

What is a Circuit Breaker?

A circuit breaker is basically a switch to interrupt the flow of current.

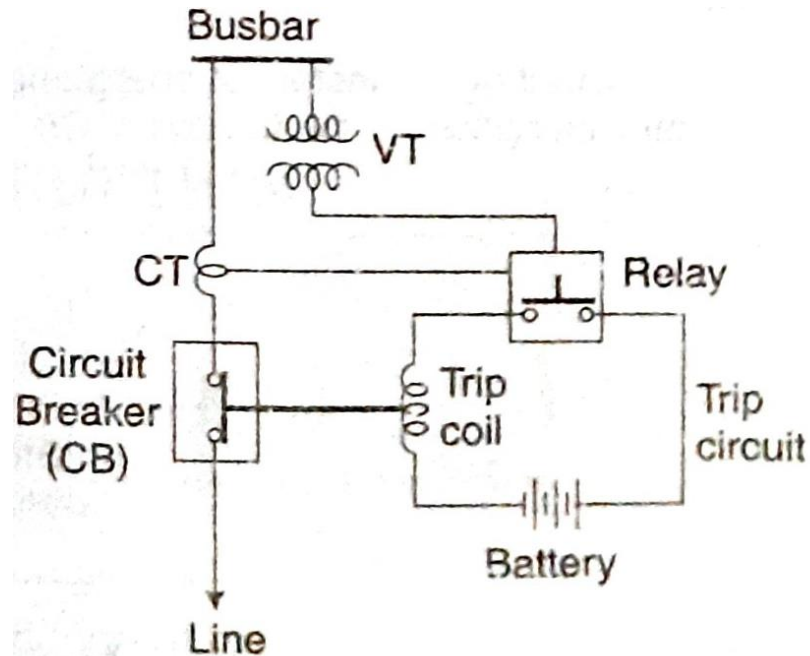
- It opens on relay command.
- It has to handle large voltages and currents.
- The inductive nature of power system results in arcing between the terminals of a CB.
- CBs are categorized based on the interrupting medium used.
- A Circuit Breaker (CB) is basically a switch used to interrupt the flow of current. It opens on relay command. The relay command initiates mechanical separation of the contacts. It is a complex element because it has to handle large voltages (few to hundreds of kV's) and currents (in kA's). Interrupting capacity of the circuit breaker is therefore expressed in MVA

Power systems under fault behave more like inductive circuits. X/R ratio of lines is usually much greater than unity. For 400 kV lines, it can be higher than 10 and it increases with voltage rating. From the fundamentals of circuit analysis, we know that current in an inductive circuit (with finite resistance) cannot change instantaneously. The abrupt change in current, if it happens due to switch opening, will result in infinite di/dt and hence will induce infinite voltage. Even with finite di/dt , the induced voltages will be quite high. The high induced voltage developed across the CB will ionize the dielectric between its terminals. This results in arcing. When the current in CB goes through the natural zero, the arc can be extinguished (quenched). However, if the interrupting medium has not regained its dielectric properties then the arc can be re-struck. The arcing currents reduce with passage of time and after a few cycles the current is finally interrupted.

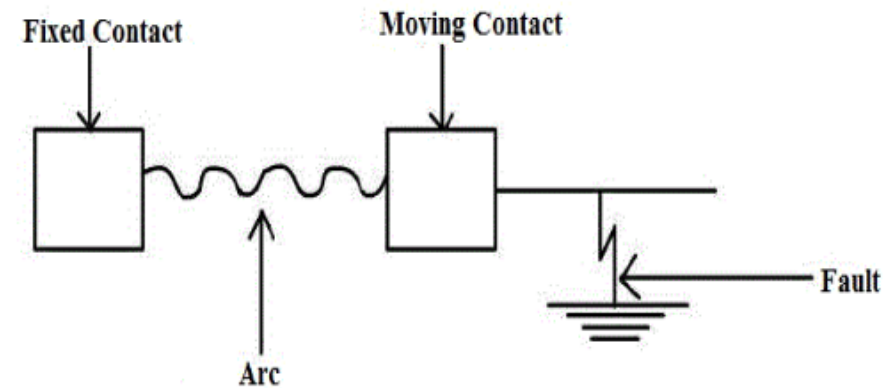
Usually CB opening time lies in the 2-6 cycles range. CBs are categorized by the interrupting medium used. Minimum oil, air blast, vacuum arc and SF_6 CBs are some of the common examples. CB opening mechanism requires much larger power input than what logical element relay can provide. Hence, when relay issues a trip command, it closes a switch that energizes the CB opening mechanism powered by a separate dc source (station battery). The arc struck in a CB produces large amount of heat which also has to be dissipated.

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.



Trip circuit of CB

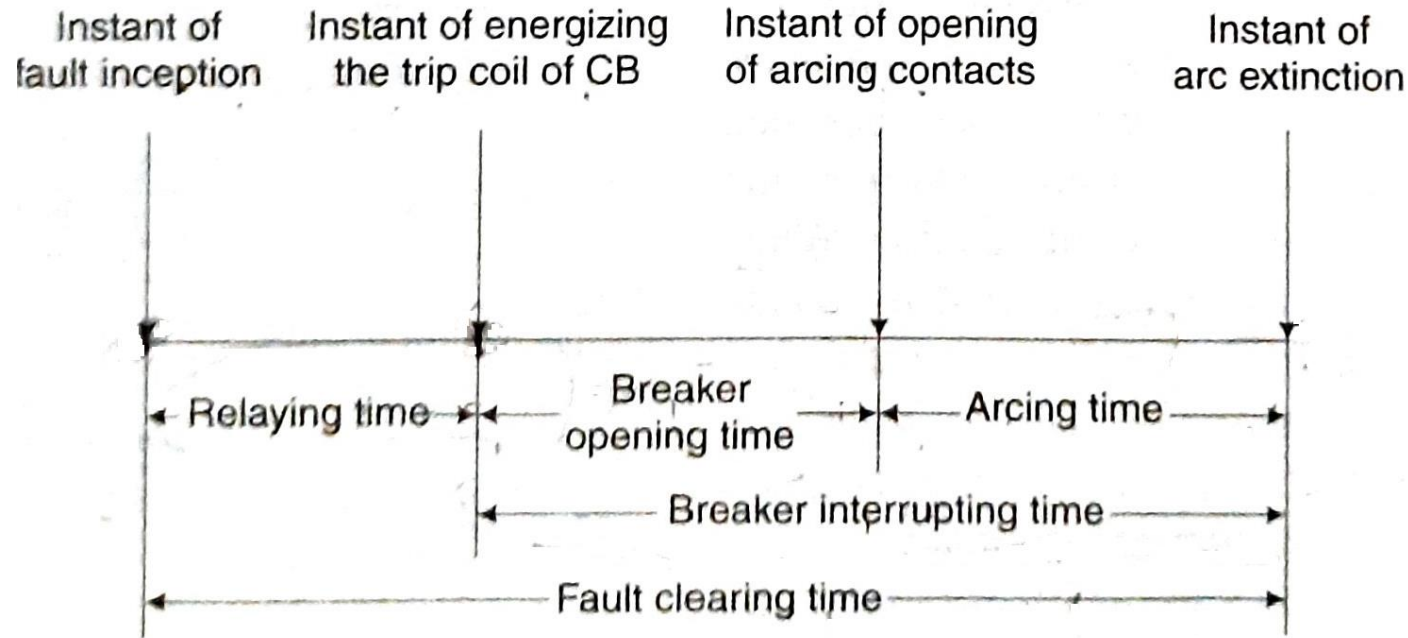


fig(m)

Separation of the contacts of the circuit breaker

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 part.
- 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. Current 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

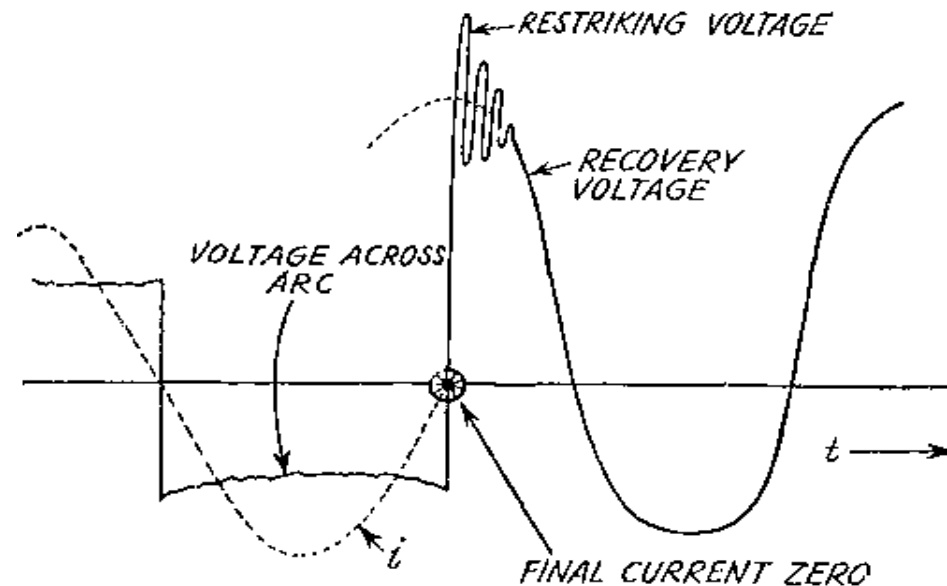
Cooling of the arc brings about recombination of ionized particles, cooling is brought by bringing the arc (ionized gas) in contact with cooler air.

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

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

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 C.B. 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.

In a.c. circuit-breakers the arc is interrupted at a current zero, as zero current position offer most favourable situation for this where residual ionization is small. At current zero, the space between c.b. 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.

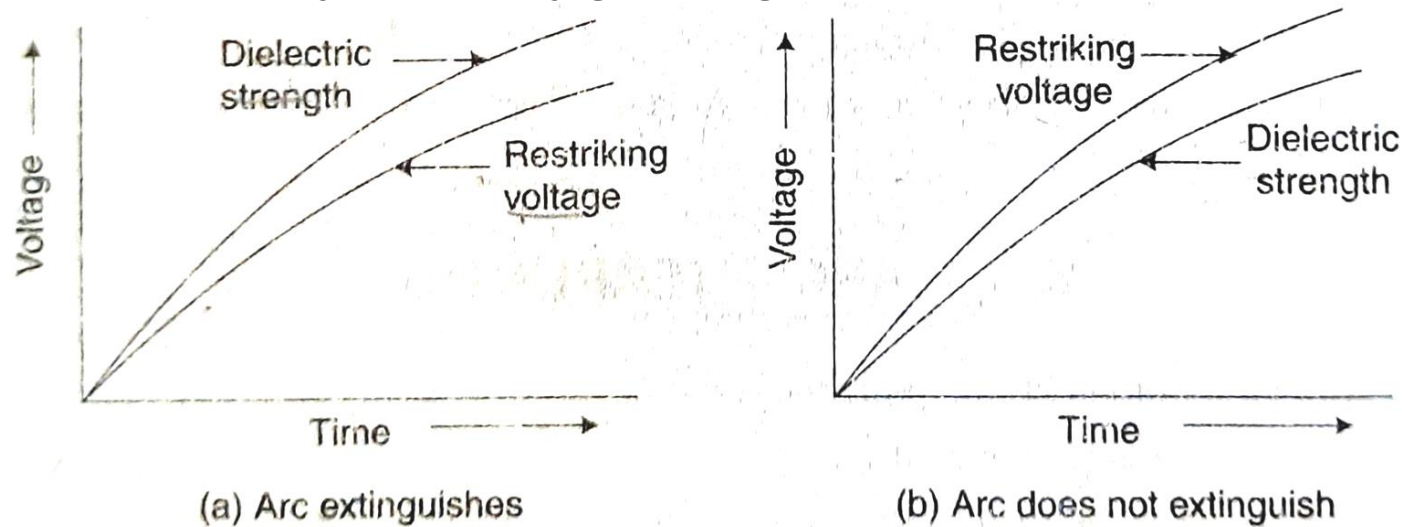
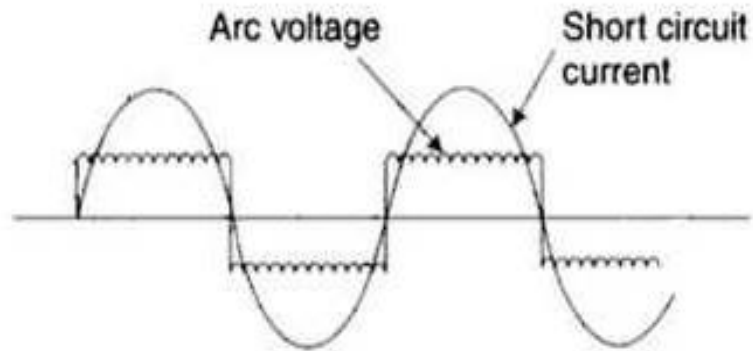
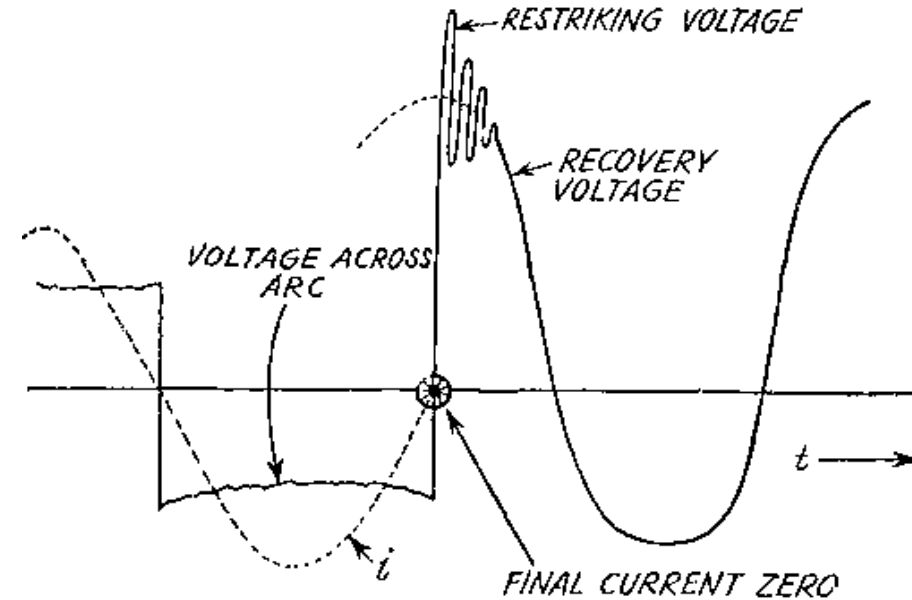


Fig. Recovery rate theory

ARC VOLTAGE



Restriking Voltage and Recovery 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 normalise 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 ckt, power frequency component is due to system voltage

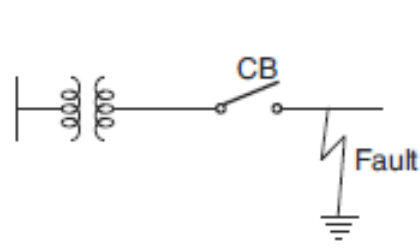
The frequency of transient component is given by
$$F_n = \frac{1}{2\pi\sqrt{LC}}$$

F_n = frequency of transient voltage, Hz

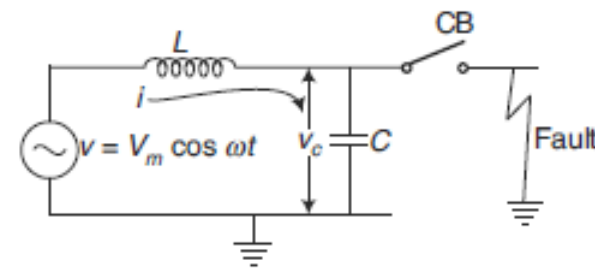
L = Equivalent inductance, Henry

c = Equivalent capacitance, farad

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



(a)



(b)

Restriking Voltage

Fig. 14.8 (a) Fault on a feeder near circuit breaker (b) Equivalent electrical circuit for analysis of restriking voltage

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

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.

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

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

$$\int \frac{idt}{C} = \frac{q}{C} = v_c$$

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

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

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

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

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

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.

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

= Restriking voltage

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

= $2 \times$ peak value of the system voltage

The Rate of Rise of Restriking voltage (RRRV)

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

$$= \omega_n E \sin \omega_n t$$

The maximum value of RRRV = $\omega_n E$

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

Example. 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:

- The frequency of transient oscillation
- The maximum value of restriking voltage across the contacts of the circuit breaker
- The maximum value of RRRV

(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

$$v_c = V_m [1 - \cos \omega_n t]$$

The maximum value of the restriking voltage = $2V_m$

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

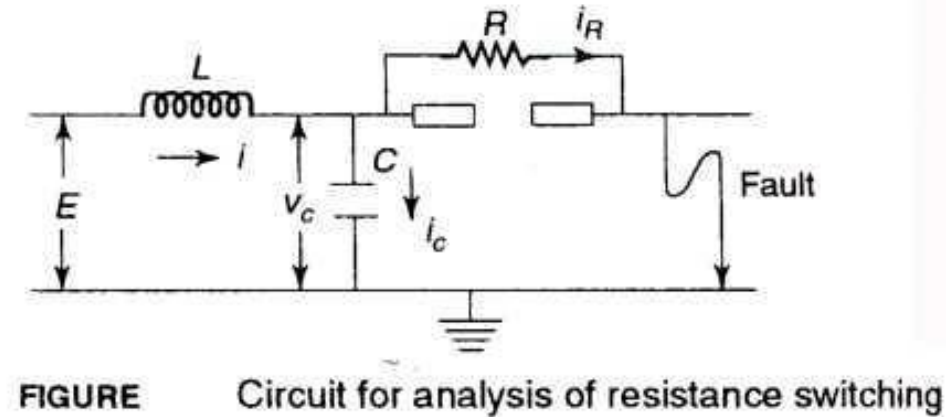
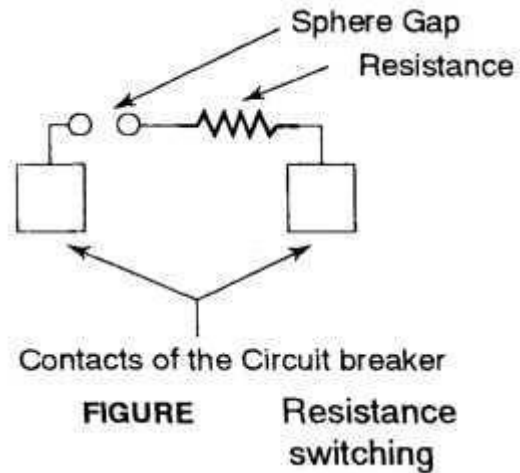
(c) The maximum value of RRRV = $\omega_n V_m$

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

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

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

Resistance Switching



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

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

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

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

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

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 root of the quadratic equation in the denominator should be real. For this, the following condition should be satisfied.

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

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

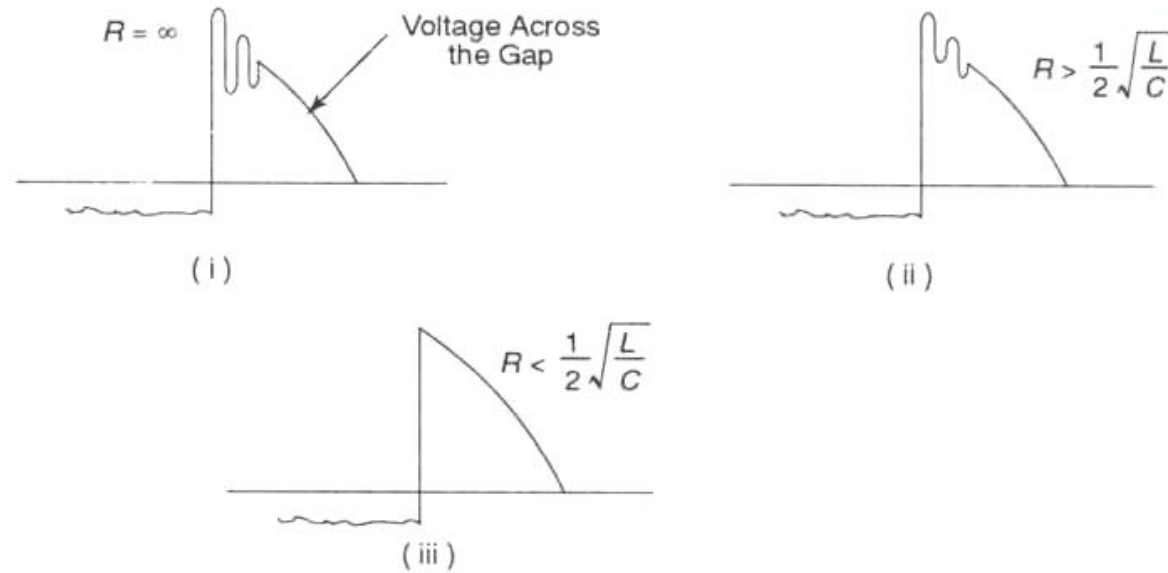


FIGURE Transient oscillations for different values of R

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

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

Example In a 220 kV system, the reactance and capacitance up to the location of circuit breaker is 8Ω and $0.025\mu\text{F}$, respectively. A resistance of 600 ohms is connected across the contacts of the circuit breaker.

Determine the following:

- Natural frequency of oscillation
- Damped frequency of oscillation
- Critical value of resistance which will give no transient oscillation
- The value of resistance which will give damped frequency of oscillation, one-fourth of the natural frequency of oscillation

Solution:

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

$$\begin{aligned} \text{(i) Natural frequency of oscillation} &= \frac{1}{2\pi} \sqrt{\frac{1}{LC}} \\ &= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}}} \\ &= 6.304 \text{ kHz} \end{aligned}$$

(ii) Frequency of damped oscillation is given by

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

$$\begin{aligned} &= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times (600)^2}} \\ &= \frac{1}{2\pi} \sqrt{\frac{10^{10}}{6.36} - \frac{10^{10}}{9}} = 3.413 \text{ kHz} \end{aligned}$$

(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

$$\frac{1}{4} \times 6.304 \text{ kHz} = 1576 \text{ Hz}$$

$$\begin{aligned} 1576 &= \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}} \\ &= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times R^2}} \end{aligned}$$

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

Therefore, $R = 520.8 \Omega$.

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

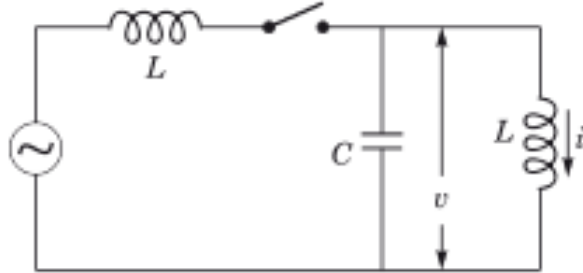


Fig. Circuit diagram illustrating interruption of low inductive current.

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

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

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

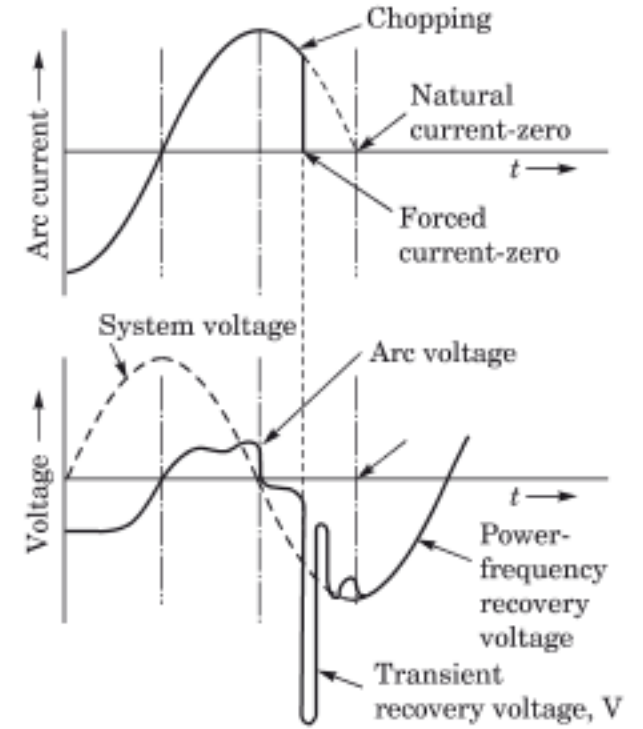


Fig. Interruption of low magnetizing currents.

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 $2500\mu\text{F}$. The inductance is 30H.

Solution: The full load current of the transformer

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

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

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

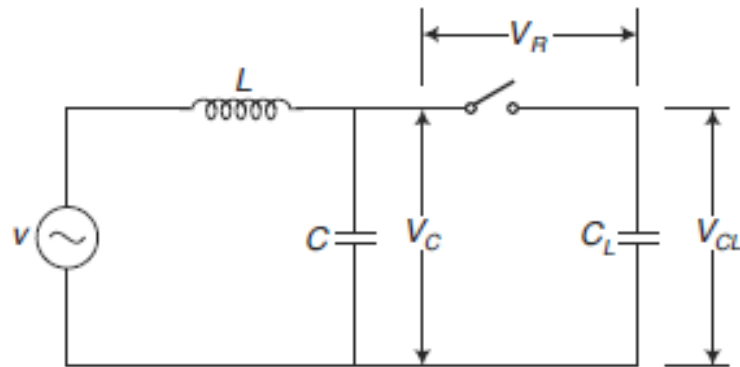
$$\frac{1}{2} Li^2 = \frac{1}{2} Cv^2$$

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

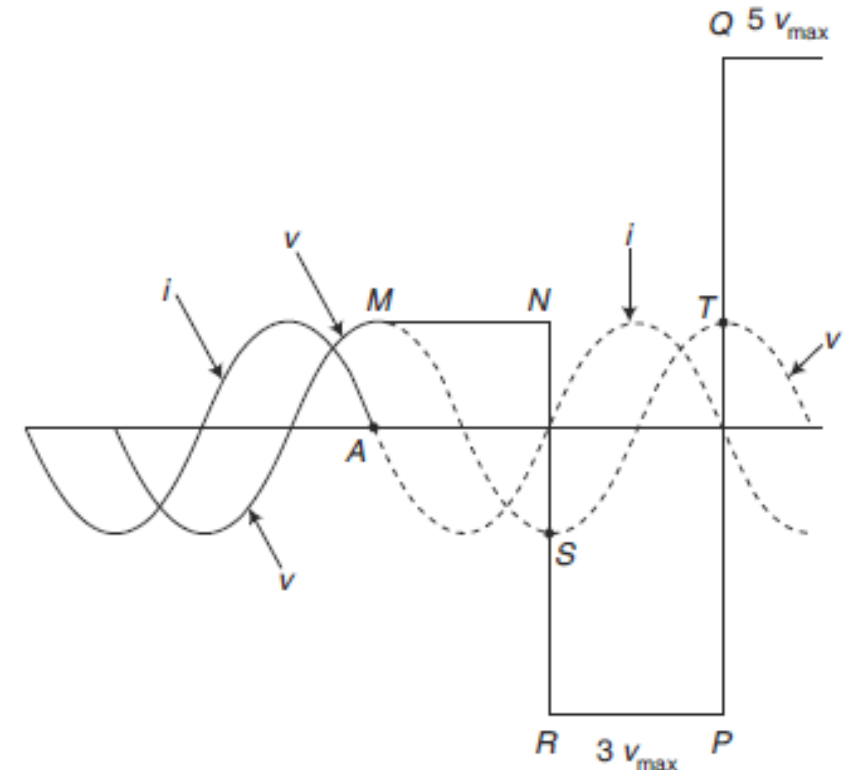
$$\therefore v = 2829 \text{ kV}$$

Interruption of Capacitive Current

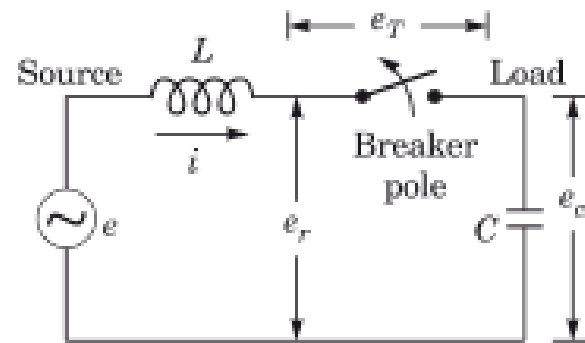
The interruption of capacitive current produces high voltage transients across the gap of the circuit breaker. This occurs when an unloaded long transmission line or a capacitor bank is switched off. Figure 14.13(a) shows an equivalent electrical circuit of a simple power system. C represents stray capacitance of the circuit breaker. C_L represents line capacitance. The value of C_L is much more than C . Figure 14.13(b) shows transient voltage across the gap of the circuit breaker when capacitive current is interrupted



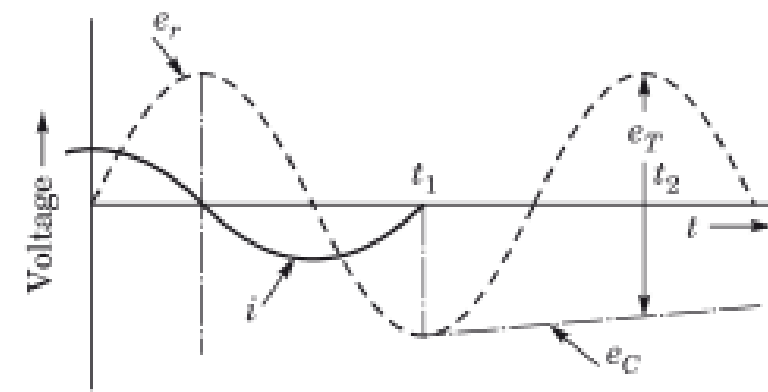
(a) Electrical circuit of a simple power system



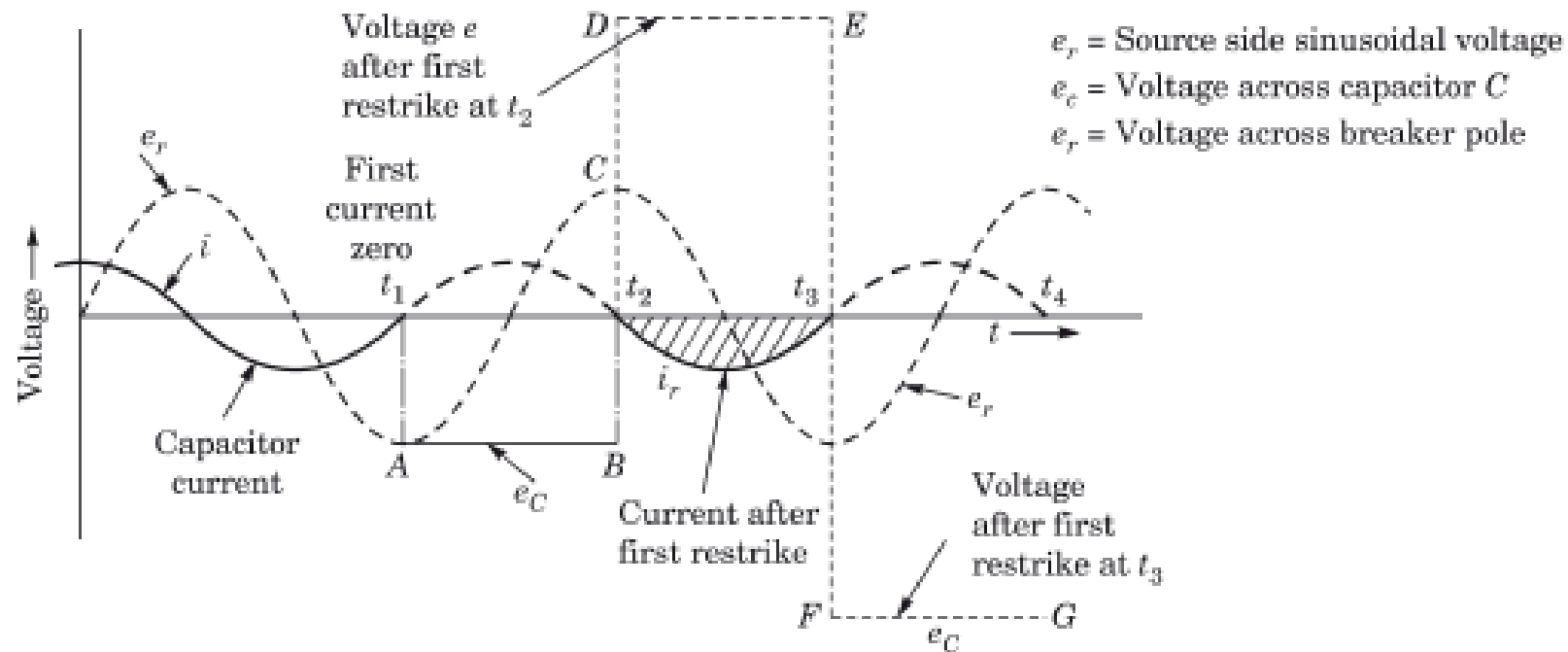
(b) Transient voltage across the gap of the circuit breaker



(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

Out of the various ways of classification of circuit breakers, the general way and the most important method of classification is on the basis of medium used for insulating and 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 (SF) 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:

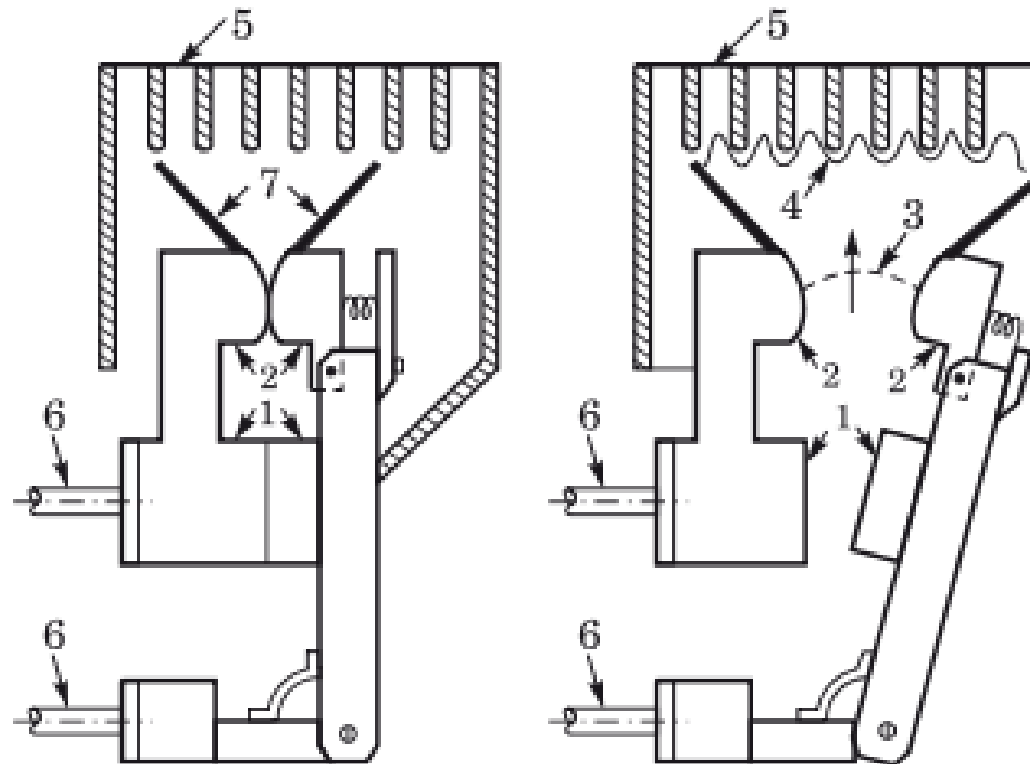
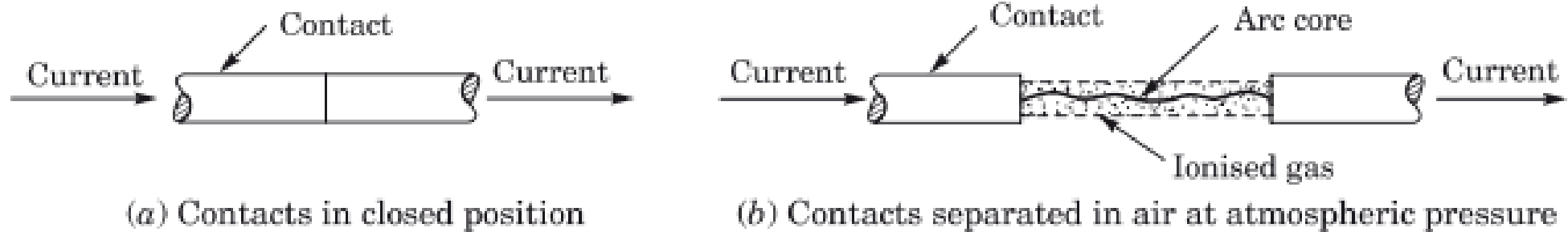
460 V, 400-3500 A, 40-75 kA.

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



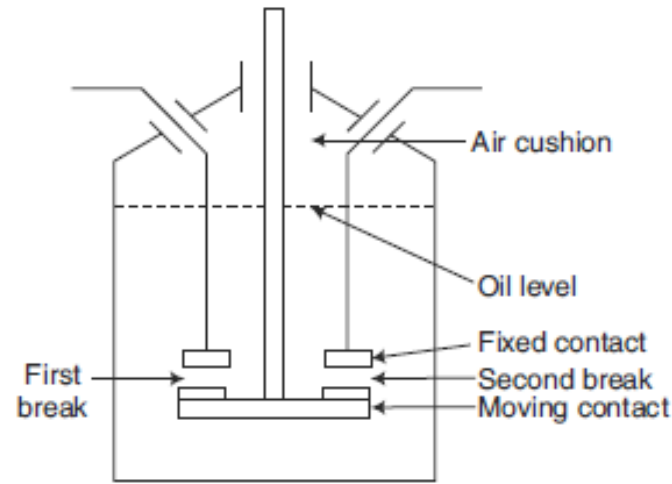
1. Main contacts
 2. Arcing contacts
 3. Arc rising in the direction of the arrow
 4. Arc getting split
 5. Arc splitter plates
 6. Current carrying terminals
 7. Arc runners
- (I) Contacts closed (II) Contacts open
Principle of air-break circuit-breaker

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

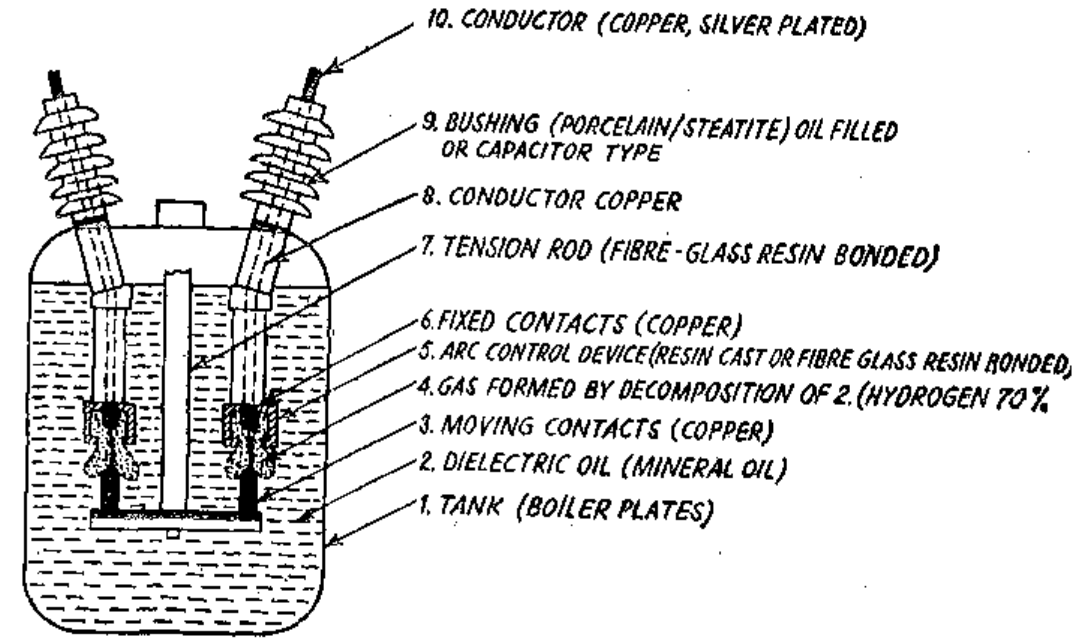
Bulk oil Circuit Breaker

The main features that have an important bearing upon the performance of a plain-break oil circuit breaker are:

- Length of break.
- Speed of contact movement.
- Head of oil above contacts.
- Clearance to earthed metal adjacent to contacts.



Plain-break oil circuit breaker



Bulk oil circuit-breaker with arc control device.

In these the gases produced during arcing are confined to small volumes by the use of an insulating, rigid arc chamber (Arc Control Device or arc control pots) surrounding the contacts. Thus, higher pressures can be developed to force the oil and gas through or around the arc to extinguish it. These small, high pressure resistant chambers are known as arc control pots or sometimes as explosion pots

A large gaseous pressure is developed because a large amount of energy is dissipated within the tank. Therefore, the tank of the circuit breaker is made strong to withstand such a large pressure. When gas is formed around the arc, the oil is displaced. To accommodate the displaced oil, an air cushion between the oil surface and the tank is essential.

The air cushion also absorbs the mechanical shock produced due to upward oil movement of oil.

Sufficient level of oil above the contacts is required to provide substantial oil pressure at the tank so it prevent escape of liberated hydrogen gas from oil to air, thus prevent formation of explosive mixture,

Certain gap between the contacts must be created before the arc interruption occurs. To achieve this speed of the break should be as high as possible, Welding of contacts may result on short-circuit interruption if the speed of contact movement is slow

The Double breaks in series provide rapid arc elongation (increases the length of the arc such that arc resistance increases), but this arrangement has the disadvantage of unequal voltage distribution across the breaks.

Minimum oil circuit breaker.

The advantages of minimum oil circuit breaker are

- The quantity of oil required is small.
- The space requirement is reduced.
- The risk of fire is reduced.

Disadvantages

- Due to smaller quantity of oil, the degree of carbonisation is increased.
- The gases are difficult to remove from the contact space in time.
- The dielectric strength of the oil deteriorates rapidly as degree of carbonisation is high

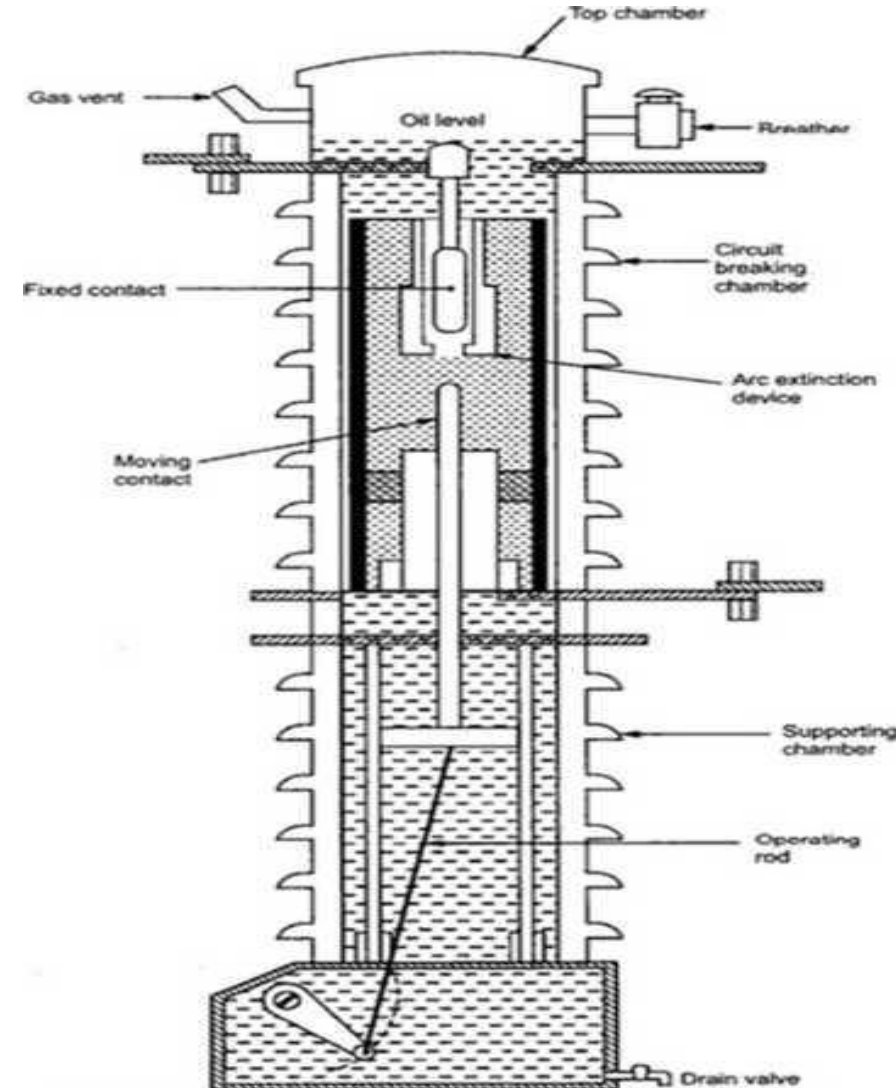


Fig. Construction of minimum oil circuit breaker

Air Blast Circuit Breaker

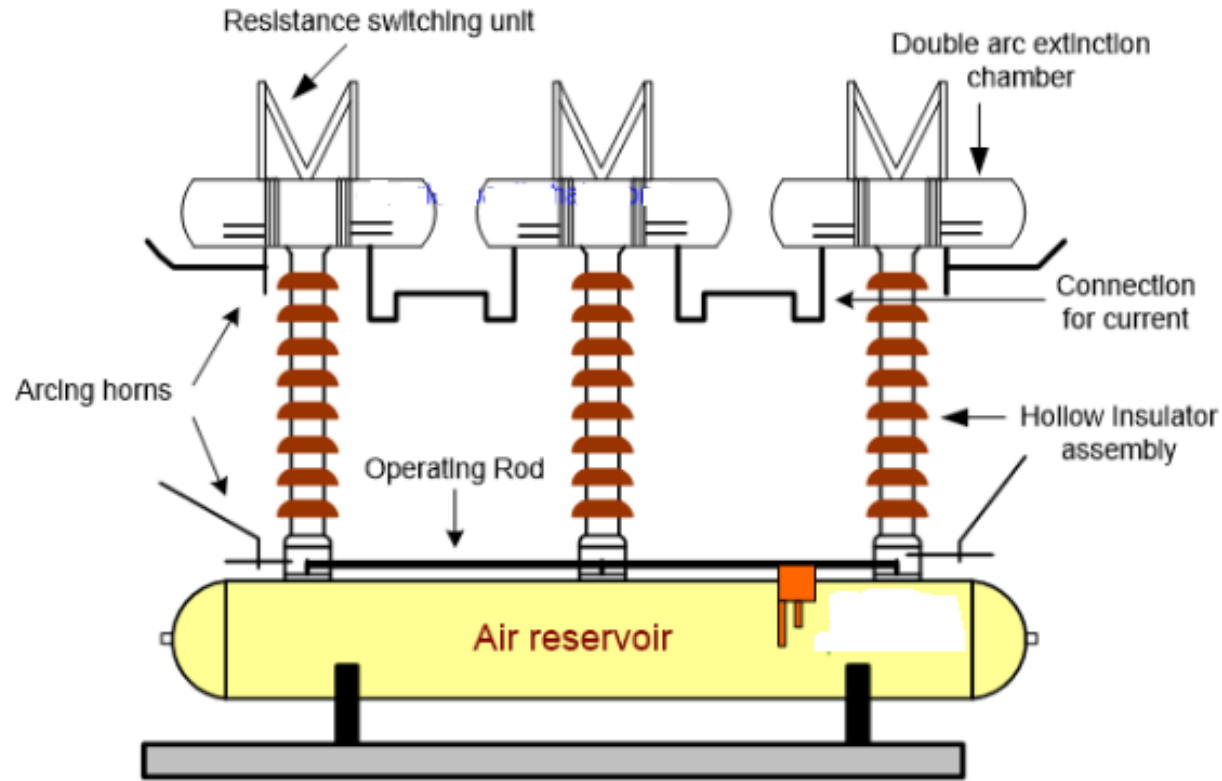
Air blast circuit breakers are suitable for operating voltages of 132 kV and above. They have also been used in 11 kV-33 kV range for certain applications. At present, SF₆ circuit breakers are preferred for 132 kV and above. Vacuum circuit breakers are preferred for 11 kV-33 kV range. Therefore, the 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/cm²) 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.

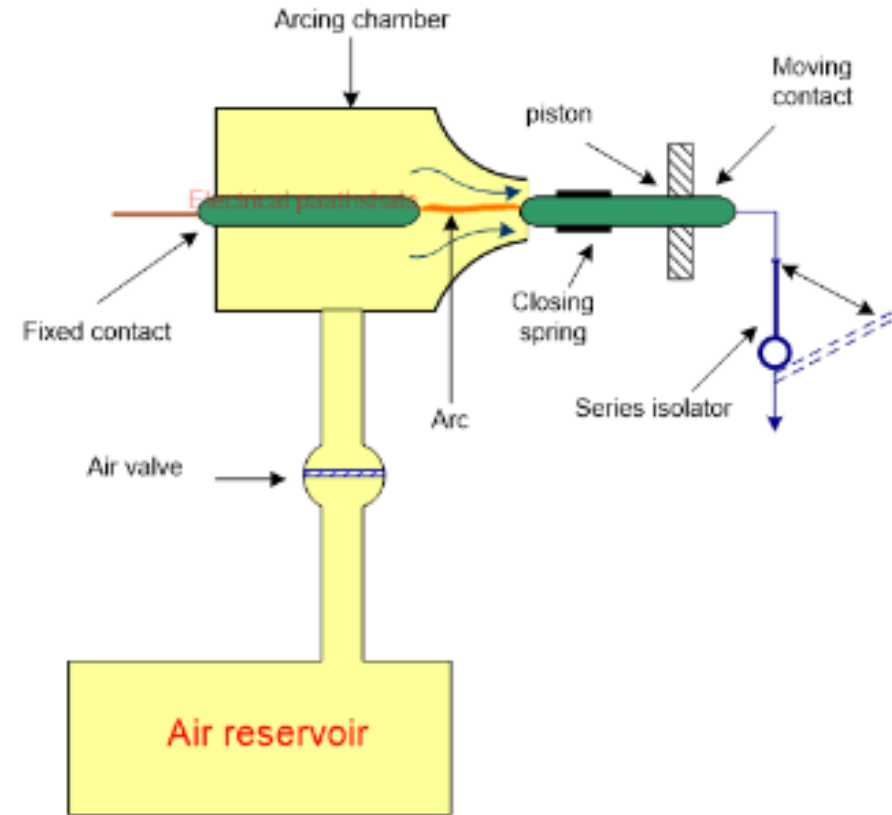
Air blast circuit-breakers are used today from 11 to 1100 kV for various application. They offer several advantages such as faster operations, suitability for related operation auto reclosure etc.

They are used for interconnected lines and important lines when rapid operation is 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) satisfactorily at natural zero. High pressure (60 kg/cm²) are used for breakers above 400 kV.



Air blast circuit breaker



Axial blast air circuit breaker

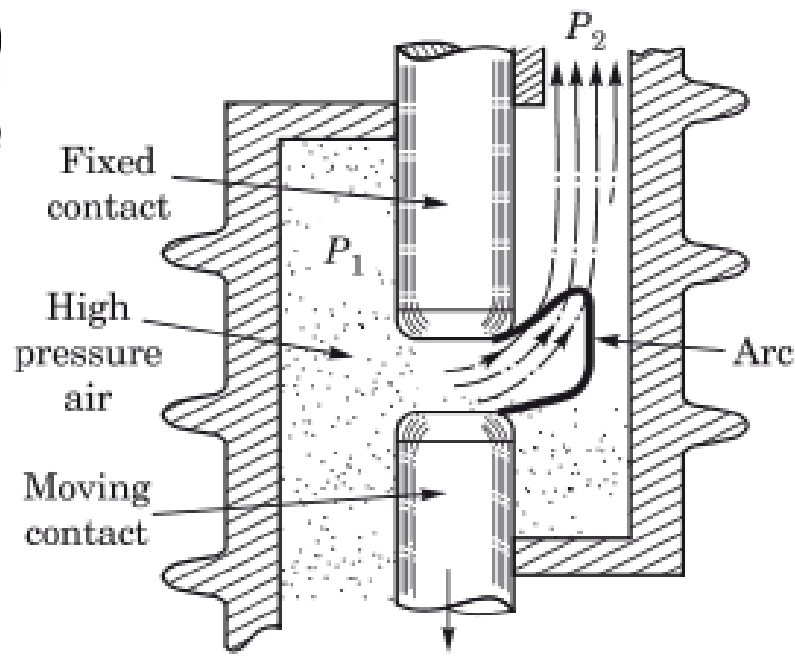


Fig. (a) Flow of air in Air-blast C.B.

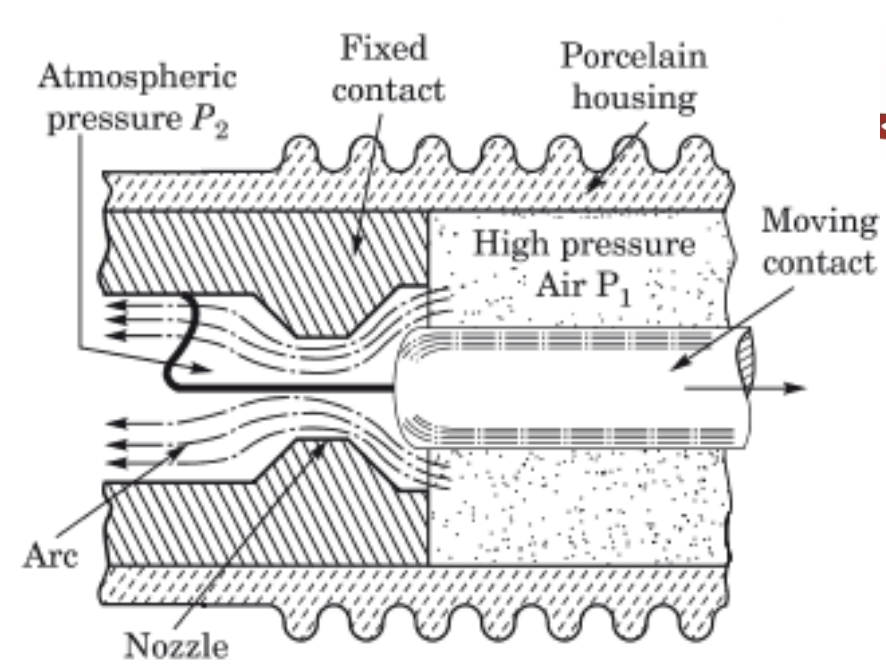


Fig. (b) Axial flow.

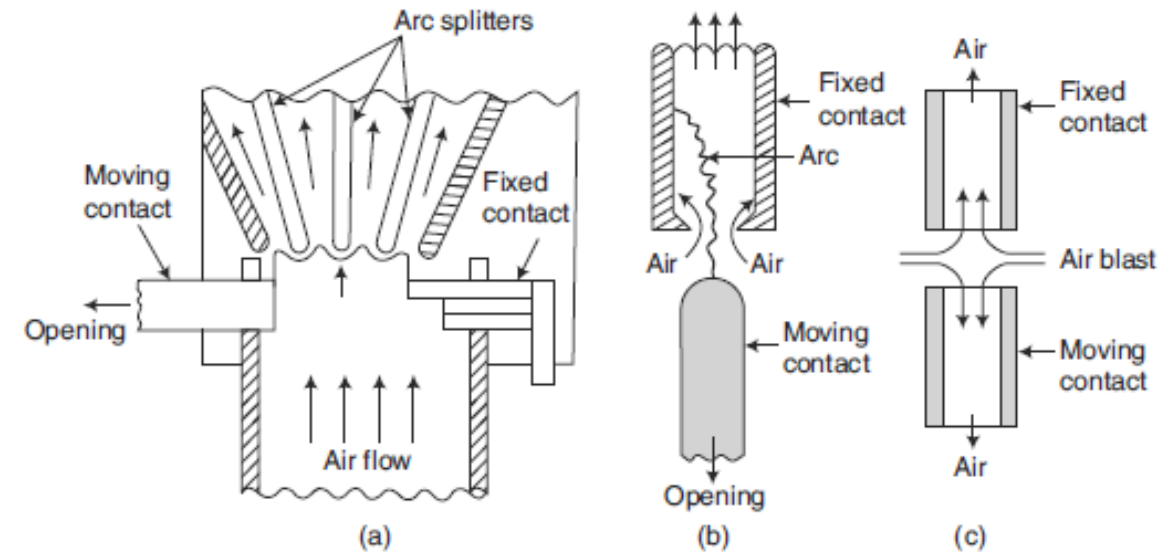
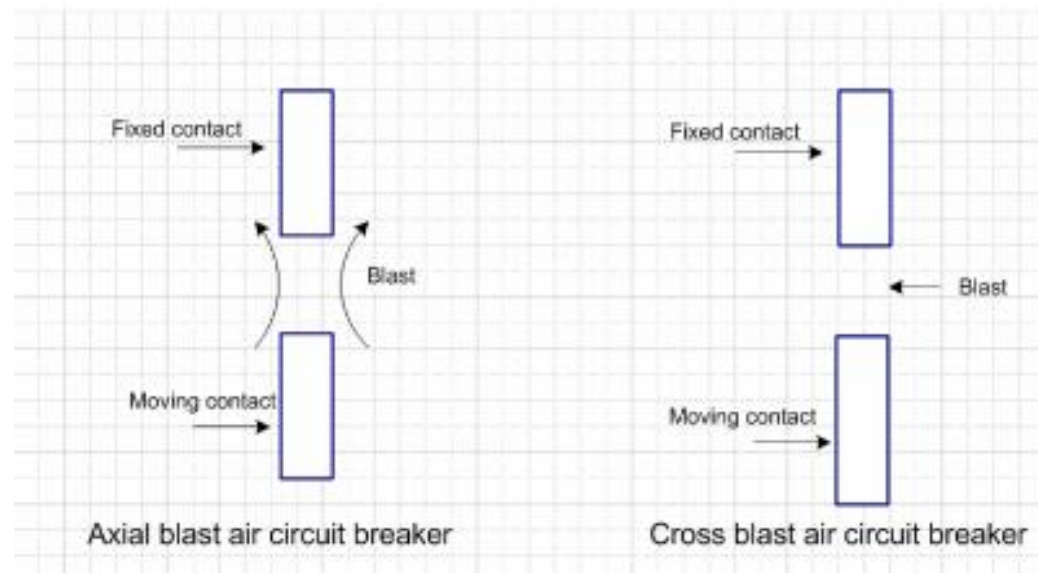


Fig. 14.21 (a) Cross-blast circuit breaker (b) Single blast type axial-blast circuit breaker (c) Double blast type (or radial-blast type) axial-blast circuit breaker

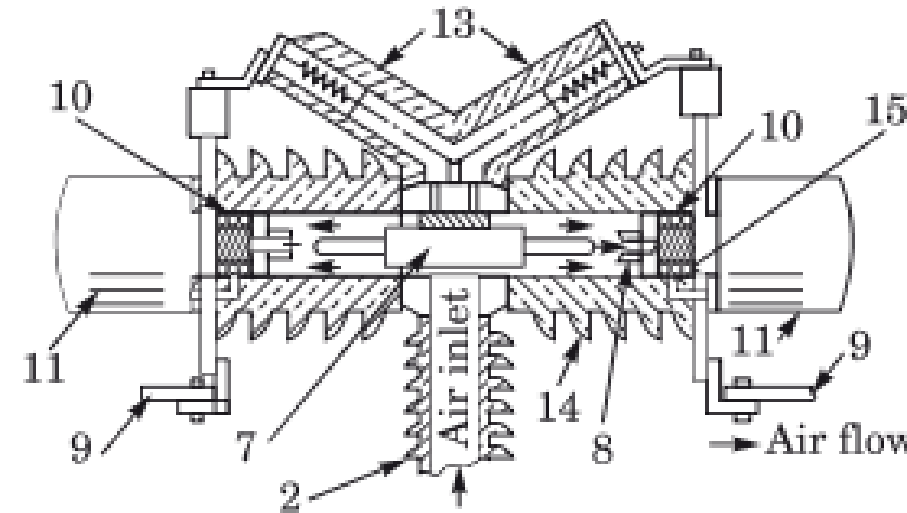
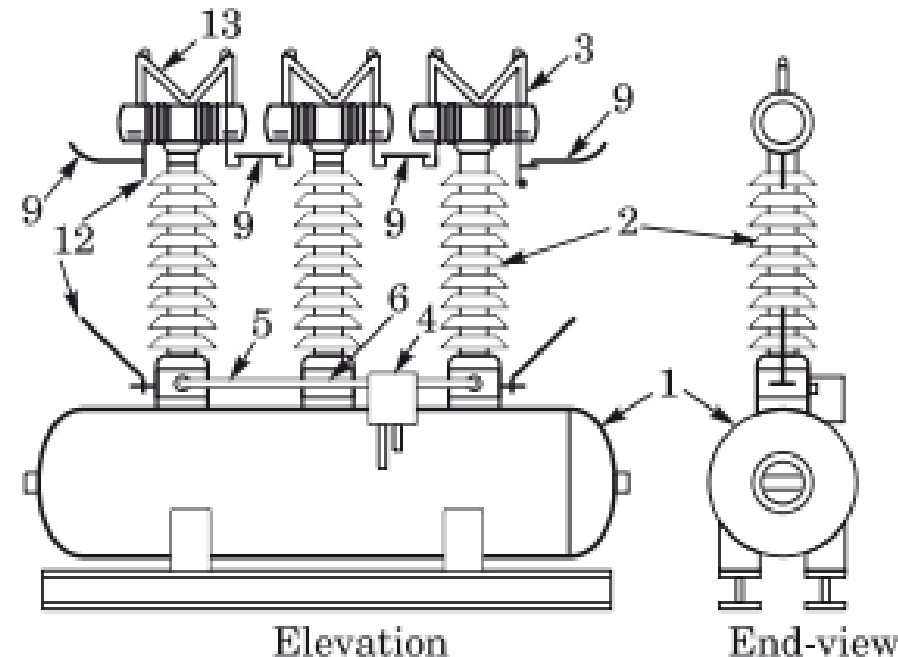


Fig. (b) Details of (3) Double arc extinction chamber.



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)



The axial blast type

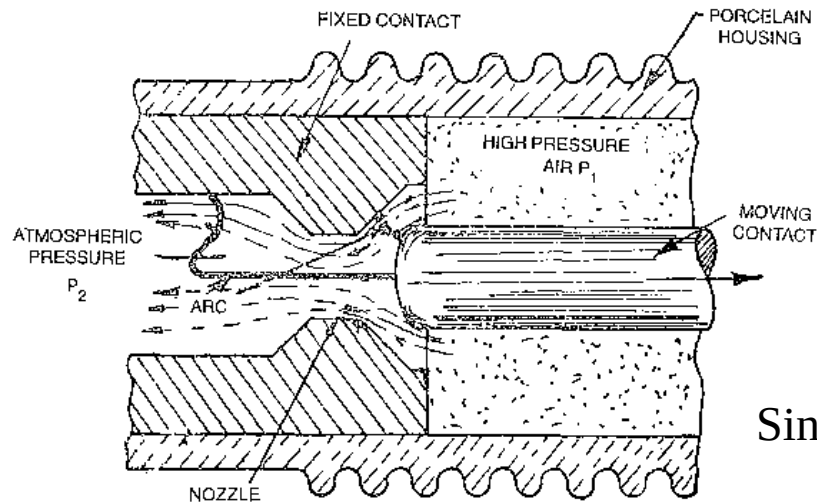
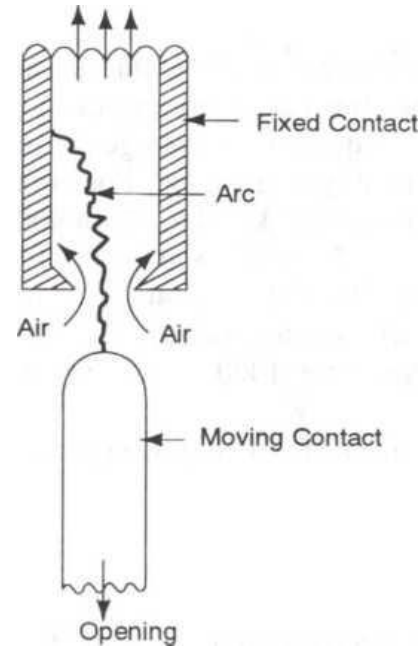


Fig. (a) Axial Flow.

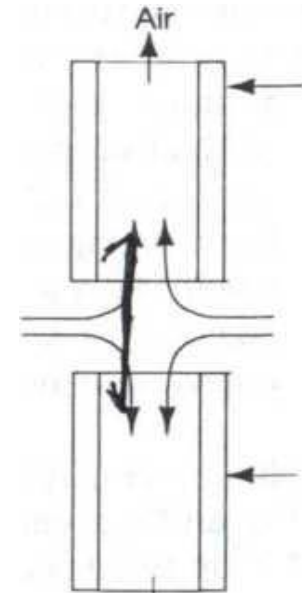
Axial blast type – In this type, the blasting of air is done directly along the path of arc, as shown in figure below.

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.

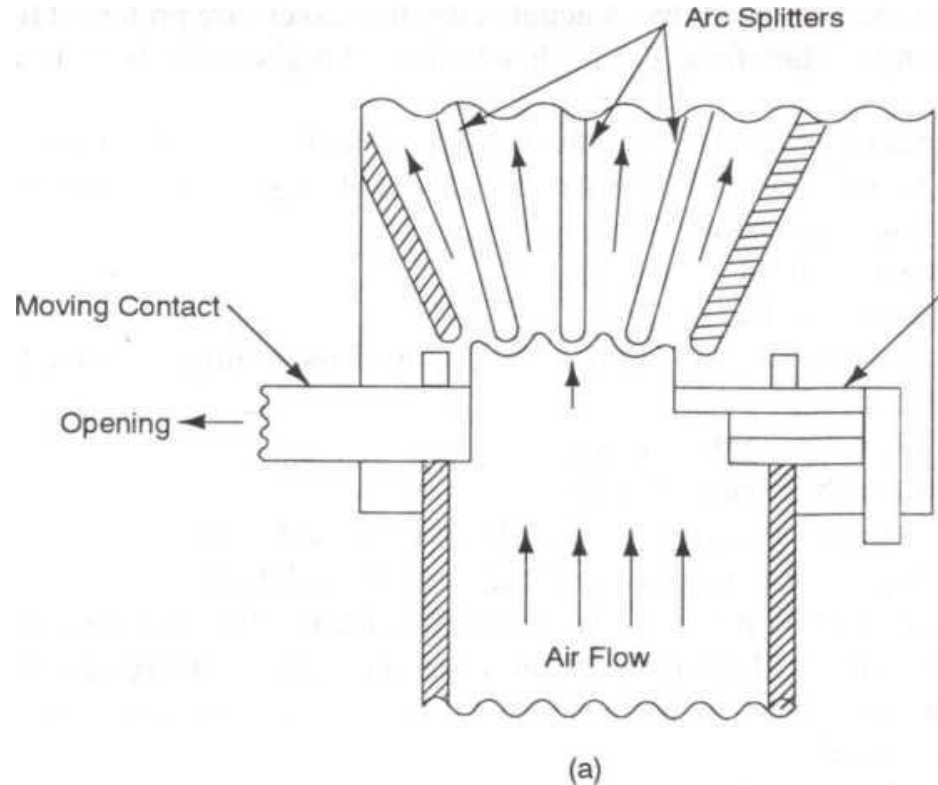
Single blast type axial-blast circuit breaker



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



Cross-blast circuit breaker



The advantages of air blast circuit breakers over oil circuit breakers are:

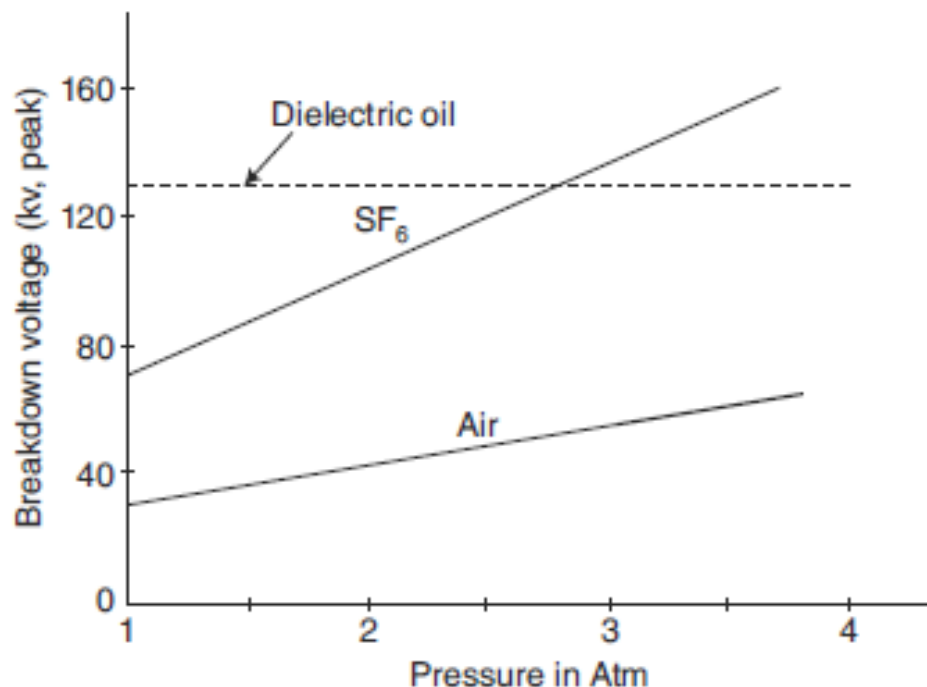
- Cheapness and free availability of the interrupting medium, chemical stability and inertness of air.
- High speed operation.
- Elimination of fire hazard.
- Short and consistent arcing time and therefore, less burning of contacts.
- Less maintenance.
- Suitability for frequent operation.
- Facility 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 SF₆ Insulated Switchgear (GIS)

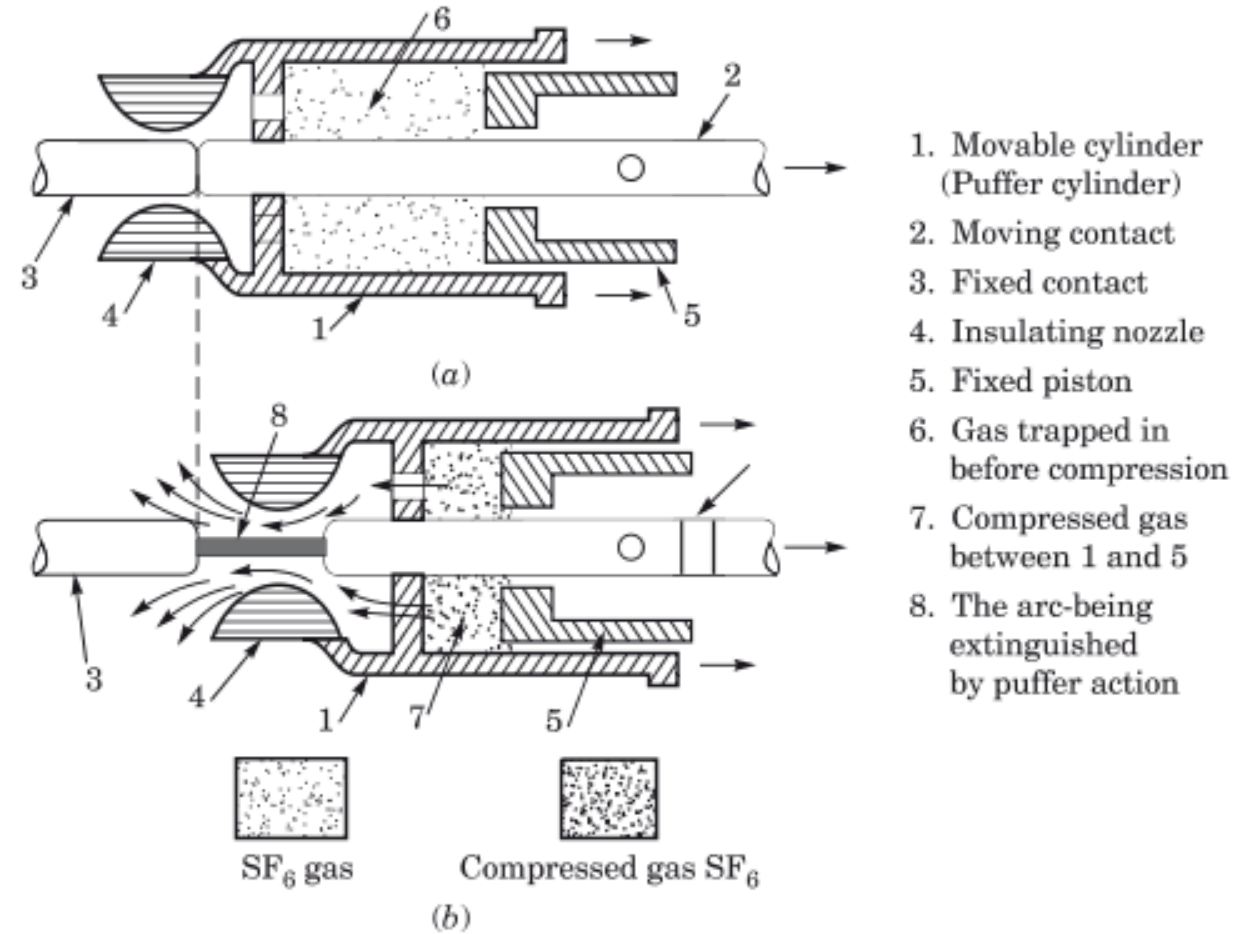
Rated voltage kV	36	72	145	245	400	500
Rated currents Amp.	1200 to 2000	1200 to 2000	2000 to 3000	2000 to 4000	2000 to 4000	2000 to 4000
Rated breaking current kA	32	32	32	50	50	50
Breaking capacity MVA	1800	3500	7500	10,000	35,000	50,000
Operating time cycles	3	3	3	2.3	2	2
Power frequency voltage withstand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

Breakdown voltages of SF₆, air and dielectric oil as a function of pressure

Puffer-type SF₆ circuit breakers

This type of circuit breakers are also sometimes called single-pressure or impulse type SF₆ circuit breakers.

In this type of breakers, SF₆ gas is compressed by a moving cylinder system 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 SF₆ 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.

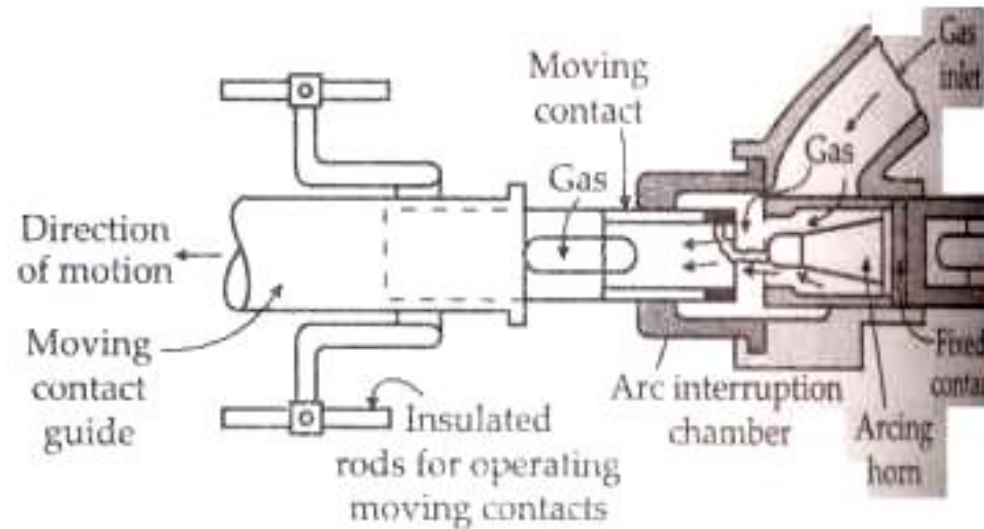


Fig. Constructional layout of SF₆ breaker.

MERITS OF SF₆ CIRCUIT-BREAKERS

- Outdoor SF₆ 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 SF₆ gas is small

MERITS OF SF₆ CIRCUIT-BREAKERS

- Ample overload margin. For the same size of conductors, the current carrying ability of SF₆ circuit-breakers is about 1.5 times that of air blast circuit-breakers because of superior heat transferability of SF₆ gas.
- The breaker is silent and does not make sound like air-blast-circuit breaker during operation.
- The sealed construction avoids the contamination by moisture, dust, sand etc. No costly compressed air system like Air Blast CB.
- The maintenance required is minimum, the breaker may need maintenance once in four to ten years!
- Ability to interrupt low and high fault currents, magnetising currents, capacitive current, without excessive over-voltages. The SF₆ gas circuit-breaker can perform the various duties like clearing short-line faults, opening unloaded transmission lines capacitor switching transformer, reactor switching etc. much smoothly.
- Excellent insulating arc extinguishing physical and chemical properties of SF₆ gas is the greater advantage of SF₆ breakers. No frequent contact replacement

SOME DEMERITS OF SF₆ CIRCUIT-BREAKER

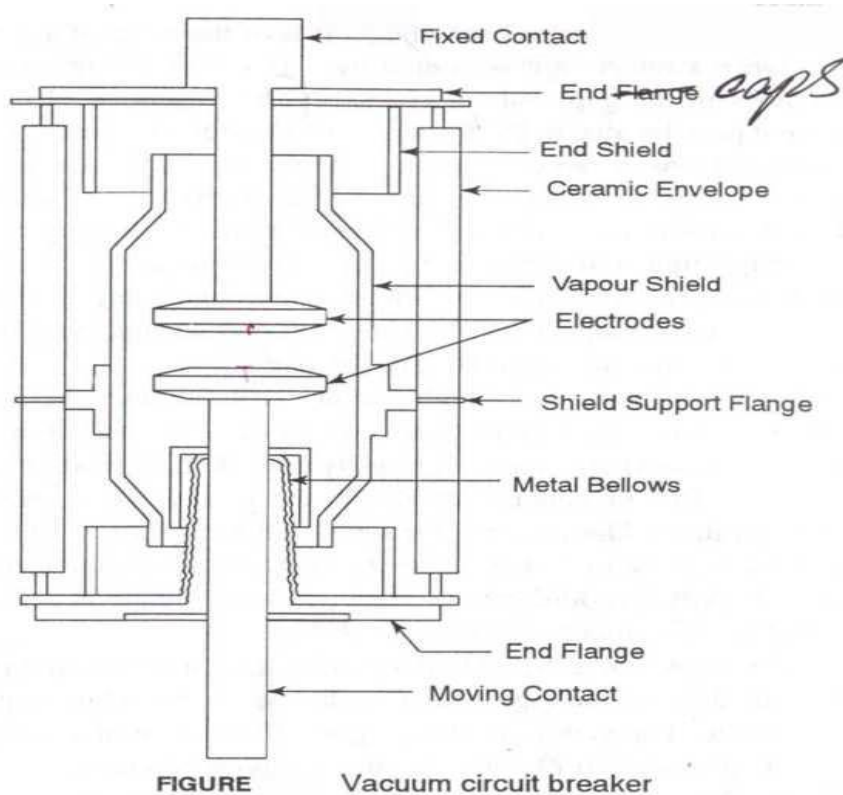
- Sealing problems arise. Imperfect joints lead to leakage of gas.
- In this case of leakage in the breaker tank, this gas, being heavier than air settles in the surroundings and may lead to suffocation of the operating personnel. However, it is non- poisonous
- Arced SF₆ gas is poisonous and should not be inhaled or let-out.
- Influx of moisture in the breaker is very harmful to SF₆ gas circuit-breakers. Several failures reported due to this cause.
- Mechanism of higher energy level is necessary for puffer type SF₆ 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 dielectric strength and arc interrupting ability of high vacuum is superior to those of porcelain, oil, air and SF₆ at atmospheric pressure. SF₆ at 7 atm. pressures and air at 25 atm. pressure have dielectric strengths higher than that of high vacuum. The pressure of 10⁻⁵ mm of mercury and below is considered to be high vacuum. Low pressures are generally measured in terms of torr; 1 torr being equal to 1 mm of mercury. It has now become possible to achieve pressures as low as 10⁻⁸ torr.

In high vacuum, of the order of 10⁻⁵ mm of mercury, the mean free path (Collision Path B/W Molecules) of the residual gas molecules becomes very large. It is of the order of a few metres. Therefore, when contacts are separated by a few mm in high vacuum, an electron travels in the gap without making collision

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.

SELECTION OF CIRCUIT BREAKERS

The choice of circuit breakers for various voltage ranges

Table 14.1 Types of circuit breakers		
<i>Type</i>	<i>Arc Quenching Medium</i>	<i>Voltage Range and Breaking Capacity</i>
Miniature circuit breakers	Air at atmospheric pressure	400-600V; for small current rating
Air-break circuit breaker	Air at atmospheric pressure	400 V-11 kV; 5-750 MVA
Minimum oil breakers	Transformer oil circuit	3.3 kV-220 kV; 150-25000 MVA
Vacuum circuit breakers	Vacuum	3.3 kV-33 kV; 250-2000 MVA
SF ₆ circuit breakers	SF ₆ at 5 kg/cm ² pressure	3.3-765 kV; 1000-50,000 MVA
Air blast circuit breakers	Compressed air at high pressure (20-30 kg/cm ²)	66 kV-1100 kV; 2500-60,000 MVA

Selection of circuit breakers

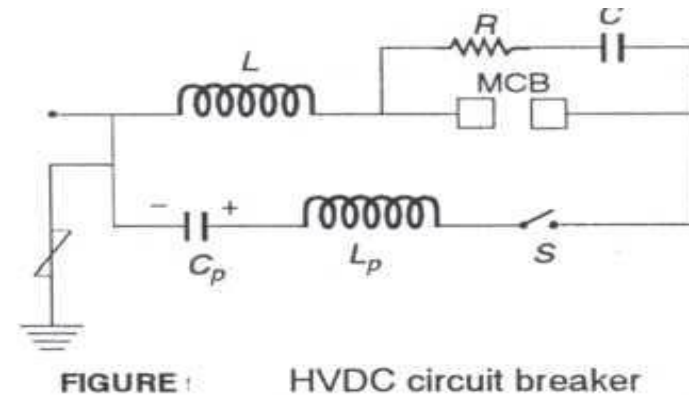
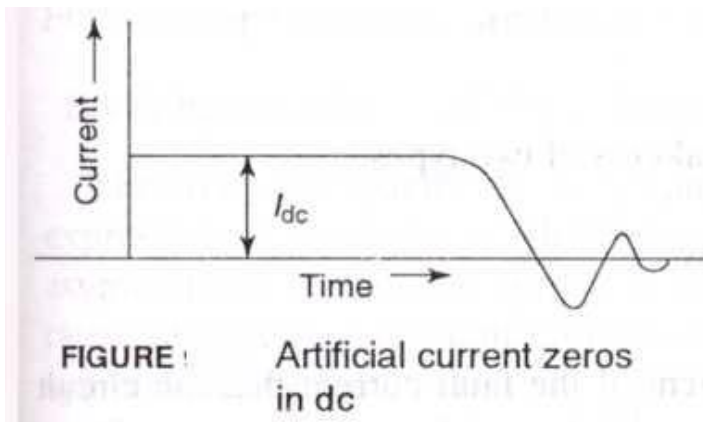
Table 14.2 Selection of circuit breakers		
Rated Voltage	Choice of circuit Breakers	Remark
Below 1 kV	Air-break CB	
3.3 kV-33 kV	Vacuum CB, SF ₆ CB, minimum oil CB	Vacuum preferred
132 kV-220 kV	SF ₆ CB, air blast CB, minimum oil CB	SF ₆ preferred
400 kV-760 kV	SF ₆ CB, air blast CB	SF ₆ is preferred

Earlier oil circuit breakers were preferred in the voltage range of 3.3 kV-66 kV. Between 132 kV and 220 kV, either oil circuit breakers or air blast circuit breakers were recommended. For voltages 400 kV and above, air blast circuit breakers were preferred. The present trend is to recommend vacuum or SF₆ circuit breakers in the voltage range 3.3 kV-33 kV. For 132 kV and above, SF₆ circuit breakers are preferred. Up to 1 kV, air break circuit breakers are used. Air blast circuit breakers are becoming obsolete and oil circuit breakers are being superseded by SF₆ and vacuum circuit breakers.

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



The main circuit breaker MCB may either be an SF6 or vacuum circuit breaker. R and C are connected in parallel with the main circuit breaker to reduce dv/dt after the final current zero. L is a saturable reactor in series with the main circuit breaker. It is used to reduce dI/dt before current zero. C_p and L_p are connected in parallel to produce artificial current zero after the separation of the contacts in the main circuit breaker MCB. A nonlinear resistor is used to suppress the transient overvoltage which may be produced across the contacts of the main circuit breaker.

Rating of Circuit Breaker

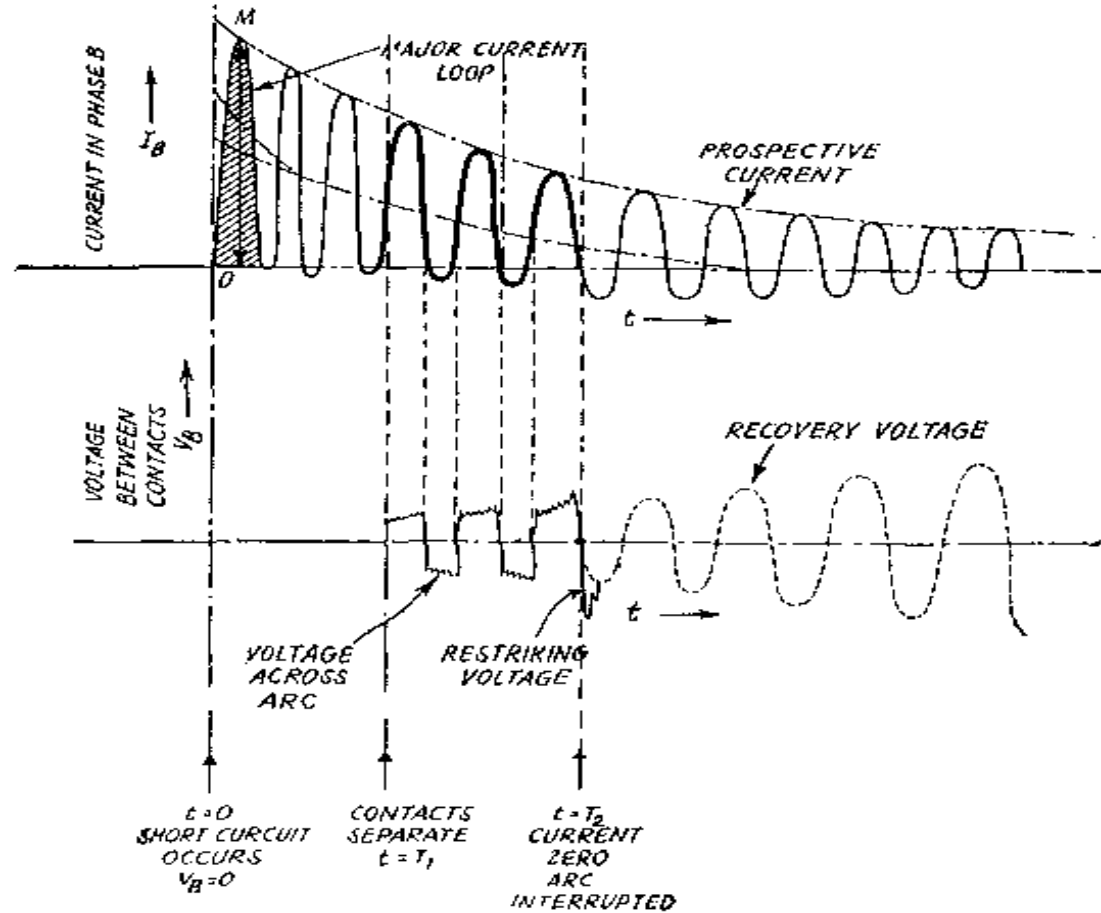


Fig. Oscillogram of current and voltage during fault-clearing.

Rated Short Circuit-Breaking Current

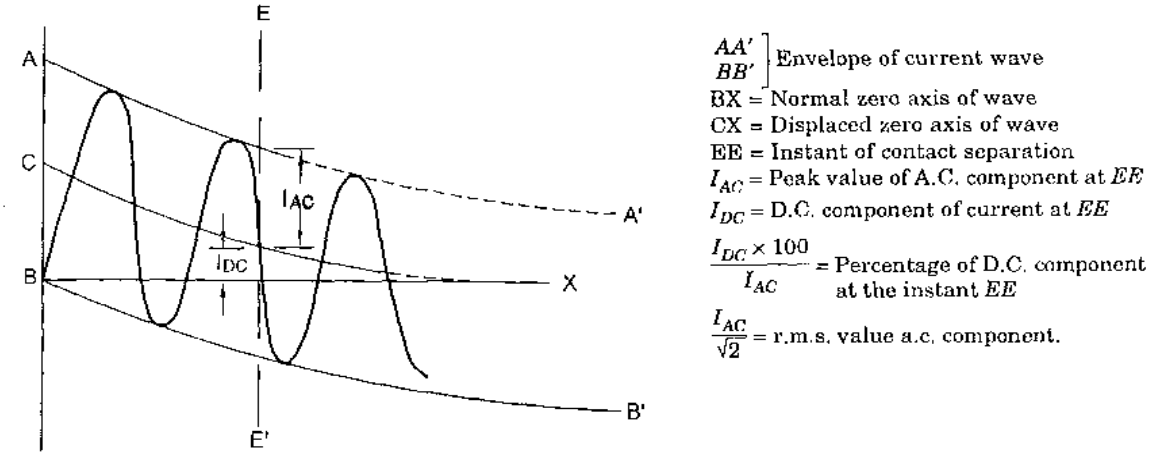


Fig. Determination of breaking current.

The breaking current is expressed by two values :

- (1) the r.m.s. value of a.c. component at the instant of contact separation EE , given by

$$\frac{I_{AC}}{\sqrt{2}}$$

- (2) the percentage d.c. component at the instant of contact separation given by

$$\frac{I_{DC} \times 100}{I_{AC}}$$

The r.m.s. values of a.c. components are expressed in kA, the standard values being 8, 10, 12.5, 16, 20, 25, 31.5, 40, 45, 63, 80 and 100 kA.

The earlier practice was to express the rated breaking capacity of a circuit breaker in terms of MVA given as follows:

$$MVA = \sqrt{3} \text{ kV} \times \text{kA}$$

where MVA = Breaking capacity of a circuit-breaker

kV = Rated voltage

kA = Rated breaking current.

Rated Short-circuit Making Current

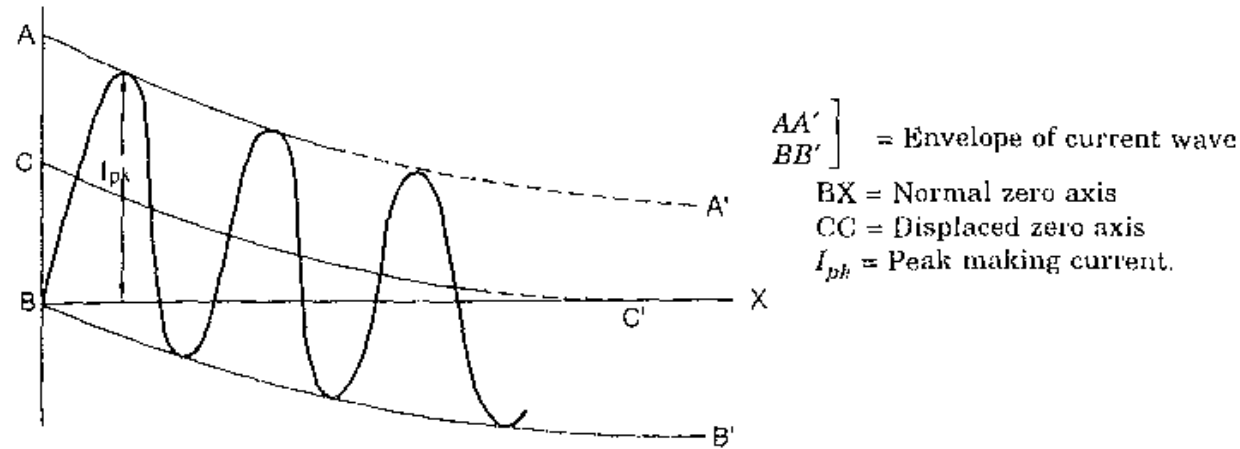


Fig. . Determination of peak making current.

current test. The rated short-circuit making current of a circuit-breaker is the peak value of first current loop of short-circuit current (I_{pk}) which the circuit-breaker is capable of making at its rated voltage

The rated short-circuit making current should be least 2.5 times the r.m.s. value of a.c. component of rated breaking current.

$$\begin{aligned} \text{Rated making current} &= 1.8 \times \sqrt{2} \times \text{Rated short-circuit breaking} \\ &= 2.5 \times \text{Rated short-circuit breaking current.} \end{aligned}$$

the factor $\sqrt{2}$ converts the r.m.s. value to peak value. Factor 1.8 takes into account the doubling effect of short-circuit-current during the first quarter cycle. with consideration to slight drop in current

If a CB closes on clearing the fault the current would increase to high value during 1st half cycle (first current loop). The highest peak value is reached during 1st current loop, this peak value is called **making current**

Short-time Current Rating

The circuit breaker must be capable of carrying short-circuit current for a short period while another circuit breaker (in series) is clearing the fault. The rated short-time current is the rms value (total current, both A.C. and D.C. components) of the current that the circuit breaker can carry safely for a specified short period

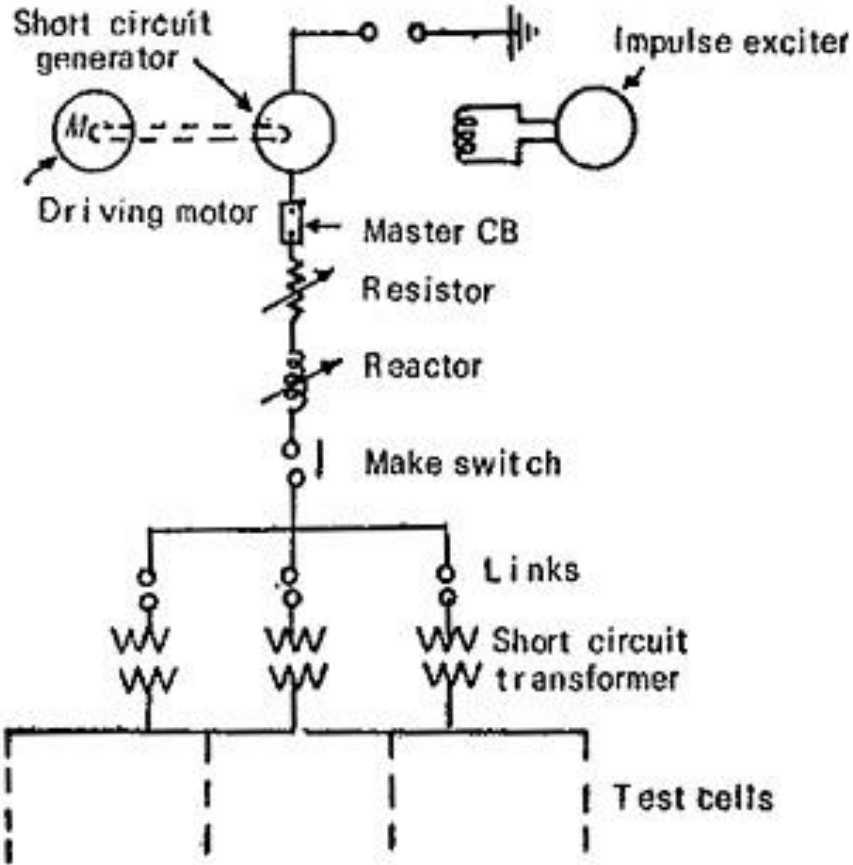
Rated Voltage, Current and Frequency

In a power system, the voltage level at all points is not the same. It varies, depending upon the system operating conditions. Due to this reason manufacturers have specified a rated maximum voltage at which the operation of the circuit breaker is guaranteed. The specified voltage is somewhat higher than the rated nominal voltage.

The rated current is the rms value of the current that a circuit breaker can carry continuously without any temperature rise in excess of its specified limit.

The rated frequency is also mentioned by the manufacturer. It is the frequency at which the circuit breaker has been designed to operate. The standard frequency is 50 Hz. If a circuit breaker is to be used at a frequency other than its rated frequency, its effects should be taken into consideration.

Short-circuit Testing Stations of circuit breaker



Short circuit test

During this test the rated short-time withstand current will be applied to the CB. The ratings of the circuit breaker can be checked by doing this test. This test is done in short circuit testing stations, such as field type testing stations and also the laboratory type testing stations.

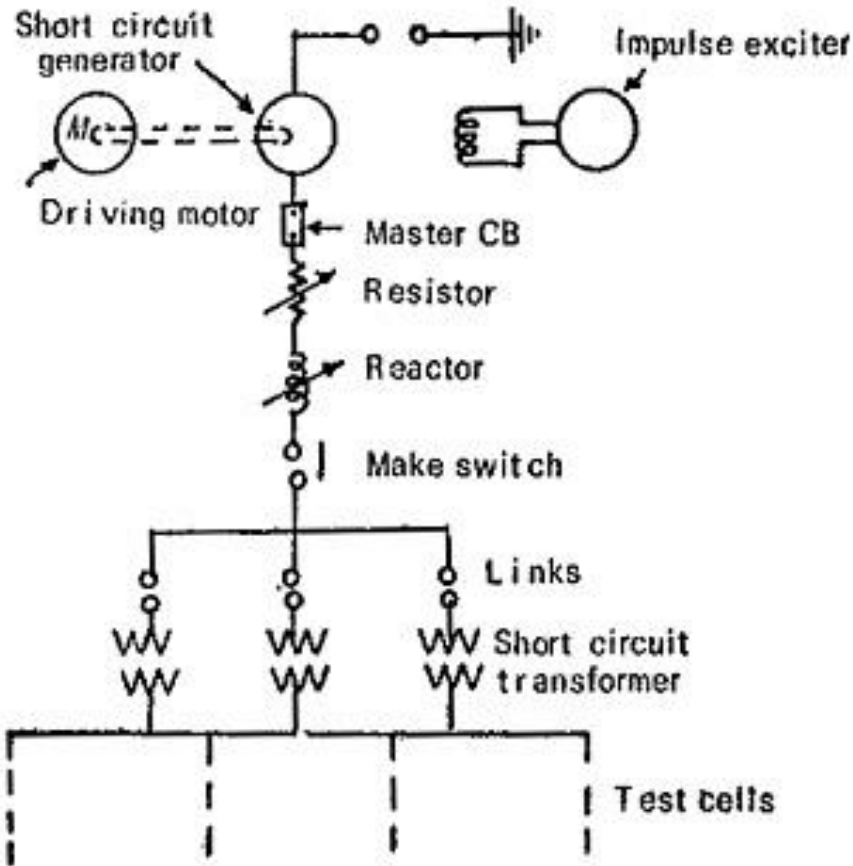
The short circuit test is classified into two types and they are direct testing and indirect testing.

In the direct testing method, the power supply system is used as the source

By doing this test we could determine the ability of the CB to safely interrupt the fault current, making and breaking capacity of the CB at different load currents.

FIGURE 18.1 Basic circuit of short-circuit test plant.

Short-circuit Testing Stations of circuit breaker



The magnitude of the test voltage and the short-circuit current can be selected within wide limits by adjusting generator excitation and connection of the transformers. Further limitation and variation of current independent of voltage can be effected by means of tapped resistors and reactors. This also serves to control the power factor.

The circuit is closed by a specially designed make switch, designed for closing on very heavy currents, but never called on to break currents. Synchronized closing is controlled by means of a small pilot generator coupled to the generator shaft and can be very accurately set to occur at any instant within the voltage wave.

FIGURE 18.1 Basic circuit of short-circuit test plant.

In this way the phase position at the commencement of short circuit can be selected and a short-circuit current either fully symmetrical or with any degree of symmetry can be produced. In order to avoid unnecessary destruction in the event of failure of circuit breaker under test, the master circuit breaker is provided as a backup protection and opens.

The testing station are of very compact design with short connection for short circuit so that the generator output may be utilized to full extent. They have very high natural frequency and by adding capacitors any desired frequency can be obtained. The breaker to be tested is enclosed in a test cell made of reinforced concrete having a provision of observation while test is in progress.

The recording equipment is located in a control room which is suitably remote from the test cell but situated so as to allow the test breaker to be observed. The control operations are carried out from the control room.

The important indirect Testing Methods include the following :

Unit Testing. Which means testing one or more units separately.

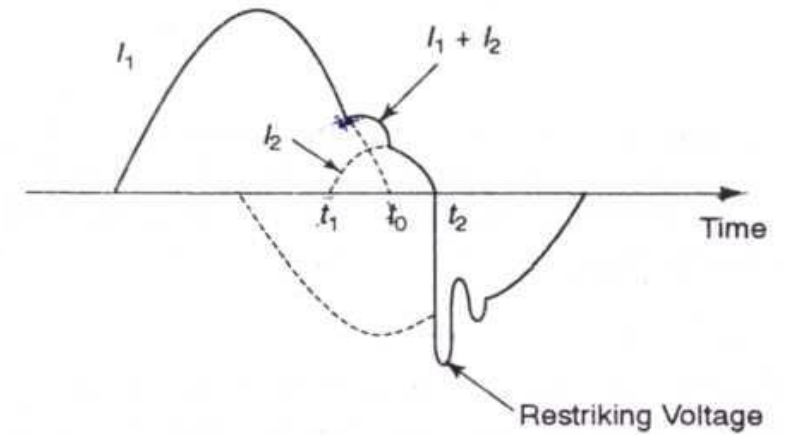
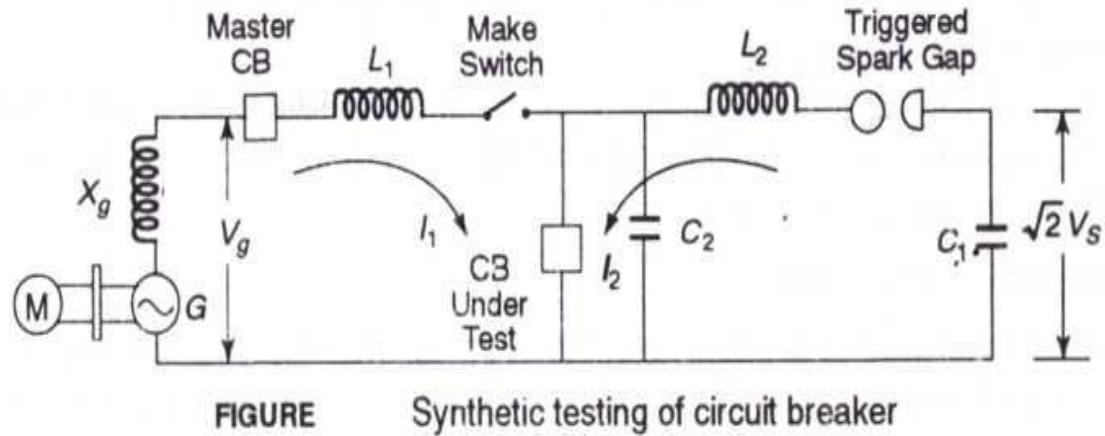
Synthetic Testing. In which the current source providing short circuit current and voltage source supplying restriking and recovery voltage are different.

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.



Capacitance test

In this test a capacitor is charged by a D.C. voltage source. Capacitor is connected in series with an inductor and making switch. The breaker is connected 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 behaviour 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

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 V_2 obtain the time required for various current upto i_2 and plot characteristic II
- Likewise, plot characteristics III at voltage V_3 upto current i_3 , characteristic IV at voltage V_4 upto current i_1 etc where V_1 is the highest test voltage $V_1 > V_3 > V_4$ etc. i_1 is the current at voltage V_1 permitted by test plant.

On plotting the characteristic I, II, III, etc, these are extended by approximation as shown by the dotted lines. From the extended line the breaker performance can be predicated for values of current beyond range of testing station

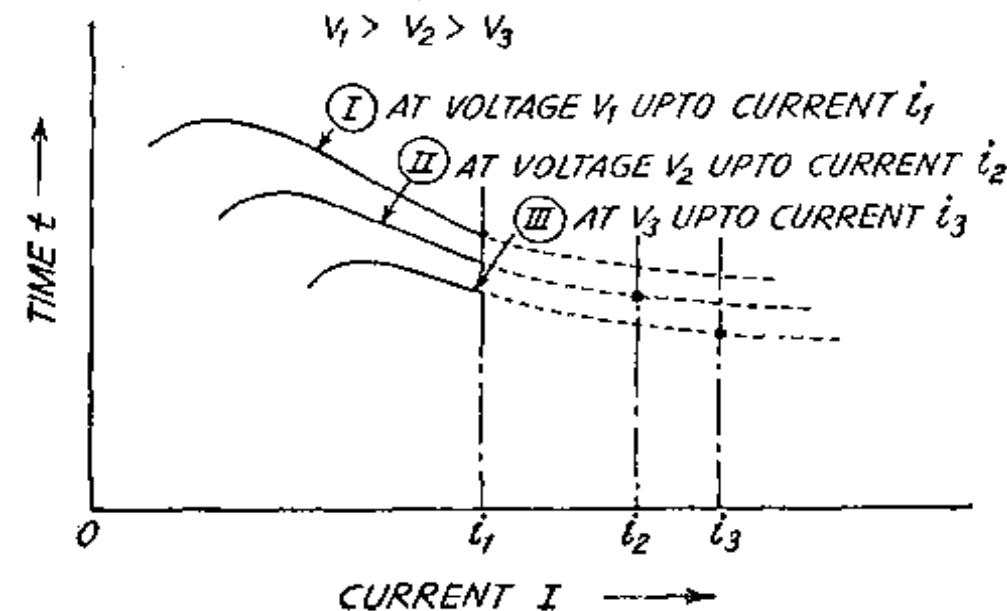
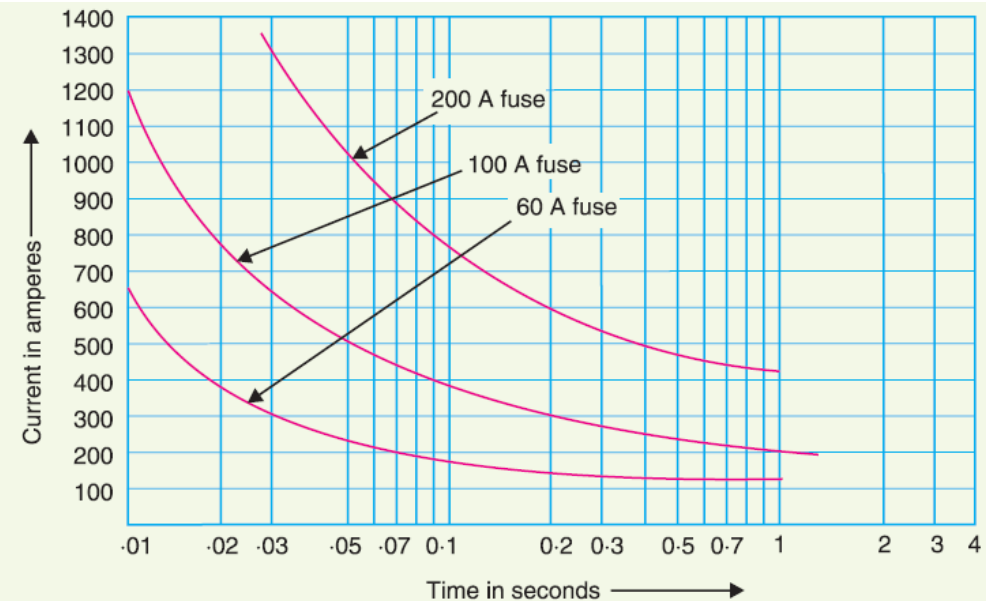
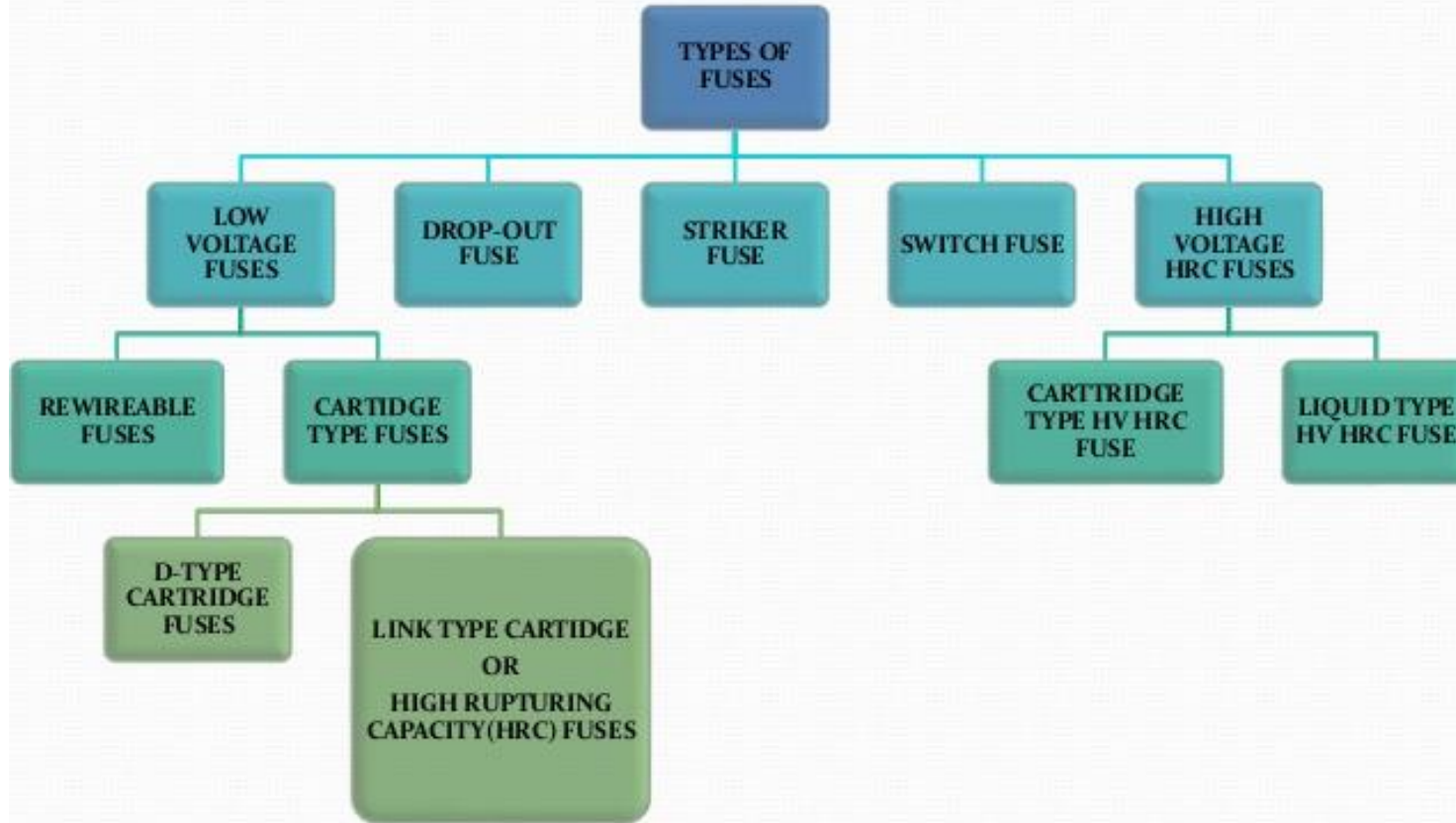


Fig. Substitution test characteristics.

TYPES OF FUSES



Advantages of Fuses

- (i) It is the cheapest form of protection available.
- (ii) It requires no maintenance.
- (iii) Its operation is inherently completely automatic unlike a circuit breaker which requires an elaborate equipment for automatic action.
- (iv) It can break heavy short-circuit currents without noise or smoke.
- (v) The smaller sizes of fuse element impose a current limiting effect under short-circuit conditions.
- (vi) The inverse time-current characteristic of a fuse makes it suitable for overcurrent protection.
- (vii) The minimum time of operation can be made much shorter than with the circuit breakers.

Advantages of Fuses

1. Operating time of the fuse is much smaller than that of the circuit breaker, for interrupting very large currents. The fuse operates in less than 5 milliseconds while interrupting large currents. Serious overheating and electromagnetic or electrodynamic forces in the system can thus be avoided.
2. The fuse does the function, viz detection and interruption of current unlike a circuit breaker which can only interrupt the fault current and requires elaborate equipment for detection of fault current(i.e., relays, current transformer, etc.). The low-voltage air circuit breakers and moulded-case circuit breakers are, however, fitted with thermal and electromagnetic releases.
3. The sealed cartridge fuses are silent in operation and do not emit flame.
4. Fuse is the cheapest form of protection.
5. Fuse requires no maintenance

Disadvantages of Fuses

- (i) Considerable time is lost in rewiring or replacing a fuse after operation.
- (ii) On heavy short-circuits, *discrimination between fuses in series cannot be obtained unless there is sufficient difference in the sizes of the fuses concerned.
- (iii) The current-time characteristic of a fuse cannot always be co-related with that of the protected apparatus.
- (iv) Poor Protection against small over current

Discrimination between two fuses is said to occur if on the occurrence of a short-circuit or overcurrent fault, only the desired fuse operates

Disadvantages of Fuses

It takes longer time to replace a fuse than to reclose a circuit breaker. This drawback is often exaggerated, especially with modern cartridge fuses, some of which can be replaced quite quickly. It may, in practice, take longer to trace a blown fuse, if it is not fitted with an indicating device, than to replace it. Usually far more time is consumed in checking the faulty circuit; hence this disadvantage of more time in replacement loses its significance.

The fuse gives comparatively poor protection against small overcurrents. A circuit breaker can be set to trip on as little as 5% overcurrent while the semi-enclosed fuse has a fusing factor (ratio of minimum fusing current to the rated current) of about 1.75.

A modern cartridge fuse can, however, be obtained with fusing factor as low as 1.25. The values lower than 1.25 are not recommended if unwanted blowing of fuse-element due to momentary system abnormalities is to be avoided.

Desirable Characteristics of Fuse Element

The function of a fuse is to carry the normal current without overheating but when the current exceeds its normal value, it rapidly heats up to melting point and disconnects the circuit protected by it. In order that it may perform this function satisfactorily, the fuse element should have the following desirable characteristics :

- (i) low melting point *e.g.*, tin, lead.
- (ii) high conductivity *e.g.*, silver, copper.
- (iii) free from deterioration due to oxidation *e.g.*, silver.
- (iv) low cost *e.g.*, lead, tin, copper.

The above discussion reveals that no material possesses all the characteristics. For instance, lead has low melting point but it has high specific resistance and is liable to oxidation. Similarly, copper has high conductivity and low cost but oxidises rapidly. Therefore, a compromise is made in the selection of material for a fuse.

Fuse Element Materials

The most commonly used materials for fuse element are lead, tin, copper, zinc and silver. For small currents upto 10 A, tin or an alloy of lead and tin (lead 37%, tin 63%) is used for making the fuse element. For larger currents, copper or silver is employed. It is a usual practice to tin the copper to protect it from oxidation. Zinc (in strip form only) is good if a fuse with considerable time-lag is required *i.e.*, one which does not melt very quickly with a small overload.

The present trend is to use silver despite its high cost due to the following reasons :

- (i) It is comparatively free from oxidation.
- (ii) It does not deteriorate when used in dry air.
- (iii) The coefficient of expansion of silver is so small that no critical fatigue occurs.
Therefore, the fuse element can carry the rated current continuously for a long time.
- (iv) The conductivity of silver is very high. Therefore, for a given rating of fuse element, the mass of silver metal required is smaller than that of other materials. This minimises the problem of clearing the mass of vapourised material set free on fusion and thus permits fast operating speed.

- (v) Due to comparatively low specific heat, silver fusible elements can be raised from normal temperature to vapourisation quicker than other fusible elements. Moreover, the resistance of silver increases abruptly as the melting temperature is reached, thus making the transition from melting to vapourisation almost instantaneous. Consequently, operation becomes very much faster at higher currents.
- (vi) Silver vapourises at a temperature much lower than the one at which its vapour will readily ionise. Therefore, when an arc is formed through the vapourised portion of the element, the arc path has high resistance. As a result, short-circuit current is quickly interrupted.

Important Terms

- (i) **Current rating of fuse element.** It is the current which the fuse element can normally carry without overheating or melting. It depends upon the temperature rise of the contacts of the fuse holder, fuse material and the surroundings of the fuse.
- (ii) **Fusing current.** It is the minimum current at which the fuse element melts and thus disconnects the circuit protected by it. Obviously, its value will be more than the current rating of the fuse element

For a round wire, the approximate relationship between fusing current I and diameter d of the wire is

$$I = k d^{3/2}$$

where k is a constant, called the **fuse constant**. Its value depends upon the metal of which the fuse element is made.

The value of k for different materials as given in the table below :

S. No.	Material	Value of k	
		d in cm	d in mm
1	Copper	2530	80
2	Aluminium	1873	59
3	Tin	405.5	12.8
4	Lead	340.6	10.8

The fusing current depends upon the various factors such as :

- (a) material of fuse element
- (b) length – the smaller the length, the greater the current because a short fuse can easily conduct away all the heat
- (c) diameter
- (d) size and location of terminals
- (e) type of enclosure used

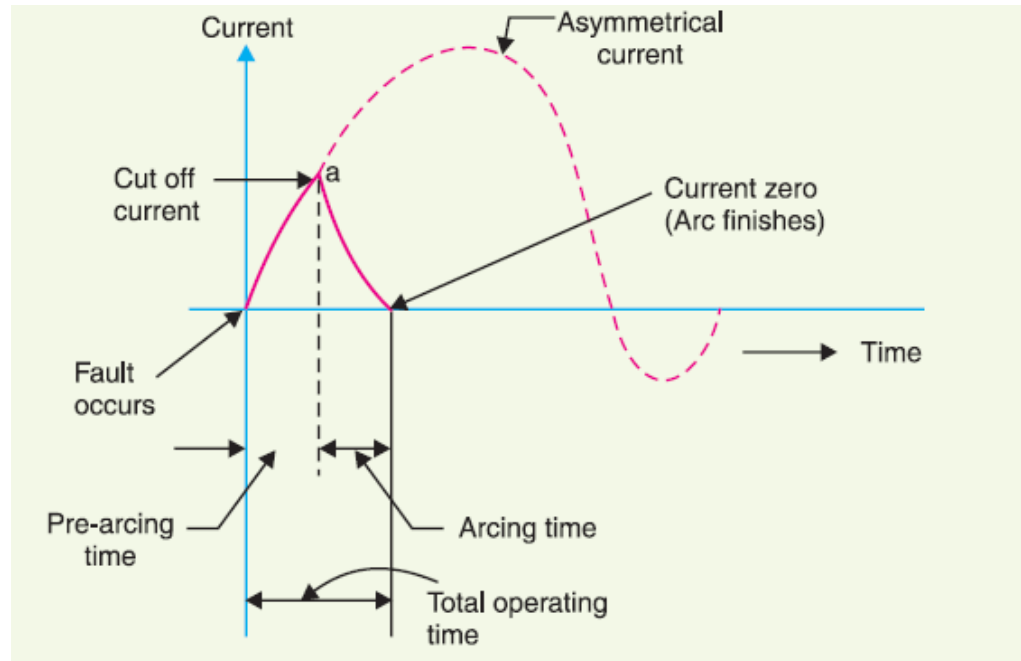
(iii) Fusing factor. It is the ratio of minimum fusing current to the current rating of the fuse element *i.e.*

Fusing factor = Minimum fusing current/Current rating of fuse

Its value is always more than one. The smaller the fusing factor, the greater is the difficulty in avoiding deterioration due to overheating and oxidation at rated carrying current

On the occurrence of a fault, the fault current has a very large first loop due to a fair degree of asymmetry. The heat generated is sufficient to melt the fuse element well before the peak of first loop is reached (point 'a' in Fig.). The current corresponding to point 'a' is the cut off current. The cut off value depends upon :

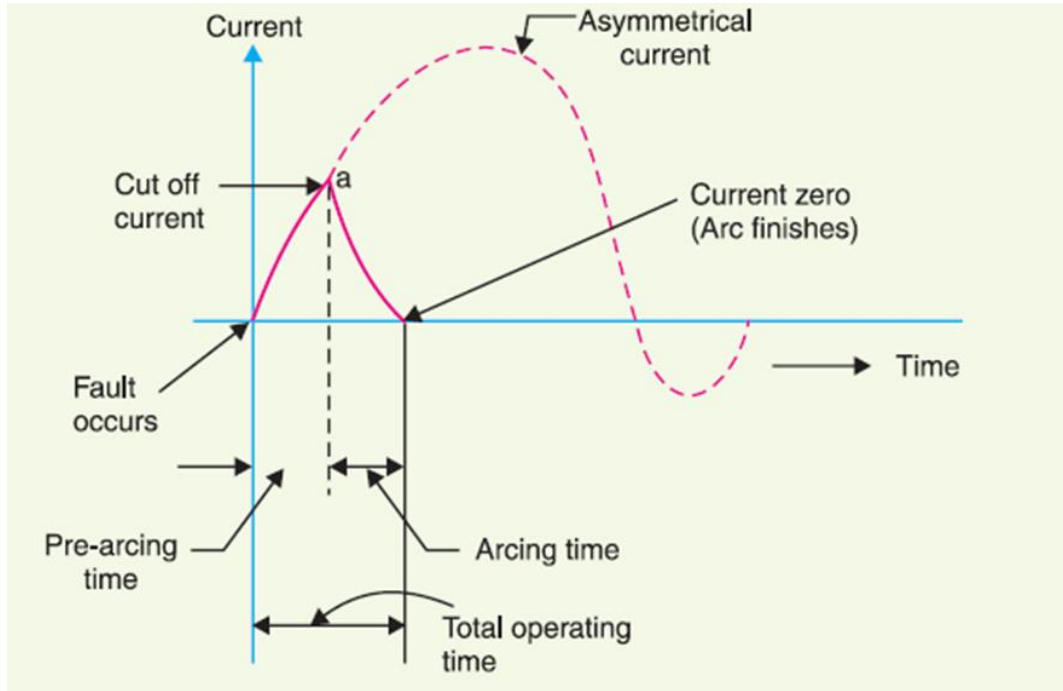
- (a) current rating of fuse
- (b) value of prospective current
- (c) asymmetry of short-circuit current



Prospective Current. Fig. shows how a.c. current is cut off by a fuse. The fault current would normally have a very large first loop, but it actually generates sufficient energy to melt the fuseable element well before the peak of this first loop is reached. The *r.m.s.* value of the first loop of fault current is known as prospective current. Therefore, prospective current can be defined as under:

It is the r.m.s. value of the first loop of the fault current obtained if the fuse is replaced by an ordinary conductor of negligible resistance.

(v) Cut-off current. It is the maximum value of fault current actually reached before the fuse melts.



(vi) Pre-arcing time. It is the time between the commencement of fault and the instant when cut off occurs. When a fault occurs, the fault current rises rapidly and generates heat in the fuse element. As the fault current reaches the cut off value, the fuse element melts and an arc is initiated. The time from the start of the fault to the instant the arc is initiated is known as pre-arcing time. The pre-arcing time is generally small : a typical value being 0.001second

(vii) Arcing time. This is the time between the end of pre-arcing time and the instant when the arc is extinguished.

(viii) Total operating time. It is the sum of pre-arcing and arcing times.

It may be noted that operating time of a fuse is generally quite low (say 0.002 sec.) as compared to a circuit breaker (say 0.2 sec or so). This is an added advantage of a fuse over a circuit breaker. A fuse in series with a circuit breaker of low-breaking capacity is a useful and economical arrangement to provide adequate short-circuit protection. It is because the fuse will blow under fault conditions before the circuit breaker has the time to operate.

Types of Fuses

Fuse is the simplest current interrupting device for protection against excessive currents. Since the invention of first fuse by Edison, several improvements have been made and now-a-days, a variety of fuses are available. Some fuses also incorporate means for extinguishing the arc that appears when the fuse element melts. In general, fuses may be classified into :

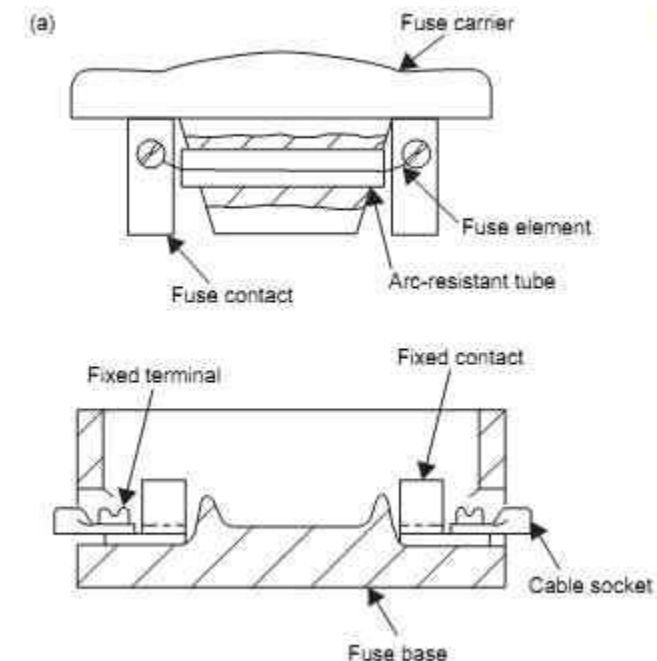
- (i) Low voltages fuses
- (ii) High voltage fuses

Low Voltage Fuses

Low voltage fuses can be subdivided into two classes viz.,

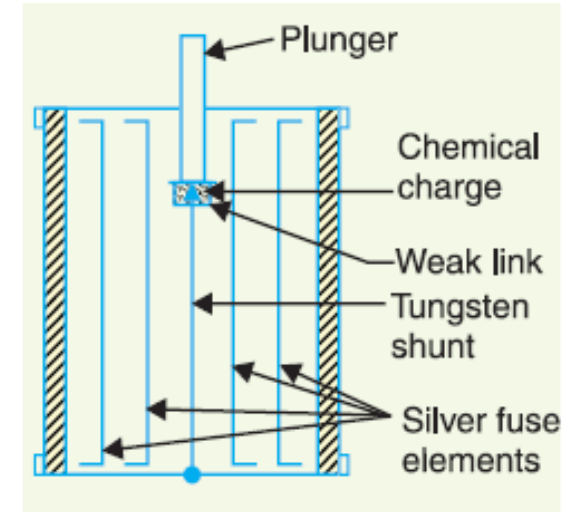
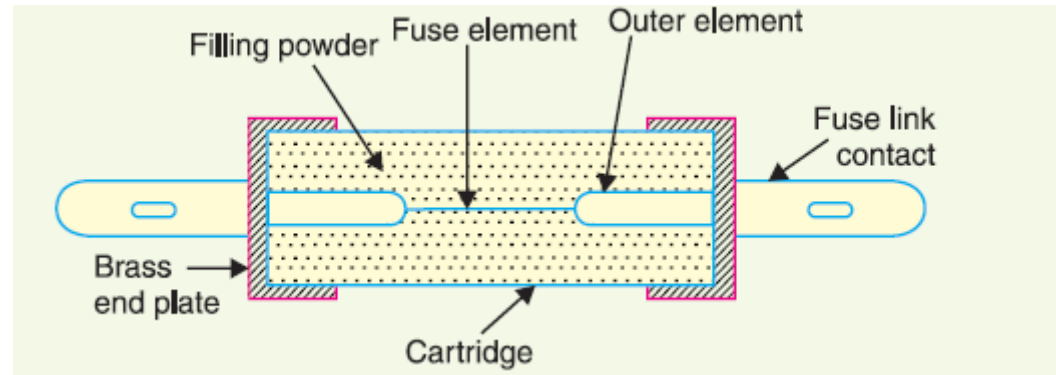
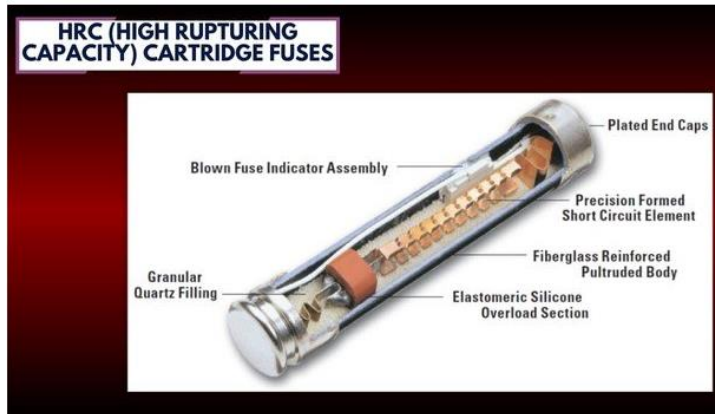
- (i) Semi-enclosed rewirable fuse
- (ii) High rupturing capacity (H.R.C.) cartridge fuse.

Semi-enclosed rewirable fuses are made upto 500 A rated current, but their breaking capacity is low *e.g.*, on 400 V service, the breaking capacity is about 4000 A. Therefore, the use of this type of fuses is limited to domestic and lighting loads.



High-Rupturing capacity (H.R.C.) cartridge fuse.

Low voltage H.R.C. fuses may be built with a breaking capacity of 16,000 A to 30,000 A at 440V. They are extensively used on low-voltage distribution system against over-load and short circuit conditions



H.R.C. fuse with tripping device

Advantages

- (i) They are capable of clearing high as well as low fault currents.
- (ii) They do not deteriorate with age.
- (iii) They have high speed of operation.
- (iv) They provide reliable discrimination.
- (v) They require no maintenance.
- (vi) They are cheaper than other circuit interrupting devices of equal breaking capacity.
- (vii) They permit consistent performance.

Disadvantages

- (i) They have to be replaced after each operation.
- (ii) Heat produced by the arc may affect the associated switches.



High Voltage Fuses

Cartridge type.

High voltage cartridge fuses are used upto 33 kV with breaking capacity of about 8700 A at that voltage. Rating of the order of 200 A at 6.6kV and 11 kV and 50 A at 33 kV are also available.

RT16 Series filled and enclosed cartridge knifecontactor fuse-link



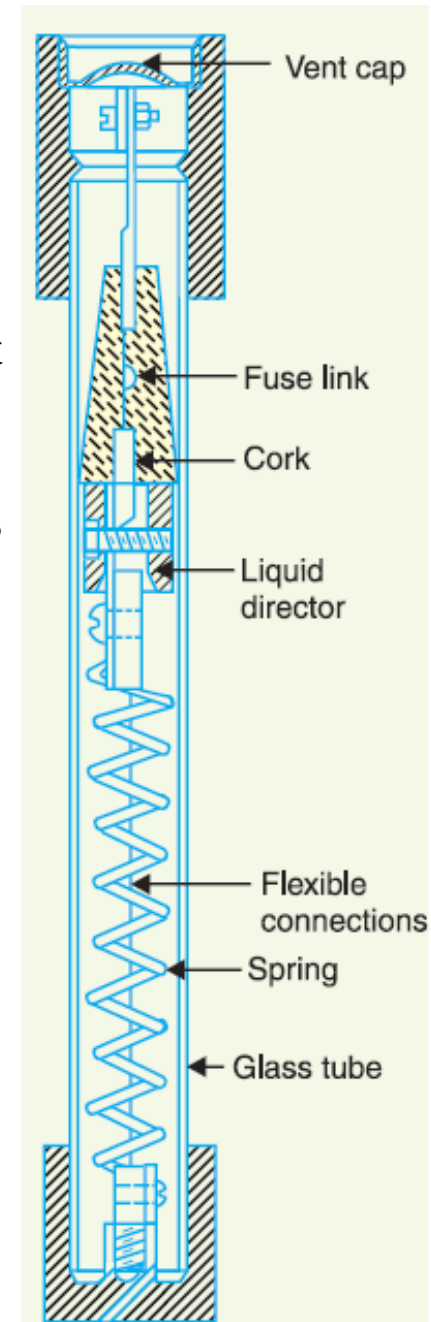
RT12 / RT15 Connecting Bolt Type Fuse-Link



Liquid type

These fuses are filled with carbon tetrachloride and have the widest range of application to H.V. systems.

They may be used for circuits upto about 100 A rated current on systems upto 132 kV and may have breaking capacities of the order of 6100 A.



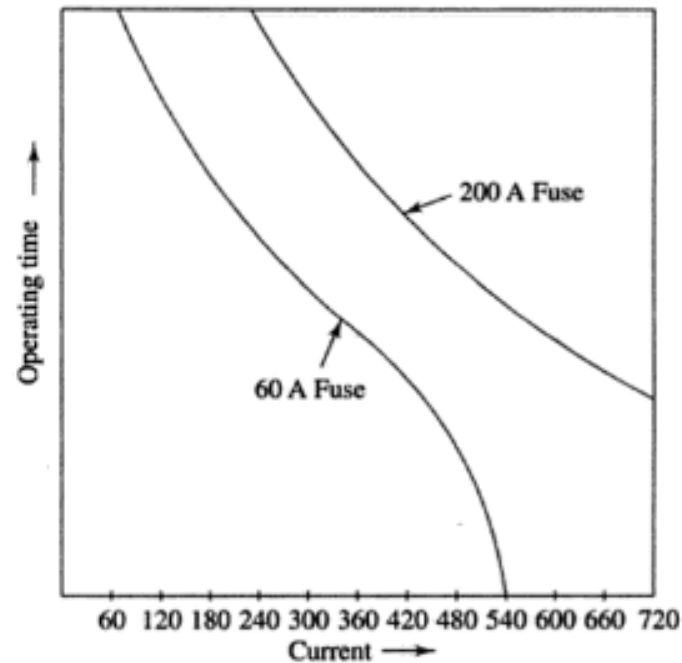
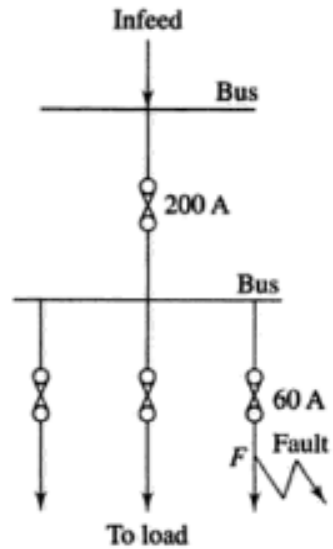
Difference Between a Fuse and Circuit Breaker

It is worthwhile to indicate the salient differences between a fuse and a circuit breaker in the tabular form.

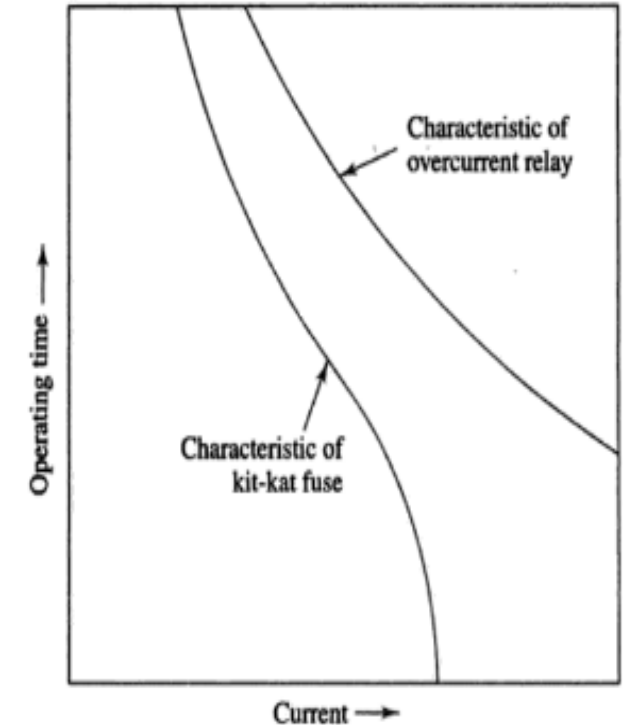
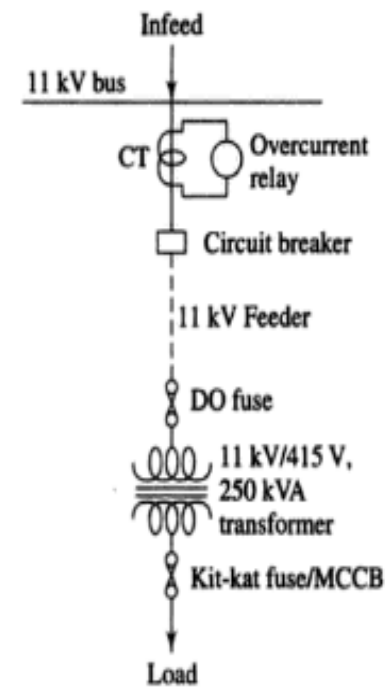
S. No.	Particular	Fuse	Circuit breaker
1.	<i>Function</i>	It performs both detection and interruption functions.	It performs interruption function only. The detection of fault is made by relay system.
2.	<i>Operation</i>	Inherently completely automatic.	Requires elaborate equipment (<i>i.e.</i> relays) for automatic action.
3.	<i>Breaking capacity</i>	Small	Very large
4.	<i>Operating time</i>	Very small (0.002 sec or so)	Comparatively large (0.1 to 0.2 sec)
5.	<i>Replacement</i>	Requires replacement after every operation.	No replacement after operation.

Discrimination:- Discrimination between two fuses is said to occur if on the occurrence of a short-circuit or overcurrent fault, only the desired fuse operates

Discrimination between Two Fuses



Discrimination between a fuse and over current relay



Protection of Overhead Transmission Lines from Direct Lightning Strokes by Ground Wires

The two methods of protecting overhead transmission lines against lightning strokes are:

(i) Overhead ground wires and (ii) Expulsion protector tubes.

(i) Protection of Overhead Transmission Lines from Direct Lightning Strokes by Ground Wires:

A ground wire is a form of lightning protection employing a conductor or conductors, well-grounded at regular intervals, preferably at each support (pole or tower), and attached from support to support above the transmission line conductors.

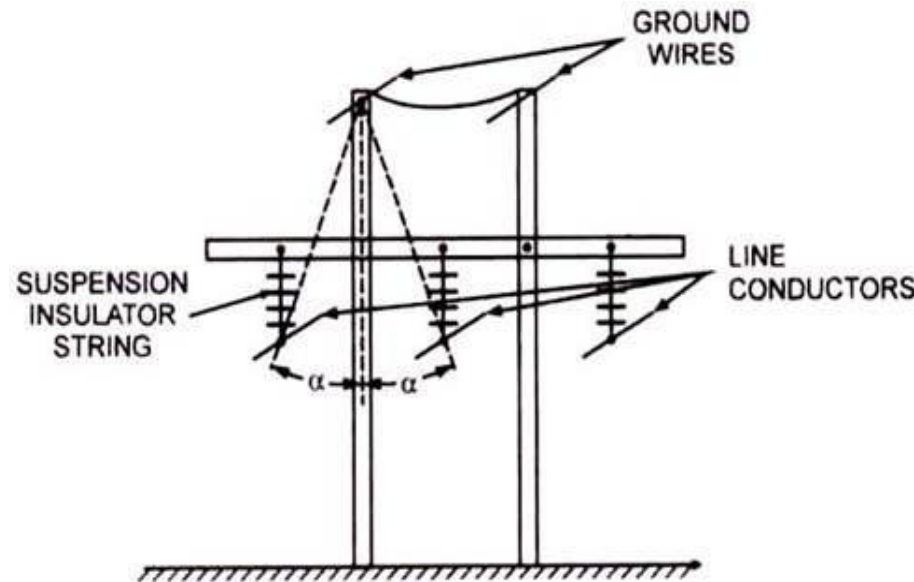


Fig. Arrangement of Ground Wires on a Transmission Line For Direct Stroke Lightning Protection

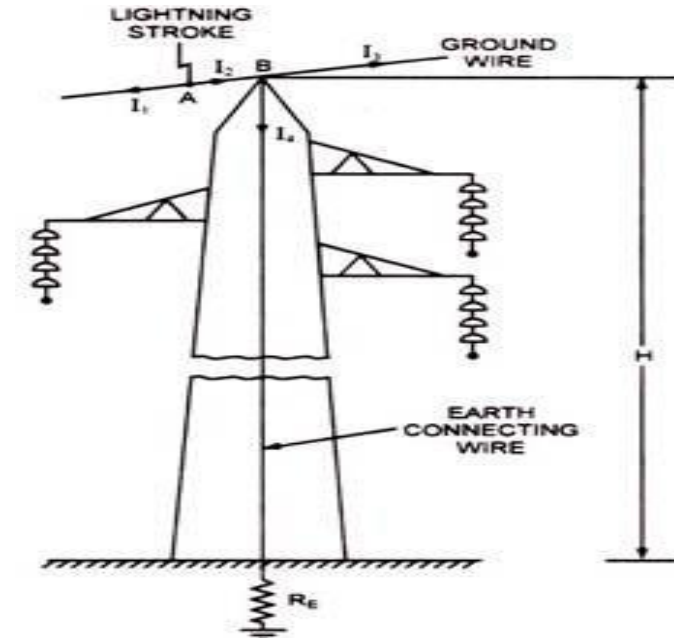


Fig. 9.12. Arrangement of Conductors and Earth Representing Lightning Current

(ii) Expulsion protector tubes.

Protection of Overhead Transmission Lines from Direct Lightning Strokes by Protector Tube:

Even after reduction in the induced voltage by using a ground wire, there still exist over-voltages in the system which must be removed by using additional protective devices such as lightning arrester that bypasses the surges to the ground. Another device that is quite common in use is the protector tube

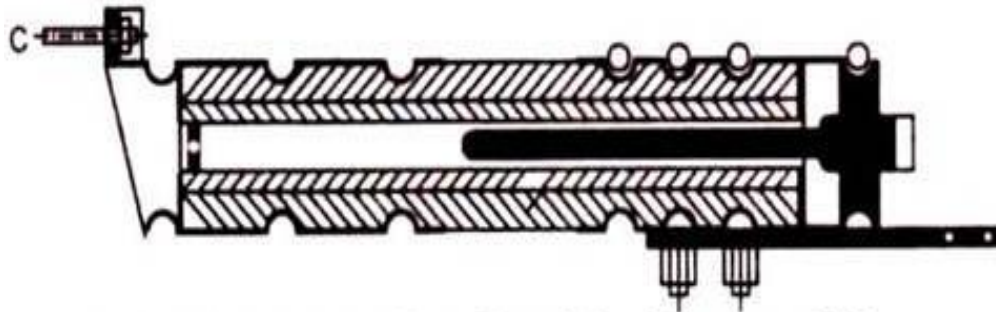
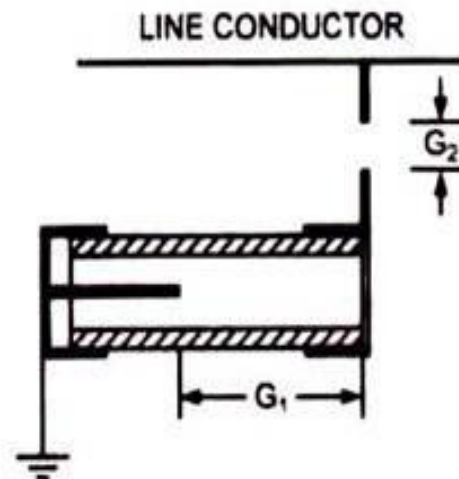
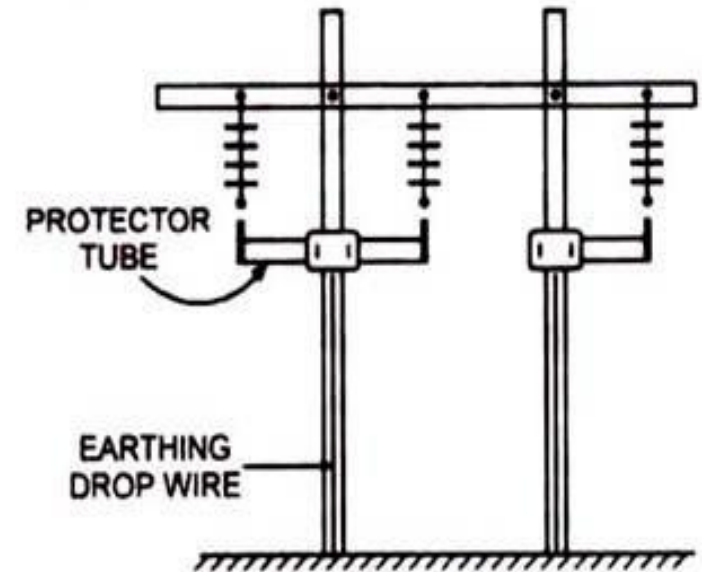


Fig. 9.15. Power Line Expulsion Protector Tube



(a) Schematic Diagram of Protector Tube Connections



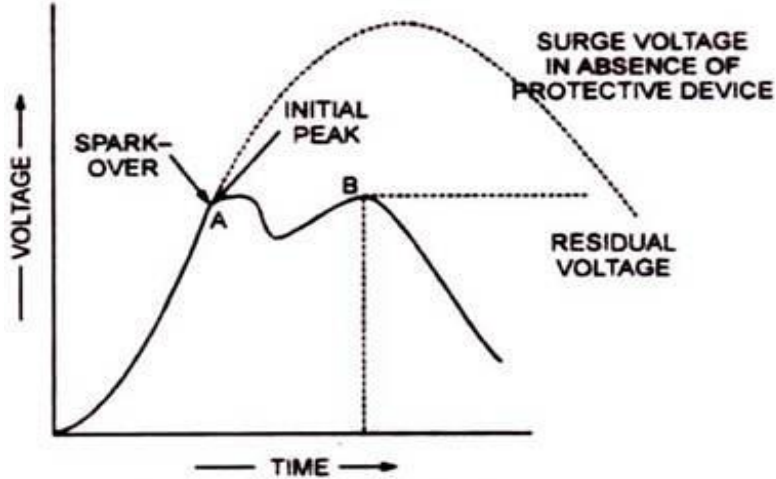
(b) Protector Tube Mounted on 110 kV Wooden Pole

Fig. 9.16. Expulsion Protector Tube

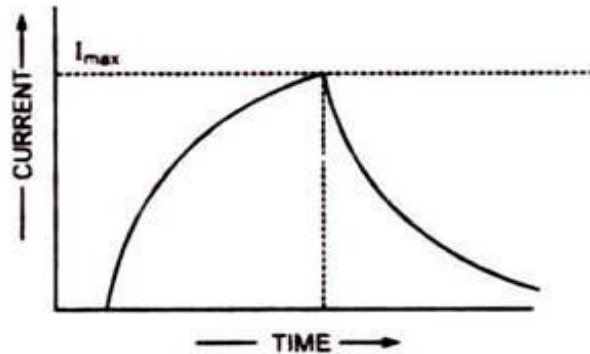
Protection of Electrical Equipment from Travelling Waves

it is absolutely necessary to provide some protective device at the power stations or substations to prevent transformers and other equipment from being subjected to travelling surges reaching there. The most common devices used for protection of equipment at the substations against travelling waves are lightning arresters or surge diverters.

A surge diverter is a device that is connected between line and earth, i.e., in parallel with the equipment to be protected at the substation.



(a) Voltage Characteristic



(b) Current Characteristic
Voltage and Current Characteristics of
Surge Diverters

Fig. 9.17

An ideal surge diverter should have the following characteristics:

- 1) 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.
- 2) 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.
- 3) 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.
- 4) The power frequency current following the breakdown must be interrupted as soon as the transient voltage has fallen below the breakdown value.

There are many types of surge diverters which are used to protect the power system.

The choice of lightning arrester depends upon the following factors:

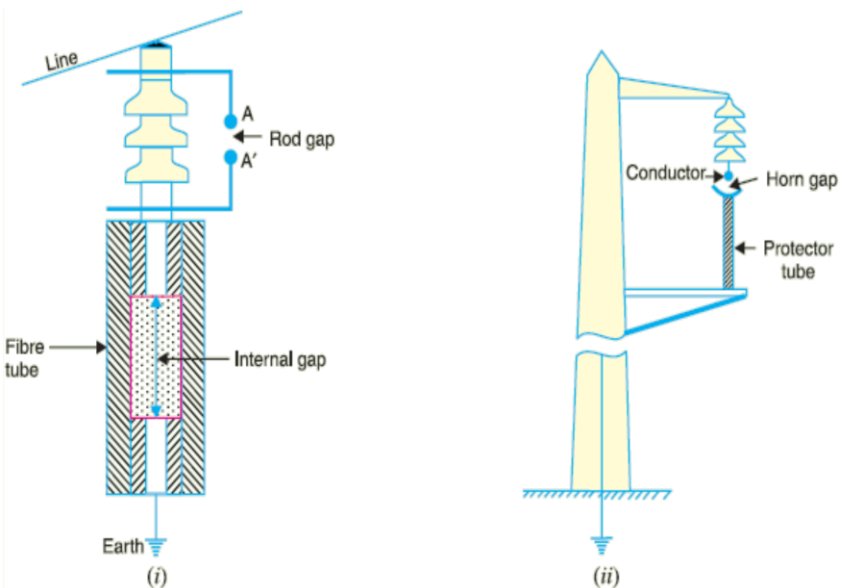
- (i) Voltage of the line.
- (ii) Frequency of the lightning.
- (iii) Cost.
- (iv) Weather conditions.
- (v) Reliability

Types of Lightning Arresters

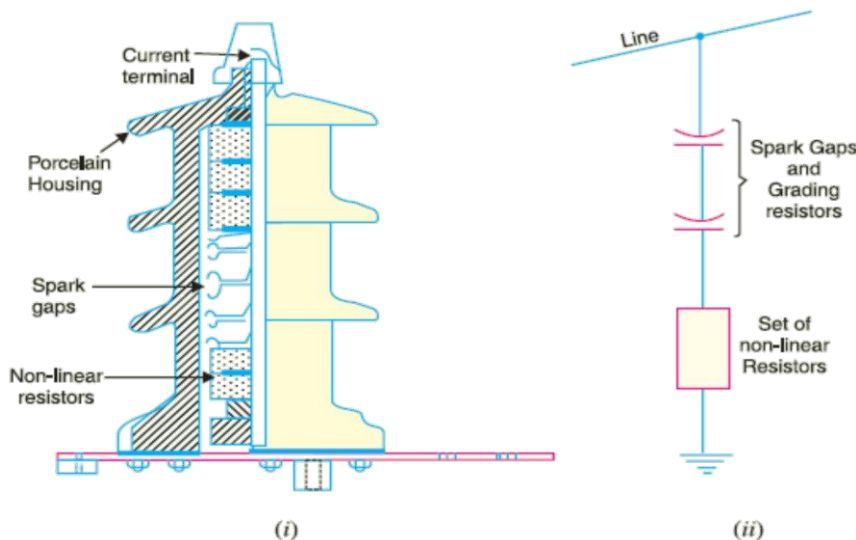
There are several types of lightning arresters in general use. They differ only in constructional details but operate on the same principle *viz.* providing low resistance path for the surges to the ground. We shall discuss the following types of lightning arresters :

1. Rod gap arrester
2. Horn gap arrester
3. Multigap arrester
4. Expulsion type lightning arrester
5. Valve type lightning arrester

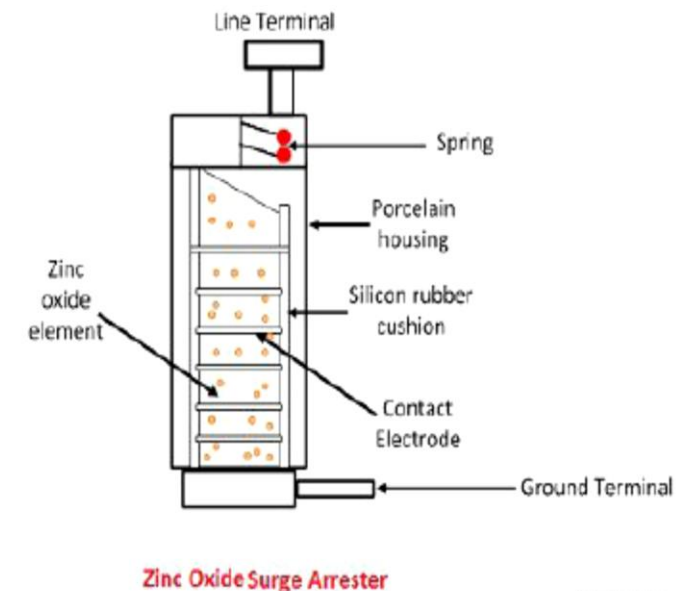
Expulsion type arrester



Valve type arrester



Metal Oxide Lightning Arrester



Insulation Coordination

Insulation Coordination is the process of determining the proper insulation levels of various components in a power system as well as their arrangements. It is the selection of an insulation structure that will withstand voltage stresses to which the system, or equipment will be subjected to, together with the proper surge arrester. The process 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 x 50 microsecond** wave.

A **1.2 x 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.

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.

Insulation Coordination

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

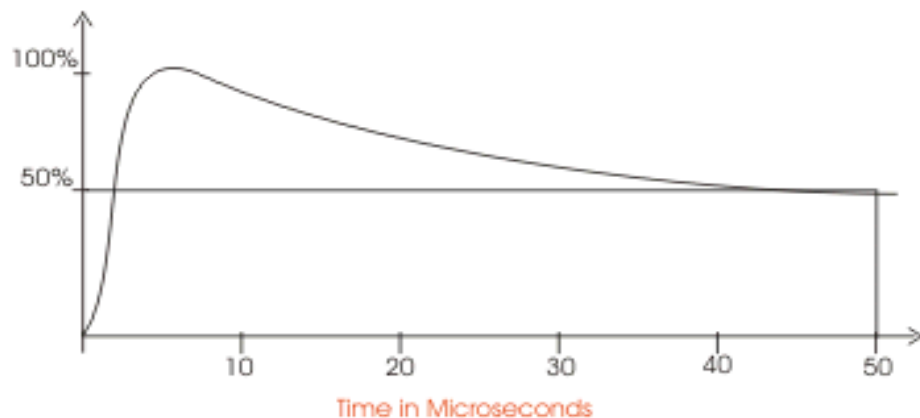
This is normally used for Flashover or puncture of insulation. It is the ratio of the impulse peak voltage to the value of the 60 Hz voltage that causes flashover or puncture. Or, it is the ratio of breakdown voltage at surge frequency to breakdown voltage at normal system frequency (60 Hz).

Basic Insulation Level

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

Impulse Voltage

As per American Standard the impulse wave shape is 1.5/40 microsecond. As per Indian Standard this is 1.2/50 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,



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

GAS INSULATED SUBSTATIONS

SF₆ gas insulated high voltage switchgear has been in commercial operation for more than 30 years. Continuous technological and design improvements of all the components during the course of the time are characterized by appreciable savings in area and volume occupied by the substation. Gas insulated substations are in service up to the highest voltage of 800 kV, meeting almost all the requirements in urban, industrial as well as rural areas. In the initial stages, the new SF₆ gas insulated substations were almost exclusively used where space limitations, site restrictions or exponential ambient conditions made it difficult to use conventional air insulated substations. However, over the last 30 years, GIS at voltage up to 800 kV in various station configurations and with various performance requirements, have been installed in increasing numbers worldwide. The modular of design of GIS offers a high degree of flexibility to meet layout requirements of both substations, as well as power station switchgear, making efficient use of available space. GIS technology has reached a stage of application and a wide range of GIS equipment up to highest voltage of 800 kV is available with many unique features.

They are:

1. Wide spread application of aluminum enclosure materials for standardized component models for all voltage ranges
2. The light weight enclosures have good conductivity, low eddy-current losses and a high resistance to corrosion
3. Easy handling, as well as reduced stresses on foundation and support structure are additional features
4. Standard arrangements can be easily modified and extended with good co-ordination between the manufacturer and the user.
5. A gas- tight barrier insulator in switchgear serve for the separation of gas compartments and prevents neighbouring switchgear parts from being affected during maintenance

The Gas insulated substation comprises the following components:

- 1 Circuit breaker
- 2 Disconnect switch
- 3 Earthing switch
- 4 Current transformer
- 5 Voltage transformer
- 6 Bus bar & connectors
- 7 Power transformer
- 8 Surge arrester
- 9 Cable termination
- 10 SF6 / air or SF6 / oil bushing

Advantages of GIS over the conventional open air substation

The application of GIS during the last fifteen years has been very rapid. The rapid growth in GIS application is due to the following special advantages:

1. Area and volume saving in construction for over or underground applications. Therefore they offer saving in land area and construction costs.
2. Insensitivity to external influences because of grounded metal enclosures.
3. Greatly improved safety and reliability due to earthed metal housing of all high voltage parts and much higher intrinsic strength of SF6 gas as insulation.
4. Short on site erection times, based on large factory assembled and tested shipping units
5. Fulfillment of aesthetic requirements with indoor applications
6. High service reliability due to non-exposure of the use of high voltage parts to atmosphere influences
7. Reduction in radio interference with the use of earthed metal enclosures
8. Use as mobile substations for transportation to load centers on standard tracks. These substations can be located closer to load centers thereby reducing transmission losses and expenditure in the distribution network.
9. More optimal life cycle costs because of lesser maintenance, down time and repair costs.
10. It is not necessary that high voltage or extra high voltage switchgear has to be installed out doors

Disadvantages of GIS

Although GIS has been in operation for several years, a lot of problems encountered in practice need fuller understanding. Some of the problems being studied are:

1. Switching operation generate Very Fast Transients Over Voltages (VFTOS).
2. VFTOS may cause secondary breakdown inside a GIS and Transient Enclosure Voltages (TEV) outside the GIS.
3. Field non-uniformities reduce withstanding levels of a GIS.
4. Prolonged arcing may produce corrosive/toxic by-products.
5. Support spacers can be weak points when arc by-products and metallic particles are present