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Circuit Breakers: An Overview of Design, Pros & Cons of Operation and Applicability

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Abstract

Circuit breakers are of prime importance as these safety devices are instrumental for proper working of electrical supply network. These devices perform the vital duty of giving protection against over-currents, short circuits, and other electrical malfunctions. These are the true super gadgets working and playing a crucial role behind the scene, the real attentive attendants of the electrical circuitry of the manufacturing and industrial sector besides that of malls, schools, colleges and offices and residential areas. This will not an exaggeration to say that in the domain of electricity network, it's always better to be safe rather than repenting later when a mishap occurs. This review throws light on different types of circuit breakers, each designed to perform a specific task, the pros and cons associated with their functioning and applicability.

Key Words: Circuit Breaker, Arc, quenching, dielectric strength, fault current

1. Introduction

The history of fuses dates back to1864, with the deployment of fusible materials i.e. thin metal wires or foils to safeguard telegraph stations from lightning strikes and protecting lighting electrical networks in the year 1864. In 1890, Thomas Edison, got the first fuse, an ordinary gadget, made up of metal having low melt temperature, patented [1]. As soon as current jumped beyond safety limits, the wire melted, breaking the circuit.

When technology was improving at an unpresented speed, in 1924, we find the entry of a smarter counterpart of fuse, the circuit breaker (CB), which was capable of interrupting current through a circuit without self-immolation. Thus in the year 1920, Hugo Stotz and Brown,

Boveri and Cie [2] made available circuit breakers, devices capable of resetting after tripping, giving electrical systems a lease of life. Electrical control panels equipped with circuit breakers, now a days are the back bone of manufacturing units. In the absence of preventive set up, equipment machinery and raw material worth billions can turn into smoke and ash within seconds. Fuses and circuit breakers thus, play role of saviors of electrical systems, continuously supervising and ensuring that overloads, short circuits, and electrical fires do not occur. These are the quick responders, acting promptly to save the whole electrical network. CBs a sort of firefighters of the electrical domain, always ready to handle a spark before it engulfs men and materials. Circuit breakers have welcomed the digital age with open arms. Smart and intelligent circuit breakers now come equipped with sensors and communication facilities, giving real-time updates about the electrical well-being of the system. It's like hiring a healthcare provider continuously monitoring and taking corrective measures.

A CB is a switching device that promptly comes into action, in case of short circuit/over current condition, to save an electrical circuit from burnout and/or damage. It immediately breaks down the path whenever it senses a large draw of power due to fault current caused by overloading. It is capable of manually breaking open the circuit for repair or fault elimination. Thus it can operate with safety and can open/close the electrical circuit to safeguard it from further problems. The operational aspects that a CB is supposed to possess are described in Fig.1[3].

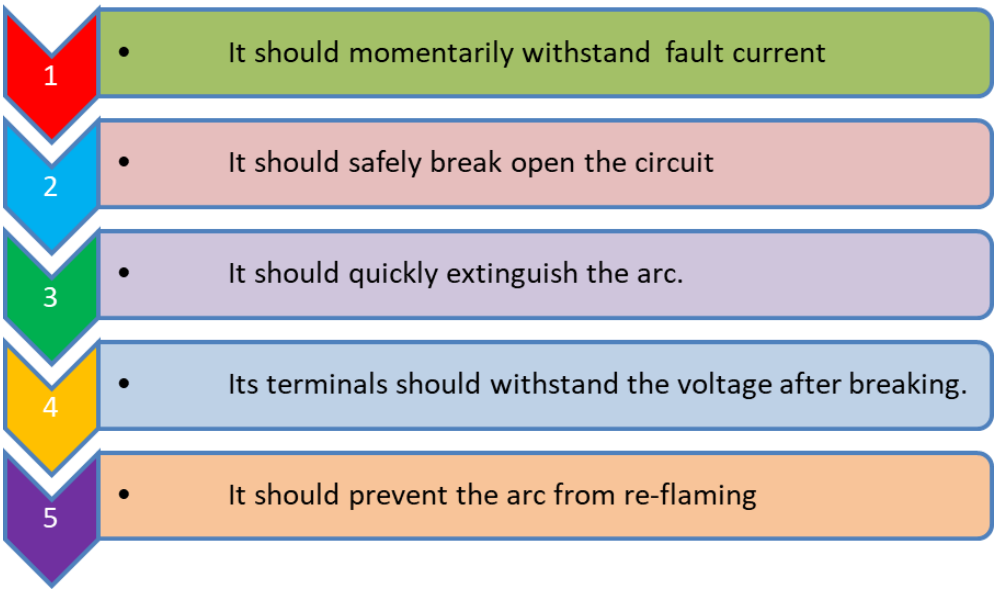


Figure.1 Operational aspects of a circuit breaker

2. Media and techniques employed for Arc quenching

An arc in a circuit breaker is invariably generated when the contacts tends to separate due to a fault condition and load is present in it. When it happens, the medium present in the vicinity of

contacts is immediately ionized due to sudden rise in temperature. This forms a resistance free passage for the current despite the contacts are in separated position at this moment. This arc if left unattended can cause explosion and damage the circuit breaker besides creating big fire hazard. A multi-faceted approach is thus required to handle the arc created during the switching of the circuit under fault condition.

2.1 Media employed for Arc quenching

The electrical arc tries to maintain the current flow through the electrical circuit at the time of break. It must be discontinued with immediate effect and the arc must be promptly extinguished to ensure health and safety the circuit breaker besides other devices connected with circuit at the time of occurrence of fault. Depending upon the type of circuit breakers, different insulating or dielectric materials are used to extinguish arc and these are shown in Fig. 2.

2.2 Techniques employed for Arc Extinction

Cooling: The heat generated from arc raises the temperature of the surrounding air causing ionization of its molecules thereby reducing the resistance. Cooling the arc will recombine the ionized molecules to recombine bringing air back into its normal state and enhance the dielectric strength of the medium. Thus increased resistance of the medium, diminishes the current, resulting in arc extinction.

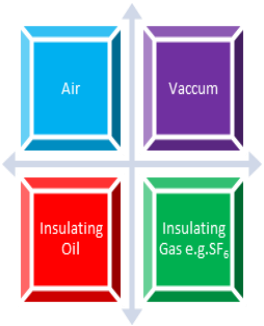


Fig. 2 Dielectric materials used in circuit breakers

Enhancing the length of arc: The arc length is in direct proportion to the potential difference. Enhancing the length of the arc by moving the contact terminals apart will raise the potential difference required to sustain it. Thus it gets extinguished.

Air Blasting: In this process an air blast from a high pressure air chamber is directed toward the arc. The ionized air molecules immediately get replaced with non-ionized ones possessing

better dielectric strength. Consequently, the resistance increases abruptly, thereby decreasing current finally leading to quenching the arc.

Diminishing cross-sectional area of arc: Another method is diminishing the cross-sectional area of arc by decreasing the contact sizes. Therefore, the voltage required for arc gets raised and it is extinguished.

Deflecting arc magnetically: In this process, a magnetic field is utilized to deflect the arc. it shifts the arc towards a section of the circuit breaker where it is cooled off and extinguished.

Bifurcating arc: In this method, the arc is bifurcated into several arcs by introducing multiple contacts over the span of the terminal. The arc thus gets splitted in large number of small arcs in series thereby increasing its length and hence resistance. Therefore, current flow is reduced and eventually arc is extinguished.

Zero current quenching: This is the most important method used in the AC circuit breaker. There are zero current amplitudes during AC cycles. The circuit is opened at the exact point of zero current. It helps in restraining the growth of arc.

Using charged capacitor in parallel: This technique is used in DC circuit breaker as there are no natural zero currents. Thus, an insulator and charged capacitor is used in parallel to generate an artificial null current in circuit to extinguish the arc.

3. Classification of Circuit Breakers:

A circuit breaker is essential for every electrical circuit to safeguard it from any kind of damage or mishap. Circuit breakers are fabricated by keeping in mind, voltage it is required to handle, the type of current involved i.e. AC or DC, size and design consideration, installation venue and medium used for suppressing flow of current to quench arc.

There are several types of circuit breakers that are classified depending upon various characteristics [4]. The flow chart shown in Fig. 3 exhibits the classification of circuit breakers.

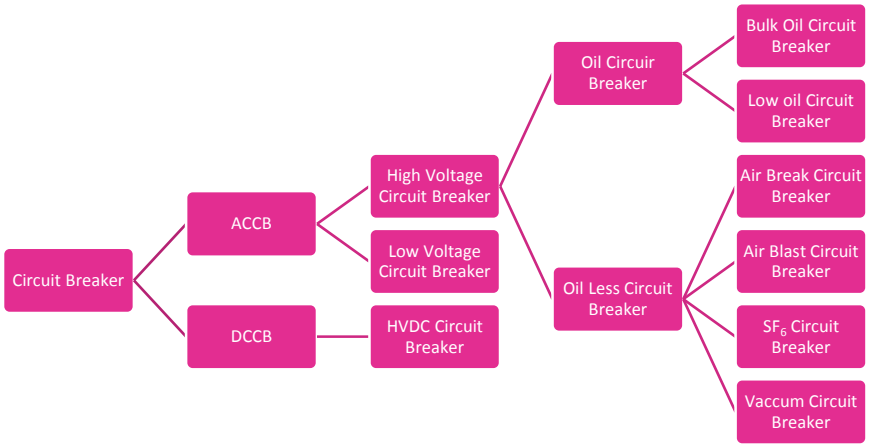


Figure. 3 Classification of circuit breakers

CBs are of two types;

- Alternating Current Circuit Breaker (ACCB)
- Direct Current Circuit Breaker (DCCB)

In the present study only ACCBs are being explored.

3.1 ACCB

In case of AC voltage as well as current crosses the zero value several times in a second depending upon the frequency of the signal. Electrical energy value at zero magnitude is null which may be used to cut off the circuit. Circuit breakers employed for AC are quite distinct from DCCBs. The repeated zero crossings in AC extend several situations within a second for an arc to extinguish on its own. The Magnitude of the arc is in direct proportion to the value of the voltage involved and depending upon the magnitude of voltage the Circuit breakers are classified as Low Voltage CBs and high voltage CBs. Low voltage arcs are easy to handle, however, high voltages arc need a more elaborate and advanced system to suppress it and hence these circuit breakers need to explored in detail.

3.1.1 High Voltage (HV) Circuit Breaker

High Voltage AC Circuit Breaker Generally, voltage is considered high if it exceeds 1kV. Such voltage has a capacity to initiate an arc that tends to be un-extinguishable [5]. Circuit breakers employed for breaking and resuming contacts at high voltages are referred as HV circuit breakers. HV circuit are of two types i.e. oil circuit breaker and oil less circuit breaker.

3.1.1.1 Oil Circuit Breaker (OCB)

In this type of CB, oil, usually transformer oil, is utilized as dielectric medium to extinct the arc. This one is the oldest circuit breaker for handling high voltage and the oil provides superior insulating properties, much better compared to air. Here contacts of CB are dipped in oil which helps to suppress arc generated during the contact separation process. As the thermal capacity of this oil is high, heat created by arc is absorbed by it. When CB contacts are separated inside oil, the inter contact separation starts growing. In the beginning, inter-connect distance is meagre with a super high voltage gradient. Consequently, the oil lying between the contacts begins ionizing and initiates an arc. Arc creates huge amount of heat vaporizing oil in its vicinity, disintegrating it into H_2 gas. The gas formed swiftly, surround the contact increases pressure enormously triggering de-ionization of the medium leading to an increase in dielectric strength (DS) of medium which finally will eliminate the arc at zero level of current. Heat absorption by oil and gas bubbles also supports arc suppression. OCBs are employed for high voltages applications [6].

On the basis of quantity of oil being used in OCBs are of two types viz. bulk oil circuit breaker (BOCB) and low oil circuit breaker (LOCB).

3.1.1.1.1 Bulk Oil Circuit Breaker (BOCB)

This circuit breaker utilizes the filled oil for extinguishing the arc besides insulating the two contacts from earthed part of the circuit breaker. It is housed in a metal enclosure which contains the oil and both contacts are dipped into it. During both breaking and making of the circuit the arc is ignited producing heat which forms gas. This gas occupies the volume inside the tank and the level of oil in the enclosure rises. Thus the enclosure should never be filled with oil up to the brim and space must be left to accommodate the gas formed, to prevent blast. Besides that, vents left for escape of the gas should never be clogged with oil and dirt and these must be cleaned regularly. BOCB are also of two types viz. Single break and double break BOCB. In the former as the name signifies, there is one stationary and one movable contact and during fault current condition, the movable one shifts towards the stationery one igniting an arc which is quenched by the gas formed [7]. In the second one there are dual stationary contacts and single movable contact. The stationary contacts are bound to the enclosure at both ends and are joined to live current wires whereas the movable one is free to move back and forth with the help of an insulating shaft.

During normal operation, the movable contact touches at both the stationary contacts whereas in short circuit/overload situation, the movable one is withdrawn by an electro mechanical device to split the contacts and igniting arcs at both contact points. Here, the arc is cut in two halves. It diminishes its Intensity and finally it is extinguished in the oil bath. The pros and cons of BOCB are described in Fig. 4.

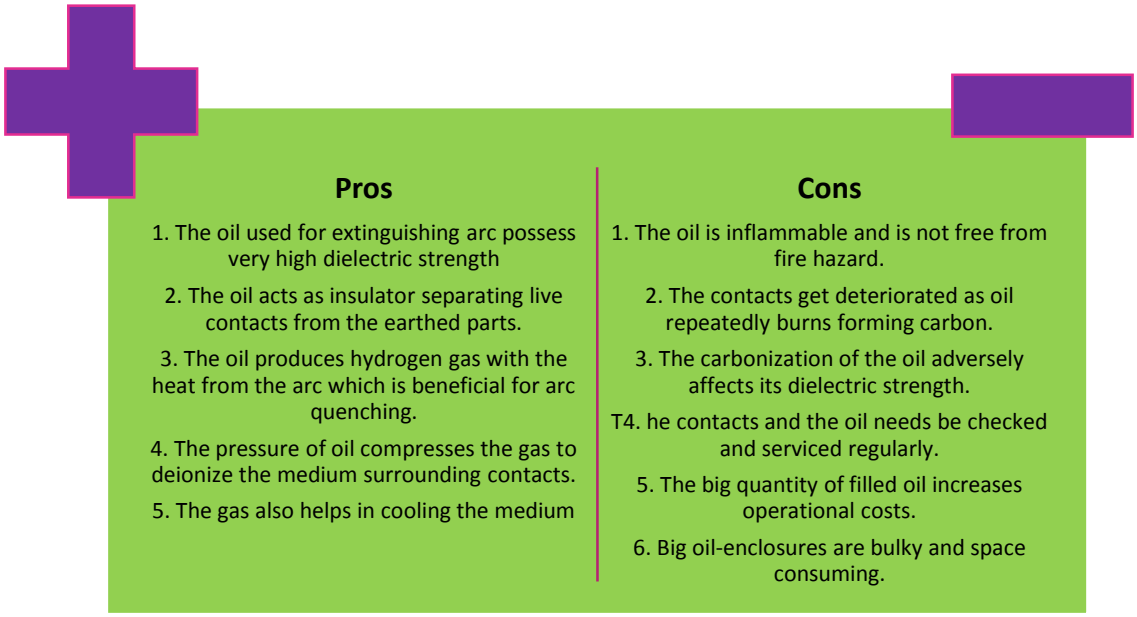


Figure. 4 Pros and cons of bulk oil circuit breaker

3.1.1.1.2 LOCB

As discussed above BOCB involves huge amount of oil for extinguishing arc. The oil being highly inflammable causes fire mishaps restraining their widespread deployment. Contrary to it the LOCB utilizes meagre quantity of oil compared to BOCB. Here the oil is merely utilized for extinction of arc rather than using it for separating the live components from earthed ones.

LOCB possess dual compartments: arc and supporting. The arc compartment is prepared using porcelain and is surrounded by an insulating sheet and oil is filled in it. This compartment is employed for arc extinction purpose. Stationary and movable contacts are housed inside the compartment as in case of BOCB. The supporting compartment made of porcelain is placed over metal compartment and is filled with oil used for insulation. The movable contact makes a movement in up and down direction via an arm mounted in supporting compartment. The movable contact is equipped with a fixed piston which forces oil in upward direction for suppressing the arc.

Under normal operation, contacts touch each other. When fault occurs the electromechanical device generated a field and the movable contact is pulled downwards resulting in arc formation. This arc is extinguished by the pressurized gas generated due to heating of oil surrounding the contact. As soon as the contact is pulled downward, a vent for release of gas opens.

3.1.1.2 Oil less circuit breakers (OLCB)

OLCBs are divided into four categories as shown in Fig. 3.

3.1.1.2.1 Air Circuit Breakers (ACB)

As the name implies, air is used in it as arc quenching medium. It is employed to handle fault current surges due to short circuit/overcurrent up to 15KV 10K Amps. It is preferred over oil circuit breaker as it uses air instead of oil thus reducing fire mishaps.

Contrary to other media, air may be utilized in several ways to quench the arc by adopting procedures like lowering temperature of the arc, enhancing arc length, arc bifurcation and blasting arc with air etc. In ACB, there is double pair of contacts i.e. main made of copper and arcing made of carbon. Under normal operation, the main contacts maintain the normal supply of current. During fault the main contacts open whereas arcing contacts remain closed.

As soon as the main contacts open up, the current will flow through the arcing contacts and hence no arc is ignited and the main contacts are safe. The arc gets generated during the opening of arcing contacts. The arc sweeps in upward direction causing cooling and increase in the length of the arc. Thus the arc is extinguished at zero current. Basically three types of ACBs viz. Plain Air, Arc-Chute and Magnetic Blow Out are employed, depending upon the requirement and feasibility [8].

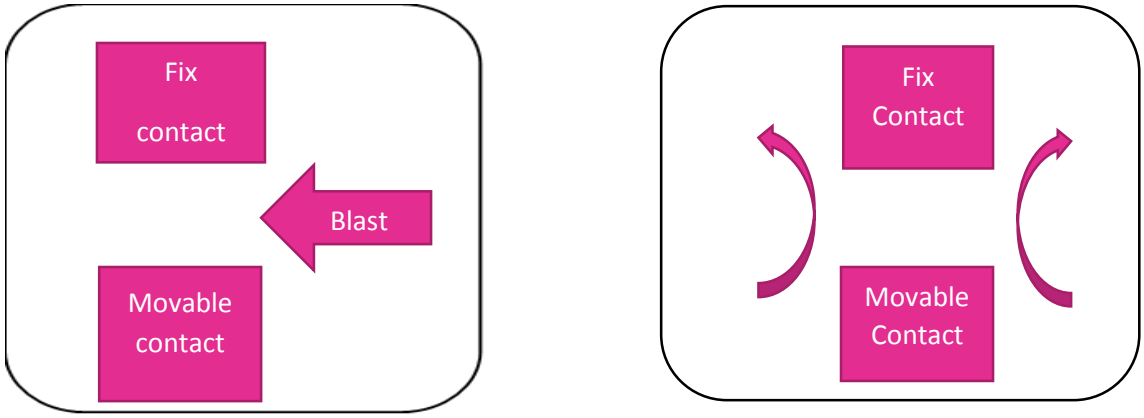
ACB is employed for the circuits involving flow of high current or we can say that ACB has applicability where overload and other fault current up to 6300A flows.

3.1.1.2.2 Air Blast Circuit Breaker (ABCB)

ARCB employ blast of compressed air for the quenching arc. The compressed air is stored in a chamber. This air coming out of the chamber through a nozzle at high velocity immediately quenches the arc. ABCBs are capable of handling voltages as high as 450KV and are used on 220KV lines in power stations. Pressurized air at about 25 kg/cm^2 pressure is utilized as a quenching medium. As nothing has to be paid for air, this types of CB are less expensive with operation at high speed. The two varieties of ARCB normally used are Cross Blast and Axial Blast CB as shown in Fig. 5.

Cross Blast Circuit Breaker: In this, high-pressure air blast is directed perpendicularly to the arc for the interruption.

Axial Blast Circuit Breaker: Here the high-pressure air is directed longitudinally with the arc. It finds best use for EHV as the interrupting channels in porcelain tubes can be fully enclosed.



(a) (b)

Figure. 5 (a) Cross blast and (b) Axial blast circuit breaker

3.1.1.2.3 Sulphur Hexa-fluoride (SF_6) CB

SF_6 is a non-flammable, insulating gas possessing very high electronegativity. It displays high capability to absorb electrons. Under Overload/short circuit conditions whenever arc gets ignited between the contacts the heat ionizes the medium and large number of free electrons are generated. These free electrons are absorbed by SF_6 molecules forming negative ions which possess much larger mass as compared to free electrons. Consequently, mobility of charge carriers gets diminishes. This improves DS of the medium, suppressing arc. The SF_6 has reportedly possess 100 times better insulation compared to air and thus have far better arc suppressing ability. The SF_6 however, is very costly. Although, SF_6 itself is not toxic yet the gases it on absorbing heat, are toxic and the emission of these is the environment is detrimental. Thus, a closed enclosure is employed for this CB where the product gases reunite after each operation. The whole system is programmed to self-monitor the pressure that is in direct proportion to its dielectric strength. Non-Puffer, Single Pressure Puffer and Double Pressure Type are the three different types of SF_6 Circuit Breaker are in operation. In non-Puffer SF_6 CB, gas under pressure is housed in an enclosure whereas the arc extinction is carried out in interrupter unit which has movable and stationary contacts which are designed in the shape of hollow cylinders [9]. The stationary contact possesses arc horns whereas the movable one has holes for pressurized gas to get released. Non-Puffer SF_6 circuit breakers were employed when these were discovered. These days improved and advanced version of this is used which is installed with a puffer cylinder. Various pros and cons of SF_6 CB are listed in Fig. 6.

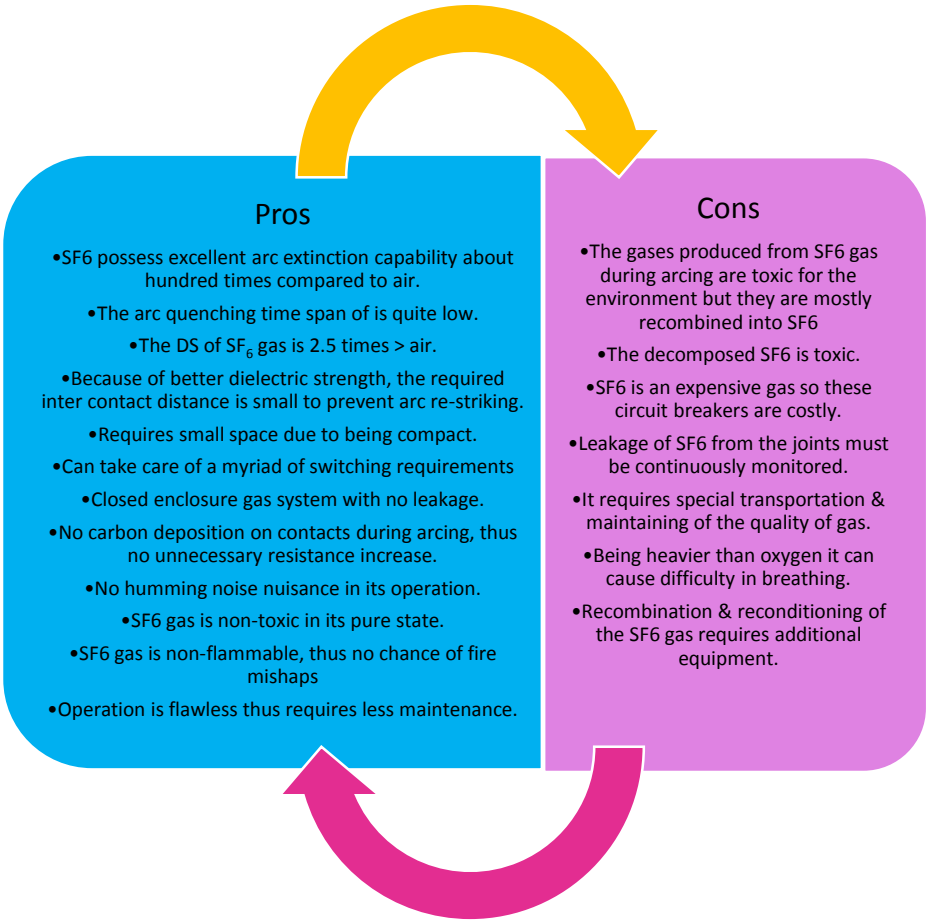


Figure. 6 Pros and cons of SF_6 circuit breaker

3.1.1.2.4 Vacuum Circuit Breaker (VCB)

In VCB vacuum is created in the enclosure housing the contacts. As vacuum has very high DS it preferred over any other medium. Due to its high dielectric strength, VCB allows even meagre gap between its contacts for successful operation. The pressure inside VCB lies between 10^{-7} to 10^{-5} Torr, which is suitable for handling voltage ranging from 22 kV to 66 kV.

The switching operation and interruption of arc takes place inside a closed enclosure known as Vacuum interrupter usually made up of a ceramic material. It consists of stationary and moving contacts circled by an arc shield which is employed for preserving dielectric strength of the vacuum by restraining deposition of the ionized metallic particulate matter on the inner side of the enclosure. The moving contact is connected to a controlled system using a bellow which seals the vacuum enclosure and ensure that no leakage takes place [10].

During a fault situation, the electromechanical actuator moves the contact and the circuit is tripped. During contact separation process formation of metal vapours takes place igniting an

arc. At the time of zero current, metal vapours condenses on contacts and dielectric strength of the medium is regained. As now the contacts are apart and vacuum is reestablished the probability of re ignition of arc is zero. As the arc is created because of the ionization of the contacts, choice of arc metal is of paramount importance plays a pivotal role for ensuring a long life performance of VCB. Hence, VCB contact material must possess qualities such as high electrical conductivity to prevent overheating during operation, high thermal conductivity to dissipate heat generated during arcing, high arc temperature withstanding strength. The contacts thus usually are made of copper-bismuth, copper-lead, and copper-chromium alloys. Vacuum Circuit Breaker or VCB is used for Medium Voltage applications. The pros and cons of VCB are mentioned in Fig.7.

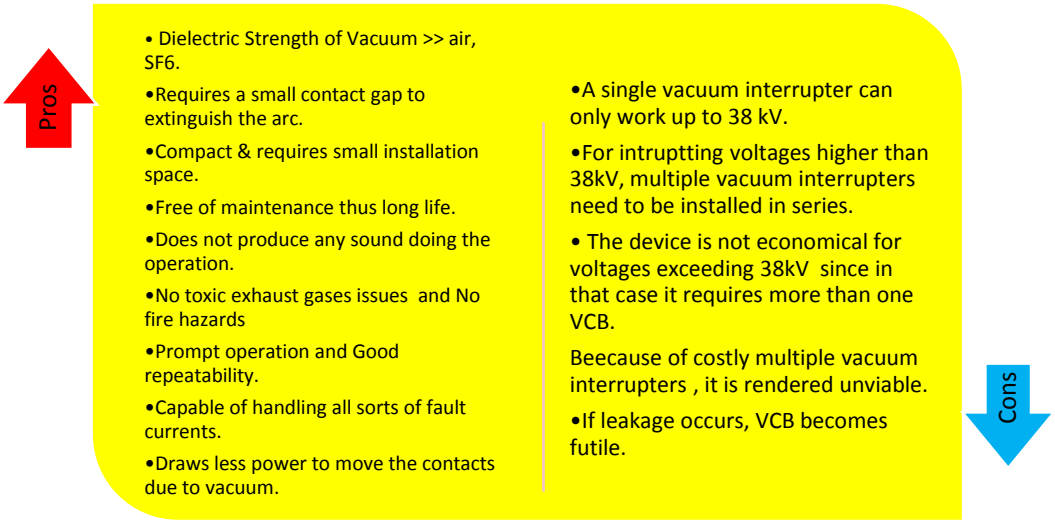


Figure. 7. Pros and cons of VCB

4. Conclusion

Circuit breakers are the most vital parts of electrical installations, standing as alert guards against any electrical faults. The wide range of circuit breakers available with specific features to meet various demands makes choice for an appropriate type of circuit breaker much easier, depending on the specific requirements and conditions of an individual. More research, however needs to be done to fabricate circuit breakers which are lightweight, occupies less space, easily portable, have quick response, pose less fire threats, more environment friendly besides being less expensive. Innovative materials including nano materials must be explored to develop circuit breakers possessing these qualities. In the light of ongoing research and developments going across the globe, it is expected that new circuit breakers with smart and intelligent features will continue to emerge to meet out the ever changing demands of modern and sophisticated electrical systems without compromising quality, reliability and safety features.

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