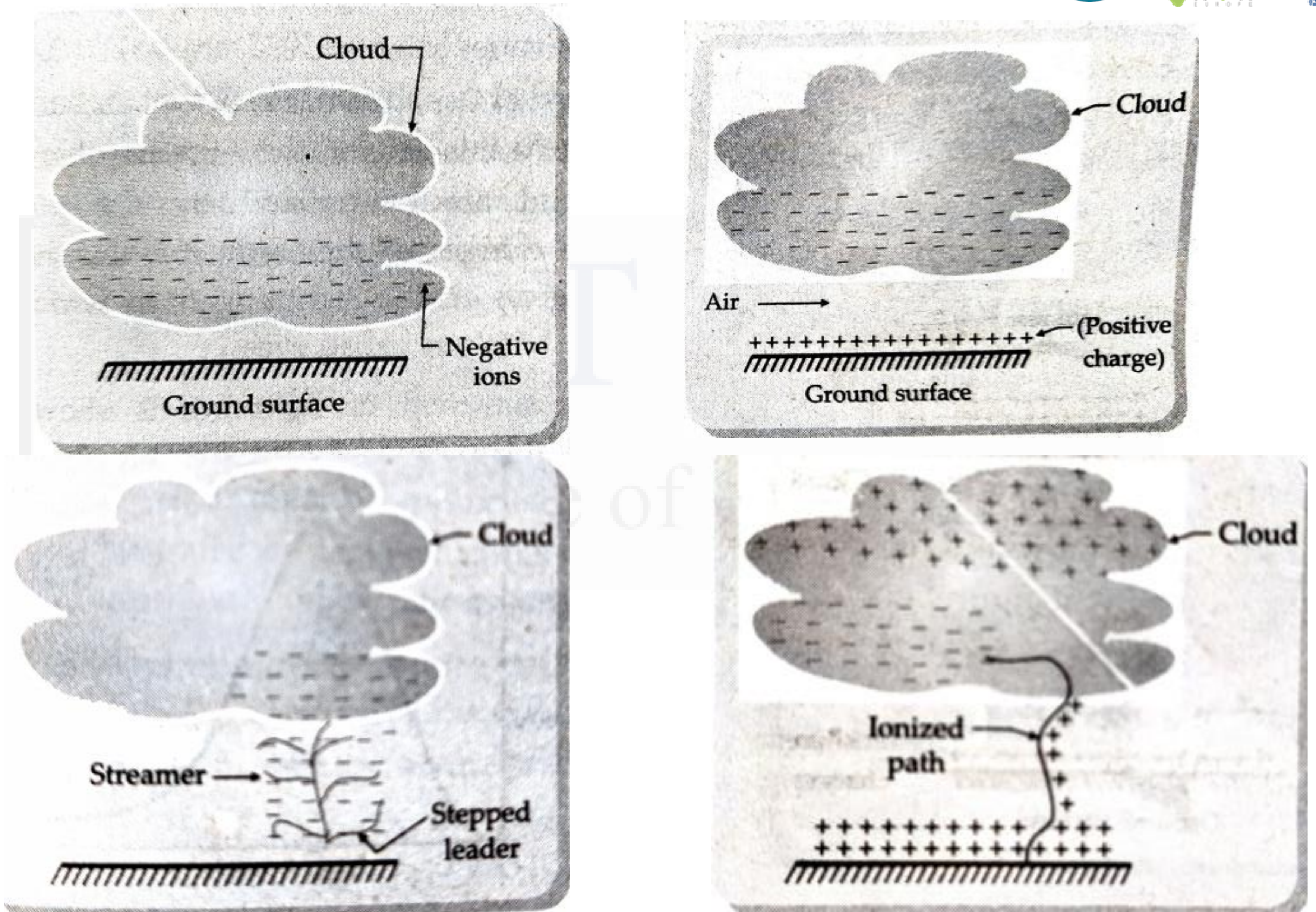
Reynolds and Mason proposed modification, according to which the thunder clouds are developed at heights **1 to 2 km above the ground level** and may extend up **to 12 to 14 km** above the ground.

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

Vlg Gradient: rate of change of electric potential (voltage) per unit distance in a given direction within an electric field.

Mechanism of Lightning Strokes



PROTECTION AGAINST OVER VOLTAGES

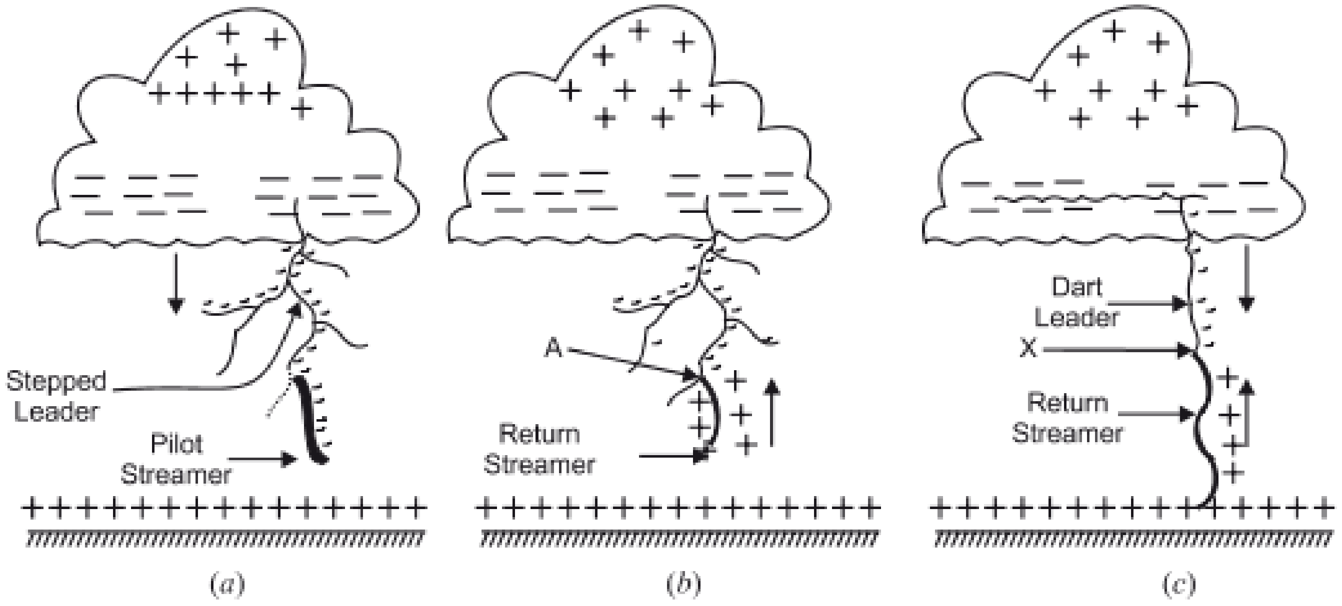
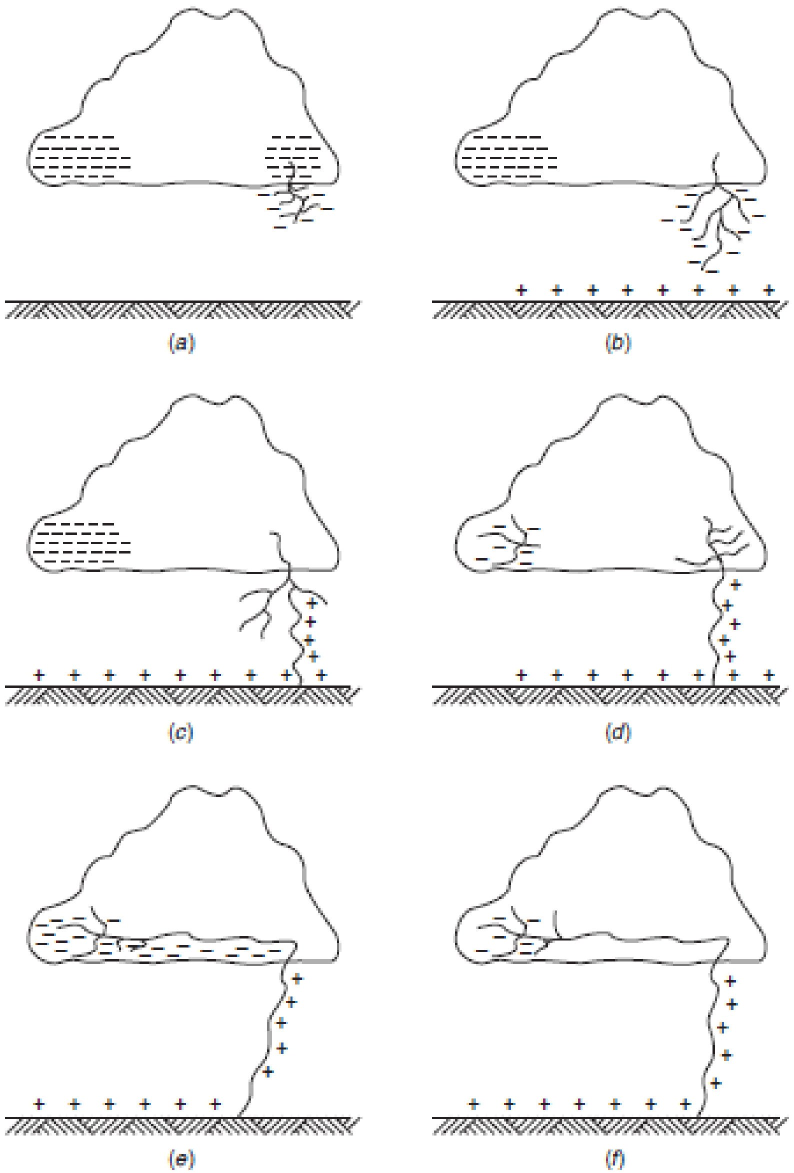


Fig. Phenomenon of lightning



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.

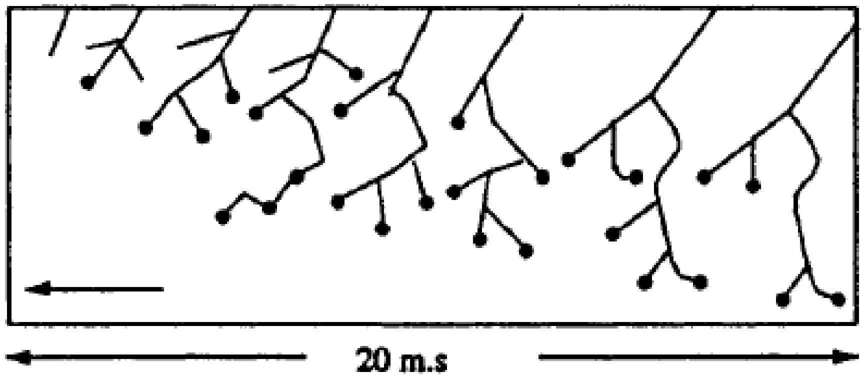
3. The total time required for such a **stepped leader** to reach the ground may be **20 ms**. The path may be quite lustrous, depending on the local conditions in air as well as the electric field gradients. Branches from the initial leader may also be formed. Since the progress of this leader stroke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

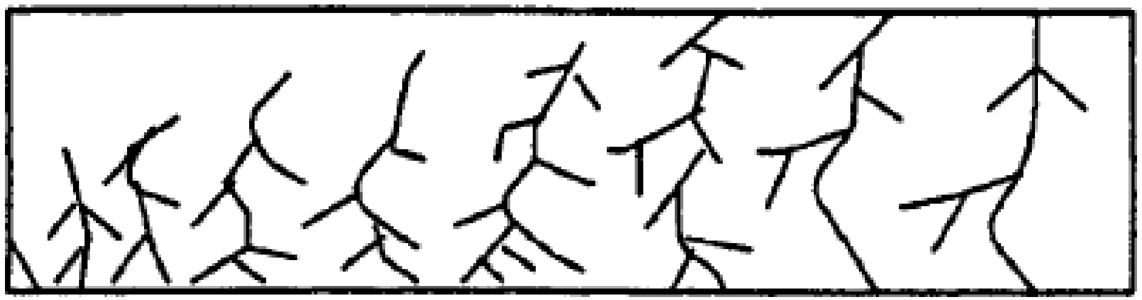
Mechanism of Lightening Stroke

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.

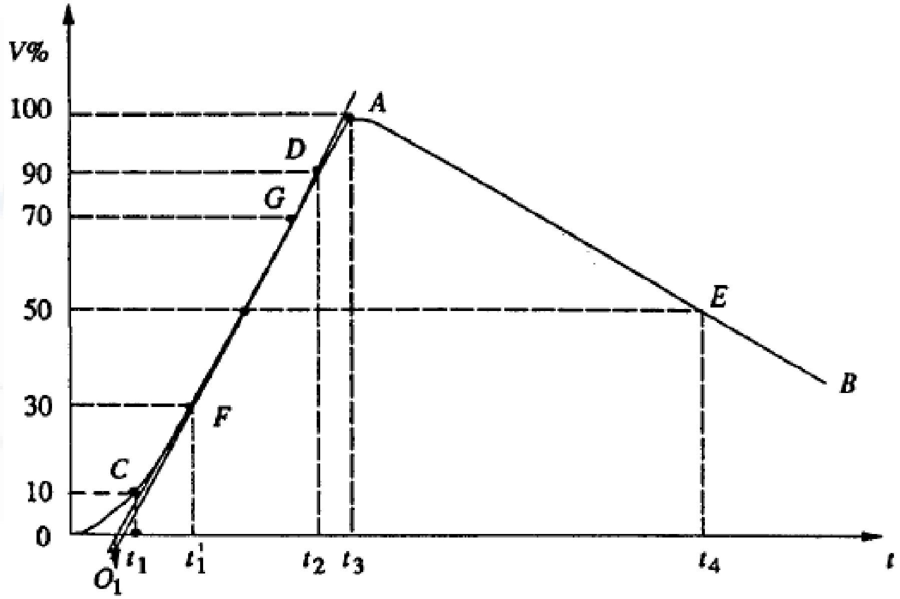




Development of the main or return stroke

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



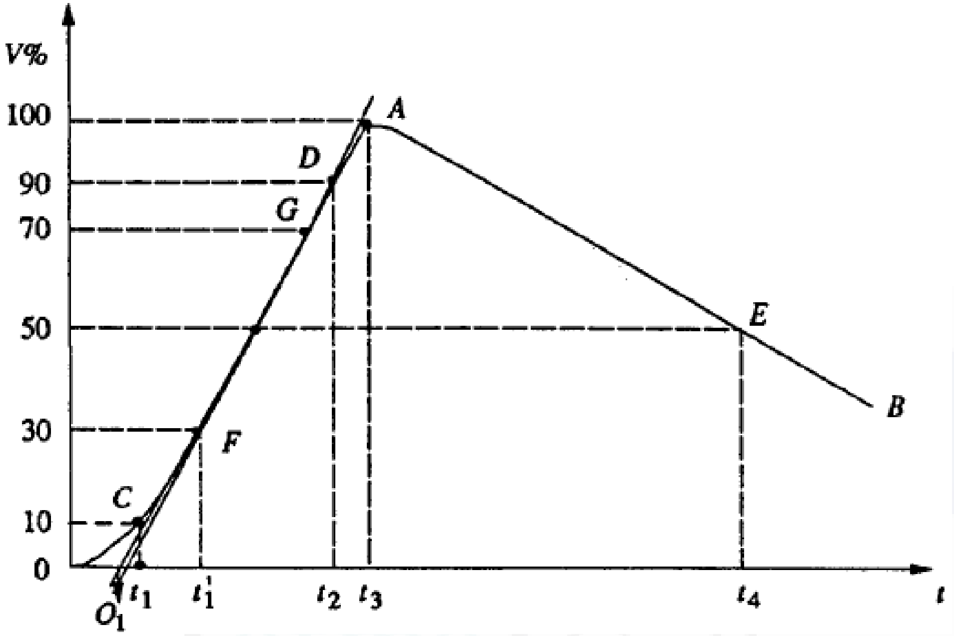
Standard Lightning Impulse

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 $V = V_0 [\exp(-\alpha t) - \exp(-\beta t)]$

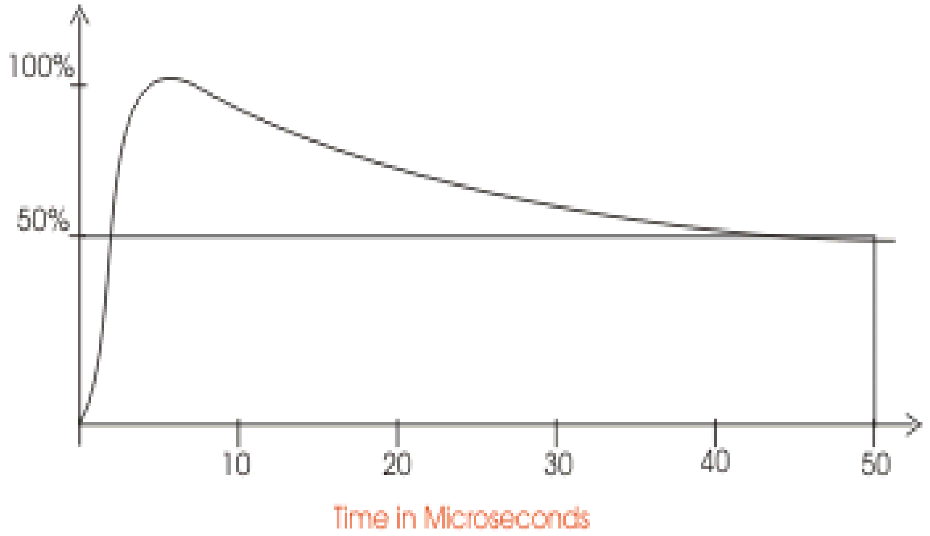
Where α and β are constants values

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,



Direct Lightening Stroke

Direct Stroke

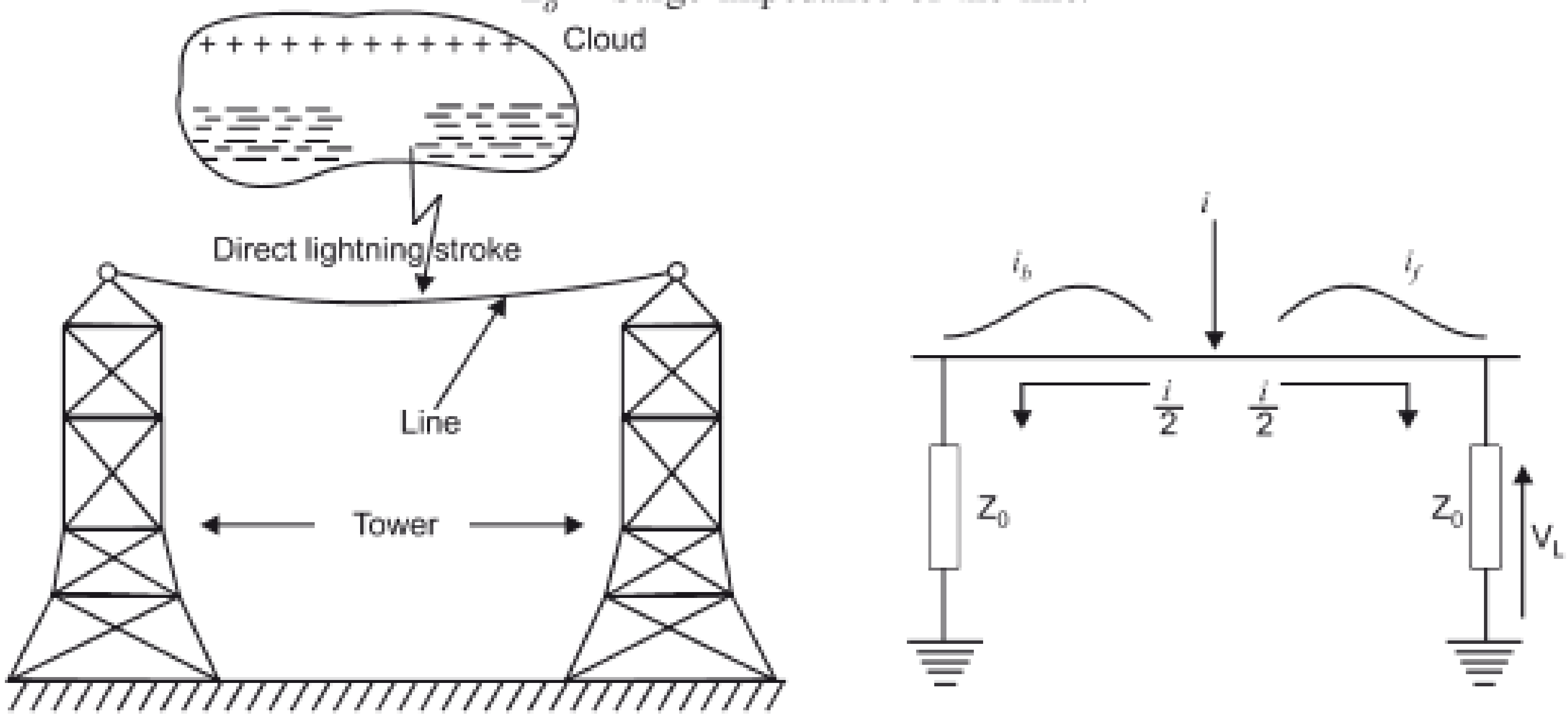
(i) Effect on Overhead Line :

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

V_L = Voltage rise at the point of strike

I_s = Stroke current

Z_o = Surge impedance of the line.



(a) (b)

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.

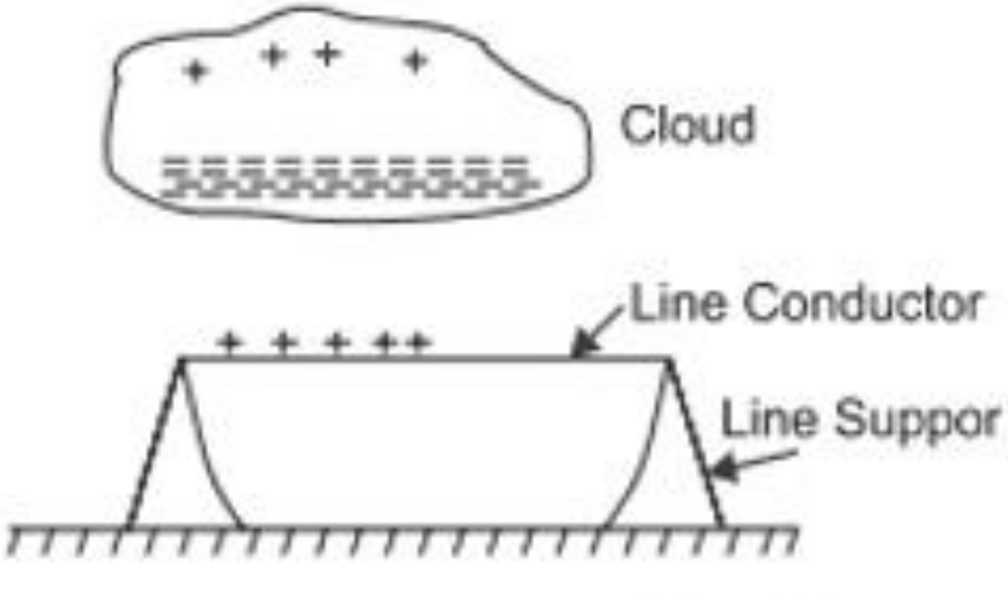
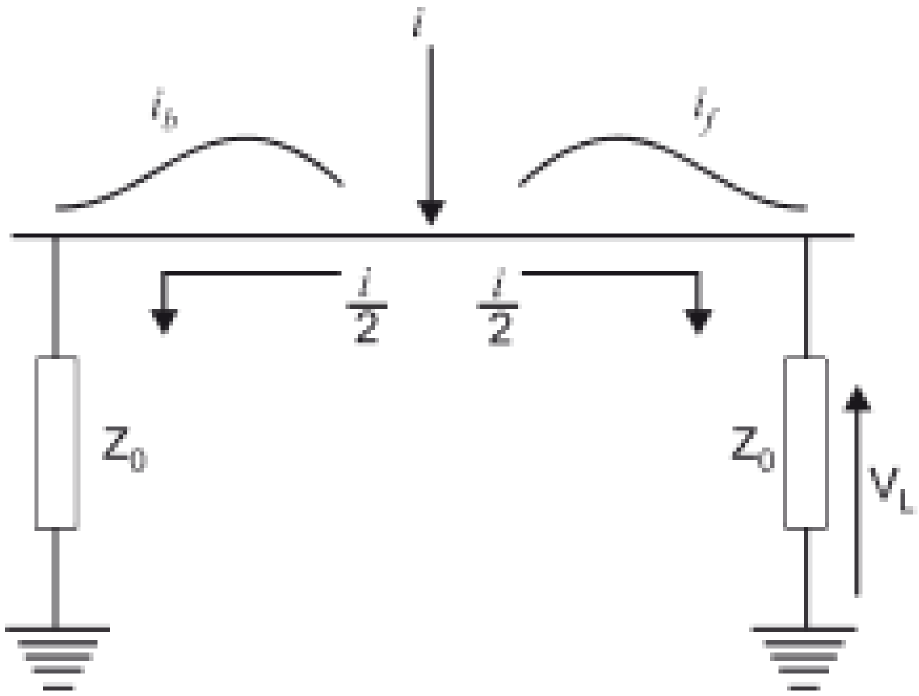


Fig. Indirect strokes



(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.

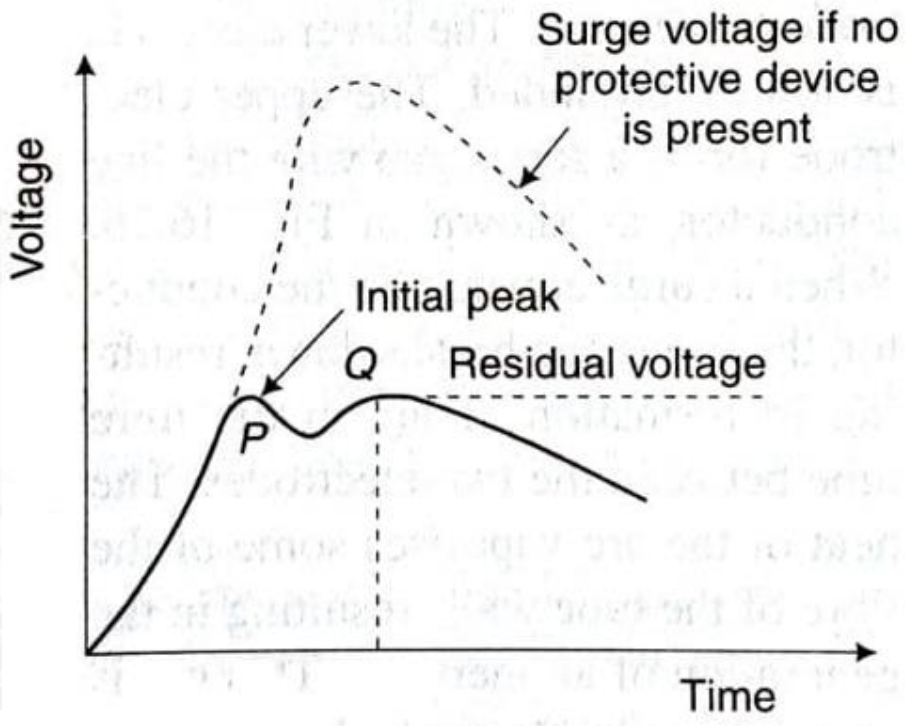


Fig. *Voltage characteristic of surge diverter*

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

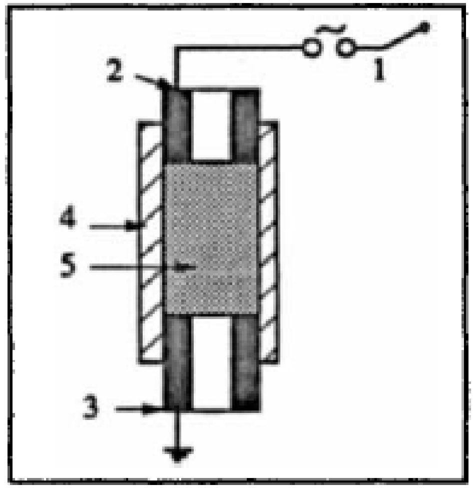
3. Multigap arrester

4. Expulsion type lightning arrester

5. Valve type lightning arrester

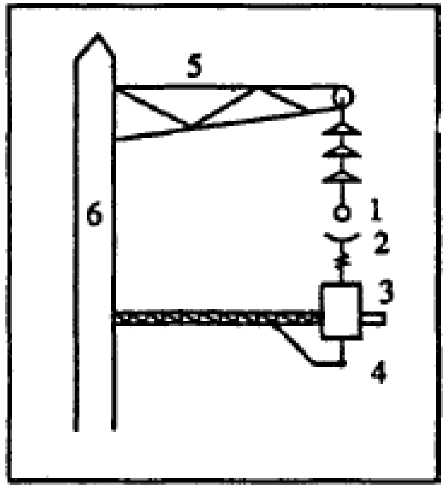
Expulsion type lightning arresters

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

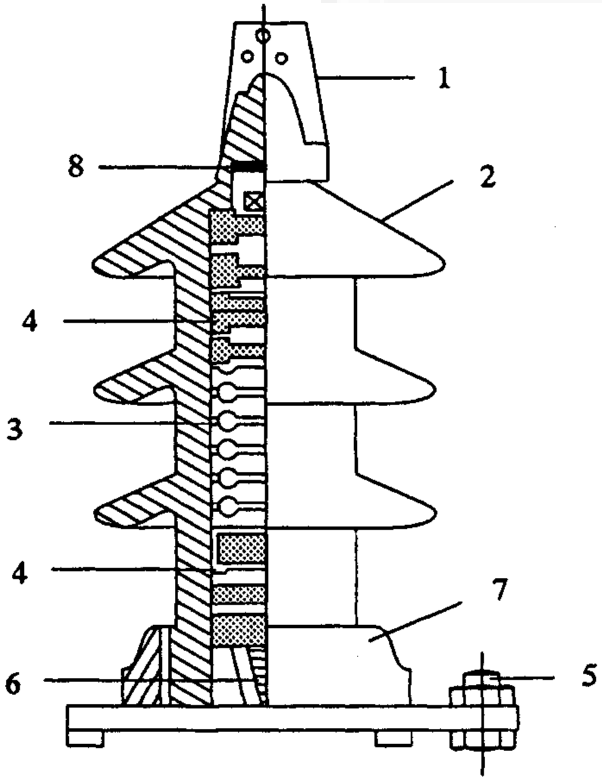


1. Line conductor on string insulator
2. Series gap
3. Protector tube
4. Ground connection
5. Cross arm
6. Tower body

Fig. b Protector tube mounting

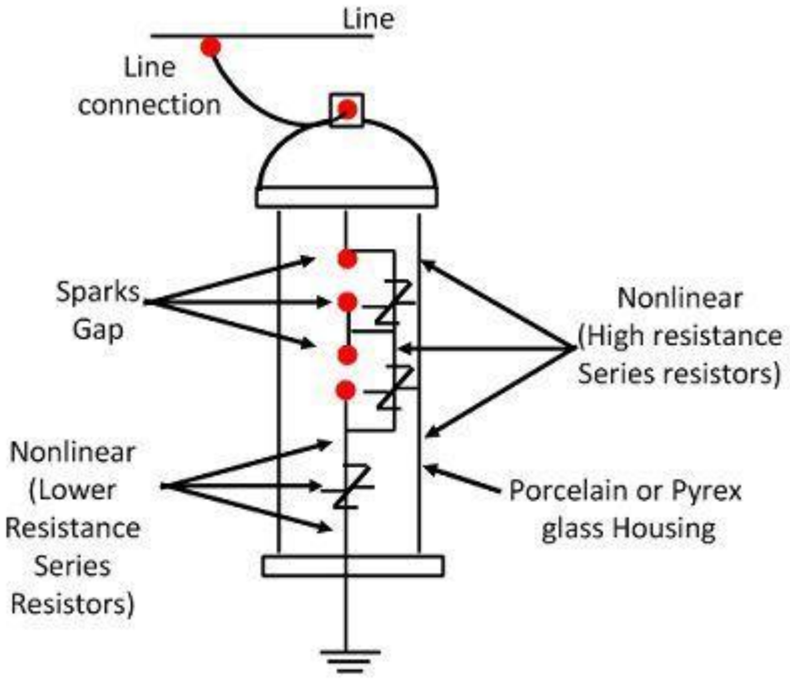
These are capable of discharging 10 to 20 kA of long duration surges (8/20μs) and 100 to 250 kA of the short duration surge currents (1/5μs).

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

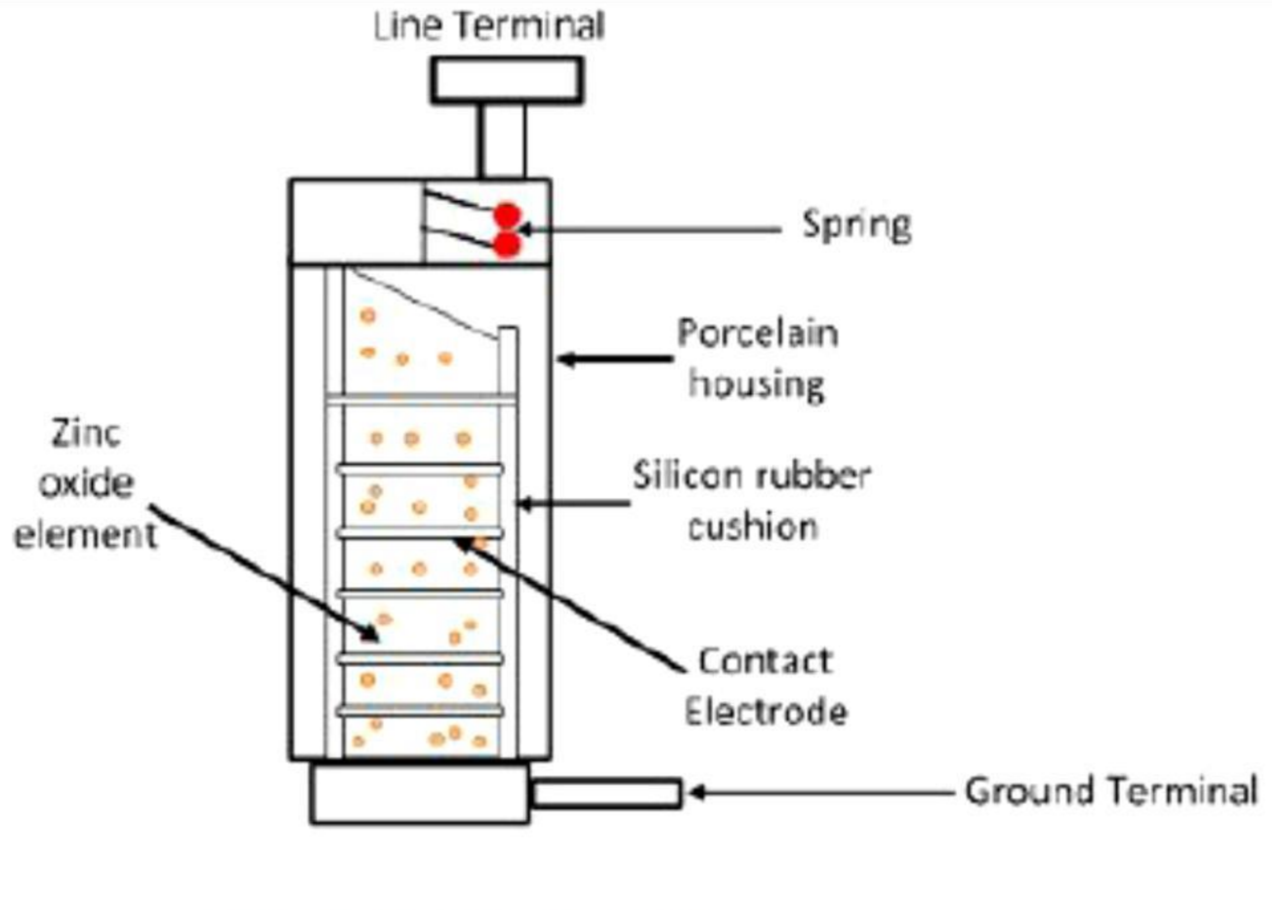
Fig. 8.23 Non-linear element surge diverter



Valve Type Lightning Arrester

Circuit Globe

Metal Oxide Lightning Arrester

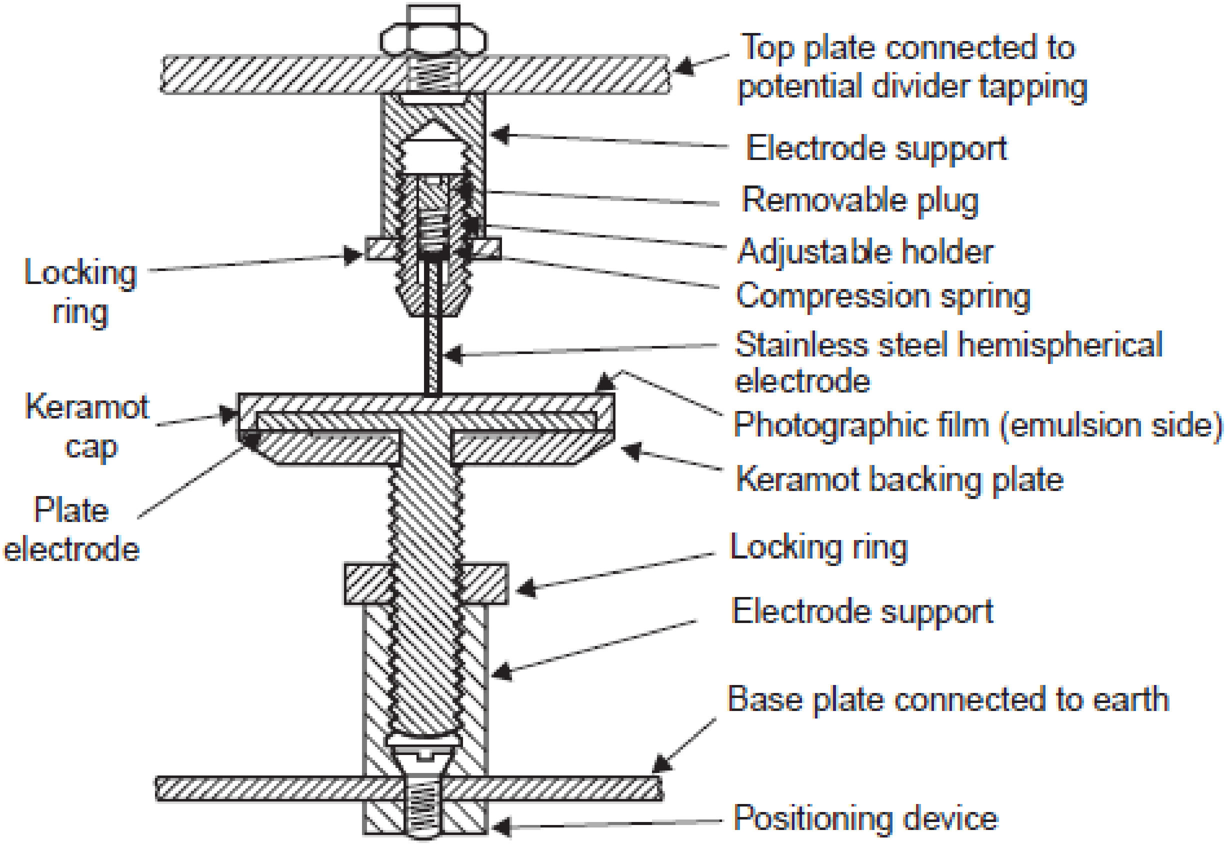


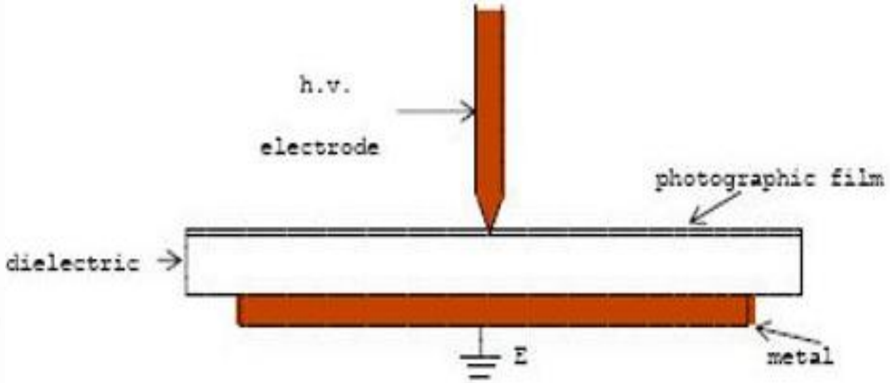
Zinc Oxide Surge Arrester

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

A **Klydonograph** is a device used to record transient high-voltage surges, such as those caused by lightning strikes, on photographic film. Here's a brief overview of how it works:

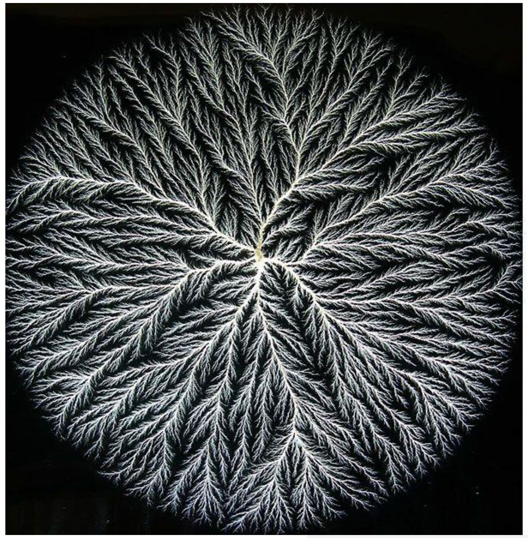
Working Principle

1. **Sulfur-Dusted Film**: The device uses a photographic film coated with sulfur dust.
2. **Voltage Surge**: When a high-voltage surge occurs, it ionizes the sulfur particles on the film, creating a visible trace.
3. **Recording**: The resulting trace varies in size and shape depending on the potential, polarity, and wave shape of the captured surge.

Applications

- **Lightning Investigation**: It was originally developed to investigate the effects of lightning on electric power lines.
- **Surge Analysis**: Used to record and analyze transient voltages in electrical systems.

Klydonograph or Surge Recorder



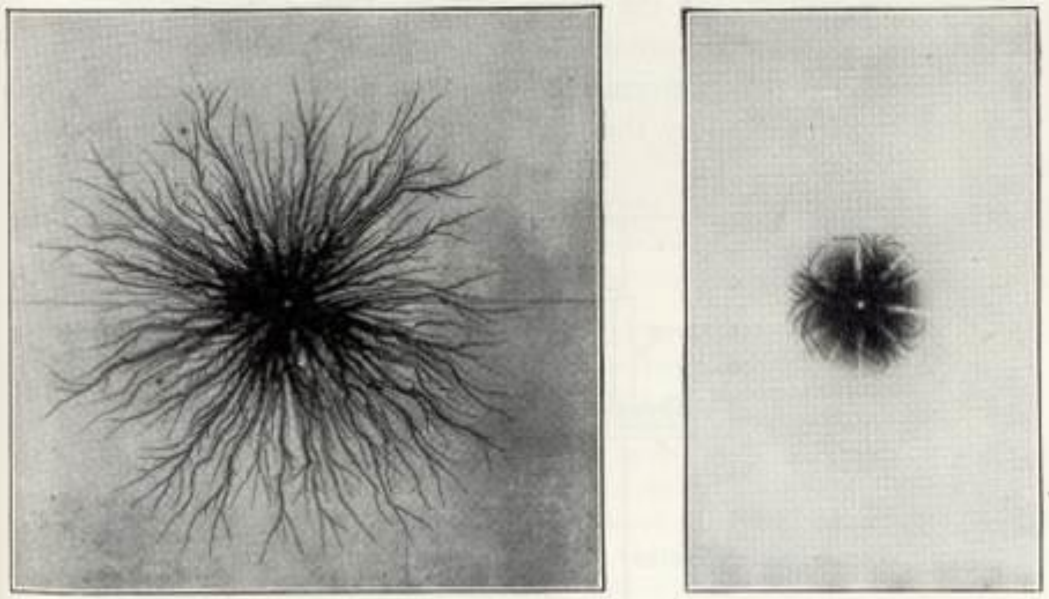


Fig. 3·2. Positive and negative photographic Lichtenberg figures produced by positive and negative surge voltages of same magnitude and wave shape.[9]

Magnetic Links

- Magnetic links are short high retentivity steel strips arranged on a circular wheel or drum. These strips have the property that the remanent magnetism for a current pulse of 0.5/5 µs these can be used for measurement of peak value of impulse currents.
- The strips will be kept at a known distance from the current carrying conductor and parallel to it. The remanent magnetism is then measured in the laboratory from which the peak value of the current can be estimated. These are useful for field measurements, mainly for estimating the lightning currents on the transmission lines and towers.
- By using a number of links, accurate measurement of the peak value, polarity, and the percentage oscillations in lightning currents can be made.

Note: Remanent magnetism, also known as residual magnetism, is the magnetization that remains in a ferromagnetic material (like iron) after an external magnetic field has been removed

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 (BIL)

- 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 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

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- Testing of Circuit Breakers.
- **Protection against Overvoltage**: Causes of Overvoltage, Lightning phenomena, Klydonograph and Magnetic Link, Protection of power stations and Substations, Insulation Coordination.

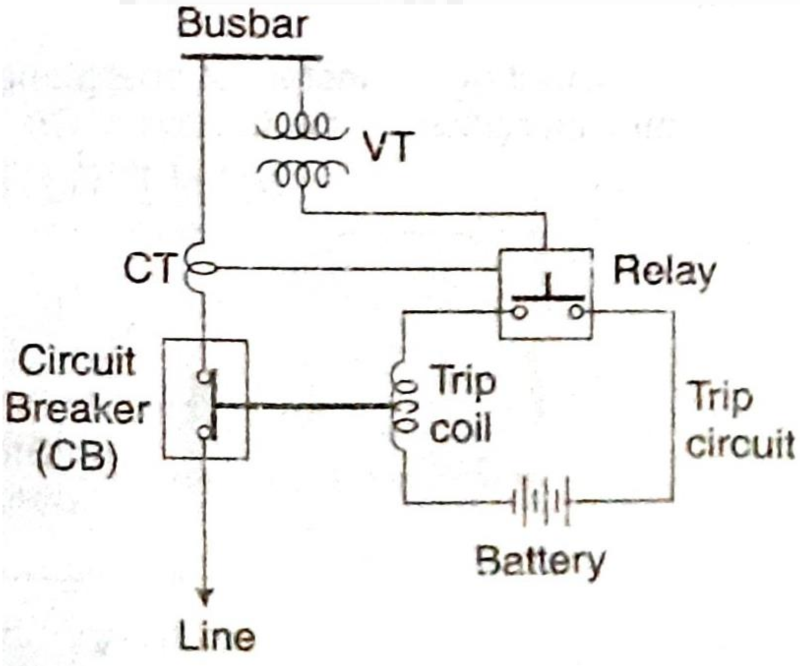
Learning Resources prescribed by University:

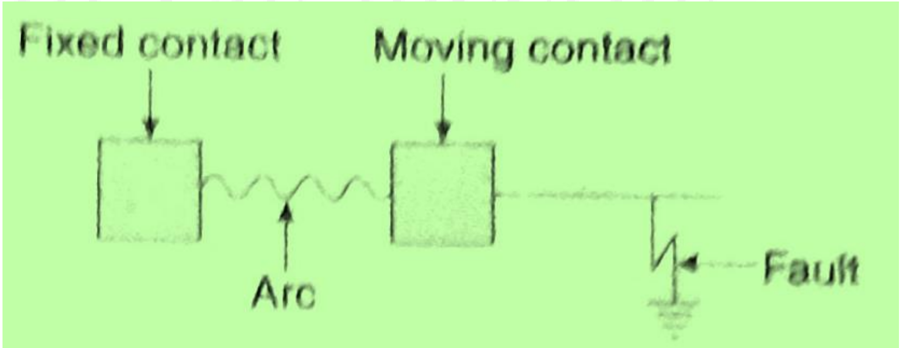
Textbook			
Power System Protection and Switchgear	**Badri Ram, D.N. Vishwakarma**	**McGraw Hill**	**2nd Edition**
Power System Protection and Switchgear	Bhuvanesh Oza et al	McGraw Hill	1st Edition, 2010
Reference Books			
Protection and Switchgear	Bhavesh et al	Oxford	1st Edition, 2011
Power System Switchgear and Protection	N. Veerappan S.R. Krishnamurthy	S. Chand	1st Edition, 2009
Fundamentals of Power System Protection	Y.G.Paithankar S.R. Bhide	PHI	1st Edition, 2009

Circuit breaker

Circuit breaker is a mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time, and automatically breaking currents under specified abnormal circuit conditions such as those of short-circuits (faults).

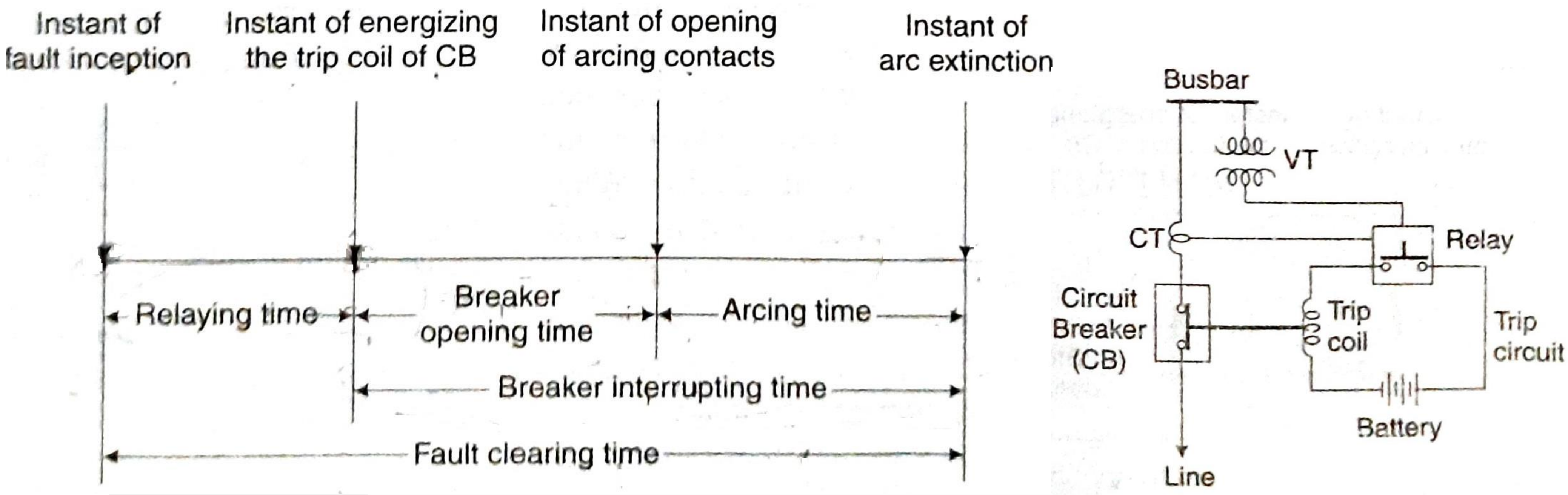
The insulating medium in which circuit interruption is performed is designated by suitable prefix, such as oil circuit breaker, air-break circuit breaker, air blast circuit breaker, sulphur hexafluoride (SF6) circuit breaker, vacuum circuit breaker, etc.





FAULT CLEARING TIME OF A CIRCUIT BREAKER

The fault clearing time is the sum of relaying time and breaker interrupting time



Relaying time = Time from fault inception to the closure of trip circuit of CB

Breaker opening time = Time from closure of the trip circuit to the opening of the contacts of the circuit Breaker..

Arcing time = Time from opening of the contacts of CB to final arc extinction.

Breaker interrupting time = Breaker opening time + arcing time

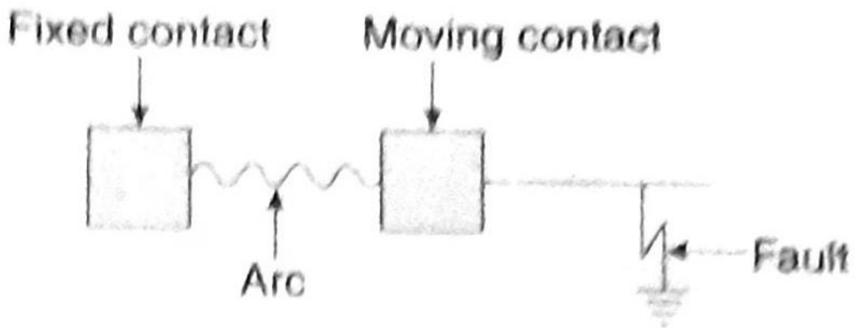
Fault clearing time = Relaying time + breaker interrupting time

- The relaying time for electromechanical relays can vary from about one cycle to five cycles.
- Static relays are faster than electromechanical relays. Numerical relays give very fast operation and their relaying time is within one cycle.
- The contact opening time of the circuit breaker may be between about one and three cycles.
- The arcing time is now generally between one and two half-cycles, depending upon the instant in the current half-cycles at which the contacts apart.
- Therefore, fast relays and modern circuit breakers make it possible to achieve fault clearance in as little as about three cycles of 50 Hz current, but the time varies considerably from system to system and in some cases in different parts of one system.

Arc Interruption

These circuit breakers employ various techniques to extinguish the arc resulting from separation of the current- carrying contacts. The mode of arc extinction is either

1. High resistance interruption
2. zero-point interruption



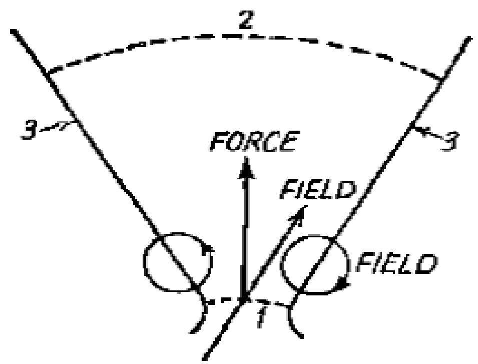
High resistance interruption.

The resistance of the arc (current path) is increased with time rapidly so as to reduce the current to value insufficient to maintain the arc. The arc resistance can be increased by lengthening, splitting, cooling the arc

This method is not suitable for large-current interruption. This can be employed for Low power AC and DC circuit breakers.

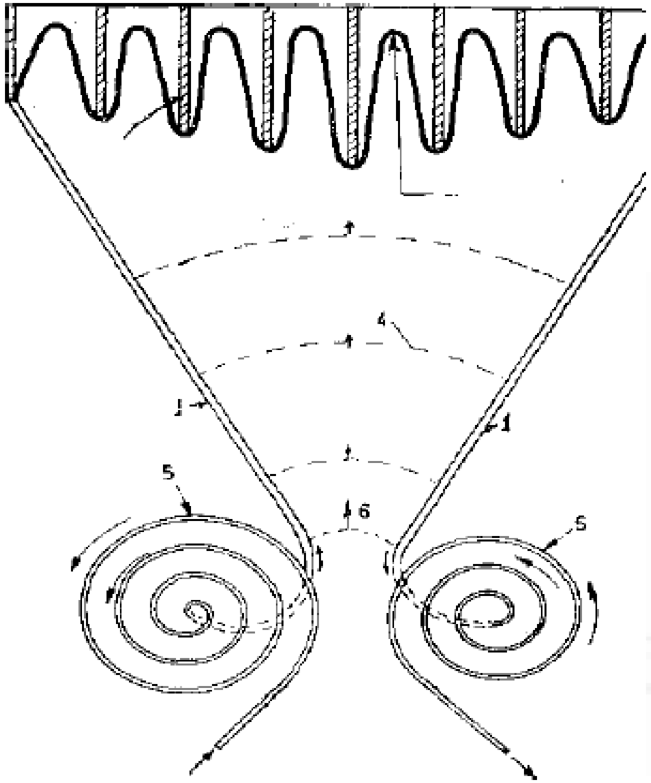
Splitting of Arc

Lengthening the arc by means of arc runners



Function of the arc runners.

1. Initial position of arc
2. Final position of arc.
3. Arc runners(in vertical plane)
4. Field (in horizontal plane)
5. Force due to electrodynamic forces (in vertical plane)



1. Arc runner (metallic)
2. Arc splitters
3. Elongated arc
4. Arc in process of travelling
5. Blow-out coils (metallic)
6. Origin of Arc

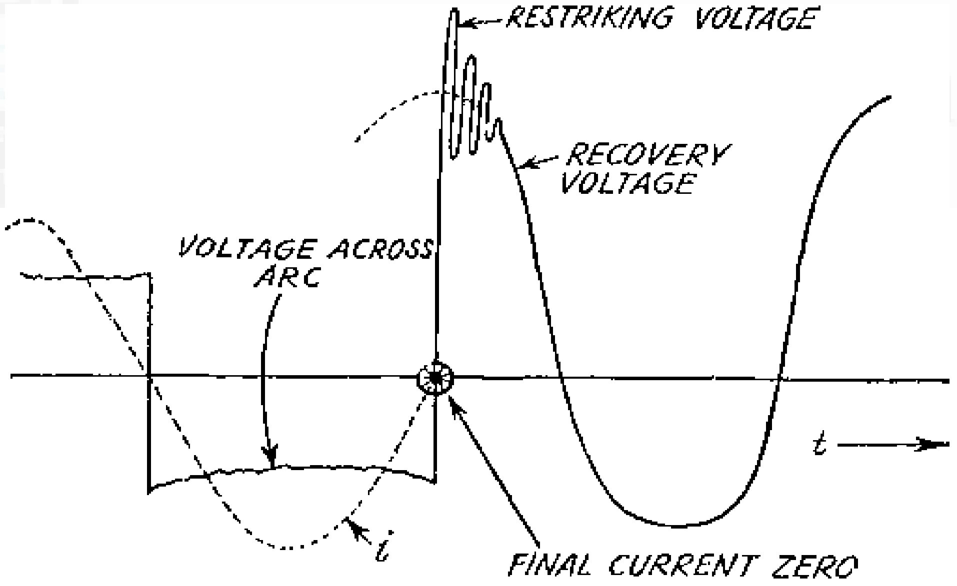
Cooling of Arc.

Cooling of the arc brings about recombination of ionized particles, cooling is brought by bringing the arc (ionized gas) is contact with cooler air.

If a gas containing positive ions and electrons there is a tendency for these to come together and combine to form a neutral atom. This phenomenon is termed as recombination. Recombination takes place directly in gas, and is important in the process of arc extinction

Current zero interruption.

This method is employed in a.c arc interruption The arc is interrupted at natural current zero of the alternating current wave and the dielectric strength of the contact-gap is increased to such an extent that it can withstand the voltage stress across it. This method is employed in a.c. arc interruption. Actually the alternating current passes through zero 100 times per seconds in 50 cycle's current wave. At every current zero the arc vanishes for a brief moment.



Current zero interruption

- At current zero, the space between contacts is deionized quickly by introducing fresh unionized medium such as oil or fresh air, or SF6 gas, between the contacts.
- The dielectric strength of the contact space increases to such an extent that the arc does not continue after current zero.
- A high voltage may appear across the contacts. The voltage may re-establish the arc if the dielectric strength of gap is less than the restriking voltage. In that case the arc continues for another half cycle and may get extinguished at next current zero.

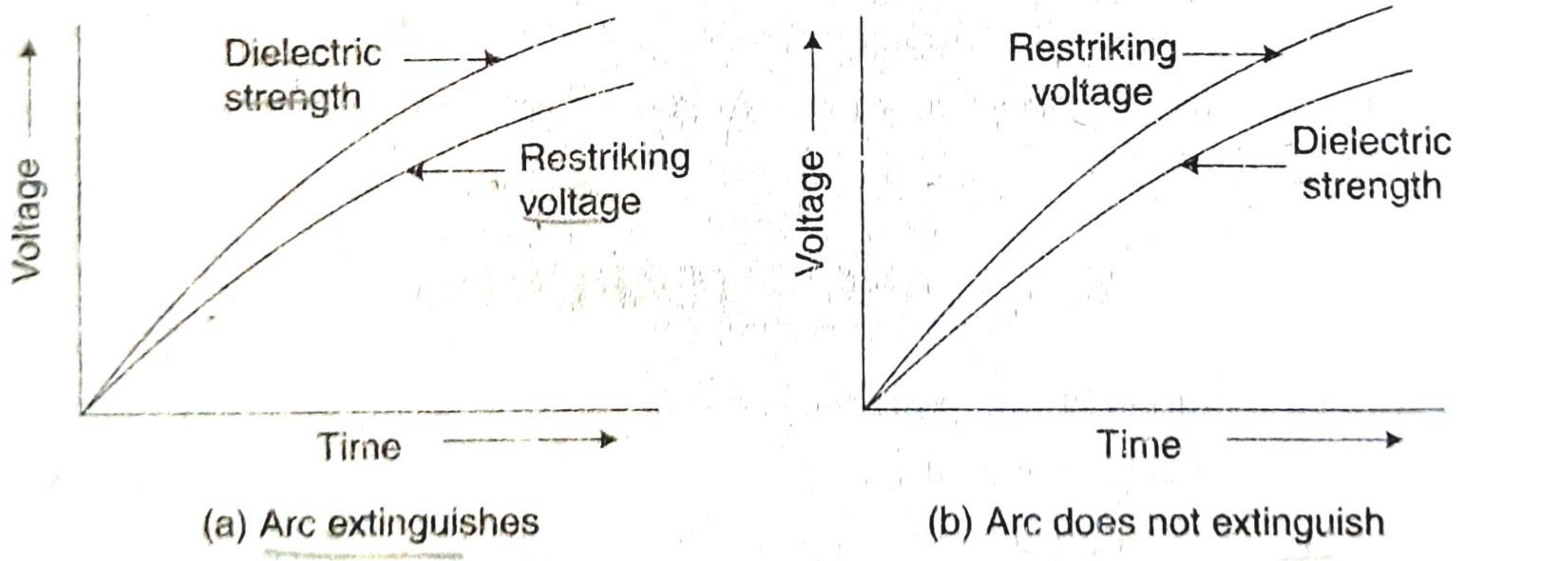
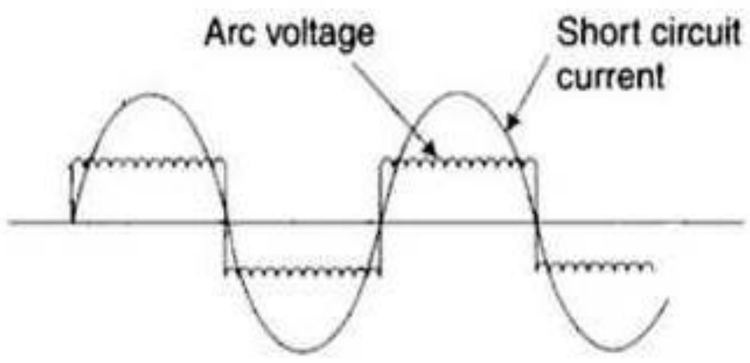
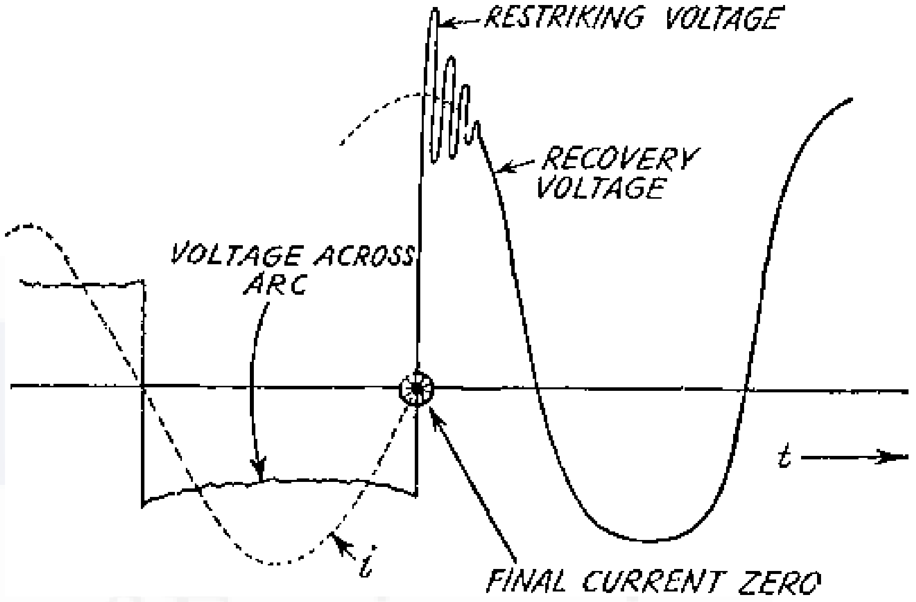


Fig. *Recovery rate theory*

Restriking Voltage and Recovery Voltage

ARC VOLTAGE





- The voltage across the contacts of circuit breaker is arc voltage when the arc exists. This voltage becomes system voltage (power frequency voltage (50Hz)) when the arc is completely interrupted.
- The arc is extinguished at the instant of Current Zero, the voltage across the breaker terminal does not normalize instantaneously but it oscillates and there is a transient condition.
- At the instant of arc getting interrupted a high frequency voltage appears across the contacts (Breaker pole) which is superimposed on power frequency (50 Hz) system voltage Is known as **restriking voltage**

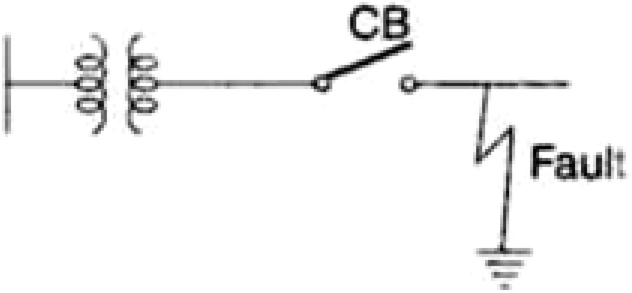
This high frequency transient voltage tries to restrike the arc**; hence it is called restriking voltage or transient recovery voltage (TRV). Such voltage has a power frequency component plus** an oscillatory component, the oscillatory transient component is due to inductance and capacitance in circuit, power frequency component is due to system voltage

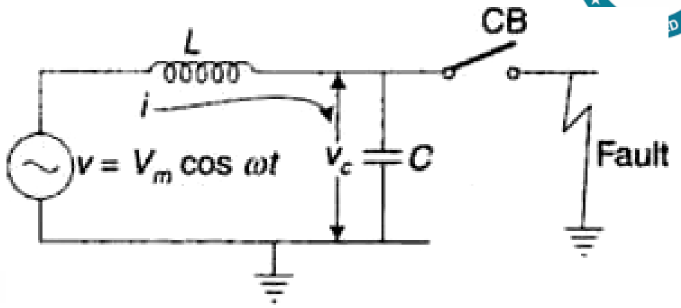
The frequency of transient component is given by $$Fn = \frac{1}{2\pi\sqrt{LC}}$$

Fn = frequency of transient voltage, Hz
L = Equivent inductance, Henry
c = Equivent capacitance, farad

This transient oscillatory component subsides (vanishes) after few micro sec(less than 0.1 mile sec) and the normal frequency system voltage is established after arc is completely extinguished, this voltage which appear across breaker contact after arc is finally extinguished is called **recovery voltage.**

Restriking Voltage





(b)

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = E$$

where E is the system voltage at the instant of arc interruption. As the transient oscillation is a fast phenomenon, E can be regarded as a constant for a short duration.

$$i = \frac{dq}{dt} = \frac{d(Cv_c)}{dt},$$ where v_c = voltage across the capacitor.

Therefore, $$\frac{di}{dt} = \frac{d^2(Cv_c)}{dt^2} = C\frac{d^2v_c}{dt^2}$$

$$\int \frac{i\,dt}{C} = \frac{q}{C} = v_c$$

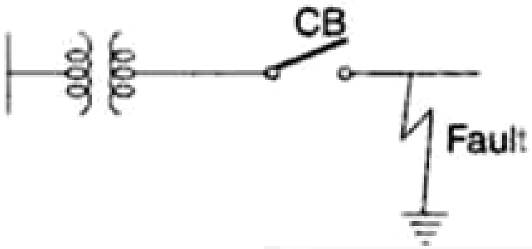
Substituting these values in the equation given above, we get

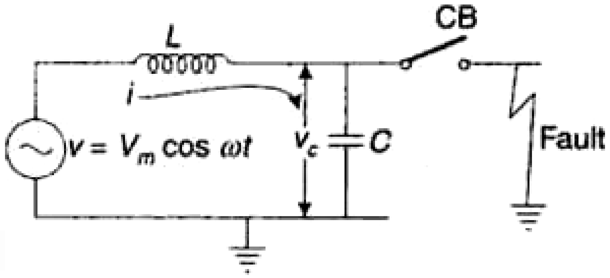
$$LC\frac{d^2v_c}{dt^2} + v_c = E$$

Taking Laplace Transform of both sides of the equation, we get

$$LC\,S^2v_c(S) + v_c(S) = \frac{E}{S}$$

Restriking Voltage





(b)

or $$v_c(S)\,[LCS^2 + 1] = \frac{E}{S}$$

or $$v_c(S) = \frac{E}{S[LCS^2+1]} = \frac{E}{LCS\left(S^2 + \frac{1}{LC}\right)}$$

$$w_n = \frac{1}{\sqrt{LC}}, \quad \text{therefore,} \quad \frac{1}{LC} = w_n^2$$

or $$v_c(S) = \frac{w_n^2 E}{S(S^2 + w_n^2)} = \frac{w_n E}{S}\left(\frac{w_n}{S^2 + w_n^2}\right)$$

Taking the inverse Laplace, we get

$$v_c(t) = w_n E \int_0^t \sin w_n\, t$$

$$= w_n E \left[\frac{-\cos w_n t}{w_n}\right]_0^t$$

As $v_c(t) = 0$ at $t = 0$, constant $= 0$.

$$v_c(t) = E\,(1 - \cos w_n t) \quad \text{or} \quad v_c(t) = E\left(1 - \cos \frac{1}{\sqrt{LC}}\, t\right)$$

$$= \text{Restriking voltage}$$

The maximum value of restriking voltage $= 2\,E_{\text{peak}}$

$$= 2 \times \text{peak value of the system voltage}$$

The Rate of Rise of Restriking voltage (RRRV)

$$= \frac{dE}{dt}(1 - \cos w_n t)$$

$$= w_n E \sin w_n t$$

The maximum value of RRRV $= w_n E$

$$= w_n E_{\text{peak}}$$

For a 132 kV system, the reactance and capacitance up to the location of the circuit breaker is 3 ohms and 0.015 μF, respectively. Calculate the following:

(a) The frequency of transient oscillation.

(b) The maximum value of restriking voltage across the contacts of the circuit breaker.

(c) The maximum value of RRRV.

Solution

(a) The frequency of transient oscillation

$$L = \frac{3}{2\pi 50}, \quad f = 50, \text{ the system frequency}$$

$$= \frac{3}{100\pi} = 0.00954 \text{ H}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{0.00954 \times 0.015 \times 10^{-6}}}$$

$$= \frac{10^5}{2\pi \times 1.1962} = \frac{10^5}{7.5241} = 13.291 \text{ kHz}$$

(b) The restriking voltage

$$v_c = E\,[1 - \cos w_n t]$$

The maximum value of the restriking voltage $= 2\,E_{\text{peak}}$

$$= 2 \times \frac{132}{\sqrt{3}}\sqrt{2} = 215.56\ \text{kV}$$

(c) The maximum value of RRRV $= w_n E_{\text{peak}}$

$$= 2\pi f_n \times \frac{132}{\sqrt{3}} \times \sqrt{2} \times 1000$$

$$= 2\pi \times 13.291 \times 1000 \times \frac{132}{\sqrt{3}} \times \sqrt{2} \times 1000\ \text{V/s}$$

$$= 9010.45 \times 10^6\ \text{V/s} = 9.01045\ \text{kV}/\mu\text{s}$$

Resistance Switching

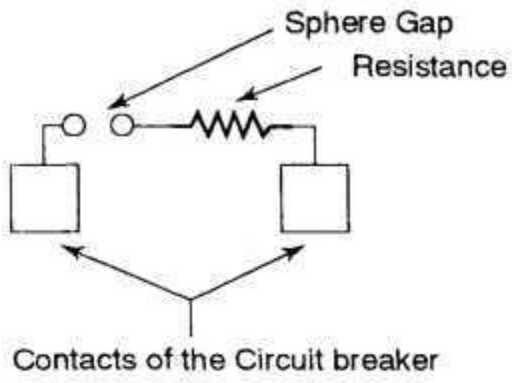


FIGURE Resistance switching

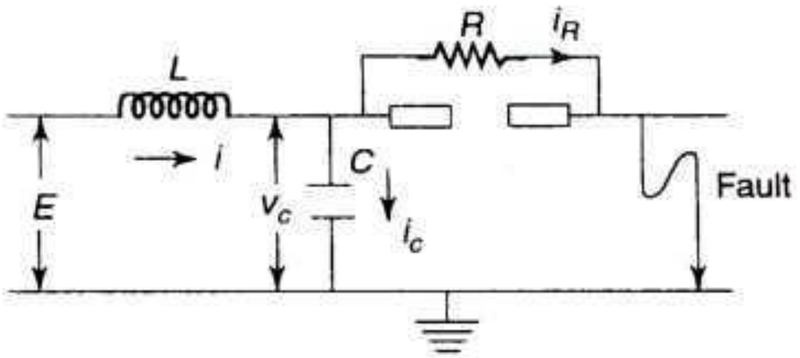


FIGURE Circuit for analysis of resistance switching

To reduce the restriking voltage, RRRV and severity of the transient oscillations, a resistance is connected across the contacts of the circuit breaker. This is known as resistance switching. The resistance is in parallel with the arc. A part of the arc current flows through this resistance resulting in a decrease in the arc current and increase in the deionisation of the arc path and resistance of the arc. This process continues and the current through the shunt resistance increases and arc current de-creases. Due to the decrease in the arc current, restriking voltage and RRRV are reduced.

The resistance may be automatically switched in with the help of a sphere gap as shown in Fig. The resistance switching is of great help in switching out capacitive current or low inductive current

The voltage equation is given by

$$L\frac{di}{dt}+\frac{1}{C}\int i_C\,dt = E \quad \text{and} \quad i = i_c + i_R$$

Therefore, the above equation become

$$L\frac{d(i_c+i_R)}{dt}+v_c = E$$

or

$$L\frac{di_c}{dt}+L\frac{di_R}{dt}+v_c = E$$

$$i_c = \frac{dq}{dt} = \frac{d(Cv_c)}{dt}$$

Therefore,

$$\frac{di_c}{dt} = \frac{d^2(Cv_c)}{dt^2} = C\frac{d^2v_c}{dt^2}$$

$$\frac{di_R}{dt} = \frac{d(v_c/R)}{dt} = \frac{1}{R}\frac{dv_c}{dt}$$

Substituting these values in the main equation, we get

$$LC\frac{d^2v_c}{dt^2}+\frac{L}{R}\frac{dv_c}{dt}+v_c = E$$

Taking Laplace Transform, we get

$$LCS^2 v_c(S) + \frac{L}{R} S\, v_c(S) + v_c(S) = \frac{E}{S}$$

Other terms are zero, as $v_c = 0$ at $t = 0$

or
$$LCv_c(S)\left[S^2 + \frac{1}{RC} S + \frac{1}{LC}\right] = \frac{E}{S}$$

or
$$v_c(S) = \frac{E}{SLC\left[S^2 + \frac{1}{RC} S + \frac{1}{LC}\right]}$$

For no transient oscillation, all the roots of the equation should be real. Or root is zero, i.e. $S = 0$ which is real. For the other two roots to be real, the roo of the quadratic equation in the denominator should be real. For this, tl following condition should be satisfied.

$$\left[\left(\frac{1}{2RC}\right)^2 - \frac{1}{LC}\right] \geq 0 \quad \text{or} \quad \frac{1}{4R^2C^2} \geq \frac{1}{LC}$$

or
$$\frac{4}{LC} \leq \frac{1}{R^2C^2} \quad \text{or} \quad R^2 \leq \frac{LC}{4C^2}$$

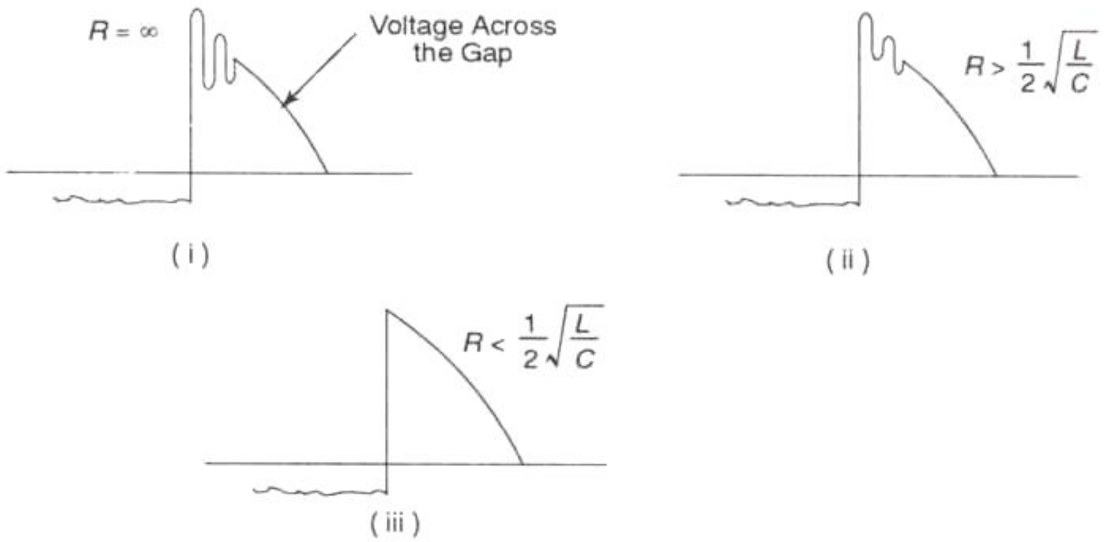


FIGURE Transient oscillations for different values of R

or $$R^2 \leq \frac{1}{4} \cdot \frac{L}{C} \quad \text{or} \quad R \leq \frac{1}{2}\sqrt{\frac{L}{C}}$$

Therefore, if the value of the resistance connected across the contacts of the circuit breaker is equal to or less than $\frac{1}{2}\sqrt{L/C}$ there will be no transient oscillation. If $R > \frac{1}{2}\sqrt{L/C}$, there will be oscillation. $R = \frac{1}{2}\sqrt{L/C}$ is known as critical resistance. Figure 9.9 shows the transient conditions for three different values of R. The frequency of damped oscillation is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}}$$

In a 220 kV system, the reactance and capacitance up to the location of circuit breaker is 8 Ω and 0.025 μF, respectively. A resistance of 600 ohms is connected across the contacts of the circuit breaker. Determine the following:

(a) Natural frequency of oscillation.

(b) Damped frequency of oscillation.

(c) Critical value of resistance which will give no transient oscillation.

(d) The value of resistance which will give damped frequency of oscillation, one-fourth of the natural frequency of oscillation.

Solution

$$L = \frac{8}{2\pi 50} = \frac{8}{100\pi} = 0.02544 \text{ H}$$

(i) Natural frequency of oscillation $= \dfrac{1}{2\pi}\sqrt{\dfrac{1}{LC}}$

$$= \frac{1}{2\pi}\sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}}}$$

(ii) Frequency of damped oscillation is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times (600)^2}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{10^{10}}{6.36} - \frac{10^{10}}{9}} = 3.413 \text{ kHz}$$

(iii) The value of critical resistance

$$R = \frac{1}{2}\sqrt{\frac{L}{C}} = \frac{1}{2}\sqrt{\frac{0.02544}{0.025 \times 10^{-6}}} = 504.35\,\Omega$$

(iv) The damped frequency of oscillation is $\frac{1}{4} \times 6.304$ kHz $= 1576$ Hz

$$1576 = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times R^2}}$$

or $$1576 = \frac{1}{2\pi}\sqrt{\frac{10^{10}}{6.36} - \frac{10^{16}}{25R^2}}$$

Therefore, $R = 520.8\ \Omega$.

Interruption of Low Magnetizing Current (Current Chopping)

The necessity of interrupting small inductive current arises while disconnecting transformers on no load. No-load currents of transformer, i.e. magnetizing currents are almost at zero power factor lag, the current is smaller than normal current rating of the breaker. The breaking of such a low current presents a sever duty on the circuit-breaker

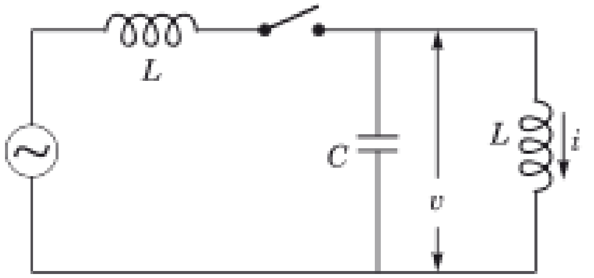


Fig. Circuit diagram illustrating interruption of low inductive current.

$$\frac{1}{2} L i^2 = \frac{1}{2} C v^2 \text{ joules}$$

$$v = i \sqrt{\frac{L}{C}}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

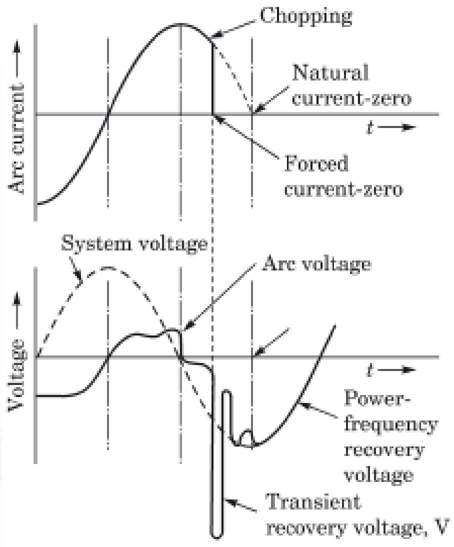


Fig. Interruption of low magnetizing currents.

When interrupting low inductive currents such as magnetizing currents of transformer, shunt reactor, **the rapid deionization of contact space and blast effect may cause, the current to be interrupted before its natural zero. This phenomenon of the interruption of current before its natural zero is called current chopping.**

In such a situation, the energy stored in the Inductance (magnetic field) appears in the form of high voltage across the stray capacitance at the moment of current Interruption, which will cause restriking of the arc.

A circuit breaker interrupts the magnetising current of a 100 MVA transformer at 220 kV. The magnetising current of the transformer is 5% of the full load current. Determine the maximum voltage which may appear across the gap of the breaker when the magnetising current is interrupted at 53% of its peak value. The stray capacitance is 2500 μF. The inductance is 30 H.

Solution The full load current of the transformer

$$= \frac{100 \times 10^6}{\sqrt{3} \times 220 \times 10^3} = 262.44 \text{ A}$$

$$\text{Magnetising current} = \frac{5}{100} \times 262.44 = 34.44 \text{ A}$$

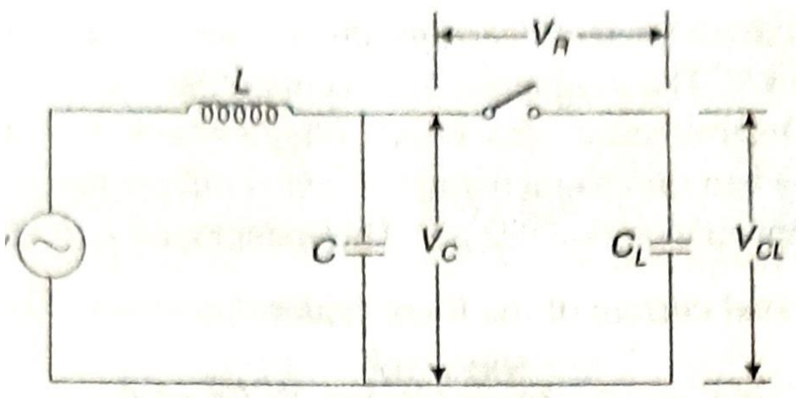
$$\text{Current chopping occurs at } 0.53 \times 34.44\sqrt{2} = 25.83 \text{ A}$$

$$\frac{1}{2} Li^2 = \frac{1}{2} Cv^2$$

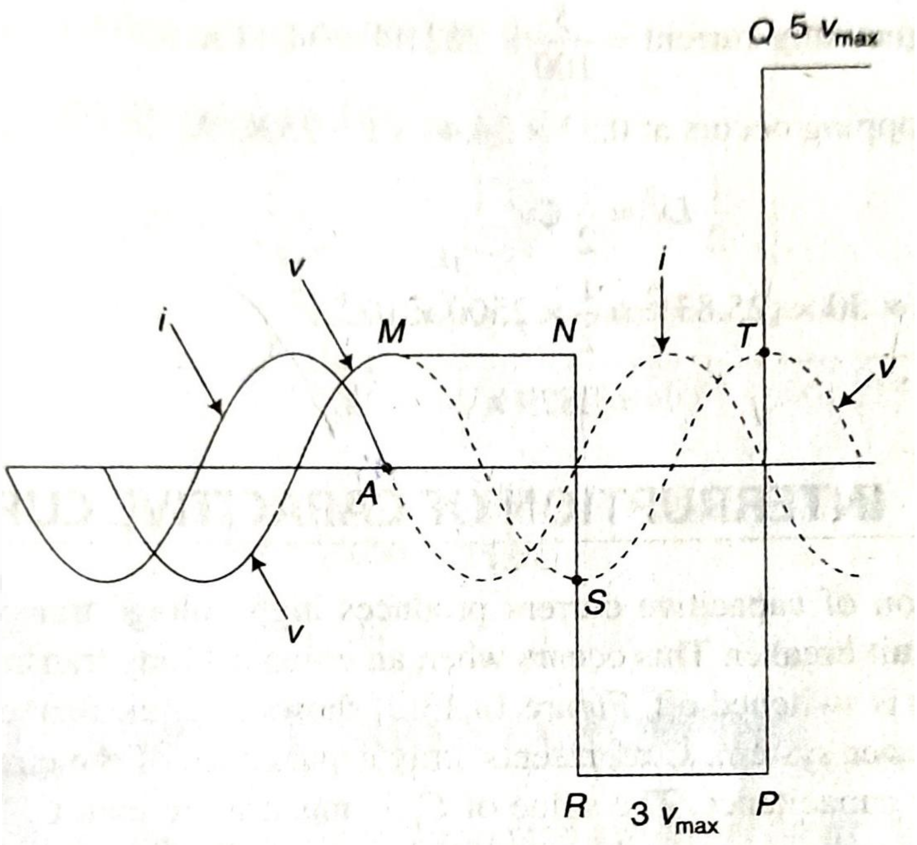
$$\therefore \quad \frac{1}{2} \times 30 \times (25.83)^2 = \frac{1}{2} \times 2500 \times 10^{-6} v^2$$

$$\therefore \quad v = 2829 \text{ kV}$$

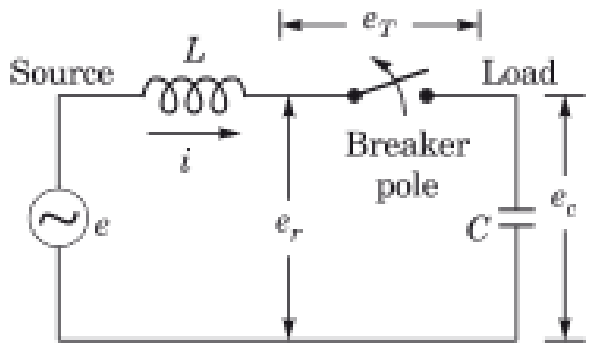
Interruption of Capacitive Current



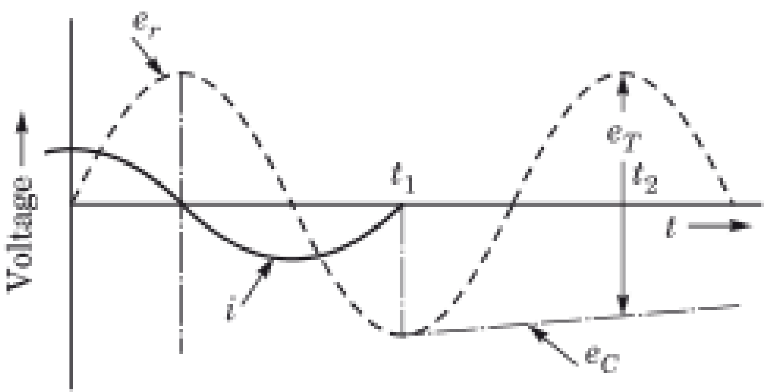
(a) Electrical circuit of a simple power system



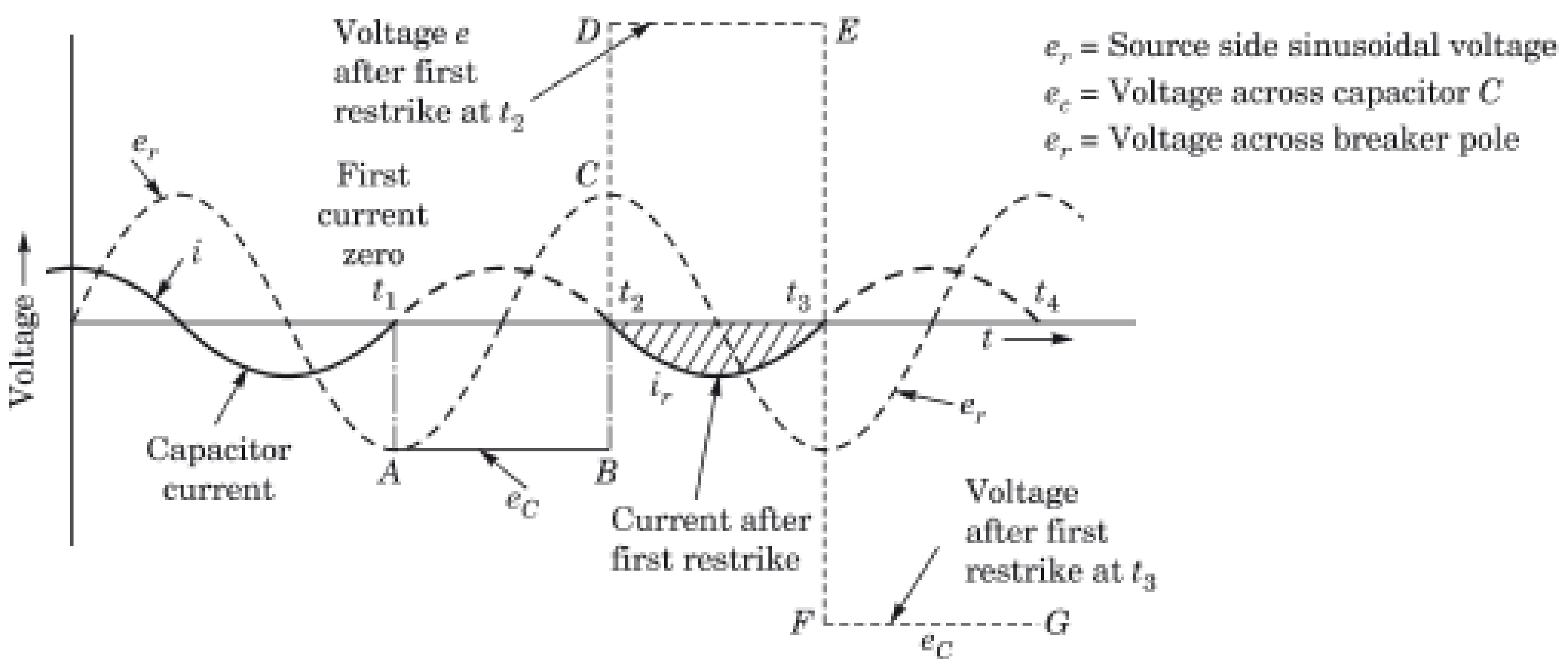
(b) Transient voltage across the gap of the circuit breaker



(a) Single phase representation of star connected 3 ph. capacitor bank



(b) Waveform of clean interruption without restrike (at t_1 current i is interrupted)



(c) Waveform for restrikes

Fig. Switching of capacitive currents for opening operation.

CLASSIFICATION OF CIRCUIT BREAKER

Circuit breakers can be classified using the different criteria such as, intended voltage application, location of installation, their external design characteristics, insulating medium used for arc quenching, etc.

Classification Based on Voltage Circuit breakers can be classified into the following categories depending on the intended voltage application.

(i) Low Voltage Circuit Breaker (less than 1 kV)

(ii) Medium Voltage Circuit Breaker (1 kV to 52 kV)

(iii) High Voltage Circuit Breakers (66 kV to 220 kV)

(iv) Extra High Voltage (EHV) Circuit Breaker (300 kV to 765 kV)

(v) Ultra High Voltage (UHV) Circuit Breaker (above 765 kV)

Classification Based on Location

Circuit breakers based on their location are classified as

(i) Indoor type

(ii) Outdoor type

Low and medium voltage switchgears, and high voltage Gas Insulated Switchgears (GIS) are categorised as Indoor Switchgears, whereas the Switchgears which have air as an external insulating medium, i.e. Air-Insulated Switchgear (AIS), are categorised as outdoor Switchgears.

Classification Based on External Design

Circuit breakers can be classified into following categories depending on their external design.

(i) Dead tank type

(ii) Live-tank type

This classification is for outdoor circuit breakers from the point of view of their physical structural design.

Classification Based on Medium Used for Arc Quenching

Depending on the arc quenching medium employed, the following are important types of circuit breakers

(i) Air-break circuit breakers:

(ii) Oil circuit breakers (tank type of bulk oil and Minimum oil circuit-breaker)

(iii) Air blast circuit breakers

(iv) Sulphur hexafluoride (SF6) circuit breakers (Single pressure or Double Pressure).

(v) Vacuum circuit breakers

The development of circuit breakers outlined above has taken place chronologically in order to meet two important requirements of the power system which has progressively grown in size. Firstly, higher and higher fault currents need to be interrupted, i.e., breakers need to have larger and larger breaking capacity. Secondly, the fault interruption time needs to be smaller and smaller for maintaining system stability.

AIR BREAK CIRCUIT BREAKER

Air-breaker circuit-breakers are used in d.c. circuits and a.c. circuits upto 12 kV. They are generally indoor type and installed on vertical panels or indoor draw-out type switchgear.

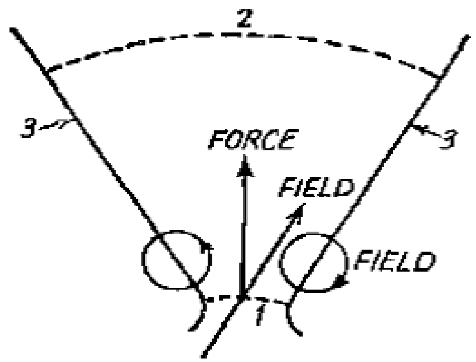
They are widely used in indoor medium voltage and low voltage switchgear. Typical reference values of ratings of air-break circuit-breakers are:

460 V, 400—3500 A,	40—75 kA.
3.3 kV, 400—3500 A,	13.1—31.5 kA.
6.6 kV, 400—2400 A,	13.1—20 kA.

Magnetic field is utilised for lengthening the arc in high voltage air-break circuit-breakers.

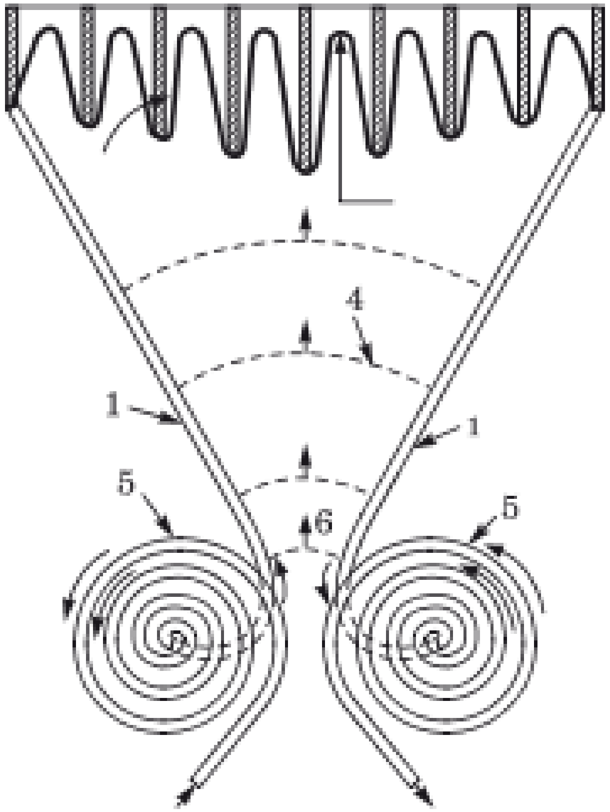
AIR BREAK CIRCUIT BREAKER

Lengthening the arc by means of arc runners

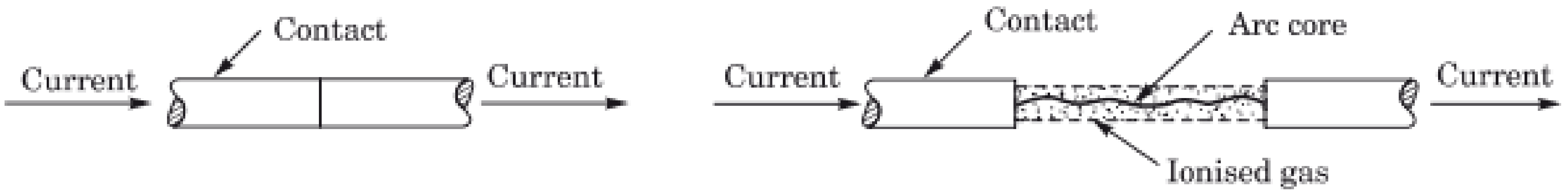


Function of the arc runners.

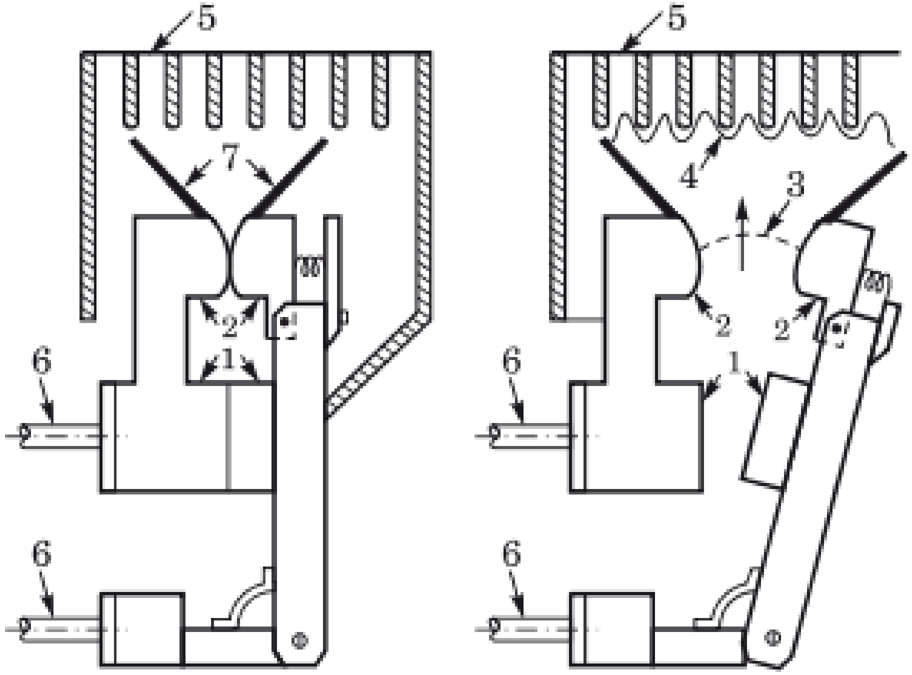
1. Initial position of arc
2. Final position of arc.
3. Arc runners(in vertical plane)
4. Field (in horizontal plane)
5. Force due to electrodynamic forces (i
vertical plane)



1. Arc runner (metallic)
2. Arc splitters
3. Elongated arc
4. Arc in process of travelling
5. Blow-out coils (metallic)
6. Origin of Arc



(a) Contacts in closed position (b) Contacts separated in air at atmospheric pressure



1. Main contacts
2. Arcing contacts
3. Arc rising in the direction of the arrow
4. Arc getting split
5. Arc splitter plates
6. Current carrying terminals
7. Arc runners

(I) Contacts closed (II) Contacts open

Principle of air-break circuit-breaker

Fig. Arc extinction is air-break circuit-breaker.

Air Blast Circuit Breaker

Air blast circuit breakers are suitable for operating voltages of 132 kV and above. They have also been used in 11 kV-33 kV range for certain applications. At present, SF6 circuit breakers are preferred for 132 kV and above. Vacuum circuit breakers are preferred for 11 kV-33 kV range. Therefore, the air blast circuit breakers are becoming obsolete.

In air blast circuit-breaker (also called compressed air circuit-breaker) high pressure air (at 20-30 kg/cm) is used as an arc quenching medium, this high pressure is forced over the arc through a nozzle at the instant of contact separation. The ionized gas between the contacts is blown away by the blast of the air. After the arc extinction the chamber is filled with high pressure air, which prevents restrike of arc.

Air blast circuit-breakers are used today from 11 to 1100 kV for various application. They offer several advantages such as faster operations, suitability for related operation auto reclosure etc.

They are used for inter onnected lines and important lines when rapid operation in desired.

In the air blast circuit-breakers that air pressure used for the arc interruption is constant and does not depend on the arc current. The air pressure is of such magnitude that it can break rated breaking current (say 40 kA) satisfactory at natural zero. High pressure (60kg/cm^2) are used for breakers above 400 kV.

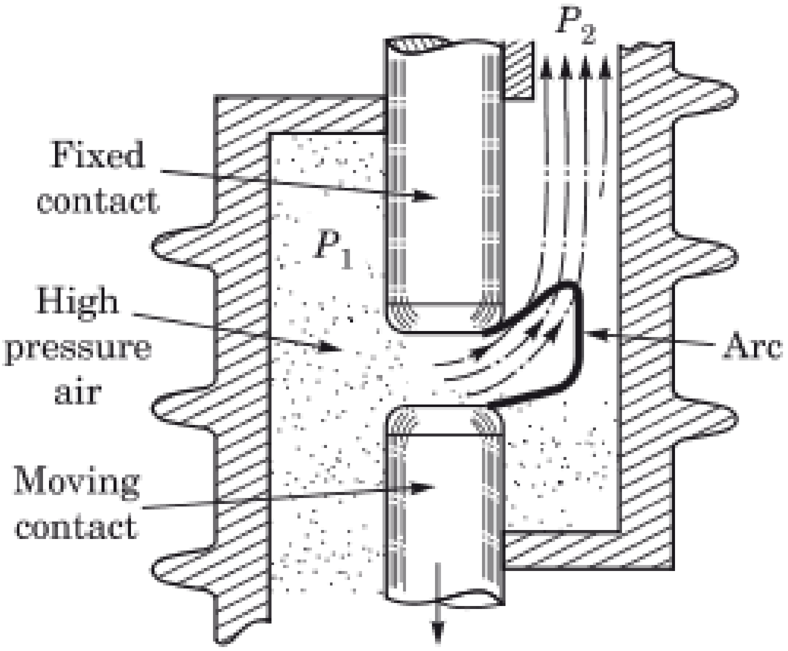


Fig. (a) Flow of air in Air-blast C.B.

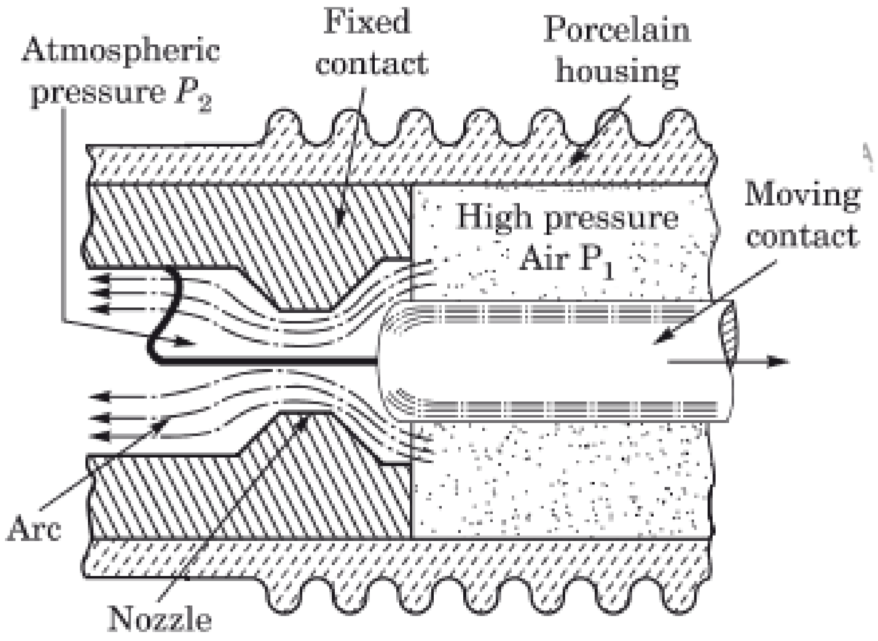
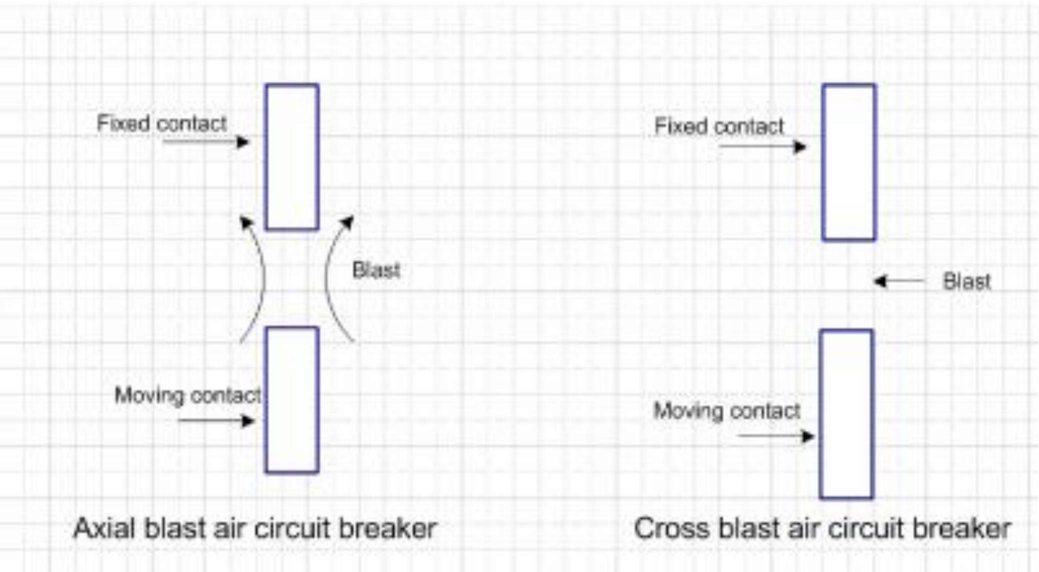


Fig. (b) Axial flow.



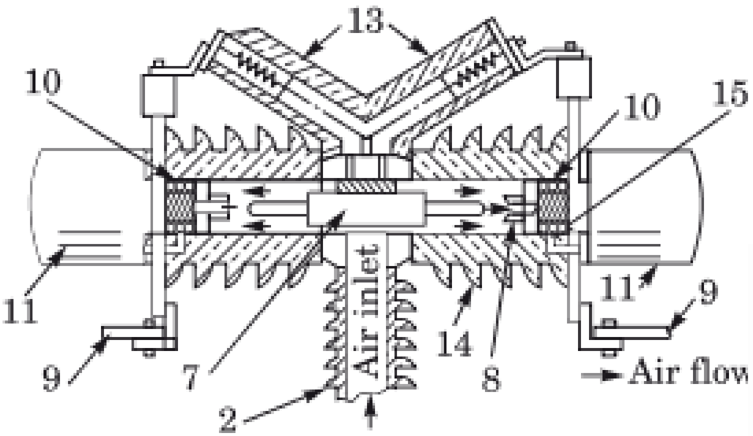
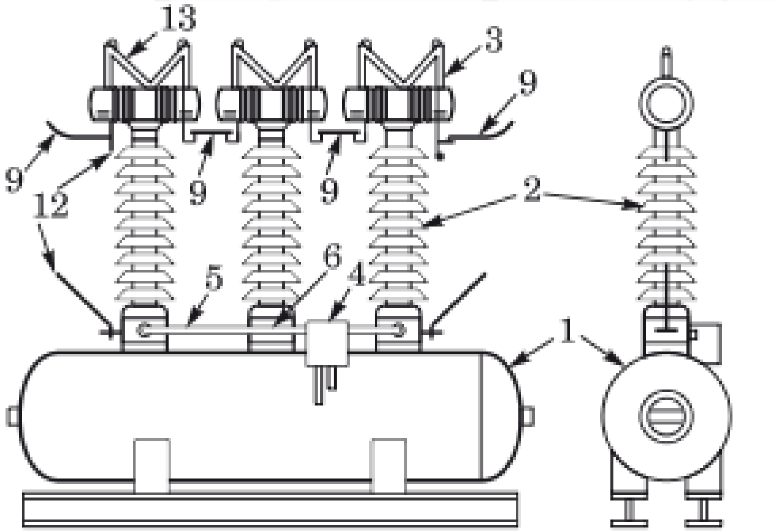
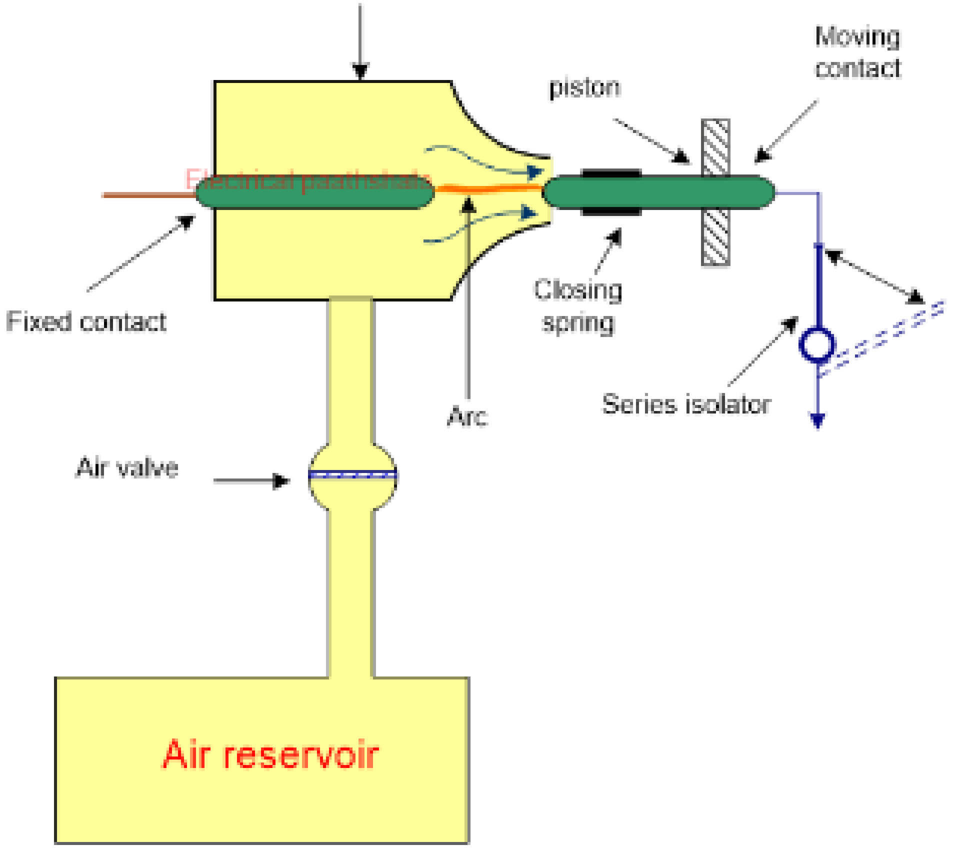


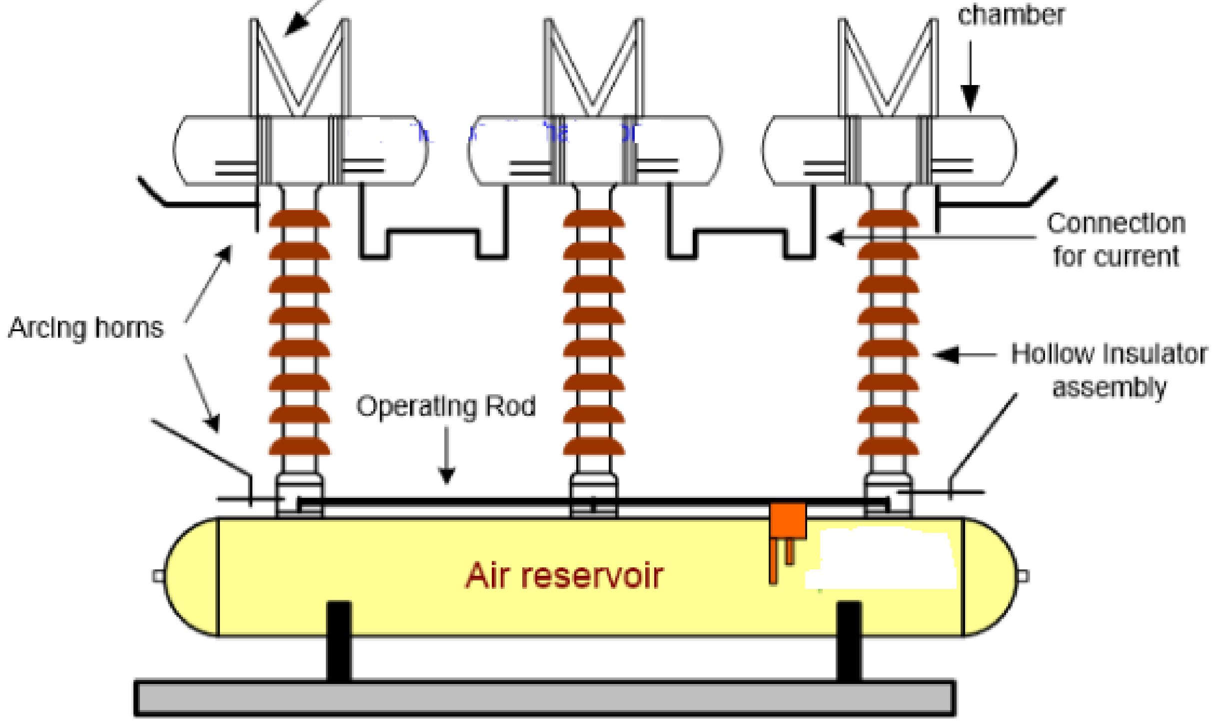
Fig. (b) Details of (3) Double arc extinction chamber.



S.No.	Item
15.	Port
14.	Enclosure
13.	Resistance switching unit
12.	Arcing horns optional
11.	Openings for air outlet
10.	Compression springs
9.	Connection for current
8.	Moving contact (in 3)
7.	Fixed contact (in 3)
6.	Pneumatic valve
5.	Operating rod
4.	Pneumatic operating mechanism
3.	Double arc extinction chamber
2.	Hollow insulator assembly
1.	Tank air reservoir (receiver)



Axial blast air circuit breaker



Air blast circuit breaker

The axial blast type

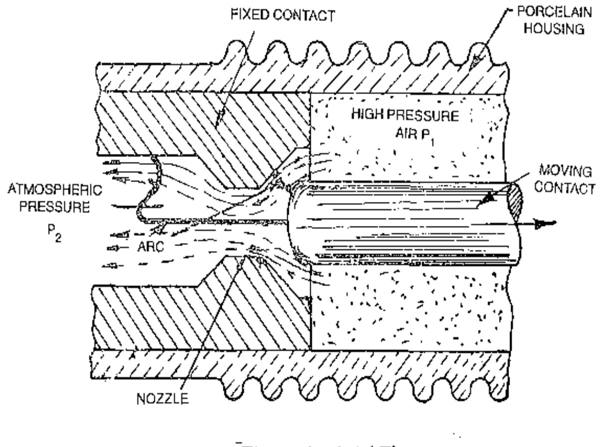
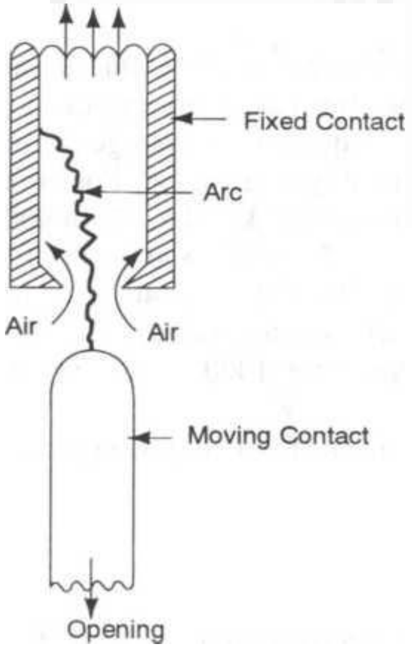


Fig. (a) Axial Flow.

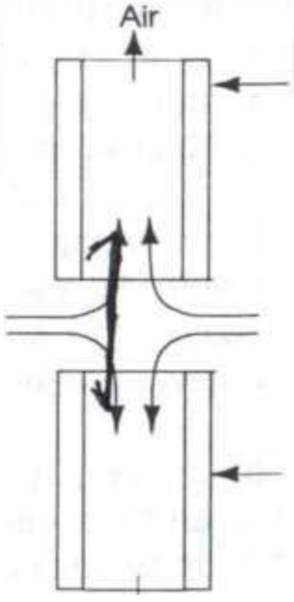
Axial blast type – In this type, the blasting of air is done directly along the path of arc, as shown in figure below.

Cross blast type-in this type, the blasting of air is directed at right angle to the arc path, as shown in the figure below.

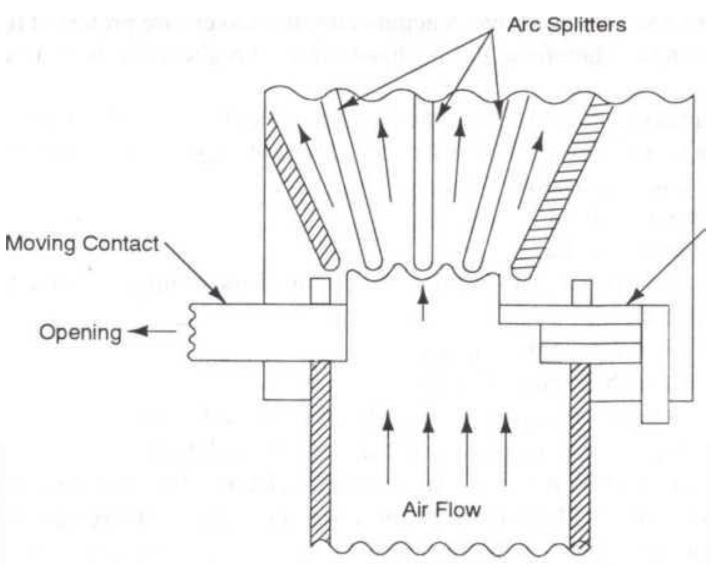
Single blast type axial-blast circuit breaker



Double blast type (radial-blast type)
axial- blast circuit breaker



Cross-blast circuit breaker



(a)

<u>The advantages of air blast circuit breakers over oil circuit breakers are</u>:

- Cheapness and free availability of the interrupting medium, chemical stability and inertness of air.
- High speed operation.
- Elimination of fire hazard.
- Short and consistent arcing time and therefore, less burning of contacts.
- Less maintenance.
- Suitability for frequent operation.
- Facility for high speed reclosure

The disadvantages of an air blast circuit breaker are as follows.

- An air compressor plant has to be installed and maintained, Required more auxiliary components.
- Upon arc interruption the air blast circuit breaker produces a high-level noise when air is discharged to the open atmosphere. In residential areas, silencers need to be provided to reduce the noise level to an acceptable level, not suitable in residential area
- Problem of current chopping.
- Problem of restriking voltage

SF6 Circuit Breakers

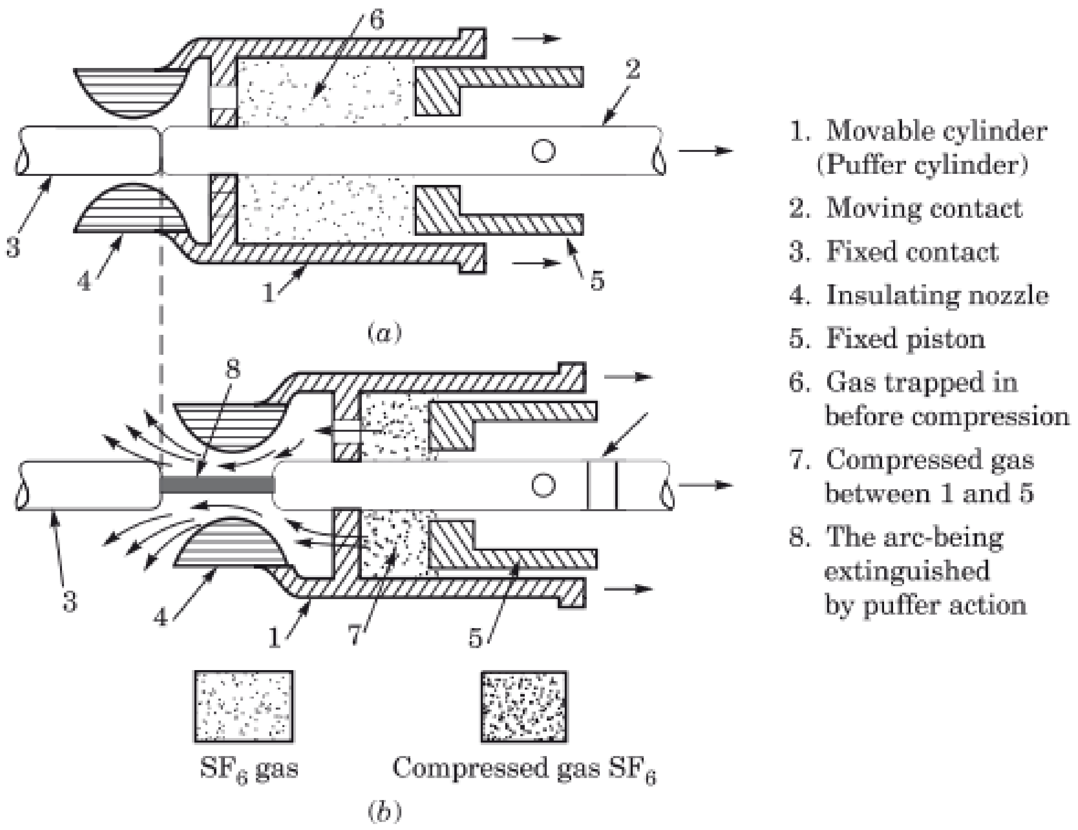
Sulphur hexafluoride (SF6) is heavy gas its density is five times that of air, having good dielectric strength and excellent arc quenching (Interrupting) property

Typical Ratings of SF_6 Insulated Switchgear (GIS)

Rated voltage kV	36	72	145	245	400	500
Rated currents Amp.	1200 to 2000	1200 to 2000	2000 to 3000	2000 to 4000	2000 to 4000	2000 to 4000
Rated breaking current kA	32	32	32	50	50	50
Breaking capacity MVA	1800	3500	7500	10,000	35,000	50,000
Operating time cycles	3	3	3	2.3	2	2
Power frequency voltage withstand kV_{rms}	75	160	275	460	680	840
Impulse voltage withstand $kV_{p,}$ peak	170	400	550	1050	1425	1800

Puffer-type SF_6 circuit breakers

This type of circuit breakers are also called single-pressure or impulse type SF_6 circuit breakers. In this type of breakers, SF6 gas is compressed by a moving cylinder system called puffer cylinder and is released through a nozzle to quench the arc.



(a) Breaker fully closed (b) Contacts separated, puffing action in progress.
Fig. Puffer action principle.

Non Puffer Type SF_6 Circuit Breaker

The interruption of the arc is achieved by the action of sulphur hexafluoride gas forcing gas at high pressure flows through tubes leading to interrupter units at a high speed and producing both axial and cross blast effects.

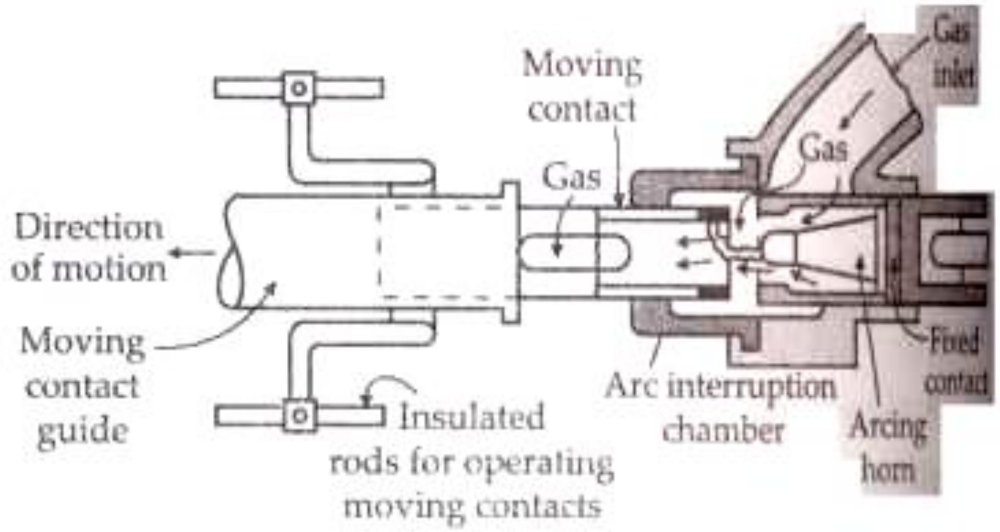


Fig. Constructional layout of SF_6 breaker.

MERITS OF SF_6 CIRCUIT-BREAKERS

- Outdoor SF_6 CB is simple less costly, maintenance free
-
- Due to outstanding arc quenching property of SF6 the arcing time is very small. This reduces contact erosion
- During arcing of SF6 breaker, no carbon dioxide is formed and hence no reduction of dielectric strength
- SF6 breaker is compact in size and electrical clearances are drastically reduced
- The gas is non-inflammable and chemically stable. The decomposition products are not explosive. Hence there is no danger of fire or explosion.
- Same gas is recirculated in the circuit. Hence requirement of SF_6 gas is small

DEMERITS OF SF6 CIRCUIT-BREAKER

- Sealing problems arise. Imperfect joints load to leakage of gas.
- In this case of leakage in the breaker tank, this gas, being heavier than air settles in the surroundings and may lead to suffocation to the operating personnel. However, it is non- poisonous
- By products of Arced SF_6 gas (SO2, HF,etc) is poisonous and should not be in inhaled or let-out.
- Inflow of moisture in the breaker is very harmful to SF_6 gas circuit-breakers. Several failures reported due to this cause.
- Mechanism of higher energy level is necessary for puffer type SF_6 breakers. Lower speeds due to friction, misalignment can cause failure of breaker.
- The internal parts should be cleaned thoroughly during periodic maintenance under clean, dry environment. Dust of Teflon and sulfides should be removed

Vacuum Circuit Breaker

The arc interruption process in vacuum interrupters is quite different from that in other types of circuit-breakers. The vacuum as such is a dielectric medium and arc cannot persist in ideal vacuum. However, the separation of current carrying contacts causes the vapour to be released from the contacts surface giving rise to plasma. Thus, as the contacts separate, the contact space is filled with vapour of positive ions liberated from the contact material. The vapour density depends on the current in the arc. During the decreasing mode of the current wave the rate of release of the vapour reduces and after the current zero, the medium regains the dielectric strength provided vapour density around Contacts has substantially reduced.

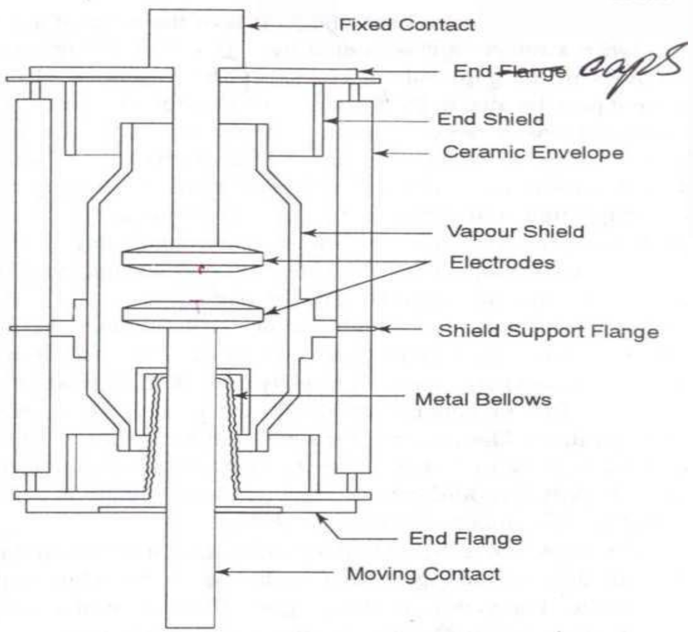


FIGURE Vacuum circuit breaker

High Voltage DC Circuit Breakers

- In ac circuits, current passes through natural current zeros, and hence it is possible to design ac circuit breakers to interrupt large currents. This feature is not available in dc.
- If a high current is suppressed abruptly in dc, a very high transient voltage appears across the contacts of the circuit breakers. Therefore, in dc circuit breakers, some external circuits have to be provided to bring down the current from full value to zero, smoothly without suppressing it suddenly.
- The additional circuit creates artificial current zeros which are utilized for arc interruption as shown in above Fig

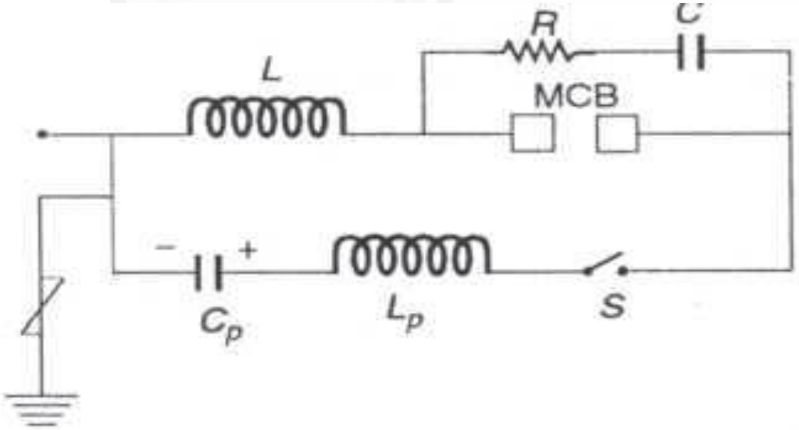


FIGURE HVDC circuit breaker

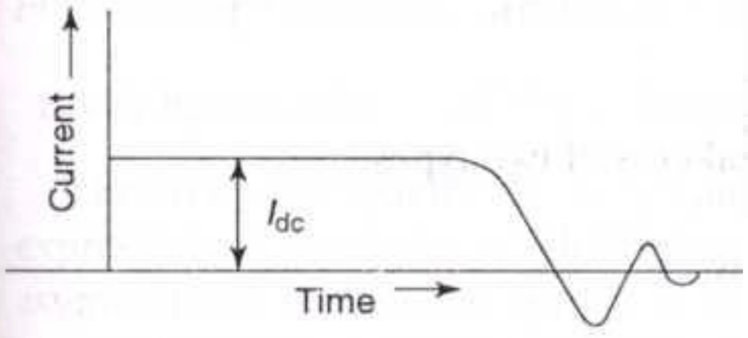


FIGURE Artificial current zeros in dc

INDIRECT TESTING METHODS

The important indirect Testing Methods include the following :

- **Unit Testing**. Which means testing one or more units separately.
- **Synthetic Testing.** In which the current source providing short circuit current and voltage source supplying restriking and recovery voltage are different.
- **Substitution Tests.** These are conducted for oil circuit breaker; the characteristics of current versus time are obtained for different voltages. The performance beyond the tested values is determined by approximation.
- **Compensation Tests.** Which are conducted on oil circuit-breakers in critical range of low current by a suitable compensation such as increased frequency, increase restriking voltages etc.
- **Capacitance Tests.** The capacitor which is charged by a voltage source is discharged through the breaker. An oscillatory circuit provides restriking voltage

Synthetic Testing. In which the current source providing short circuit current and voltage source supplying restriking and recovery voltage are different.

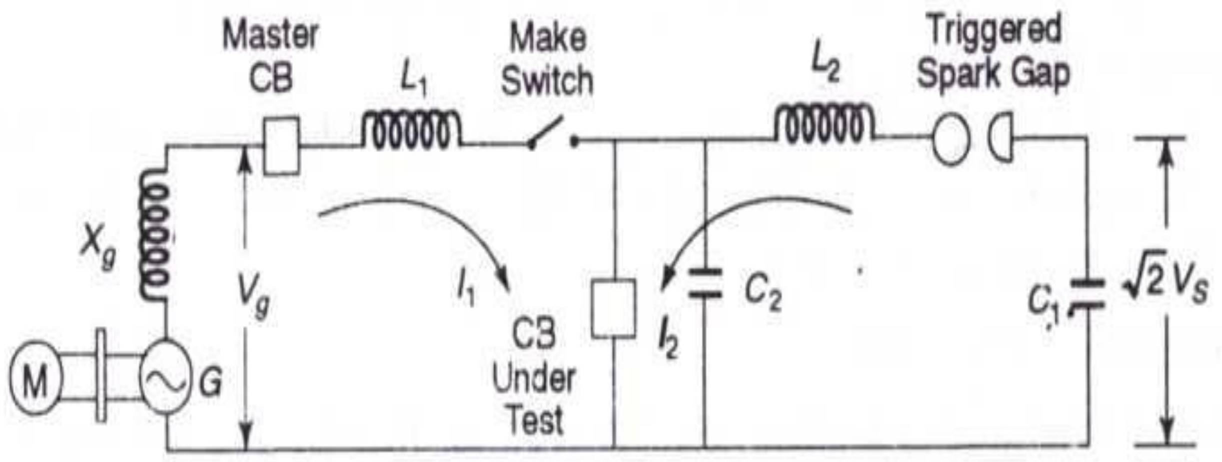


FIGURE Synthetic testing of circuit breaker

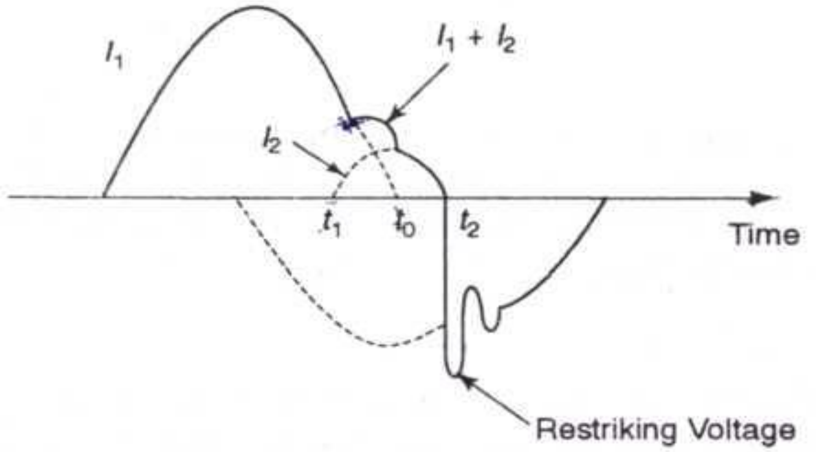


FIGURE Waveform during synthetic testing

Capacitance test

- In this test a capacitor is charged by a D.C. voltage source.
- Capacitor is connected in series with an inductor L and making switch.
- The breaker is connected in parallel across the capacitor C and L from oscillatory circuit.
- The circuit-breaker under test is opened and voltage across the capacitor is discharged through the arc.
- The arc gets extinguished at a current zero.
- This test is used for investigating the behavior of the breaker towards restriking voltage

Compensation test

- Oil circuit-breakers have internal source of extinguishing energy.
- For low currents extremely difficult extinguishing conditions may be experienced because of insufficient pressure build up.
- The characteristics of the breaker in critical range are ascertained by compensation test.
- These tests are conducted in critical range.
- In the test, the pressure in the arc extinction device, lengths and durations of arc etc. are recorded, test being conducted at reduced voltage.
- The reduction in voltage is compensated by some other factor such as:
  - Increased frequency.
  - Applying impulse voltage at current zero.
  - The pressure in the tank of an oil circuit breaker is given by $P=K\,V^{0.5}\,I^{0.2}$

SUBSTITUTION TEST

In substitution test a number of tests at closely graduated capacities are conducted on the breaker with internal source of extinguishing energy. Characteristics of arc duration and current to interrupted are plotted These are development tests

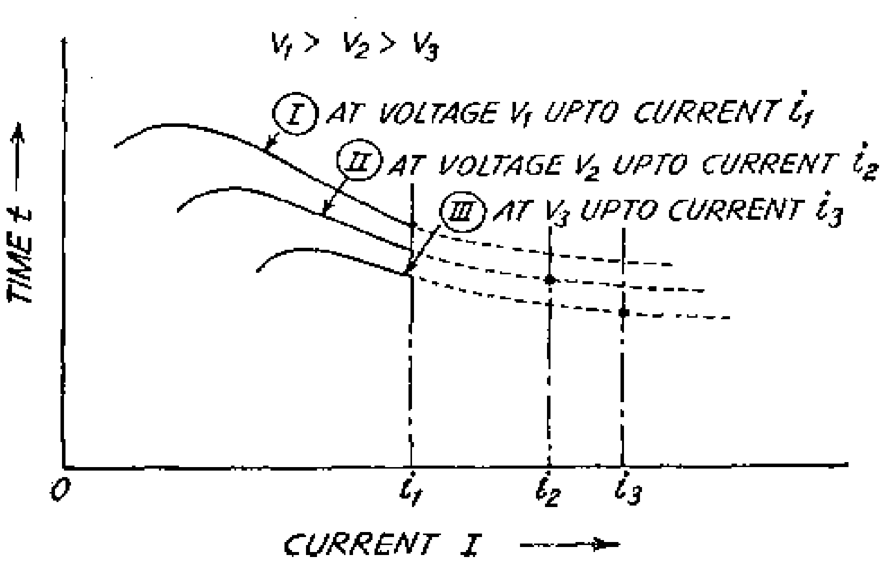


Fig. Substitution test characteristics.

The substitution test is conducted as follows:

- Test the breaker at full voltage and upto current permitted by the capacity of the plant, i.e. current i_1 of characteristic I.
- Test the breaker at reduced voltage upto current i_2 permitted by the test plant at reduced voltage V2 obtain the time required for various current upto i_2 and plot characteristic II
- Likewise, plot characteristics III at voltage V3 upto current i3, characteristic IV at voltage V4 upto current i_1 etc where V1 is the highest test voltage V1> V3 > V4 etc. i_1 is the current at voltage V1 permitted by test plant.
- On plotting the characteristic I, II, III, etc, these are extended by approximation as shown by the dotted lines. Form the extended line the breaker performance can be predicated for values of current beyond range of testing station

THANK YOU