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ORIGINAL RESEARCH ARTICLE

APPLICATIONS OF VARIOUS TYPES OF CIRCUIT BREAKERS IN ELECTRICAL POWER SYSTEMS: A REVIEW

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ABSTRACT

This paper presents a review on the applications of various types of circuit breakers (CB) used in electric power transmission and distribution. Circuit breakers are majorly classified under direct current (DC) or alternating current (AC) system. It shows that the most suitable way of classifying circuit breakers is on the level of voltage rating which is broadly grouped under direct current (DC) or alternating current (AC) circuit breakers. However, reviewed literatures did not clearly distinguish the respective applications of the different types of circuit breakers as applied to DC and AC power network. The DC circuit breakers which comprises of mechanical, solid-state and hybrid breakers are mostly applied in domestic and industrial applications that employ the use of direct current (DC) especially in high voltage direct current (HVDC) network system for the protection of electrical devices. AC circuit breakers are grouped in high voltage and low voltage forms. The low voltage CB comprises of miniature and molded case circuit breakers used majorly in domestic and commercial installations. The high voltage circuit breakers are further subdivided into oil and oil-less forms. The oil-less CB is made up air, vacuum and sulphur hexafluoride (SF_6) circuit breakers. These high voltage circuit breakers are majorly applied in high voltage and extra high voltage transmission systems for protection of power system equipment and electrical machines.

1.0 Introduction

Circuit breaker is one of the major power system components in electric power transmission and distribution. A good circuit breaker must be capable of clearing and isolating faulted sections of the power circuit rapidly and clearly (Balan *et al*., 2016). The research on circuit breaker is never ending due to its significance in power system circuits. Circuit breaker is a mechanical device that have the potential of interrupting fault currents by splitting separable contacts and reclosing it after faults clearance, in addition performs the work of a switch. Its purpose is to open and close the network to prevent the effects of fault and to connect/disconnect components of the electrical grid. It can be utilized manually during line maintenance while it is operated automatically during fault on the line (Anderson, 1999; Khan, 2008; Umran, 2016; Obi *et al*., 2021). Under healthy operating conditions, the fixed and movable contacts of the breakers stay closed and will not automatically operate until unhealthy operating conditions occur on the system. During unhealthy (fault) conditions, the relay senses the fault and sends a tripping signal to the circuit breaker for opening of the faulted section. The circuit breaker tripping coils get energized after receiving this fault signal and the movable contacts are tugged apart by some mechanism, thereby opening the circuit on which it protects. When the circuit breaker contacts are tugged apart under conditions of fault, an electric arc is struck between them. The highest value of current that can be interrupted by a circuit breaker without any harm to the system is known as interrupting or rupturing current. The circuit breaker rupturing current sustain until the discharge halts. During healthy operating conditions the contacts are in closed position, whereas during unhealthy conditions the breaker contacts move to interrupt the current flow that give rise to an electric arc between the contacts. This arc generated during the separation of the circuit breaker contacts produces tremendous heat that can result to system damage or to the circuit breaker itself as well as delaying the process of current interruption. The ratings of circuit breakers are in mega volt-amp (MVA), and heavy-duty circuit breakers can break-in some thousand amperes of high short circuit currents (Mehta and Mehta, 2008; Bansal, 2019).

The main functions of circuit breakers in power circuit are to sustain fault current without distortion due to magnetic forces under fault conditions, to switch load currents, to break fault currents as well as operating current. They are employed in the power system to shield it from any unwanted fault by opening or breaking the circuit to interrupt the fault current. They are rated in terms of the number of poles, rated frequency, rated making capacity, rated voltage and current, short-term rating, and operating duty (Hewitson *et al*., 2004; Wadhwa, 2012; Alharbi and Habiballah, 2020).

Some authors have worked on the circuit breakers and its applications to the operation of power system. In Rao and Gajjar (2008), Mayr arc model with steady time parameter and cooling power is applied to develop SF6 breaker model in (PSCAD). It is observed from their results that for the effective interruption of an electric arc, the location of fault should be within the critical length, cooling power should be optimal for the given fault vicinity and the presence of the capacitances across the circuit breaker is required. In Jing and Bing (2014), the characteristics of magnetic instantaneous acting trip in normally low voltage molded case circuit breakers (MCCB) are analyzed using finite element method. The simulation result demonstrates that MCCB has good prospect in optimizing the design and protection performance. Gao *et al*. (2017) compared DC semiconductor circuit breaker and Sulphur hexafluoride (SF6) circuit breaker with transverse magnetic field (TMF) for DC transmission. Their results showed that semiconductor breakers have fast breaking speed, while semiconductor switches may be connected in series and parallel with the high voltage circuit breakers. Different types of circuit breakers and their applications were reviewed by Goh *et al*. (2017) which include Sulphur hexafluoride (SF6), oil, vacuum, air, and DC breakers which made up of solid-state DC and hybrid DC breaker. Chen and Ke (2018) discussed modeling and simulation circuit breaker operated on high voltage system with the aid of power system computer aided (PSCAD). From their results, the current and voltage when the circuit breaker cuts current flow in different positions are primarily harmonious as based on the instituted model of the circuit breaker. Liang *et al*. (2018) investigated on a new synthetic test of direct current (DC) vacuum circuit breaker. They analyzed the breaking process of DC circuit breaker, the basic principle of AC synthetic test and parameters analysis, and also presented a new synthetic test circuit topology of the breaker. Al Mashakbeh (2019) presented a survey on the importance of electrical circuit protection devices which showed that most industries use circuit breakers and fuses as the electrical circuit protection devices for protecting their circuits from different hazardous conditions. Fatigue assessment and ductile multi-body dynamic analysis of 550 kV high voltage circuit breaker was performed by Kim (2019) to predict fatigue life of the circuit breaker. Sedhuraman *et al*. (2019) evaluated the performance of smart intelligent circuit breaker (SICB). Their results showed that SICB can reduce and rectify the pre-fault by itself without human interface. Basic classification of different types of circuit breaker in power system transmission and distribution are reviewed by Alharbi and Habiballah (2020). They classified them based on their operation, voltage level and packaging, and this helps in protecting power system equipment and devices from dangerous fault current. Yang *et al*. (2020) presented the technical growth, mainly the topology, test technology, and technology of protection and control of high voltage direct current (HVDC) circuit breaker and their applications in voltage source converter high voltage direct current (VSC-HVDC) transmission project. Shah *et al*. (2020) presented simulation of hybrid high voltage direct current (HVDC) circuit breaker with super-conducting fault current limiter (SFCL) for fault current limiting with the aid of MATLAB software. From their given results, the current limiting by super-conducting fault current limiter (SFCL) particularly repressed the DC fault current and notably reduced the current interruption stress for superconducting DC circuit breaker components.

From the reviewed literatures, it is seen that the review of different types of circuit breakers as applied to dc and ac power networks were lacking in their analysis. As a result, different types of circuit breakers were categorized under dc and ac networks. Their current carrying capacities and voltage levels as well as their applications to power system network are also noted down.

2. Materials

2.1 Classifications of Circuit Breakers used in Electrical Power Transmission and Distribution.

There are various classes of circuit breakers as applied to power system. They are broadly classified as DC and AC circuit breakers which are based on the type of current they operate on in the power network. In AC circuit breakers, they are classified based on the level of operating voltage, by the location of installation, by means of interruption and by its external design.

As based on the level of voltage operation, circuit breakers are classified as low voltage circuit breakers with operating voltage up to 1 kV and high voltage circuit breakers with operating voltage beyond 1 kV. The high voltage circuit breakers are subdivided into circuit breakers with operating voltage of 70 kV and below, and those with operating voltage of 132 kV and above. All high voltage circuit breakers are categorized in two main categories which are oil and oil-less circuit breakers (Gupta, 2015).

As based on location of installation, circuit breakers can be classified as outdoor and indoor circuit breakers. The major distinction between the two is on the enclosures, casing, and the place of installation. The indoor type circuit breakers are specified to be installed in protected enclosures such as in buildings or protected casing for protection against weather conditions. While the outdoor type circuit breakers do not demand any shielding, protection or casing. They have stronger enclosure arrangements as compared to the indoor type (Wadhwa, 2012).

As based on the means of interruption of fault current on the line, circuit breakers can be classified as oil, air-break, air-blast, vacuum, and Sulphur hexafluoride (SF_6) circuit breaker (Alharbi and Habiballah, 2020).

As based on the design of external structure, circuit breakers can be classified as dead tank and live tank circuit breakers. These are also found to be types of outdoor circuit breakers. The live tank circuit breakers have its enclosures and interrupters mounted above the ground level, while the dead tank circuit breakers have its enclosures and interrupters mounted on the ground (Choonhapran, 2007).

2.2 Types of AC Circuit Breakers used in Electrical Power Transmission and their Applications

There are different categories of circuit breakers used in the transmission and distribution of electrical power.

2.3 Low Voltage Circuit Breakers

These types of circuit breakers are widely applied in domestic settings as well as in industrial and commercial applications. They include molded case circuit breaker (MCCB) and miniature circuit breaker (MCB) (Pierre and Jean-Jacques, 2009; Norazizah and Noramalina, 2019).

2.3.1 Miniature Circuit Breaker (MCB)

The MCBs as shown in Figure 1 are mostly applied for domestic and commercial installations, with operating voltage between 220 and 400 V and current range from 6 Amps to 63 Amps. The current to interrupt cannot be higher than 100 Amp and the interruption characteristics are not usually adjustable. Generally, they are provided with thermal or magneto-thermal devices and the housing cannot be opened to develop any maintenance of the device (Lucius, 2016).

Figure 1: Miniature circuit breaker (JW Tech, 2017)

2.3.2 Molded Case Circuit Breaker (MCCB)

The MCCB as shown in Figure 2 is used in distribution of electric power. It is designed basically to protect electrical circuits and equipment that operates on low voltage below 600 V. It can interrupt currents up to 2500 Amp. Additionally, this device allows to adjust the interruption current. The operational principle is also thermal or magneto-thermal and the components are located inside an insulating molded case. These devices are designed in order not to be opened for maintenance, so the contacts cannot be replaced. All MCCBs are fast enough to restrict the quantity of the prospective current let-through, and some are fast enough to be designated as current-limiting circuit breakers. They can be used in heavy duty applications such as welding machines, protecting generators, protecting motors, protecting feeders and protecting capacitor banks (Das, 2012; Aio, 2013).

Figure 2: Molded case circuit breaker (Global Sustainable Energy Solutions, 2017)

2.4 High Voltage Circuit Breakers

High voltage circuit breakers are specified and designed to interrupt current flow at natural current zero and hold out against the pressure and tension bring about by dielectric on the procedure of interruption. They are applied in high voltage and extra-high voltage transmission systems. They are extremely classified as oil and oil-less circuit breakers. The oil circuit breakers are subdivided into minimum or low oil circuit breakers and bulk oil circuit breakers. The oil-less circuit breakers are sub-categorized as air-break, air blast, vacuum, and sulphur hexafluoride (SF6) circuit breaker (Suwanasri *et al*., 2013; Umran, 2016; Obi *et al*., 2021).

2.4.1 Oil Circuit Breaker (OCB)

Oil circuit breakers are the category of high voltage circuit breakers used in transmission of electrical energy which make use of oil for the extinguishing of arc during the separation of the breaker contact. They consist of minimum or low oil circuit breakers and bulk oil circuit breakers. Low oil circuit breakers operate with minimum quantity of oil which inhibit the interrupting unit in an insulating chamber at the live potential, and sometimes refer to as the live tank circuit breakers due to the oil tank is insulated from the ground. While the bulk oil circuit breakers uses large amount of oil as quenching medium and also for insulating media between earth parts of the breaker and current-carrying contacts, and occasionally designated as dead tank circuit breakers due to the tank is held at earth potential. The contact separation is done under oil which serves as an insulation between the live parts due to its high dielectric strength as shown in Figure 3. As the contact is separated underneath the insulating oil, an arc is struck between them. The quenching of an electric arc during contact separation is made possible by two processes. Firstly, the hydrogen gasoline has excessive conductivity of heat and cools the electric arc, hence supporting the de-ionization of the medium between the contacts. Secondly, the gasoline sets up agitation in the oil and compels it into the space between contacts, thus removing the arcing products from the path of an arc which leads to extinguishing of arc and the circuit current is interrupted. The ratings of oil circuit breakers range from 25 MVA at 2.5 kV to 5000 MVA at 230 kV while they are applied for voltage range of 33 kV to 220 kV and breaking capacities of 1500 MVA to 7500 MVA. The merits of oil as a medium for arc quenching are: it has the ability to cool and flow into the space after current zero and electric arc goes out, assimilation of energy by breakdown of oil, oil presents a cooling surface, while the demerits are the high-value of oil maintenance, reduction of dielectric strength of the oil due to the pollution by carbon particles and high in flammability of the oil (Hewitson *et al*., 2004; Mehta and Mehta, 2008; Alharbi and Habiballah, 2020).

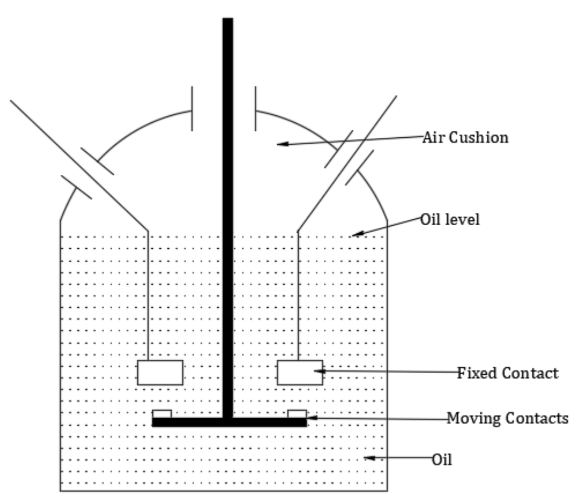

Figure 3: Oil circuit breaker (Bansal, 2019)

2.4.2 Air-Break Circuit Breaker

The air-break circuit breaker is fitted in a chamber that surrounds the contacts which is known as arc chute as shown in Figure 4. It uses air at atmospheric pressure as a means of interrupting the fault current, mostly used in low voltage applications with the high interrupting current. They are applied on the system that operates on the range of 400 V to 12 kV and rupturing capacities of 500 MVA (Gupta, 2015).

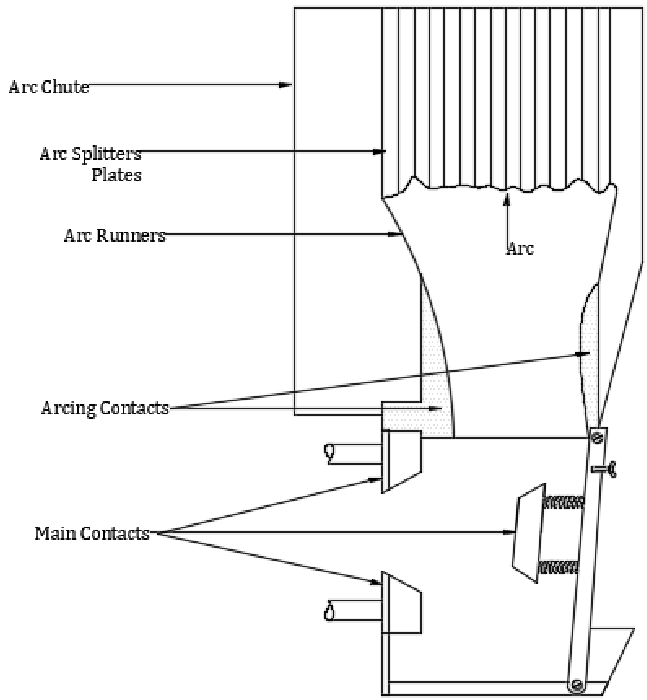

Figure 4: Air-break circuit breaker (Mehta and Mehta, 2008)

2.4.3 Air-Blast Circuit Breaker

This type of circuit breaker as shown in Figure 5 is applied when the system operating voltage is 132 kV and above. They make use of compressed air at pressure of 20 – 30 kg/cm^2 as a means of arc extinguishing during the separation of breaker contacts. They have the following merits: elimination of fire hazard, the regular expenses for oil replacement are avoided, the fault current to be interrupted are independent due to the energy required for the extinction of an electric arc is gotten from high air pressure, short arcing time, consistent breaking time, chemical stability of air, small in size and suitability for repeated operation. Their demerits are: current chopping and restriking voltage, along with high-level noise during the operation and maintenance of the air compressor plant, arc extinguishing properties of the air are inferior, and regular maintenance of the compressor plant which gives the air-blast is required. Air blast circuit breakers are categorized into cross blast, radial blast and axial blast. Figure 5 shows axial blast type of air circuit breaker. Air-blast circuit breakers are applied in low voltage as well as high voltage systems. It is also used for protection of transformers, capacitors, and generators (Bansal, 2019).

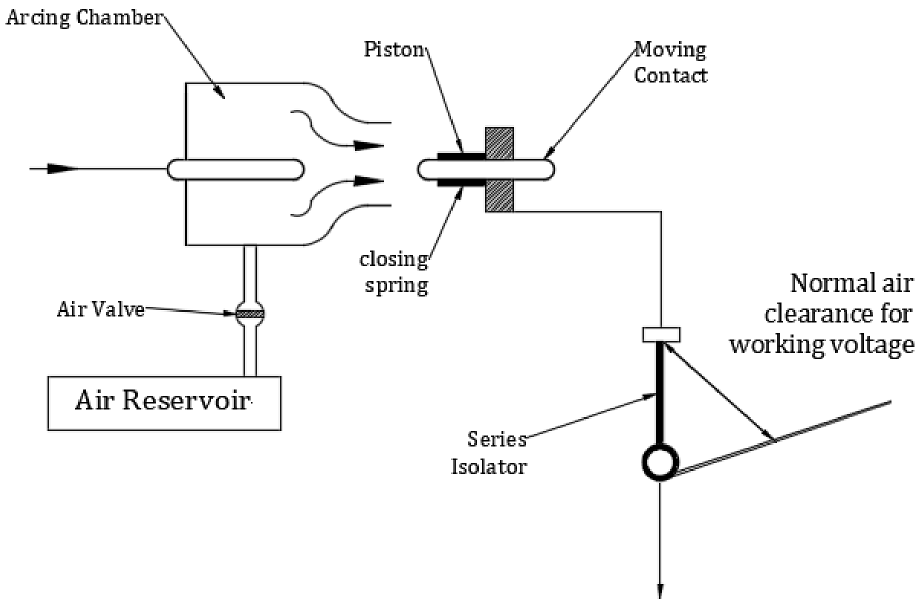

Figure 5: Air-blast circuit breaker (Goh *et al*., 2017)

2.4.4 Vacuum Circuit Breaker

The dielectric strength of vacuum is very much higher than other interrupting mediums thereby it makes use of the higher dielectric strength of the vacuum for arc extinction and the rate of dielectric recovery of vacuum is much faster than that of air. The contact separation and movement is very small, on the order of millimetres instead of centimetres, which makes the role of these breakers and their potential of extinction of an arc very fast. The movable and fixed contacts are set up inside an inalterably shut vacuum interrupter as shown in Figure 6. The process and method of the arc quenching is coordinated by a metal surface phenomenon during parting of their contacts. In other words, the arc is not quenched by the medium of interruption however via the use of metal vapour. The vacuum arc can only be cooled down via the usage of a magnetic field which can move the arc over the contact surfaces. The capabilities of vacuum circuit breakers for fault-current interruption are similar to SF6 breakers. They are available in the medium range of voltage up to about 35 kV and at 25 kV single phase (50 kV equivalent) as dual bottle assemblies for electric traction. Vacuum switches as load-break switches comprising of a series of group of vacuum bottles are obtainable up to 245 kV. These breakers are less bulky, it has high dielectric strength, it requires less power for control operation, more efficient, release of low arc energy, negligible maintenance, low-value, very reliable, compact, and longer life. However, it requires high level technology for the fabricating vacuum interrupters which is costly and also requires supplementary surge suppressor in parallel with each phase for interruption of small magnetizing currents. They are generally applied in capacitor switching, shunt reactor switching, transformer switching and line dropping (Choonhapran, 2007; Khan, 2008).

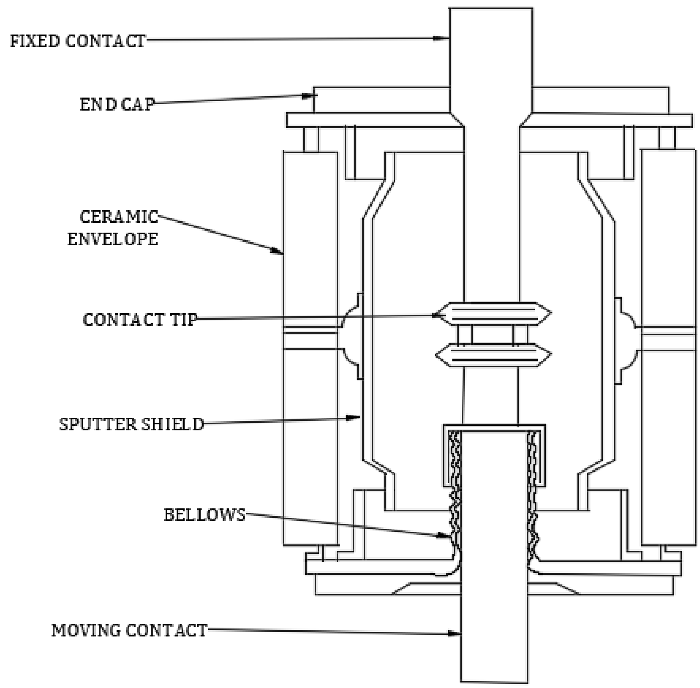

Figure 6: Vacuum circuit breaker (Gupta, 2015)

2.4.5 *Sulphur Hexafluoride (SF_6) Circuit Breaker*

SF6 breakers were developed in the 1960s and quickly set off as the favoured choice for wide areas of high and medium voltage applications. They are made up of single pressure type and double pressure type SF_6 CBs. The contacts of the breaker are opened by the flow of high-pressure SF_6 gas and an electric arc is struck between them as shown in Figure 7. The conducting free electrons in the electric arc are quickly apprehended by the means of gas to form moderately motionless negative ions. This loss of conducting electrons in the arc rapidly builds up sufficient and adequate insulation strength to quench the arc. The dielectric strength of SF_6 at atmospheric pressure is roughly equal to that of air at the pressure of 10 atm. Temperatures in the order of 30000 kelvin (K) are expected to be encountered in arcs in SF_6 and these are, well beyond the detachment temperature of the gas (about 2000 K); nevertheless, nearly all the decomposition products are electronegative so that the dielectric strength of the gas recovers quickly after the arc has been quenched. Filters are made available to ensure the decomposition products are harmless and only a chunk of fluorine reacts with metallic parts of the breaker. The advantages of SF_6 CBs includes: SF_6 gas CBs can control all known switching phenomena, they have a high degree of reliability, it is highly electronegative, SF_6 gas CBs require minimum maintenance, arc reignition is minimized due to the chemical properties of SF_6, contact detachment in SF_6 gas CBs is least due to dielectric strength provided by the high-pressure SF_6, the closely packed design of SF_6 gas CBs significantly minimizes the space demands and costs of building installation, and the lower- and medium-current ratings of SF_6 gas CBs are very economically satisfied by the modular design. While the demerits of SF_6 CBs are the high-value of the SF_6 gas used in the circuit breakers, SF_6 has to be reconditioned after every operation and the high pressure of SF_6 gas will absorb all the conducting free electrons which leads to extinction of the arc. SF_6 circuit breakers comprises single-interrupter SF_6 CB which is applied up to 220 kV, two-interrupter SF_6 CB which is applied up to 400 kV and four-interrupter SF_6 CB which is applied up to 715 kV (Weedy *et al*., 2012; Turan, 2014).

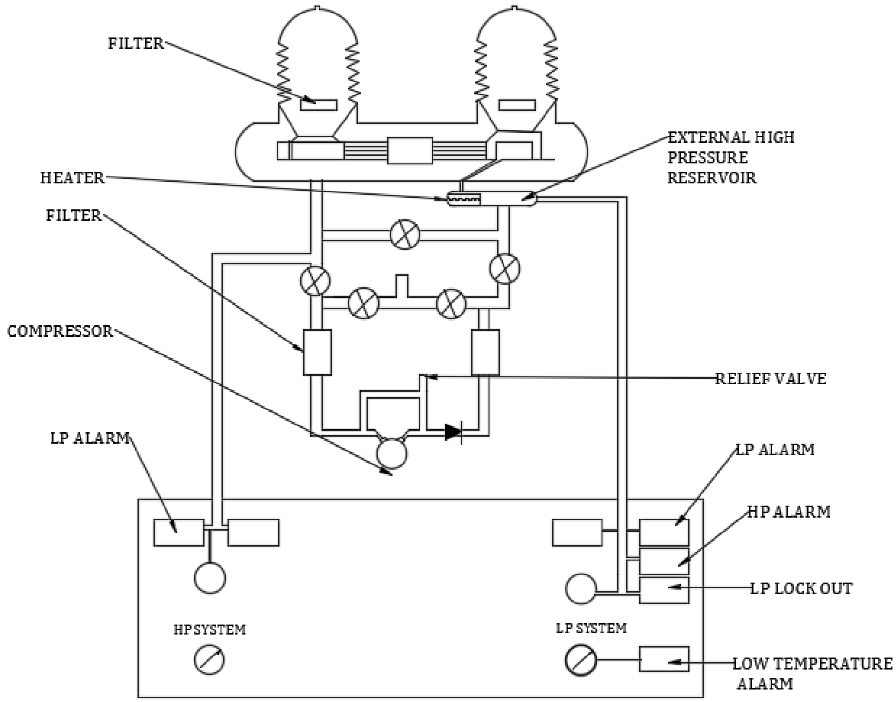

Figure 7: Sulphur hexafluoride circuit breaker (Wadhwa, 2012)

2.5 Types of DC Circuit Breakers used in DC Power Network

The direct current circuit breaker (DCCB) is the key piece of equipment used in high voltage direct current (HVDC) network system for the protection of electrical devices that operate with direct current. (Siemen, 2017; Stanley, 2018). The DCCB comprises solid-state, mechanical and hybrid breakers. The hybrid dc circuit breaker is the combination of solid-state and mechanical circuit breakers (Atmadji and Sloot, 1998; Meyer *et al*., 2005; Yao *et al*., 2019; Zheng *et al*., 2019). The HVDC circuit breaker operates based on commutation principle, giving artificial current zeros. The dc circuit breakers have not commonly been used in HVDC network system because of its high cost, complex nature and redundancy (Rao, 2013). The dc waveform of the breakers does not have natural current zero-crossing point, so the dc arc is more difficult to extinguish than the ac arc (Grieshaber, 2010; IEEE Standards Association, 2010). Therefore, in designing a HVDC circuit breaker, formation of artificial current zero, obviating of restrikes and dissipation of stored energy, are the few issues that have to be solved for maximum optimization and reliable operation and interruption of short circuit current (Shrishti *et al*., 2019). The creation of artificial current-zero is the major problem experienced in extinguishing of arc in dc circuit breakers. This can be successfully achieved by:

i. Connecting a series resonant L-C circuit across the main contact of a conventional circuit breaker as shown in Figure 8. In this process, the main current is interrupted indicating discharge of capacitor C through inductance L and setting up of oscillatory current by the main contact M and supplementary contact S_1, hence, artificial current zeros are produced and the circuit breaker main contact M is opened at a current zero.

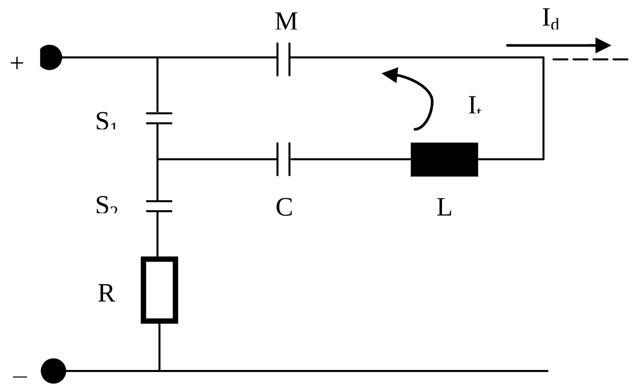

Figure 8: HVDC circuit breaker with series resonant L-C (Norum, 2016)

ii. Diverting the main current I_d to the capacitor C which is initially uncharged as shown in Figure 9. In the process of diverting the main current I_d to the Capacitor C, the breadth of current to be interrupted by the breaker reduces. When the main CB contact M opens, I_d is detracted to the capacitor C, thereby reducing the current to be interrupted by the main contact M of the circuit breaker.

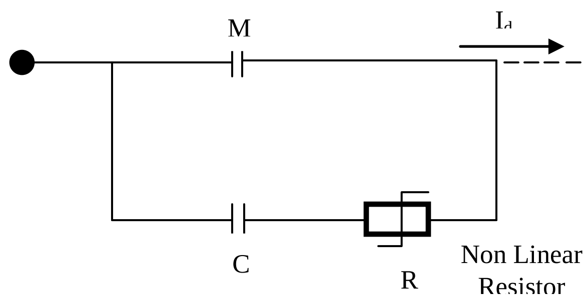

Figure 9: HVDC circuit breaker with non-linear resistance (Zheng *et al*., 2019)

The self-excited oscillation mechanical DCCB utilizes the negative resistance attribute of a dc arc, to allow the LC oscillation arm and the main current arm to conduct self-excited oscillation to give rise to the current zero-crossing points. Hence, the creation of the oscillating current is dependent on the arc properties and if interruption time is unduly lengthy, the short circuit current is hard to interrupt. These type of circuit breakers are widely applied in high-voltage dc power transmission, uninterrupted power supply (UPS), energy intensive industries, renewable energies and energy storage, railway transportation and ships (Kevin, 2007; IEEE Standards Association, 2010; Xiang *et al*., 2014; Gupta, 2015; Xiang *et al*., 2017; Secheron, 2020; Yang *et al*., 2020,).

2.6 Differences in Alternating Current (AC) and Direct Current (DC) Circuit Breaker Applications

Alternating Current (AC) circuit breaker cannot be interchangeably used or applied in Direct current (DC) circuits for some workable basis revealed in this review;

Alternating current (AC) circuit breakers need additional insulation than direct current (DC) circuit breakers. Insulation material in circuit breaker is of utmost importance in circuit breaker efficient operation (Csanyi, 2014; Kong *et al*., 2016).

In AC circuits, current and voltage intersect the zero after every half cycle because of the frequency, magnitude and direction change at time interval. In DC circuits zero cross is unfeasible in view of the fact that neither the current nor voltage has frequency since they are constant, hence DC melts circuit breaker contacts faster (Chan, 2015; Xiang *et al*., 2017).

Direct current (DC) arc is stronger than alternating current (AC) arc because of the steady state status of the electrons that create the arc consequent upon breaking a DC circuit via a circuit breaker. In AC circuit, the applied voltage and current change direction and magnitude thereby relaxing flow of electrons hence, weaker arc is created (Huo *et al*., 2017).

3. CONCLUSION

On the review of applications of different categories of circuit breakers, it is observed that the most suitable way for classifying circuit breakers is on the level of voltage rating which is broadly grouped under DC or AC circuit breakers. It is noted that in the operation of dc circuit breakers, artificial current zero is created by connecting a series resonant circuit with inductor and capacitor across the main contact of a CB and by diverting the main current to the capacitor so that the breadth of current to be interrupted becomes smaller, since there is absence of current zero on dc waveform. The DC circuit breakers are mostly seen in domestic and industrial applications that operate with direct current (DC) and contains additional arc extinguishing measures, while AC circuit breakers are mostly used in low voltage, high voltage and extra high voltage transmission and distribution system for the protection of electrical machines, transformers, capacitors, generators, switching of loads in industrial and commercial settings, and in railway electrifications. The AC and DC circuit breakers cannot be interchangeably applied as they are differently used in AC and DC network respectively.

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