

## UNIT-IV

# Converter Faults and Protection

### Converter Faults:

Fault is basically an undesirable condition that exists because of any abnormality in the system. Faults should be avoided as far as possible. However, the occurrence of faults is inevitable. There are various faults which exist in a converter station. They are,

1. Arc Back
2. Misfire
3. Commutation Failure
4. Current Extinction
5. Arc-through
6. Short Circuit in a Bridge

### 1. Arc Back

Arc back is a phenomenon in which a valve loses its capability to block in reverse direction and hence conduction takes place even in the reverse direction. This fault is of severe type, non-self clearing fault and causes severe stresses on the transformer windings. Therefore when this type of fault is detected we need to block the converter valves and open the backup A.C. breaker. The factors that are responsible for increase in arc back can be overcurrent, high peak inverse voltage, high rate of rise of inverse voltage etc.

Arc back can be eliminated by using a bypass valve placed across the converter bridge on the valve side. The bypass valve has higher current rating than ordinary valves and can carry direct currents for 1 minute. Under normal conditions, bypass valve is blocked and direct current flows through converter valves. Under abnormal conditions, the bypass valve is unblocked and the converter valves are blocked, now the current flows through the bypass valve. To retain the normal operation, again the bypass valve is needed to be blocked and other converter valves to be unblocked.

### 2. Misfire

Misfire takes place when the required gate pulse is missing and the incoming valve fails to ignite.

Misfire can occur in both rectifier and inverter stations. But the effects are more pronounced in the case of an inverter compared with that of a rectifier. The effects of misfire is commutation failure and arc-through. However, the probability of such faults is very less in modern stations. This type of fault is of self clearing type.

### 3. Commutation Failure

Commutation failure is nothing but the failure of the completion of commutation before the reversal of commutating voltage takes place. The minimum value of extinction angle that is to be maintained is given by

$$\gamma = 180 - \alpha - \mu$$

However, at the inverter side of HVDC systems, the extinction angle is regulated to a higher value than the valve specification to allow control adjustments and also leave an adequate safety margin for unforeseen events in the power system.

Commutation failure is not caused because of any malfunctioning of the valves but due to the conditions of the circuit outside the valve bridge. Factors such as voltage drop, phase shifts or sudden increase in D.C. current may cause commutation failure.

Commutation failure can be mostly seen in inverters than rectifiers, because the causes which can lead to commutation failure in an inverter are high D.C. current or low alternating voltage. But in a rectifier, commutation failure can take place only because of failure in the firing circuit.

Let us try to understand the concept of commutation failure for the circuit shown in figure (1).

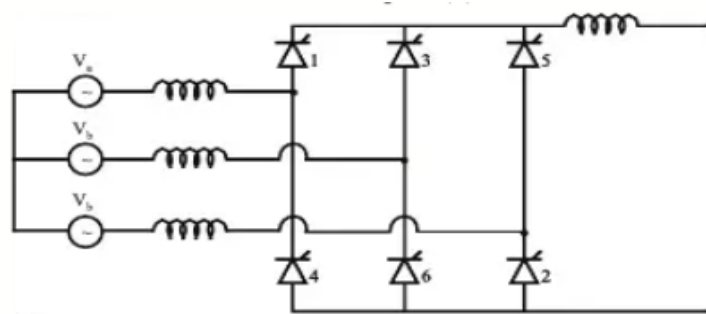


Figure (1): Circuit Diagram

Assume that initially valves 1 and 2 are conducting. Now, because of increased D.C. current or decreased A.C. Voltage or any other cause, valve 1 fails to extinguish. Therefore valve 1 carries full link current and the current in valve 3 becomes zero. Hence, valve 3 extinguishes and valve 1 continues its conduction.

Next, when valve 4 fires, the short circuit of the bridge takes place, as valves in the same arm conducts. This causes the voltage across valve 5 to be negative and hence it does not conduct. Valve 4 gets extinguished and valve 6 is fired next. Hence, the normal operation is retained back. Therefore, it can be said that single commutation failure is self clearing.

There will be no power flow in the D.C. system, for the period during which the valves 1 and 4 in the same arm are conducting since the inverter D.C. voltage is zero.

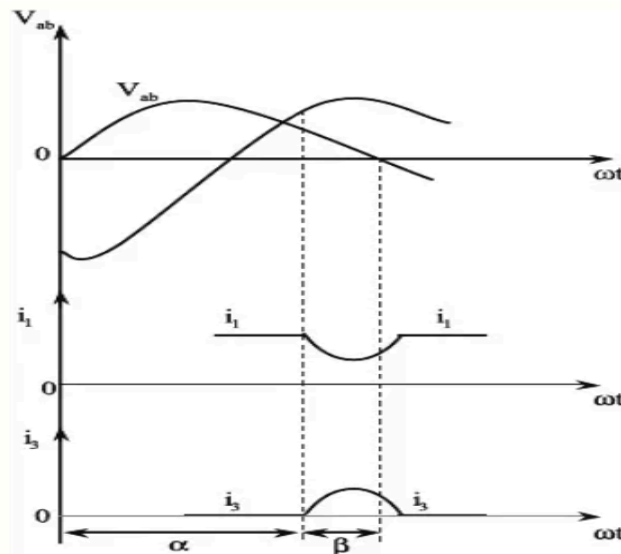


Figure (2): Commutation Failure

The effect of single commutation failure are,

1. The A.C. current ceases to flow during the period when both the valves in a particular arm simultaneously conduct.
2. The value of the bridge voltage is zero for a period greater than one-third of a cycle, during which D.C. current increases.

Double commutation failure can also take place in a converter station. It is the failure of two successive commutes in the same cycle. Double commutation failure is very severe. However, they rarely take place. This double commutation failure is also self-clearing. In some cases, if they persist for longer duration, converter differential protection can be used.

If a commutation failure is detected, the next firing instant is advanced by constant extinction angle control. In case, the failure is caused by low A.C. voltage, following an A.C disturbance, the normal voltage will return and prevent further commutation failures by clearing the disturbance.

A commutation failure in a bridge can cause several sequence commutation failures in the series connected bridges. Hence, the initial rate of rise of current has to be sufficiently limited by connecting the smoothing reactor in the circuit. The recovery of a bridge from commutation failure depends mostly on the magnitude of A.C. voltage and the current control in the link.

#### **4. Current Extinction**

This is also one of the faults which occurs in a converter station. Current extinction takes place in a converter station when the current through a valve reaches a value less than the holding current. This fault may cause the overvoltages to take place in the valve. This fault is very much pronounced in case of short pulse firing. In present day systems, fresh firing pulses are given to the valve, when it is actually supposed to conduct.

#### **5. Arc-through:**

Arc-through is the failure to block a valve during a scheduled nonconducting period. A malfunction in the gate pulse generator can fire a valve which is actually not supposed to conduct, but is in the state of forward bias. This malfunction is primarily because of failure of negative grid pulse, early occurrence of positive grid pulse etc. This fault mainly takes place in an inverter, where the voltages across the valve are mostly positive.

The effects of an arc-through are,

- (i) Short circuit occurs pretty frequently unless arc-through is removed.
- (ii) When the two valves in a particular arm conduct simultaneously, A.C. current ceases to flow.

(iii) Delay angle is reduced.

An arc-through is self clearing provided the causes that led to the fault are transient. This failure basically takes place because of the failure of a grid. i.e. if the negative grid bias is either abstract or insufficient fire-through takes place. Valve starts to conduct first after the anode becomes positive with respect to cathode and does not wait for a negative pulse.

## 6. Short Circuit in a Bridge:

As the valves are kept in a valve hall with air conditioning, their probability of occurrence is very low. They may sometimes occur because of flashover in bushings. This fault mostly occurs in rectifiers. If this fault occurs at the instant of firing at  $\alpha = 0$ , it is said to be the worst case. This fault is cleared by blocking the pulses when fault current is zero.

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## Protection against over currents in HVDC converters:-

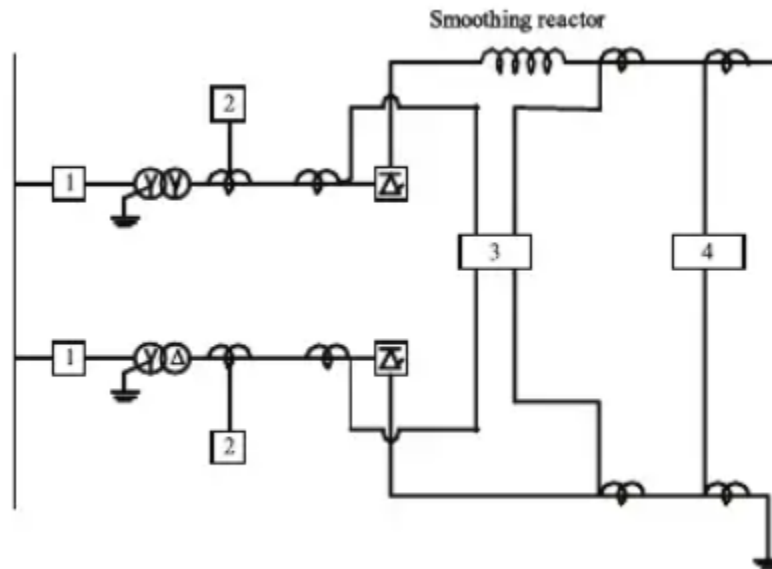
### Types of overcurrents:

**Overcurrent:** Overcurrent is the condition wherein, the current flowing through the conductor or any electrical equipment is higher than the rated current of that conductor or electrical equipment. This overcurrent generates excess heat which can damage the conductors. The types of overcurrent can be overload, short circuit or earth faults.

**Overload:** If the current flowing through a conductor is more than the rated current, overload takes place. Overload doesn't cause damage instantaneously. Hence, some overload can be allowed for some duration. Overloads for longer durations can lead to insulation failure.

**Short Circuit:** A short circuit is another type of overcurrent. A short circuit generally takes place when two wires touch each other. Hence, it causes low resistance which can increase the value of current by many folds. As the value of these currents is very large, hence these overcurrents should be laid off as soon as possible.

**Protection Against Overcurrents:** As these overcurrent can be very dangerous, hence they call for protection against them. To understand the protection scheme consider a converter station as shown in figure below.



**Figure: Overcurrent Protection of a Converter**

The abnormal conditions or the fault are sensed by following protection systems.

1. Group differential protection
2. Overcurrent protection
3. Pole differential protection.

In the figure numbers denotes the following,

- 1 -Circuit breaker
- 2-Over current protection
- 3 - Group differential protection
- 4 - Pole differential protection.

The group differential protection system:

- provides basic protection against the faults in a converter such as arc backs, arc-through, commutation failure, misfire etc.
- It compares A.C current to the D.C current on the valve side of the converter transformer and on the line side of the reactor.
- It gives fast protection against ground faults. In addition to the main protection system, a backup protection system should also be provided for reliability.
- This backup protection is given by overcurrent protection.

- The level of overcurrent in this system is kept higher than the level for group differential protection so that it should not trip the circuit for faults outside the converter station.
- This system is designed in such a way that for higher values of current, it acts quickly and for lower values of current it acts a bit slow.

The pole differential protection system:

- provides protection against temporary earth faults by blocking the converter valves for earth faults lasting for longer durations, circuit breakers should be opened.
- The earth faults are sensed based on the value of differential current. i.e., if the differential current sensed by the relay is zero, then there is no fault. Otherwise, if the relay senses some value, then there exists a fault.

The faults which produce an overcurrent are mainly of 3 types,

1. The first one being the line faults. They occur frequently and can be controlled by controlling the current.
2. The second one being the internal faults. They cause high overcurrents. These are infrequent.
3. The third fault may be the commutation failure at inverters. They occur quite frequently.

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### **Protection against overvoltages:-**

**Overvoltage:** Every electrical equipment is designed to operate at a certain maximum supply voltage. If the voltage in the equipment is increased beyond its maximum limit, it is known as overvoltage.

There are various types of overvoltages based on duration of their lasting and even on their nature.

They are,

**1. Temporary Overvoltages:** These overvoltages are of short power frequency. The main causes of temporary overvoltages such as,

(i) Load rejection

(ii) Zero resonance

(iii) Phase to earth faults i.e., single line to ground, double line to ground, 3-phase to ground etc.

**2. Switching Surges:** These overvoltages are of short duration. The effects of these overvoltages are

very much pronounced when the voltage is greater than 300 kV. The causes of these voltages are,

- Resonance effects when switching transformer feeders.
- Line energisation especially at the remote end of line that is energized.

**3. Lightning Overvoltages:** These overvoltages occur for a very short duration. The effects of this overvoltage are far more pronounced compared to the above two types. As the name itself suggests, the primary cause of this overvoltage is lightning strikes.

**Protection Against Overvoltages:** All these overvoltages can cause considerable damage and hence the power system equipment calls for protective devices against these overvoltages. The power system can be protected against lightning

surges by using shielding methods which do not allow the formation of arc between line conductor and ground. The examples of shielding methods is use of surge arresters and spark gaps. The protection against temporary overvoltages can be provided using non-shielding methods, which even allows the arc to form but makes the provision to suppress the arc. The examples of non shielding methods are use of ground wires.

### **Protection Schemes**

**Temporary Overvoltages:** The temporary overvoltages can be protected by,

- Using inverse overvoltage relays and circuit breakers.
- Using fast acting static VAR sources.

**Switching Overvoltages:** Switching overvoltages can be protected by,

- Using surge absorbers with circuit breakers.
- Using restrike free circuit breakers.

**Lighting Overvoltages:** Lighting overvoltages can be protected by,

- Using surge arresters and spark gaps.
- With the help of neutral grounding.
- Using overhead earthed conductors.

### **Note:-**

1. As frequent operation of the arresters can damage them, hence their operation should not be frequent.
2. At several parts of the system, it is required to maintain proper coordination between insulation and overvoltage protection.

3. Surge arresters should surely be used for the equipment with non self restoring insulation, so that the overvoltage stresses on them can be reduced. To ensure this, the protection level of the surge arresters should be kept lower compared to the breakdown voltage of insulation.

### **Surge Arresters:-**

The overvoltage surges can damage electrical equipment and their insulation. Hence, they call for protection against them. One of the equipment which can provide the protection is a surge arrester.

**Surge Arrester:** A surge arrester is a device connected between a conductor and ground, to protect the electrical equipment against high voltage surges. It is also known as a lightning arrester as it provides protection against lightning. The surge arrester diverts the lightning or switching surges from the equipment towards the ground.

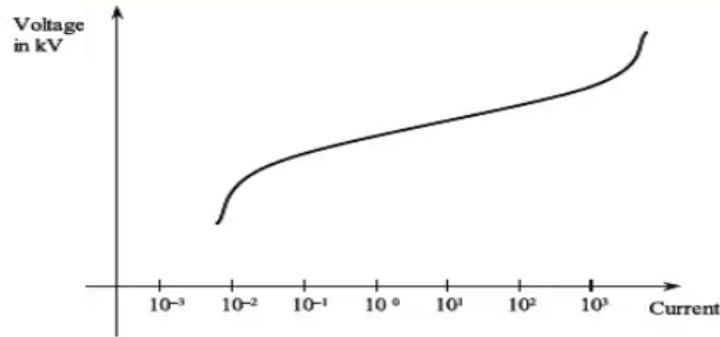
**Principle:** Surge arresters are normally connected across the equipment to be protected. Under normal operating voltage, the impedance offered by a surge arrester is very high. Hence, as the current always chooses a low resistance path, equipment can perform its normal function. When an overvoltage takes place, it causes the drop in the impedance of the surge arrester. Thus, the flow now will be through surge arrester rather than the main path i.e., electrical equipment. Thus, saving the equipment from the overvoltage surges. As soon as the overvoltage surge vanishes, the impedance of the surge arrester is regained back. Thus, it can be said that a surge arrester offers high impedance to low voltage surges and low impedance to high voltage surges. Arresters are very fast acting devices with reaction time of around  $1/10^9$  of a second.

There are basically two types of surge arrester designs.

1. They are gapless arresters
2. Zinc Oxide (ZNO) arresters.

Due to high energy dissipation in D.C surges, mostly ZNO arresters are used as they have high energy absorbing capability.

The V-I characteristics of ZNO arresters are shown in figure below.



**Figure: V-I Characteristic of Zinc Oxide (ZNO) Arrester**

At normal operating voltage, the current flowing through the arrester is less than a few milliamperes and at twice the normal operating voltage, the current through the arrester reaches thousands of amperes. This property helps it to eliminate series connected spark gaps. Above a particular voltage level, the characteristic becomes almost flat. Thus, the characteristic of an arrester can be precisely selected keeping in mind the insulation withstand capacity of the equipment to be protected.

The surge arresters should possess the following properties.

- The material should be stable during the discharge and after the discharge.
- Arresters should have accurate protective characteristics, below the voltage withstand capability of protected equipment.
- It should have enough ability to discharge the current surge and dissipate the energy in the surge causing no effect to the protective characteristic.

In many applications, instead of using a single column of discs, multiple columns of discs are used, which are connected in parallel. They operate one after the other in a sequence. This type of arrester is made by selecting discs in such a way that voltage for each column is the same at a predetermined current.

### **Advantages**

1. They are able to withstand severe stresses such as overvoltages.
2. They have the capability of handling high energy inputs.
3. They are robust.
4. No maintenance is required.

## Smoothing Reactor:-

A smoothing reactor is a high inductance coil, connected in series with the converter to reduce the ripple current on the D.C side of the system.

### Necessity of Smoothing Reactor

A smoothing reactor is a very crucial component in a HVDC system. Basically, the D.C current from the rectifier has superimposed harmonic components called ripple. As the smoothing reactor is connected in series with the rectifier, whole load current flows through it. The smoothing reactor being an inductor with high value provides high impedance to the harmonic currents. Thus, their magnitude is reduced and current becomes smoother. Due to high inductance, the current stores

high energy  $\left( e = \frac{1}{2} LI_d^2 \right)$  in the coil.

Due to the property an inductor possesses that the current in it cannot change instantaneously, pulses and fluctuations in the waveform are smoothed.

A smoothing reactor serves the following functions

1. Serves as a buffer between the converters and the D.C lines.
2. They decrease the harmonic voltages and currents in the D.C line.
3. They smoothen the ripples in the D.C current. They reduce the commutation failure in inverters.
4. They limit the crest current due to the occurrence of short circuit on D.C lines.
5. Consequent commutation failures in inverters are prevented using smoothing reactor by reducing the
6. rate of rise of direct current in the bridge.
7. They reduce the requirements of A.C and D.C filters.
8. They reduce the steepness of current and voltage surges coming from the D.C line. Thereby reducing
9. the stresses on the converter valve and valve surge arresters.
10. They reduce the current transients generated during abrupt changes in D.C power flow.

## **D.C Breakers:-**

Depending upon the variables of interest the D.C circuit breaker are classified into four types. They are,

1. Voltage capability
2. Current capability
3. Energy capability
4. Switching time.

**1. Voltage Capability:** The voltage capability of a circuit breaker is related with two kinds of parameters. The first one is the voltage during the interruption process whereas the other one is the voltage during steady-state operation and the transients of the system. By using the combination of converter control and isolators with circuit breakers, the requirements of breaker voltage can be maintained at lower levels. But, this combination does not yields good results. However, the best performance can be achieved in terms of lower energy absorption and energy switching time with high permissible voltage.

**2. Current Capability:** During faulty conditions, the currents will be higher than the normal rated currents, such currents are brought down below rated level by controlling the converters in the circuit.

**3. Energy Capability:** The energy capability of a circuit breaker depends upon many factors such as, inductance, converter current and voltage, voltage of the circuit breaker and the duty cycle. However, to obtain required energy capability, a series connected modules are employed.

**4. Switching Time:** The switching time of circuit breaker depends upon the time requirement to generate a trip signal, to separate the contacts in main circuit breaker, to commutate current to Z, to commutate current from Z to R2 etc. However, the time required to generate a trip signal is kept small, usually about 2 ms and the time required to separate the contacts in main circuit breakers is maintained around 10ms. By using charged capacitors in the commutation circuit, the time required to commutate the current to Z and further to Ra can also be reduced.

The fault clearing is one of the basic applications of D.C circuit breakers. However, in a two

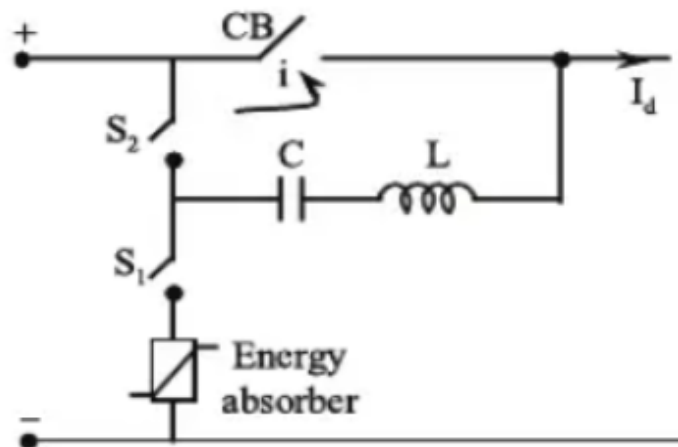
terminal D.C systems, switching times circuit breakers are employed to feed parallel D.C. lines, converters and to transfer current from ground to metallic return during mono-polar operation.

### Principle of Current Interruption in D.C Circuit Breakers

The major problem with D.C circuit is the absence of natural current zeroes unlike in A.C circuits, where we have natural zeroes so that the arc is quenched resulting in satisfactory operation of circuit breaker. The other problem in D.C circuit is very high energy stored in the reactor. When the circuit breaker contacts open, an arc is drawn and it is very much necessary that this energy should be dissipated to interrupt the arc current. This arc burns until total energy is dissipated and by this time, circuit breaker gets damaged. Then how to interrupt this current? The answer is by creating artificial zeroes in the D.C current waveform.

There are basically two types of commutating circuits to create such artificial zeroes. They are active commutating circuit and the other being passive commutation circuit.

The circuit diagram for an active one is shown in figure (1) below.



**Figure (1)**

The arrangement consists of a circuit breaker, commutation circuit consisting of capacitance and an inductor through a switch  $S_2$  and energy absorber through switch  $S_1$ .

During the normal operation, circuit breaker CB and switch  $S_1$  remain closed. The capacitor C charges up to the maximum value of voltage available i.e., the voltage, through energy absorber. To interrupt the circuit current  $I_d$  switch  $S_1$  is opened and switch  $S_2$  is closed by the operating mechanism. Now, the capacitor starts discharging through the commutating circuit and CB. Due to the discharging

of capacitor through L, an oscillatory current sets-up resulting in several artificial current zeroes. Finally, the CB gets opened at any one of the artificial zeroes that are created.

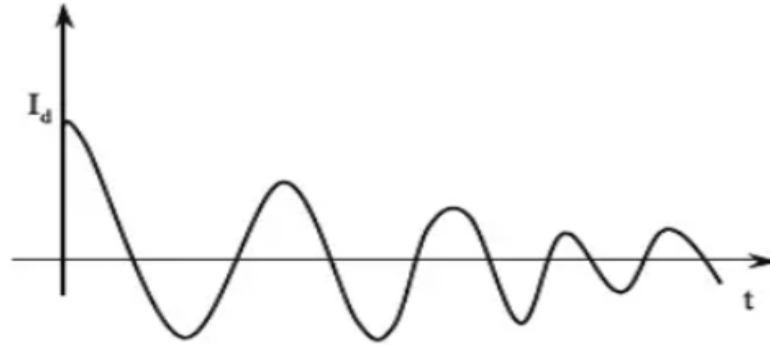


Figure (2)

Another type of arrangement for creating artificial current zeroes is shown in figure (3). Here the current  $I_c$  is interrupted by diverting it to the capacity and consequently the amount of current to be interrupted by the breaker gets reduced. Initially the capacitor is uncharged. When the circuit breaker CB opens then the purpose for which capacitor is placed takes place i.e., diversion of current to the capacitor and consequently reduction of the current which is to be interrupted takes place.

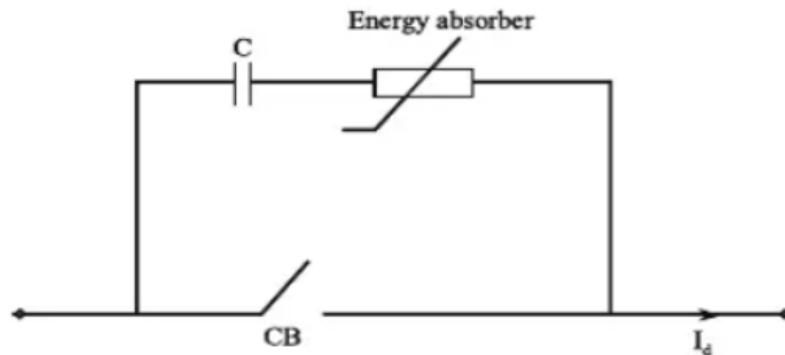


Figure (3)

### Types of Circuit Breakers:

A circuit breaker is a device which protects the electrical equipments of a power system from over-voltages and over currents by breaking the circuit under fault condition and hence stopping the fault current to flow through the equipment.

There are various types of circuit breakers, whose classification depends on the converter control, timings of the breaker and TRV capability. They are,

1. Type A HVDC breaker
2. Type B HVDC breaker.

## **1. Type A HVDC Breaker**

- (i) It is a very fast acting circuit breaker.
- (ii) It does not depend on converter control to bring down the D.C. voltage.
- (iii) It has high voltage and current capabilities.
- (iv) The breaker reduces the fault current before it reaches its peak value.
- (v) This breaker is very complex and costly.
- (vi) The operating time of this circuit breaker is less than 15 ms which is less than A.C circuit breaker.

## **2. Type B HVDC Breaker**

Type B circuit breakers are not fast acting like type A breaker. They depend on the converter control action to bring down the value of fault current. Type B circuit breakers are further classified based on the Transient Recovery Voltage (TRV) withstand capability as,

- (a) Type B1 circuit breaker
- (b) Type B2 circuit breaker.

### **(a) Type B1 Circuit Breaker:**

1. This breaker has full TRV capability and full voltage capability but it has less current interruption capability. This breaker takes much more time compared to type A but lesser time compared to B2.
2. This circuit breaker operates after the fault current is reduced to a lesser value by converter control.
3. This breaker is simpler and cheaper compared to type A breaker.

### **(b) Type B2 Breaker**

1. This breaker has reduced TRV capability, voltage capability and current capability.
2. This breaker takes more operating time among all the breakers.
3. It operates after the fault current is reduced to a very less value by converter control
4. This breaker is simpler and cheaper among all the breakers.

There is another type of circuit breaker called Metallic Return Transfer Breaker (MRTB).

### **Metallic Return Transfer Breaker (MRTB)**

1. It is based on the principle of artificial current zero.
2. MRTB circuit breaker is used in bipolar HVDC systems in one of the two terminal stations.
3. The bipolar mode is changed to monopolar mode if there exists faults on any one of the poles.
4. It is highly recommended that while transfer of bipolar mode to monopolar mode, there should be no interruption of flow of power.
5. When a fault exists on any pole, converter valves of that pole are blocked by thyristor control and consequently the pole gets blocked.
6. The circuit is deenergized by changing the mode from rectifier to inverter and the fault is left to deionize. After some time, the line is energized.
7. In case, the fault still remains, the circuit is again deenergized. If the fault vanishes, the line is energized and normal bipolar service is allowed.
8. If the fault continues, the operation in monopolar mode takes place with other healthy pole resulting in earth return.
9. However, if the fault takes place in the converter pole, monopolar operation with two live poles is carried out and no earth return takes place.

### **Importance of corona loss in dc transmission:**

The phenomenon of hissing sound, violet glow accompanied with the production of ozone gas due to the ionization of air surrounding the conductor, when the voltage gradient exceed a particular value is called corona. In D.C transmission system, corona is related with field distribution rather than surface stress. When corona occurs in a D.C. transmission system, then due to the discharge a current pulse is generated resulting in increase in power loss and causing in radio interference, television interference and audible noise.

In a D.C. transmission system, if,

V = Pole to ground voltage

n = Total subconductors

r = Radius of each conductor

K = Coefficient of conductor surface

g = Maximum gradient of conductor surface

$\delta$  = Relative air density

$$g_0 = 22.8 \text{ kV/cm}$$

H = Mean height of conductor

S = Spacing of pole.

$$K = \left(\frac{2}{\pi}\right) \tan^{-1}\left(\frac{2H}{S}\right)$$

Then reduction in power of the D.C. transmission system  
i.e., power loss due to corona is given by,

$$P_{\text{corona}} = (2VK + 2V) K_c nr^2 \left(\frac{g - g_0}{4}\right) \times 10^{-3} \text{ kW/circuit-km}$$

The above expression gives corona loss under normal (fair) weather conditions but in rainy weather conditions this loss in the D.C system increases by a factor of 10 to 1. At the time of conductor design, it is very important to consider the corona inception voltage. Under fair weather conditions the corona inception voltage must have 25% of margin above the surface voltage gradient at the maximum value of operating voltage. Severe radio interference due to corona take place if this margin is 0% under bad weather conditions. If the corona losses are not limited to 5 kW/km in a D.C transmission system under bad weather conditions, then there would be a high power loss in the line route of the D.C system resulting in reduced power at the receiving end. Therefore, at the time of conductor design, It is very important to consider the corona losses.

### Radio Interference

Radio interference is also known as radio influence. It occurs in the band region of 0.5 to 1.6 MHz. In HVDC lines, the effect of radio interference is more predominant in positive conductor rather than in negative conductor. It is expressed in millivolts per meter or in decibels above  $1\mu$  V/m. Mathematically it is given as,

$$RI = 25 + 10 \log n + 10 \log r + 1.5 (g - g_0)$$

Where,

$n$  = Number of sub-conductors

$r$  = Radius of each sub-conductor in cm

$g$  = Max. conductor surface gradient at operating volt age (kV/cm)

$g_0 = 22 \delta$  (kV/cm)

$\delta$  = Relative density of air.

In negative conductors, the value of radio interference is lower by 20db. However, in bipolar links, the radio interference is symmetric about the positive pole and attenuates inversely as the square of the distance from the conductor. Upto 50 meters and inversely as the distance greater than 50 meters.

### Television Interference

The television interference is caused due to sparking. It occurs in the VHF band (30-300 MHz) and UHF band (300 MHz - 3000 MHz). In D.C. lines, it is mainly caused, due to ion currents. During the bad weather conditions the TVI is more severe. However, during regular rains, the ionized paths get shorted, vanishing the sparking, which further vanishes the television interference. The empirical formula for calculation of TVI is given as,

$$TVI = RI - 20 \log_{10} \left[ f \left( 1 + \frac{(R/H)^2}{(15/H)^2} \right)^{1/2} \right] + 3.2$$

### Audible Noise

The portion of the acoustical energy spectrum that lies in the sonic range is known as audible noise. It is generally expressed in decibels. Mathematically, it is given as,

$$db = 20 \log \left( \frac{P_S}{P_R} \right)$$

Where

$P_S$  = Sound pressure level

$P_R$  = Reference pressure level.

The positive polarity conductor is the primary source of an audible noise. The distress produced by an audible noise varies linearly with the conductor surface voltage gradient. In converter transformers, the effect of audible noise is negligible. It is because of the presence of harmonics, which counter balances the audible noise, at lower flux densities in core.