9

Vacuum Interrupter and Vaccum Circuit-Breaker

Introduction—Historical review—Electrical Breakdown in High Vacuum—Arc Extinction in Vaccum—Construction of Vacuum Interrupter—Summary.

9.1. INTRODUCTION

When two current carrying contacts are sparated in a vacuum module, an arc is drawn between them. An intensely hot spot is created at the instant of contact separation from which metal vapour shoot off, constituting plasma. The amount of vapour in the plasma is proportional to the rate of vapour emission from the electrodes, hence to the arc current. With alternating current arc, the current decreases during a portion of wave, and tends to zero. Thereby the rate of vapour emission tends to zero and the amount of plasma tends to zero. Soon after natural current zero, the remaining metal vapour condenses and the dielectric strength builds up rapidly, and restriking of arc is prevented.

This principle is used in vacuum circuit-breakers.

The vacuum circuit-breaker comprises one or more sealed vacuum-interrupter units per pole. The moving contact in the interrupter is connected to insulating operating rod linked with the operating-mechanism. The contact travel is of the order of a few millimetres only. The movement of the contacts within the sealed interrupter unit is permitted by metal-bellows.

The range of vacuum switching devices includes :

— Vacuum interrupters rated 3.6/7.2/12/36 kV for indoor metalclad switchgear (Ch. 15).

— Vacuum interrupters rated 1.2/3.6/7.2 kV for indoor metal enclosed control gear (Ch. 15).

— Vacuum interrupters rated 3.6/7.2/36 kV for outdoor procelain housed, single interrupter per pole, circuit-breaker (Fig. 9.8).

— Multi-interrupter outdoor porcelain-housed circuit-breakers for 72.5 kV and above, (Now obsolete). For 72.5 kV and above vacuum Circuit breakers are not used for Voltages above 36 kV.

The structural configuration of the switchgear mentioned above is quite different, through the basic interrupter unit is based on same principle of operation.

For voltages upto 36 kV, vacuum circuit breakers employing is single interrupter unit have become extremely popular for metal-enclosed switchgear arc-furnace installations, auxiliary switchgear in generating stations and other industrial applications.

Single Phase 25 kV, 25 kA Vacuum Circuit-breaker having two interrupters per pole are used for railway track-side 25 kV Single Phase substations. Vacuum switching devices have several merits such as high speed of dielectric recovery after rapid and silent operations, suitability for repeated operations, simple operating mechanisms, freedom from explosion, flexibility design, long of life etc.

The unique merits of vacuum interrupters are small contact travel and less weight of moving parts. The vacuum interrupters have a very long life of the order of several thousand operations

on rated normal current. However for outdoor installations the external insulation requirements must be fulfilled and the advantages of high dielectric strength of vacuum cannot be fully utilised. Some recently developed 36 kV-GIS utilize SF_6 gas as an insulation and vacuum-interrupters for arc-interruption. Such GIS are commercially manufactured in India (1995). Vacuum Switchgear has been described in Sec. 15.5.

9.2. ELECTRICAL BREAKDOWN IN HIGH VACUUM

The pressures below about 10^{-5} mm of mercury are considered to be high vaccum. The charged particles from one electrode moving towards the other electrode at such a pressure are unlikely to cause collision with residual gas molecules. Hence ionization by collosion of particles with atoms and molecules is less in vacuum relative to that in gas.

Keeping a small gap (0.5 mm) between electrodes in vacuum if the voltage is gradually, increased at a certain voltages the gap breaks down and current increases suddenly, this phenomenon is called Vacuum Breakdown or Vacuum Spark.

Pressure remaining constant, the nature of the characteristic depends on the surface condition, material of electrodes.

Secondary emission takes place by bombardment of high energy on the surface of electrodes. Next, the electron emission takes place from the surface of the electrodes by virtue of intense heat. The current leaves the electrodes from a few spots. The current densities are high at these spots. The arc consists of a thin column of plasma. The core of the arc has high temperatures of the order of 6000°K to 15,000°K. At such temperatures the emission takes place from the surface of the electrodes, called Thermal Emission Summarising electron emission from the contact is the cause for arc formation in a vacuum switching device. The electron emission takes place in various ways such as Field Emission. Thermal Emission, Secondary Emission etc.

Table 9.1. Voltage Withstand values of 24 kV Vacuum Interrupters

Contact Gap mm	2	5	10
Power frequency withstand kV rms	40	80	100
Impulse withstand kV*	80	150	200

*Limit of impulse withstand by external flashover.

(*a*) **Conditioning of Electrodes**

If vacuum gap is continuously sparking over, the breakdown voltage increases and then reaches a value when the gap is conditional. Thereafter the spark-over voltage remains consistent.

(*b*) **Material of Contact and Surface Finish**

The creep of material, occluded gases in the material and the chamber create special problems in vacuum circuit breakers.

(*c*) **Dielectric Recovery after Sparking**

The vacuum gap regains its dielectric strength at a rate of about 20 $kV/\mu s$ after a spark over. The rate of recovery depends upon design features of the interrupter.

(*d*) **Effect of Contact Material**

The breakdown alternating voltages for the same vacuum pressure and the same contact gap vary with the contact materials.

(*f*) **Insulation strength**

The insulation strength of vacuum can be determined by applying the d.c. voltage till breakdown occurs. The insulation strength is given by the average of the highest voltage at which no spark occurs and the first value of voltage at which spark does occur. The insulation strength depends on the material of contact surface.

The dielectric strength of vacuum is relatively high and therefore, a small contact travel is usually enough to withstand the recovery voltage.

9.3. ARC EXTINCTION IN VACUUM INTERRUPTERS

The arc interruption process in vacuum interrupters is quite diferent 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 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.

While interrupting a current of the order of a few hundred amperes by separating flat contacts under high vacuum. The arc generally has several parallel paths, each arc-path originating and sinking in a hot spot of current. Thus the total current is divided in several parallel arcs. The parallel arcs repel each other so that the arc tends to spread over the contact surface. Such an arc is called diffused arc. The diffused arc can get interrupted easily.

At higher values of currents of the order of a few thousand amperes, the arc gets concentrated on a small region and becomes self-substained arc. The concentrated arc around a small area causes rapid vaporisation of the contact surface.

The transition from diffused arc to be concentrated arc depends upon the material and shape of contact the magnitude of current and the condition of electrodes. The interruption of arc is possible when the vapour density varies in phase with the current and the arc remains in the diffused state. The arc does not strike again if the metal vapour is quickly removed from the contact zone.

Thus the arc-extinction process in vacuum circuit-breaker is related to a great extent to the material and shape of the contacts and the technique adopted in condensing the metal vapour. The contact geometry is so designed that the root of the arc keeps on moving so that the temperature at one point on the contact does not reach a very high value.

The rapid building up of dielectric strength after final arc extinction is a unique advantage of vacuum circuit-breaker. They are ideally suitable for capacitor switching as they can give restrike free performance.

The vacuum circuit-breakers interrupt the small currents before natural current zero causing current chopping. However the chopping level depends on material of contact.

9.4. CONSTRUCTION OF A VACUUM INTERRUPTER

— 'Interrupter' is the sub-assembly a complete pole in which the arc interruption takes place.

There are two basic forms of vacuum interrupters.

— Interrupter suitable for a single unit per pole.

— Interrupter suitable for multi-unit per pole.

The interrupter is general consists of the following parts :

1. Enclosure (Ref. Fig. 9.3)

The enclosure is made of impermeable insulating material like glass. The enclosure must not be porous and should retain high vacuum of the order of 10^{-10} torr.

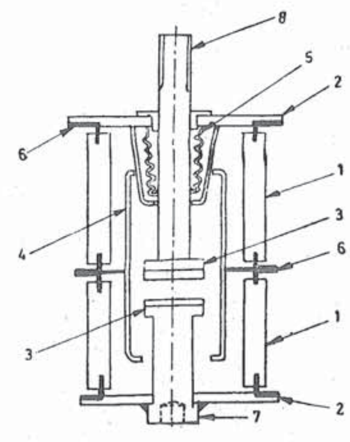
2. End Flanges

The two end-flanges are made of non-magnetic metal.

The end-flanges support the enclosure fixed contact, vapour condensing shields, bellows, and the protective-cover for the bellows :

3. Contacts

The contacts are made of large stem with large disc-shaped faces. The disc is provided with symmetrical groovers in such a way that the segments of the two contacts are not in the same line.



1. Enclosure Glass.
2. Eng Flanges. Non-magnetic metal.
3. Contacts.
4. Vapour condensing shield.
5. Metallic Bellows.
6. Seals.
7. Fixed contact stem.
8. Moving contact stem

Fig. 9.1. Cross-section of a typical 15 kV vacuum interrupter.

The magnetic field set-up by the components of currents with such a geometry causes the plasma of the arc to move rapidly over the contacts instead of remaining stable at one point. The concentration of the arc is thus prevented and the arc remain in diffused state. The sintered material used for contact tip is generally copper—chromium or bismuth alloy.

4. Vapour Condensing Shields

These metallic shields are supported on insulating housing such that they cover the contact region. The metal vapour released from the contact surface during arcing is condensed on these shields and is preveted from condensing on the insulating enclosure.

5. Metallic Bellows

One end of the bellows is welded to the metal-flange. The other end is welded to the moving contact. The bellows permit the sealed construction of the interrupter and yet permit movement of the contact. Stainless steel bellows are generally used in vacuum interrupters.

The bellows are covered by a protective shield.

6. Seals

The sealing techniques are similar to those used by electronic valve and power-tube manufacturers. These are like metal-glass, or metal ceramic seals.

In the swithgear installation, the interrupter is housed inside a sheet metal enclosure and the metal flanges are supported on porcelain or epoxy insulators. The moving contact is connected to the operating mechanism by means of a glass-fibre rod.

Vacuum interrupters are being increasingly used in metal-clad swithgear of voltage range 3.6 to 15 kV. The typical ratings of such vacuum interrupters are as follows :

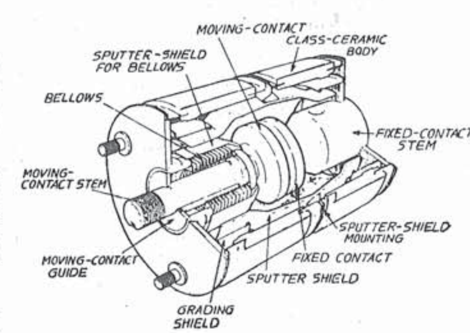


Fig. 9.2. Section of a vacuum interrupter.
[*Courtesy* : G.E.C. Switchgear Ltd. England]

Table 9.2 Typical Ratings of Vacuum Interrupters

Rated current (Amp)	*Rated breaking current (kA), rms*		
	at 7.5 kV	*12 kV*	*36 kV*
800—1600			
—2500	25	25	25
—3150	50	40	31.5

Vacuum switchgear includes vacuum iterrupters, operating mechanism, operating links enclosure etc. (Ref. Sec. 15.5).

9.5. ARC INTERRUPTION IN HIGH VACUUM

In vacuum interrupters, the arc extinction process is related with the following :

— Degree of Vacuum
— Im of Arc current
— di/dt of Arc current
— Energy dissipated from the arc
— dv/dt or TRV
— Peak of TRV
— Plasma of the arc (liberated from contact surface)

9.6. DEGREE OF VACUUM IN INTERRUPTERS

The vacuum level is expressed in Torr. (1 Torr is equivalent to a pressure represented by a barometric 'head' of 1 mm mercury). The breakdown voltage of certain contact gap varies with the absolute pressure in the vacuum interrupters as shown in Fig. 9.3. As the absolute pressure is reduced from 10^{-1} Torr, to 10^{-3} the dielectric strength (kV/mm) goes on increasing. Above 10° Torr, the characteristic in almost flat. And the dielectric strength in this region is above 12 kV peak/mm. In vacuum interrupters vacuum level of the order of 10^{-6} to 10^{-10} Torr is used. This is called high vacuum range. During the passage of time and after arc interruptions, the vacuum level goes on reducing. However it remains in the range of 10^{-5} Torr and 10^{-8} Torr. Vacuum in the range of 10^{-3} to 10^{-4} is sufficient for interruption and for withstanding impulse test voltage.

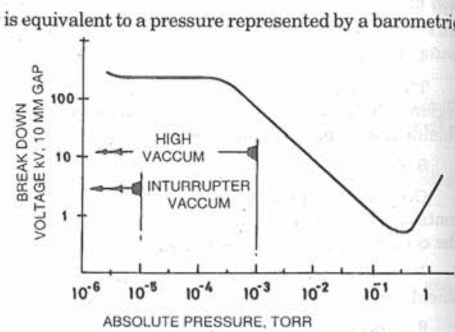


Fig. 9.3. Breakdown characteristic of a vacuum gap. (10 mm) for different vacuum levels.

9.6.1. Construction of a vacuum interrupter (Fig. 9.4)

(*Courtesy* : Siemens, West Germany)

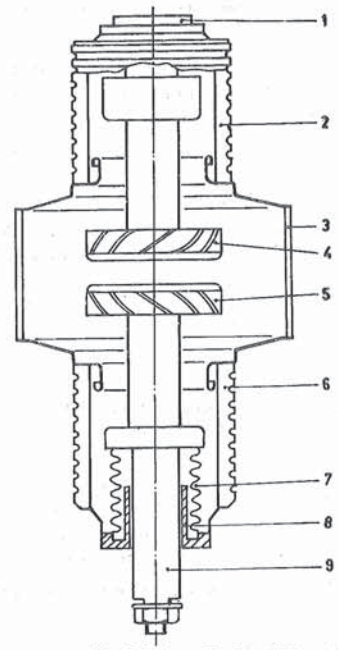
The basic design of vacuum interrupters for contactors and circuit-breakers is similar. The arcing chamber with the two stem-connected contact pieces is located between two ceramic insulators. The fixed contact piece is connected to the housing and the other (moving contact piece) is connected to the housing *via* vacuum tight metal bellow (7).

The arcing chamber (3) acts as a vapour shield. On opening a metal vapour arc is drawn between the contact pieces (4, 5) and is extinguished at current zero. The small amount of metal vapour that is not redistributed over the contact pieces condenses on the arcing chamber well. The protects the inside of the ceramic insulators against condensed metal vapour, which would reduce

the internal insulation. The metal bellow enables the moving contact stem to carry out its stroke. The stroke varies according to the rated voltage of the vacuum interrupter and is only 16 mm for 24 kV. A metal bellow must be able to withstand the movement corresponding to 30,000 make/break operations without falling. This is confirmed a long term no load tests. Fractures should not occur until after more than 200,000 such operations.

The insulators (2, 6) are made of *metallized aluminium oxide* ceramics, which permits them to be brazed to metal. There are no replaceable seals and the interrupter has a permanently sealed construction.

Vacuum tightness. All parts are either brazed or welded. Joints made in his way are not subject to ageing and the interrupter therefore remains vacuum tight throughout its working life.



One vacuum interrupter used for on pole. Refer Fig. 9.8 for end delevation of a vacuum Circuit-breaker indicating location of the Vacuum Interrupter
1. Terminal Plate
2. Insulator (Ceramic)
3. Arc Chamber (Metallic) (Condensing shield)
4. Fixed contact piece
5. Moving contact piece
6. Insulator (Ceramic)
7. Metal bellow
8. Moving contact Guide
9. Moving contact stem

Fig. 9.4. Cross-Sectional View of Vacuum Interrupter
Courtesy : Siemens, West Germany.

9.7. INTERRUPTION OF SHORT-CIRCUIT CURRENTS IN VACUUM INTERRUPTERS

There are two different interrupting ability limits of each vacuum interrupters.

1. Ability to Interrupt of power frequency current (50 Hz). This ability of vacuum interrupters is related with the contact shape, contact materials, vacuum level. Plain butt contacts are capable of interrupting power frequency currents up to about 6 kA rms. Above this value, *constricted arc* is formed and the arc is not quenched by plain butt contacts. To overcome this limitation, contact geometry is modified by providing curved grooves in the contact surface disc. Such contacts are called *spiral petal contacts, contrate (segmented) contacts.*

2. Ultimate Interrupting ability (Commutating ability)

This is related with ability to extinguish the last cathode spot in the arc root. Till the last arc root cathode spot is not extinguished, interruption cannot takes place in vacuum and the arc may continue to burn, cycle after cycle. The *ultimate interrupting ability* (commutating ability) is expressed in terms of

$$UIA = \frac{-di}{dt} \times \frac{dt}{dt}$$

where $\frac{di}{dt}$ = rate of reduction of current in arc (– ve)

$\frac{du}{dt}$ = rate of rise of TRV

UIA depends on contact material, contact shape, contact speed, degree of vacuum etc.

UIA also depend on di/dt, du/dt, I_m.

In various switching duties, severity of di/dt is different than severity of du/dt. Hence each switching duty is evaluated separately. The limit of vacuum interrupters is not due to du/dt but is due to di/dt for given du/dt.

Vacuum interrupters can withstand highest du/dt of the order of 10 kV/μs.

9.8. DESIGN ASPECTS OF VACUUM INTERRUPTERS

The complete vacuum switchtgear for voltages between 3.6 kV and 36 kV is in the form of the *Metal Enclosed Switchgear* (Ref. 15.4, 15.5, 15.19). *Vacuum Interrupters are* the 'hearts' of a vacuum switchgear. As a rule vacuum interrupters are single phase units. One vacuum interrupter is provided in each pole and the three poles with a common mechanism, linkages, frame etc. form one complete circuit-breaker unit.

9.8.1. Length of Interrupter

Ref. Fig. 9.7 cross section of a vacuum interrupter. The contact gap between fixed and moving contact (4, 5) is small (8 to 20 mm). Because of high dielectric strength of vacuum small contact travel is sufficient. The minimum length of contact gap is decided by required *impulse voltage withstand level* of the interrupter.

The length of the vacuum interrupter includes the length of the chamber and length of insultation. The total external creepage distance and clearance requirements in air (or in SF_6 gas) (Ref. Fig. 12.1 for an outdoor circuit-breaker). The definitions of creepage distance and clearances given in Sec. 12.7 apply equally to vacuum switchgear and vacuum interrupter.

The length of vacuum interrupter depends on minimum requirement of external clearance and creepage.

9.8.2. Contact Travel (Contact (Gap))

Because of high dielectrical strength of the medium, smaller contact gap is enough for withstanding TRV and impulse withstand test voltage. Typical value are :

	Minimum	In Practice
12 kV Interrupter	6—10 mm	8—20 mm
3.6 kV Contractor	2—3 mm	3—5 mm

The impulse withstand voltage requirements are considered while deciding the required contact gap.

9.8.3. Contact Shape

The dimensions and shape of the contacts are related both to the breaking current and to the normal full load current. The contact area depends on an acceptable power dissipation on full load current.

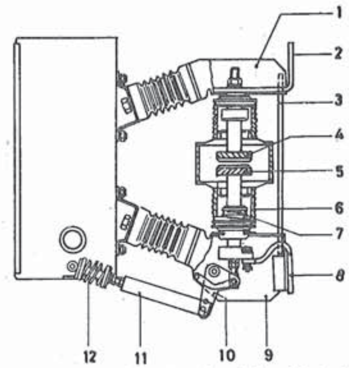
The limit of impulse voltage withstand level of vacuum interrupters is given by external flashover. *i.e.*, during the impulse test on a vacuum interrupter with open contacts flashover should occur externally.

On opening of the contact the current to be interrupted produces a metal vapour arc discharge and continues flowing through the plasma until the next current zero. The arc is extinguished and the conductive metal vapour condenses on the contact piece surfaces within a few microseconds. The dielectric strength of the break is thus reestablished very rapidly. The steady-state pressure in a vacuum interrupter is less than 10^{-9} bar. Contacts gap clearance of between 8 and 20 mm is adequate to give a high dielectric strength.

Contact size for normal Rated Current

Contact shape is selected for required and rated current. For rated current, the temperature rise should be within permissible limits. For this purpose contact stems should have sufficiently large diameter to dissipate the heat by conduction to the external heat sinks.

Because of the good thermal insulation of the vacuum medium between the contacts and the enclosure, all the heat at the contacts and in the contact stems must be removed by conduction along the stem. About 50% of the contact heat dissipation must be from each terminal of the interrupter, while maintaining the terminal below the specified temperature limits. Hence the heat sinks are provided at each terminal of the interrupter (Fig. 9.5).



1. Upper support and heat sink (copper)
2. Terminal of pole (Copper)
3. Insulator support rod
4. Fixed contact piece
5. Moving contact piece
6. Insulator
7. Metallic bellow
8. Lower terminal (copper)
9. Lower heat sink
10. Mechanism linkage
11. Glass fibre rod for the breaker pole
12. Opening spring

Fig. 9.5. Cross sectional view of a typical Vacuum Circuit-breaker (Side View)
Courtesy : Siemens (West Germany)

The temperature of contacts will be a few degree above that of the terminals, depending on the thermal resistivity of the contact stems, however the contacts are completely protected from oxidation due to surrounding high vacuum.

9.8.4. Contact size and shape for required short-circuit breaking current

The arc quenching in the vacuum interrupters depends on the contact shape and contact material. For higher rated currents the arc should be diffused. Arc should not be allowed to turn into a constricted arc. A *diffused arc* has several arc roots on contact surface. A constricted arc has a single arc root of a higher diameter and temperature (Ref. Sec. 9.3).

The diffused vacuum arc can be interrupted easily, due to the extremely short thermal lag (less than 1. μ.s) in metal vapour emission from cathode spots. If magnetic constriction of the diffuse arc into a constricted discharge occurs, large heated regions with very long thermal and vapour emission time constants (greater than 100 μ.s.) may be formed. Such large heated areas will cause emission of vapour persist beyond the current zero. This causes the arc to continue after current zero and thereby causing failure of the interrupter.

The formation of *constricted* arc is prevented special design of contact discs.

Plain butt contacts give diffused arc above the breaking currents of the order of 5 kA rms. Hence the use of plain butt contacts is limited to rated short-circuit breaking currents of 4 kA.

For short-circuit breaking currents above 4 kA, the butt contacts are in the form of either *spiral contacts* or *contrate contacts* (Fig. 9.6). *Both the design of depend for their operation on the interaction of the arc and a magnetic field to keep the arc in rapid motion, and maintain diffused arc.*

Small chopping current. Below a certain minimum current, the metal vapour arc is interrupted. Before a certain zero. ***In inductive circuits, this chopping current must therefore be as small as possible to prevent the build-up unduly high voltage surges. It depends essentially on the material used contact. With optimized chromium copper contact material it is below 5 A.***

High breaking currents. At breaking currents of between 10 and 50 kA, its self-magnetic field causes the diffused arc root covering the entire contact piece surface. In order to avoid local overheating of the contact pieces the arc must not remain stationary. A radial (additional) magnetic field caused by slotting of the contact pieces produces a force which drives the arc round the arcing rings. This is the purpose of using 'petal contacts' or 'contrate contacts'.

Minimum contacts piece erosion. The metal vapour plasma of an arc drawn in vacuum is highly conductive. As the arc voltage is only between 20 and 200 V, energy conversion in the break is also minimal. The high conductivity in conjunction with the small energy conversion and short arcing times (below 15 ms for the last-poles-to-clear) are the reasons for the insignificant contact piece erosion and long electrical life of the vacuum interrupters.

Small contact resistance. In vaccum, the contact surfaces are free of impurities and pollution layers. Materials of high conductivity are used. Consequently the contact resistance between the two outer terminations of an interrupter is about 10 micro-ohms and the heat loss is correspondingly small.

The spiral contacts, petal contacts, contrate contacts etc. are patented names of the contact shapes developed by GE (USA) and AEI (UK) and other organisation during 1960-1980.

Spiral Petal Contacts (Fig. 9.6)

These type of contacts have been developed by GE (USA). The contact tips are of flat disc shape with spiral grooves, as shown in the figure.

For smaller arc currents the arc is diffused. Due to peculiar petals in the contact, the arc roots move towards the edges. The cathode spots tend to spread towards the edge of the contact disc instead of farming single constricted arc.

For higher arc currents, the arc roots tend to move from central zone to the edges due to blow out effect of petals. Because of spiral shape of grooves, the movement of arc roots has radial and circumferential components. Thereby the arc roots are blown out of the disc. This helps in diffusing the arc.

Segmented Contact (Contrate Contact)

This contact shape is shown in Fig. 9.6. The contact tips are of cupshape with inclined segments. Because of several segments the arc roots are formed and the arc is split up in several parallel paths. These arc paths repel each other and the arc roots are pushed away from the contact face.

Arc quenching makes heavy demands on the interrupter contact pieces, since they must be designed for

— high short-circuit breaking capacity
— high dielectric strength
— small chopping current
— minimal contact piece erosion
— small contact resistance

Fig. 9.6 (*a*) Contrate (segmented) contacts

Fig. 9.6 (*b*) Contrate (segmented) contact

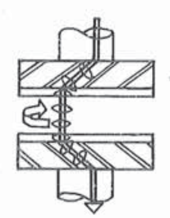


Fig. 9.6 (*c*) Spining of arc due to electromagnetic forces in contrate contacts

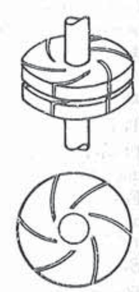


Fig. 9.6 (*d*) Petal contacts

These requirements have all been met to optimum effect, both technically and economically by basic research carried out in laboratories and development of suitable materials contact shapes and interrupter geometry, in conjunction with the most modern production methods.

This helps in diffusing the arc. Because of the cup shape of contact tip, the arc forms a ring instead of a cylinder. The contact tip material is especially selected such that the contact has low current chopping properties and non welding properties.

9.8.5. Contact Material

The contacts material for vacuum interrupters should have the following properties.

(1) High electrical conductivity.
(2) Low contact resistance
(3) High thermal conductivity
(4) Low current chopping level
(5) High arc withstand ability
(6) High melting point
(7) Low tendency to weld
(8) Easy to manufacture and economical

Some of these properties are of opposite nature. For example, low contact resistance and high arc withstand ability are rarely found in the same material. In other type of breakers, the main contacts and arcing contacts are of different materials. But in vacuum interrupters, the same contact face is used for main contact and arcing contact.

Several materials have been tried by different manufacturers. The following three materials are commonly used for vacuum interrupters :

(1) Copper-Bismuth Alloy
(2) Copper-Chromium Alloy
(3) Copper-Berrylium Alloy

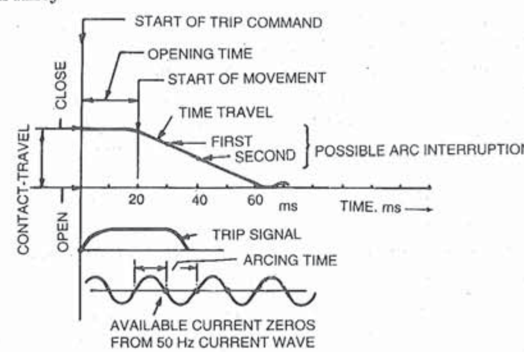


Fig. 9.7. Time-travel characteristic of moving contact of VCB. for Opening Stroke. Number of current zeros available.

9.9. Time/Travel Characteristics

The vacuum interrupters are designed for giving several thousand laod operations.

Typical values of contact travel characteristics for vacuum interrupters are given in Table 9.2.

Table 9.2. Reference Values of Contact Travel Characteristics of 12 kV Vacuum Interrupter

Contact Gap	*8 to 12 mm*
Contact Speed :	
—Opening	0.5 to 0.8 mm/ms
—Closing	0.5 to mm/ms

The time/travel characteristic during opening stroke is selected for a particular interrupter by considering :

— Total number of current zeros of 50 cycles wave form, required during the active opening stroke (Ref. Fig. 9.11).

The slope of the contact travel characteristic gives the contact speed. For higher contact speed, the slope is higher. The contact reaches final open position earlier.

Opening Speed

Assuming total travel 10 mm, assuming 50% contact travel for half cycle period (10 ms), the average opening speed will be 5/10 = 0.5 mm/ms.

Assuming 70% contact travel for half cycle period (10 ms), and half cycle period, average opening speed will be 7/10 = 0.7 mm/ms.

The choice of opening speed is based on the following conditions :

(1) The arcing time should be reasonably short. The maximum arcing time should not be greater than about half cycle of 50 Hz wave.

(2) Vacuum interrupter should be restrike free for capacitance switching. If current zero occurs near the instant of contact separation the electric strength of the interrupter in the open position is sufficiently great after half a cycle of the power frequency wave *i.e.* contact should travel fully in 10 ms to its open position.

Generally some 50-70% of full travel normally be attained in 10 ms.

Closing speed

Contact speeds in closing must fulfill two opposite conditions. Low speeds reduce mechanical stresses and shocks. A low speed of closing also reduces the mechanical stresses of the bellows and increases bellows life. A low impact velocity reduces the problems of contact bounce during closing.

On the other hand a higher speed of closing reduces the duration of prearcing and thus the amount of contact wear, the tendency to weld, and possible generation of voltage escallation due to sparking during the prearcing period. Typical speed at contact touch are 0.5 mm/ms.

9.10. CONTACT PRESSURE

Due to butt contacts high electromagnetic repulsive forces are established at the instant of prearcing period and contact will have to close against such repulsive forces. These forces are proportional to I_m^2 where I_m is peak making current.

The contact pressure in a vacuum interrupter must be sufficient (1) to give low contact resistance (2) to close effectively on to fault current and (3) to remain closed during the passage of fault current (4) it should satisfactory normal current carrying capacity.

9.11. CONTACT ACCELERATION DURING OPENING

The vacuum interrupter contacts weld to a very slight degree, and the suitable contact material having low welding tendency is selected for contact tips. The moving contact is accelerated with impact force to break the small welds.

A typical arrangement for opening the contacts of vacuum interrupters is to arrange the mechanism to accelerate as mass (which should be larger than moving contact mass) to a velocity more than of the opening velocity required. The mass then pulls off the contact, the severity of the pull being controlled by the coupling between 'hammer' and contact. This coupling sometimes has elastic material.

9.12. CONTACT EROSION

Contact erosion is caused by arcing. Erosion rate is expressed in terms of grams/coulomb is not a constant but increases with increasing current. The interrupters interrupt their full short-circuit

current some hundreds of times, and can give many thousands of operations on normal full load current.

Material is lost from the contacts in three ways: (1) melting globules (2) metal vapour evaporated from the cathode spots (3) liquid droplets thrown out of a molten metal film on the surface of the electrodes at high currents—these droplets are usually ejected by the electromagnetic forces caused by the interaction of the arc current and its own magnetic field.

Bellows

Bellows used in Vacuum Interrupters are of stainless steel. The stainless steel plate of desired composition is either rolled or hydraulically formed to get the convolutes of the bellow. Alternatively rings cut from stainless steel plates are arranged in V formation and the edges are welded-Bellow permits movement of moving contact without loss of Vacuum.

9.13. VACUUM LEVEL AND SHELF LIFE OF INTERRUPTERS

Vacuum pressure in interrupters is in the range $10^{-5} - 10^{-9}$ torr, variation occurs during the life of an interrupter. Vacuum of the order of 10^{-3} torr is sufficient for interruption.

The shelf life of vacuum interrupters is minimum 20 years and possibly much longer. When interrupters are operated the metal vapour film is deposited on the shield and contacts.

Vacuum testing may be done on sub-assemblies during manufacture by normal mass spectrometer methods or the complete interrupter may be vacuum checked during or after evacuating.

A standard procedure used by manufacture is to measure the pressure after the interrupter is sealed at intervals of about one month. The pressure can be measured using the axial magnetic field and radial electric field. The current that flow between contact and main shields gives a measure of pressure within the interrupter.

9.14. CHECKING OF VACUUM

Simple method for checking vacuum in the interrupter at site is to check the force required for pulling the moving contact. If vacuum is higher, higher force is required to pull the contact. Simple spring balance may be used to measure the pulling force. Another method is to supply power frequency test voltage to terminals of open vacuum interrupter.

Following test voltages are recommended :

— 12 kV interrupter : 15 kV to 50 kV rms.

— 36 kV interrupter 45 kV to 90 kV rms.

If vacuum is lost, the open interrupter will flashover internally on application of the test voltage.

9.15. RANGE OF VACUUM SWITCHGEAR, VACUUM CONTROLGEAR AND VACUUM CIRCUIT-BREAKERS

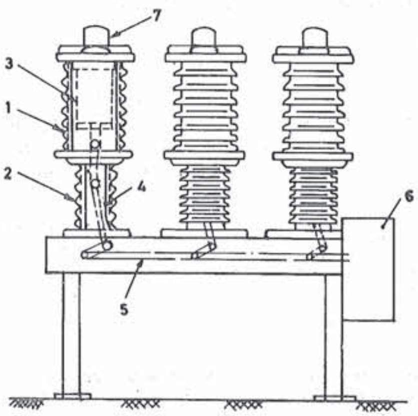
In the introduction (Sec. 9.1), the range of vacuum switching devices was mentioned. Vacuum switching device may be one of the following six types :

1. Vacuum Contactor : This is capable of several million operations on load and overload. The short-circuit interruption capability is limited. Back-up HRC fuse gives the short-circuit protection. Vacuum contactors are used in Vacuum Controlgear in the voltage range of 1.2 kV/3.6 kV/7.2 kV. It is not economical for LV controlgear in which simple air-break contactors are preferred. Vacuum controlgear uses vacuum contactors as the main switching device for normal load switching and overload switching. It may have a limited short-circuit breaking and full short-circuit making capability (Ref. Sec. 15.47 for further details).

2. Vacuum Circuit-breakers for medium voltage metal clad switchgear or metal enclosed switchgear. This type of switchgear is used mainly in industrial applications and distribution applications in the range 3.6 kV/7.2 kV/12 kV/36 kV. The vacuum circuit-breaker is the main switching device in the indoor metal-enclosed switchgear. The complete VCB has a three phase subassembly having one common mechanism housing, linkages, and three vacuum interrupters mounted on the frame by means of epoxy-resin support insulators.

3. Outdoor Vacuum, Circuit-breakers in the Kiosks. The complete vacuum circuit-breaker unit may be installed in a outdoor Kiosk. The kiosk (outdoor sheet-metal room with inclined roof)

1. Enclosure-Porcelain
2. Support procelain
3. Vacuum interrupter
4. Insulating rod
5. Linkages
6. Mechanism housing
7. Interrupter Support



1. Enclosure
2. Support procelain
3. Interrupters
4. Insulating rod
5. linkages
7. Support

Fig. 9.8. Front View of a 36 kV Porcelain-Enclosed 3 Ph. Vacuum Circuit-breaker.

Complete kiosk incorporates the vacuum circuit-breaker, kiosk, bushings, busbars, CTs, VTs, some measuring instruments. The Kiosk may be installed outdoor. Vacuum Kiosks are generally preferred for outdoor switchyard rated 12 kV and 36 kV.

They are also preferred for 25 kV track-side substations for 1-phase traction system.

4. Outdoor Procelain-housed Vacuum circuit-breakers.

Here the circuit-breaker is a three phase self-contained device having a support-structure mechanism, three poles linkages. The vacuum interrupter is housed in the upper procelain housing (Ref. Fig. 9.8). Such a circuit-breaker is preferred for 12 kV, 36 kV outdoor switchyards.

5. Single phase Roof-top Railway Circuit-breaker.

Earlier, air-blast circuit-breakers were used for such an application. Now vacuum circuit-breakers are preferred. The CB is single phase unit of low weight. It is installed on the roof of railway carriage.

6. EHV Vacuum Circuit-breakers with multiple-interrupters per pole.

Such circuit-breakers have been successfully developed and installed.

Vaccum circuit-breaker needs several interrupters connected per pole. Whereas SF_6 circuit-breakers requires only one or two interrupters per pole SF_6 circuit-breakers are less costly and have superior performance. Hence for EHV range VCB has not succeeded commercially.

9.16. MERITS OF VCBs

1. VCB is self contained does not need filling of gas or oil. They do not need auxiliary air system, oil handling system etc. No need of periodic refilling.
2. No emission of gases, Pollution free.
3. Modest maintenance of the breaker, no maintenance of interrupters. Hence economical over long period.
4. Breaker forms a unit which can be installed at any required orientation. Breaker unit is compact and self contained.
5. Non explosive.
6. Silent operation
7. Large number of operations on load: or short circuit. Suitable for repeated operating duty. Long life.
8. Suitable for capacitor switching, cable switching, industrial load switching.
9. **Constant dielectric.** There are no gas decomposition products in vacuum and the hermetically sealed vacuum interrupter keeps out all environmental effects.
10. **Constant contact resistance.** In vacuum the contacts cannot oxidize, a ract which ensures that their very small resistance is maintained throughout their life.
11. **High total current switched.** Since contact piece erosion is small, rated normal current can be interrupted up to 30,000 times and rated short-circuit breaking current on average a hundred times.

These reasons together with the economic advantages offered-have boosted acceptance of the vacuum circuit-breakers.

9.17. DEMERITS

1. The vacuum interrupter is more expensive than the interrupting devices in other types of circuit-breakers and its cost is affected by production volume. It is uneconomical to manufacture vacuum interrupters in small quantities.
2. Rated voltage of single interrupter is limited to about $36/\sqrt{3} = 20$ kV. Above 36 kV, two interrupters are required to be connected in series. This makes the breaker uneconomical for rated voltage about 36 kV.
3. Vacuum interrupters require high technology for production.
4. In the event of loss of vacuum due to transit damage or failure, the entire interrupter is rendered useless. It cannot be repaired at site.
5. For interruption of low magnetising currents in certain range, additional surge suppressors are required in parallel with each phase of a VCB.

9.18. SWITCHING PHENOMENA WITH VCB

The application details about Electrical switching phenomena associated with medium voltage vacuum circuit breakers is given in Sec. 15.22 to 15.26.

9.18.1. Reignition in Vacuum Circuit-breakers

As the contacts open, a small contact travel may interrupt the arc if the wave is passing through early period after current zero (Fig. 9.9). In such event, full TRV appears across small contact gap. The small gap (fraction of mm) cannot withstand high TRV and the arc reignites. The reignition causes high frequency oscillation in LC circuit. Such oscillations have several current zeroes with a period of few microseconds. But the cannot gap is increasing in the meanwhile. After a few mm

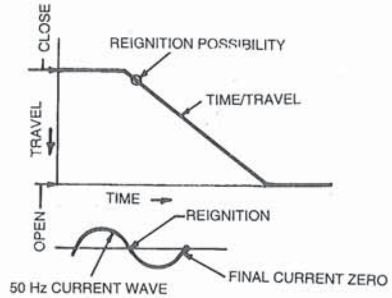


Fig. 9.9. Time-travel characteristic of Vacuum circuit-breaker contact during opening stroke, indicating reignition possibility in current wave.

gap, the reignition of high frequency wave stops and arc is quenched. Multiple reignition lasts for a period of few microseconds. Such multiple reignition may give undesirable transient overvoltages of high frequency. This problem is overcome in vacuum interrupters by selecting suitable contact material. Instead of using tungsten-copper, other materials like copper bismuth alloy, copper chromium alloy are used.

9.18.2. Capabilities of Modern Circuit breakers for Medium Voltages

— Short circuit current interruption. Upto 50 kA at 12 kV with 15 ms arcing time
— Operating duty 0—0.3 Sec—CO—1.5 Sec—CO
— Capacitive current breaking : 1000 A at 36 kV
— Parallel bank switching Inrush currents 40 kA peak, 1250 A/μs
— Repeated load switching 30,000 Switching operations on full load.

9.18.3. Switching Over-voltage Problem with VCB for Motor Switching Duty, RC Surge suppressors

While using vacuum Circuit-breakers for motor switching, over-voltages can be generated due to (*a*) Current Chopping (*b*) Multiple Reignition. Suitable RC Surge suppressors should be incorporated with vacuum switchgear to limit switching over voltages.

Current Chopping occurs at low value of current (0.1 to 20 ampere) as the vacuum gap chops the current (Ref. Sec. 3.12). Each vacuum interrupter has certain chopping level (say, 5 A).

Multiple Reignition occurs when the contact gap is too small while opening a low power factor load such as magnetising currents of transformers and also while switching off locked- rotor motors connected through long cables. The gap quenches the arc but is too small to withstand the TRV, hence breaks down again. The gap again recovers and re-ignites again. Such repeated multiple reignition gives rise to over-voltages which are harmful to the insulation of motors and transformers.

RC Surge Suppressors comprising resistance of 100 ohms and series capacitance of 0.1 μF are connected across phase and earth for each phase on load side of vacuum interrupter. The combination is called RC Surge Suppressor. This is provided with vacuum switchgear to limit switching over-voltages during low inductive current switching (Ref. Sec. 18.12). R.C. Surge Suppressor reduce the rate of rise and peak of Switching overvoltage.

Summary

Vacuum interrupters are sealed units comprising a pair of fixed and moving contact, metallic bellows, vapour condensing shield, insulating enclosure etc. Vacuum interrupters are compact and give very long operational life without any maintenance. They are popular for ratings upto 36 kV, 25 kA and are being widely used for indoor metal-clad switchgear, trackside sub-station etc.

Surge suppressors comprising non-linear resistors or resistance capacitor combination are connected on load side of vacuum circuit-breakers for limiting switching over-voltage. These are necessary for low-power factor load switching.

QUESTIONS

1. Describe the behaviour of electric arc in high vacuum.
2. Describe the construction of a vacuum interrupter and vacuum circuit-breaker.
3. State the merits of vacuum interrupter and discuss the problems involved.
4. What are the possible applications of vacuum interrupters ?
5. Explain the process of arc extinction in high vacuum.
6. With the help of neat sketches, explain the construction of a vacuum interrupter.
7. Explain current chopping in VCB. Explain the function of RC surge suppressors used with vacuum switchgear for motor switching.