Study on circuit breaking mechanism in modern HVDC power system

Prepared By:

Md. Nayeem Hossain
ID: 181-33-639

Md. Kefayet Ullah Chowdhury
ID: 181-33-669

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Daffodil International University

Dhaka, Bangladesh

DECLARATION

This is to certify that '**Md. Nayeem Hossain**' and '**Md. Kefayet Ullah Chowdhury**' completed their thesis work named "**Study on circuit breaking mechanism in modern HVDC power system**." at the Department of Electrical and Electronic Engineering, Daffodil International University, Dhaka, Bangladesh. The above thesis work, or any portion of it, has not been submitted anywhere for the awarding of any degree, and the research work has been undertaken completely without plagiarism or any violation of research ethics and precepts.

Supervised by:

Md. Rayid Hasan Mojumder
Lecturer,
Department of EEE
Daffodil International University

Submitted by:

Md. Nayeem Hossain
ID: 181-33-639
Academic year: 2018-2021

Md. Kefayet Ullah Chowdhury
ID: 181-33-669
Academic year: 2018-2021

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ABSTRACT

The innovation of high-voltage direct current (HVDC) has sparked a great deal of interest over the last few decades, attributed to the fast development of possible voltage levels, transmission capabilities and transmission lengths. These developments happened in a time when power system applications such as renewable energy production (e.g., energy produced in offshore wind power plants), power trades through asynchronous networks, undersea cables and long-distance overhead transmission lines have increased in popularity throughout the world. The VSC based High Voltage Direct Current is the best effective and dependable means of transmitting electrical power across great distances. The most challenging aspect of the VSC-HVDC system is the requirement for fast HVDC circuit breakers, as short-circuit failures cause damage to the converter valves and transmission network. The purpose of this study is to summarize HVDC circuit breaker technology, as well as recent substantial efforts within the creation of latest HVDC circuit breakers. Each technology is given a brief functional study. Furthermore, numerous technology primarily based totally on statistics accumulated from literatures are contrasted. Finally, hints for enhancing circuit breakers are provided.

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LIST OF ACRONYMS

HVDC	High voltage direct current
VSC	Voltage Source Converter
CSC	Current source converter
IGBT	insulated gate bipolar transistor
VSC-HVDC	Voltage Source Converter-High voltage direct current
CB	Circuit breaker
LCC	Line Commutated Converter
DCCB	Direct Current Circuit Breaker
SSCB	Solid state circuit breaker
UFD	Ultra-Fast Disconnector
SiC JFET	Silicon Carbide Junction Field Effect Transistor
GCT	Gate Commutated Thyristor
GTO	Gate Turn-Off Thyristor
IGCT	Insulated Gate Commutated Thyristor
WBG	Wide band gap
FET	Field-effect transistor
MOSFET	Metal oxide semiconductor field effect transistor
RCD	Resistor-capacitor diode
MOV	Metal Oxide Varistor
SiO	Silicon oxide
ZnO	Zinc oxide
TVS	Transient Voltage Suppression
MVDC	Medium voltage direct current
LCS	Load Commutation Switch
ARPA–E	Advanced Research Projects Agency–Energy
GaN	Gallium nitride
SiC	Silicon carbide

Chapter 1

Introduction

1.1 Introduction

Today's ever-increasing energy demand, longer distances between generating and load centers, and scarcity of natural resources have resulted in an unavoidable shift in the nature of power transmission. For short to medium distance power transmission HVAC is extensively used, but it's going to not be appropriate for long distance power transmission due to high charging current of cable capacitance, lacking of asynchronous operation, difficulties in controlling power flow, the necessity for reactive power compensation, skin and Ferranti effects and high losses [1-2]. For these disadvantages in HVAC transmission, the usage of high voltage direct current (HVDC) has grown up dramatically and HVDC transmission has become an economical choice for transferring high power to larger distances.

For power transmission during the earliest stages, HVDC technology with current source converter was employed. CSC-HVDC systems employ thyristors to provide relatively large power ratings with little degradation (usually about 0.7 percent). Thyristors, on the contrary hand, will solely be switched on and don't have any capacity of turn-off, therefore they can't be controlled to eliminate a fault current. In addition, CSC-HVDC systems require gigantic filters that raise capital costs; additionally it's sensitive to AC aspect faults that might lead to commutation failure [3-4]. In response to these concerns, VSC based HVDC systems are developed. Because of its swift and robust control and aptitude to handle up a consistent DC voltage although the power direction reverses. VSC utilizes insulated gate bipolar semiconductor device (IGBT) and may function with poor AC networks of offshore wind farms. As a result, VSC-HVDC structures have undergone first-rate advancement in current years. On the other hand, VSC has several drawbacks, including sensitivity to DC faults, substantial losses (typically approximately 1.6 percent) and poorer power assessments [5-6].

In particular, VSC-HVDC structures are extraordinarily prone with short-circuits problems, which could reason harm to converters & transmission network. Numerous AC and DC breakers have been made to shield converters and transmission network. DC faults are common in VSC-HVDC systems, and their prevention is critical to maintaining a stable and dependable power supply. However, an important problem with DC circuit breakers is that the reactance on the DC side is low, so it is not possible to establish a zero crossing naturally. To permit fault interruption, the current must be intentionally driven to reach the zero point. When a fault occurs, the failure current is immediately detected and discharged, allowing for quick troubleshooting. The usage of metal oxide varistors, resistors and surge arrestors are some of the technologies used to energy absorption and dissipation. AC breakers consolidated for fault interruption are mechanically protected and revel in zero crossing purpose doubly each cycle, but HVDC breakers require a resonance circuit to unnaturally push this to zero crossing point. One other concern for DC breakers is usually the magnitudes of fault current seem to be much bigger than their AC equivalents when there is a failure. This is generally related with weak DC reactance of the DC line, necessitating the employment of a fast DC breaker to terminate the fault sooner than the fault current reaches uncontrolled levels. Additionally, AC breakers have a longer reaction time and are therefore inappropriate for securing DC circuits. Current developments in semiconductor technology have shortened the time required to remove a fault [7].

Countries have a linked power system on a global scale. This guarantees that electricity is delivered where it is most required, allowing member nations to profit from the pooling of big power production stations & transmission networks, sharing rotating surpluses as well as employing the lowest energy resources accessible. All such nations remain far apart and the power supply is far away from the load center. Their needs an effective and reliable transmission technique based on the VSC-HVDC system with a multi-terminal system. A fault on one converter station in a multi-terminal system can cascade to subsequent converter stations. As a result, a rapid DC breaker is necessary to defend the VSC-HVDC system. For keeping away from harm, it is important to apply an HVDC circuit breaker capable of immediately disconnecting the faulty component from the system.

IGBT are used in the VSC-HVDC system for quick switching. These devices are noted for their quick switching action and great efficiency, which are characteristics of quick DC breakers. Modern HVDC systems use VSC as a constant current supply and use capacitors to repose energy, requiring few big filters and reactive power supplies. Furthermore, it's the capability to form its personal reactive power, allowing it to properly adjust its active power and voltage. The process of fault interruption, which is difficult to perform with DC circuit breakers, is the main problem. Because of their natural zero current crossing capabilities, AC circuit breakers may simply interrupt the problem. Issues impacting the DC CB fault interruption response time [8-9]:

I. Due to the low impedance of the DC line, the increase in fault current in the DC network is much higher than in the AC network. This necessitates the employment of a fast DC breaker.
II. In the AC network, the circuit breaker arc caused by the current breaker disappears spontaneously. The current zero crossover of the system. The zero current crossover of the DC network has to be delivered with the circuit breaker independently. One of the classic approaches is to create a resonant current to reach the zero crossing point.
III. Unlike the AC grid, DC grids store magnetic energy in the system inductance. This energy must be consumed by the DC circuit breaker through mutual inductance or a resistive device.
IV. As opposed to AC breakers, the DC circuit breaker should tolerate residual overvoltage once the current is interfered.

1.2 Circuit breaker Design Requirements

1.2.1 Classical Design

The traditional breaker unit is composed of a sequence of electrical or mechanical circuit breaking components that deflect a surge in current before shutting off that. So far, mechanical HVDC breakers have succeeded of halting DC currents in few milliseconds, but this would be sluggish and insufficient to fulfill the conditions of a dependable HVDC operation of power system. As a consequence, comprehending circuit breakers functioning aspects and fault clearing procedure may assist in emphasizing the best design prerequisites and objectives for the upgraded circuit breaker.

1.2.2 Required Architectural Factors

Total fault clearing time in an HVDC Circuit Breaker system is divided into two sections: breaking duration correlates to a rising current cycle, while fault clearance corresponds to a lowering current period [10-11]. Both of these time lengths must be taken into account in the prototype and pricing of the HVDC breaker. In practice, the breaking duration is defined mostly by protection's turnaround time and the HVDC switch's reaction time. A longer breaking time indicates that the HVDC switch has a higher maximal current breakage capability. It raises the amount of power controlled by its arrester, resulting in a more expensive HVDC breaker. As a result, it is vital to preserve the break time as brief as practical. When the utmost breakdown current capability and the breaking duration are characterized, its only variable is just the inductance of the HVDC reactor, this affects the intensity of current increases [11]. As a result, the HVDC reactor must be chosen in a quite manner so the current does not surpass the maximal breaking current rating of the HVDC breaker during the breakdown period. Unfortunately, the scalability of the HVDC reactor could be limited with concerns such as expense and grid system reliability. That duration of fault clearance has a substantial influence on the voltage configurations of the arresting gear as well as its pole voltage prevention. The smaller fault clearance signifies less energy dissipation within its arrester branch; however it simultaneously necessitates large voltage estimation in the arrester. On the converse, increasing the quantity of arrester prevention may result in greater pole-to-pole voltage ratings, raising the cost of the HVDC breaker. Likewise, in an HVDC grid coupled by HVDC wires, a short-circuit issue should be removed inside 5 ms to preclude a converter station 200 kilometers or more distant from being damaged [11]. This example illustrates the general relationship between the factors stated previously. Assuming a 2 ms breaking time using semiconducting HVDC switches, and provided the HVDC line faults develop nearby the HVDC switchyard, and with a 100 mH HVDC reactor inside a 320 kV HVDC grid, its largest growth of the fault current would be 3.5 kA/ms; coupled with 10 percent of maximal overvoltage. The HVDC breaker's minimum needed breaking capability for such a specific rated line current of 2 kA is 9 kA.

1.2.3 Standardization

In 2008, the International Electrotechnical Commission (IEC) formed a new Technical Committee spanning HVDC Transmission for DC voltages beyond 100 kV that acted like a standard for HVDC circuits and platform prototype. During first quarter of 2009, the committee created a logistic unit WG B4-52 named "HVDC grid feasibility study". Its majority of the applicants included European research organizations, corporations, various prospective users & advisors. Regarding compatibility of either a DC grid further with AC grid, the implications of remote failures (because defect in a DC grid is noticeable at a fairly considerable range), pricing, and different grid topologies in terms of reliability and controllability were all examined in WG B4. In terms of dependability, the grid structure was examined in terms of having sufficient redundancy and the necessity for net sectionalisation via HVDC breakers and safeguards for different locales. Since suitable DC breakers & safeguards seem to have been built, the WG concentrated on defining the needed breakdown current aptitudes and operative timeframes. Beginning with the standardized voltage ranges employed in Ac systems, the WG evaluated the viability of suggesting benchmark voltages of DC Grids. The working group also evaluated the components for converter station construction that needed to somehow be standardized in order for stations of various companies to just be attached to a DC grid [12].

1.3 HVDC Circuit Breakers

Existing HVDC breakers can manage HVDC currents in milliseconds and they're too sluggish for satisfy the standards of such a sustainable HVDC grid operations. Moreover, installing mechanical HVDC breakers seems to be a challenging task that necessitates the construction of additional passive elements enabling producing a resonant circuit as well as generating necessary current zero crossing so that the breaker may successfully break the current once it opens. DC interrupters are now employed as various switching responsibilities in point-to-point HVDC transmission. A neutral bus switch, a neutral bus ground switch, a metal returned transfer breaker, a ground returned transfer breaker, and a super fast bypass switch are all available for paralleled line switching [13-14]. Interrupters to terminate DC short-circuit currents are available as modest quantities, with maximal ratings of 250 kV, 8 kA or 500 kV, 4 kA that is not over than 1.6 times its authorized actual current [13-14]. Their breakdown duration seems to be on the order of 35 ms and in CSC-based technologies, the higher inductance virtues restrict the rates of growth of fault current, therefore this timeframe may not be too quick. Furthermore, the elements of those kind of breakers generally larger and more expensive than those of AC breakers having equal voltages and currents specifications. The complexity in establishing HVDC breakers might be attributable towards the strict specifications for breakers within DC systems, particularly differ significantly from those for ac CBs. One significant distinction would be the lack of natural current zero in DC systems [13-14]. The following are the basic requirements that the breakers must meet:

1. Construct a zero–crossing current to halt the fault current.
2. Disintegrate the power held by the inductance of the system.
3. Capable of maintaining the system's voltage profile after a fault current interruption.

The first two requirements constitute the basis of a dc circuit breaker, while the third isolates those from ac breakers. In addition to the above-mentioned qualities, the dc breaker must meet the following secondary requirements [8]:

1. The HVDC breaker in VSC-based applications would be sufficient to inhibit instantly.
2. The maximal voltage produced by the breaker has to be low sufficient to meet again with DC system's insulation plan. It's critical to transitioning load currents when the system will be at its standard voltage.

Extensive development and study on HVDC breakers has remained ongoing for six decades, although interest in DCCBs has waned dramatically since 1985 owing to failure to establish a rapid and brief interruption mechanism. However, fresh DCCB studies have lately sparked interest in HVDC grids. Technological advancements are developed, which eventually enhance the DCCB design and setup.

Chapter 2

Topologies of HVDC Circuit Breakers

2.1 Electromechanical Circuit Breaker

There seem to be two kinds of electromechanical dc circuit breakers they called Electro-mechanical passive resonance CB and Electromechanical active resonance CB.

2.1.1 Electromechanical passive resonance CB

The passive dc CB is a beheaded technique that's been designed for LCC–HVDC scheme [15]. Since those breakers include a long reacting time as well as bulky, massive, and greater in dimensions, enthusiasm in using them in dc grid preservation has waned. However, such breakers offer lower power wastage compared any other dc breakers. Figure 2.1 depicts a passive resonance DCCB.

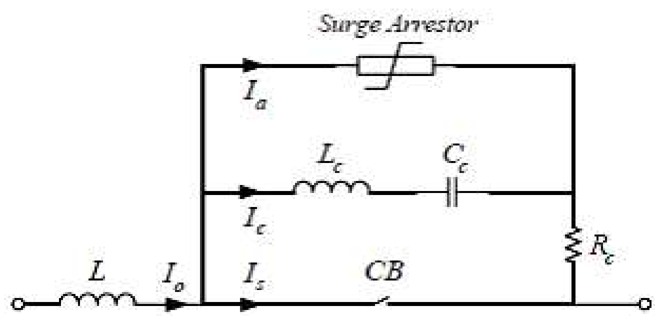


Figure 2.1: Passive resonance DCCB

Figure 1 depicts typical nominal current route. When the switch (CB) is closed during normal operation, intermittent current (I_s) flows along this route. Normally, the air blast circuit breaker is used to create interrupting circuits. By connecting a series resonant circuit with an inductor & a capacitor (L_c and C_c) zero–crossings condition is generated, forming a commutation channel. This requirement must be satisfied in order for the breaker to be tripped. During the fault, the surge arrestor absorbs energy. The interruption allows the current to oscillate among its nominal & commutation routes. This disruption operates in natural frequency. Zero–crossings occur whenever the amplitude of oscillating current becomes larger than its input current. During particular point, the switch prevents current flowing inside the nominal routes. For this reason, the capacitor will indeed be charged mostly by current flow (I_o). Assume that the capacitor voltage surpasses the voltage capabilities of a dc breaker. Surge arrestors would adapt and an ideal zero point would be formed when current decreases. This will aid in current interruption. Electromechanical high-voltage direct current circuit breakers had already been in service for several years and seem to be capable up to 500 kV [4]. The 5 kA short circuit current is cleared by this breaker in 60–100 ms [4]. The advancement of semiconductor devices has revolutionized electro - mechanical breakers particularly appealing for short-circuit fault prevention, specifically on VSC-HVDC multi-terminal networks. It is vital to study the present equation throughout the interruption process in order to comprehend the process. During a fault interruption, the mathematical formulation can be stated as [16]:

$$L_c \frac{d^2 is}{di^2} + \left(R_c + \frac{\partial_{uarc}}{\partial_{is}}\right) \frac{d_{is}}{dt} + \frac{1}{C_s} i_s = \frac{I_o}{C_c} \quad (1)$$

$$i_s = I_o \left(1 + e^{\frac{1}{2L}\left(R_c + \frac{\partial_{uarc}}{d_{is}}\right)} . \sin \omega_c t\right) \quad (2)$$

Here $\omega_c = \sqrt{\frac{1}{L_c . C_c}}$ and if $\left(R_c + \frac{\partial_{uarc}}{\partial_{is}}\right) < 0$; then 'i_s' will oscillate at a greater amplitude. In this case, the initial zero crossing of current would be sufficient to disrupt the fault, making this the perfect fault break off point enabling the DC breaker.

2.1.2 Electromechanical active resonance CB

Figure 2.2 displays an electromechanical active resonance DCCB, sometimes characterized as a two-stage intrusion technique [4]. Throughout this manner, the current oscillation sustained through the pre–charged commutation capacitor C_c will indeed grow swiftly. When current becomes commutated to the LC branches, it increases sufficiently to withstand its main CB's current. This design is also shown as a hybrid interruption method. A thyristor being commonly utilized as a disconnector & commutator inside this variety of breaker. Because this concept has multiple versions, just the two primary topologies are depicted.

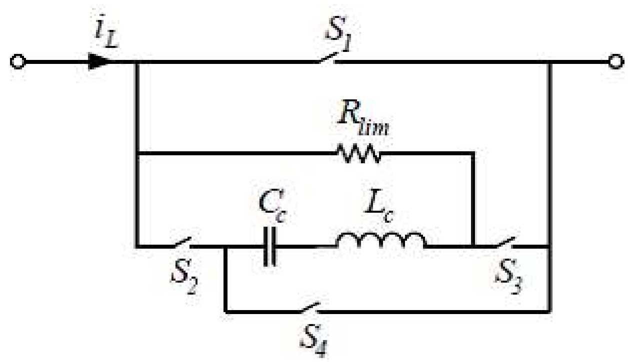


Figure 2.2: Active resonance DCCB

In the first active resonance dc breakers version, the breaker switch S_2, S_3, and S_4 are opened in a steady–state situation whereas the solitary primary breaker switch S_1 is closed. A negative starting voltage V_{c0} is applied to the capacitor C_c. When a short circuit current is detected, S_1

opens, whereas S_2 and S_3 close simultaneously. The fault is then resisted by the reverse current ascending through LC branch, resulting in such a zero–crossing as well as the current being commutated into parallel branches. When the C_c is energized, S_2 opens & the current flowing across it drops into zero. Following that, S_4 would be closed & C_c is being discharged in the cycle C_c–S_4–S_3–L_c– C_c. Whenever a zero-current happens on S_3, the circuit is turned off, as well as the main breaker current recommutates into R_{lim}–L_c–C_c–S_4. Consequently, at zero-current generation, S_4 opens and given rise to a new power homeostasis where the capacitor is fully charged.

In the second variant, current disruption is achieved only with closing the S_3. Whenever a defect is identified inside the second category, S_3 gets closed and S_1 being opened at the same time, resulting in a current–zero inside the main breaker. Once the capacitor gets entirely charged, S_3 may eventually open [17].

2.2 Solid State Circuit Breakers (SSCB)

As contrasted to electromechanical DCCB, SSCB offer a faster reaction time, are lighter, and are easier to repair and restore. Two Solid State Circuit Breaker topologies are implemented and summarized here: SSCB with parallel surge arrestors and SSCB with free-wheeling diode..

2.2.1 SSCB with parallel surge arrestors

Figure 2.3 depicts the SSCB with parallel surge arrestors

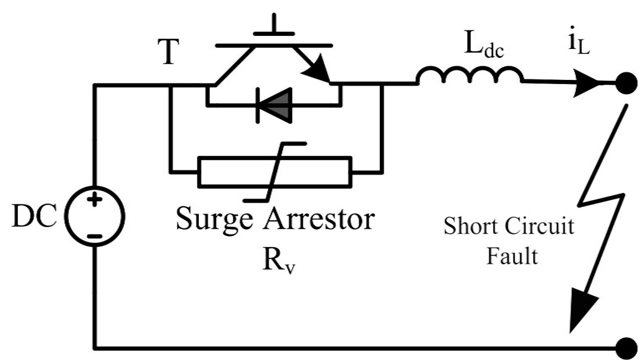


Figure 2.3: SSCB with parallel surge arrestors

During steady-state circumstances, current passes through the dc source to the load over IGBT inside CB equipped with surge arrestors. When a problem is identified, the semiconductor switch switches off; causing a fast spike in voltage till the surge arrester commences to operate. The surge arrester primarily supposed to choke/block each and every voltage larger that the grid voltage, resulting in the de–energization on line inductance. Current flowing is then shifted towards the surge arrester. The IGBT voltage being strictly constrained towards the clamping voltage of surge arrester and thus predicted to be V_{dc} + V_{margin}. When the IGBT switches off at time t = 0, the impedance at the fault spot is likewise expected to be low. When V_{margin} being provided above L_{dc} then inductor current is described by the equation [16]:

$$i_L = I_o - \frac{V_{margin}}{L_{dc}} t \quad (3)$$

Here Io seems to be the fault current amplitude at time t = 0. The timeframe required to turn off the fault current (T_{open}) is calculated by the following equation:

$$T_{open} = \frac{L_{dc}}{V_{margin}} I_o \quad (4)$$

The energy swallowed up through the surge arrestor could be calculated by the following equation:

$$W_R = \left(\frac{V_{dc}}{V_{margin}} + 1\right)\frac{1}{2} L_{dc} I_o^2 \quad (5)$$

W_R Represents the amount of energy captured and restrained with the surge arrester during fault clearance, I_o^2 represents the fault current & LC represents system inductance. Higher readings of Vdc than V_{margin} are utilized in a high voltage system to reduce the voltage throughout the IGBT and decrease conduction failures. In such a circumstance (5) becomes big, indicating that WR becomes sufficiently bigger than the accumulated energy in L_{dc} when t=0, $\frac{1}{2} L_{dc} I_o^2$. As a result, a surge arrester with a high capacity is necessary to handle the suppressed energy of an IGBT. The greater the voltage suppression throughout the IGBT, more the capacities of the surge arrestor needed [18].

2.2.2 SSCB with free–wheeling diode

Figure 2.4 depicts the SSCB with free–wheeling diode

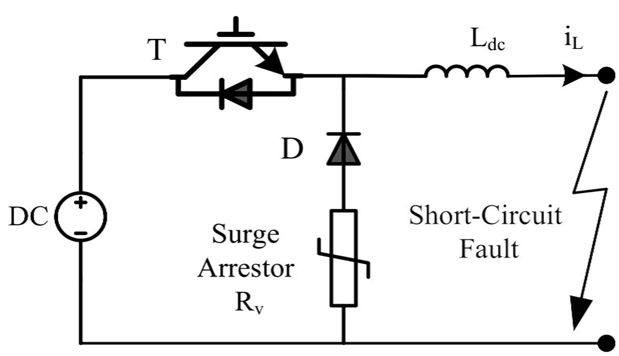


Figure 2.4: SSCB with free–wheeling diode

This design utilizes a freewheeling diode that avoids the reverse voltage impulses, thereby isolating its IGBT from voltage spikes. It moreover employs the surge arrestor as either an absorbing medium for the heat created either by fault, enabling itself to be dispersed as rapidly as feasible. This rapid heat soaking and disposal improves breaker reaction time and dependability, which is critical for CB.

During normal operation, the IGBT being turned on as well as the load current iL travels across it. Therefore, when a fault is detected when t = 0, fault current is commutated through D since T is shut off. As a result of the R_V progressively demagnetizing the inductance L_{dc}, the fault current begins to decrease. If V_V represents R_V's clamping voltage, the surge voltage in T is $V_{dc} + V_V$. Because there is no power flow through T once it is turned off, the energy assimilated throughout this breaker throughout the turn–off procedure is equivalent to $\frac{1}{2}L_{dc}I_o^2$. As a result, W_R is:

$$W_R = \frac{1}{2}L_{dc}I_o^2 \qquad (6)$$

Smaller W_R readings from (6) than in (5) imply a smaller rated and capacity for surge arrestor inside the second scheme and a lower suppressed voltage over IGBT [17-18]. Solid–state breakers provide many benefits over traditional circuit breaker methods. The elimination of mechanical components enhances SSCB reaction duration, culminating in a faster turn–off period. Furthermore, increasing the voltage along the inductor accelerates the demagnetization procedure [19]. In comparison with previous breaker technologies, the SSCB's quick turn–off mechanism confines peak current to a particular amount. As a result, SSCB has smaller power dissipation with the similar grid voltage. As a consequence, regardless of wire lengths or grid voltage, an SSCB is indeed the ideal option because to its quicker turn–off timing, lower component expense, and lower peaked current. It's not the apparent due to a fundamental flaw; its high degree of on state losses. Solid–state architecture has an advantage in high voltage grids as the power conserved per circuit breaker being adequate to produce them more inexpensive over conventional circuit breakers, while on losses are also included.

2.3 Hybrid HVDC CB

Hybrid DC circuit breakers bring up novel possibilities like rapid changeover & arc quenching. These use mechanical with solid-state electronics during switching, as its name implies. Solid-state breakers are ultra-fast, have huge switching losses, and are expensive. Mechanical breakers have minimal losses, are modest in cost, and operate extremely slowly. The hybrid switching strategy is defined as combining the benefits of both while removing the drawbacks. The hybrid CB is costly due to the utilization of electronics elements which are susceptible of short-circuit failures. Unfortunately, failures through the breaker to pinpoint the problem in a timely manner might be hazardous including both humans and the equipment being shielded. As a result, hybrid

CB began to garner a significant interest, as notably proven in [20]. Furthermore, ABB as well as ALSTOM recently created Hybrid CB demonstrators with significant advancements [8, 21]. There are numerous hybrid circuit breaker topologies at several phases of establishment, although only two garner the most emphasis. Topology 1 (Hybrid HVDC CB) is visualized in Figure 2.5.

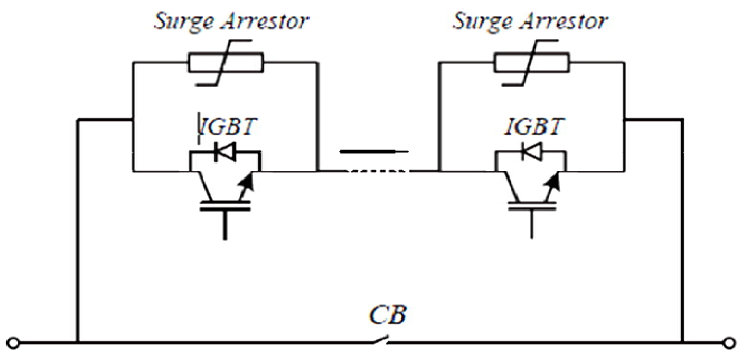


Figure 2.5: Topology 1 (Hybrid HVDC CB)

The functioning of topology 1 generally identical with the of Solid State circuit breaker, with the exception that the hybrid circuit breaker incorporates extra pairs of solid-state terminals linked through parallel. In compared with traditional breakers, hybrid HVDC CB has minimal inefficiencies & is quicker and more dependable due to the solid state switches. Figure 2.6 depicts topology 2 (Hybrid HVDC CB).

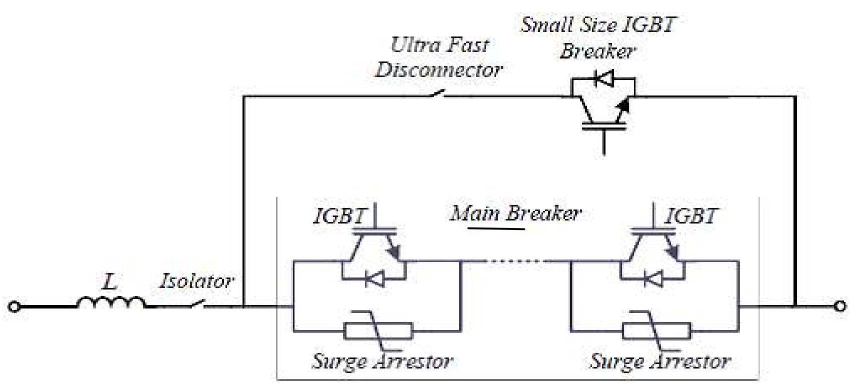


Figure 2.6: Topology 2 (Hybrid HVDC CB)

During typical functioning, current is flowing through the UFD switches as well as the tiny compact IGBT, meanwhile current is flowing through the main breaker. When there occurs the fault, the minuscule compact IGBT rapidly commutates the current towards the main breaker, which is equivalent as a solid-state circuit breaker as well as the UFD switch operates. UFD maintains minimal voltage degradation despite allowing for quick switching. The principal breaker stops the current whenever the mechanical switch lies into the opened condition. With zero-current as well as low voltage strain, the mechanical module unlocks. Once staying inside the opened position whereas the main breaker breaks, the fast disconnector would be subjected to the restoration voltage denoted by the safeguard rating of the arrester banks immediately. Recent developments in semiconductor technology have decreased the interval between fault interruptions. For example, ABB has a hybrid CB with a fault clearing time of less than 3ms and a maximum interruption current of 20KA.

Chapter 3

Electromechanical Circuit Breakers

3.1 Working principle

Electromechanical CBs are suitable for medium voltage & power applications. The functioning of these kinds of circuit breakers is based upon employing a resonant circuit to generate a current zero.

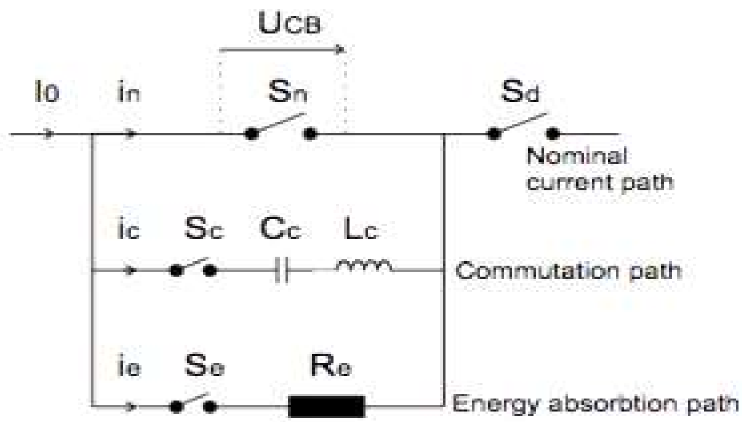


Figure 3.1: Electromechanical Circuit Breaker

The breaker is made up of three parts:

(1) The conventional current route seems to be where DC current flows and the switch being blocked under usual functioning.

(2) The commutation route is made up of a switch and a resonant circuit including an inductor as well as a capacitor which is employed to generate inverse current.

(3) The energy absorbent route is made up of a switch as well as a varistor.

When a disruption seems to be essential, current oscillating with the natural frequency (1/LC) can develop across the nominal & commutation routes. Whenever the amplitude of the oscillating current surpasses the amplitude of the incoming current, zero crossing occurs, as well as the switch could halt the current in the Normal channel. The current (Io) would keep flowing, charging the capacitor. When the capacitor voltage surpasses a certain amount that usually specified to be the circuit breakers voltage limit, the energy absorbing route would activate, causing the current to drop.

3.2 Voltage and current expansion during interruptions

The majority of commercially available HVDC circuit breakers contain distinct commutation and energy-absorbing routes. The normal path merely consists of the circuit breaker having minimal ohmic deficits in the shuttered state, which seems to be conceivable using movable metallic contacts. When such contacts are opened, an arc being formed, as well as the arcing voltage has been employed for commutating the current towards the resistive route, where the system's energy is dissipated. The commutation route seems to be a series resonance circuit that includes a capacitance C_c & an inductance L_c which causes the current to oscillate on the natural frequency $\omega_o^2 = \frac{1}{L_c C_c}$, as well as the switch S_c. the dissipation channel, which is made up of either energy absorbent linear either nonlinear resistors in series including a switch Se alternatively nonlinear ZnO varistors; this route turns partially conductive just beyond a specified supplied voltage.

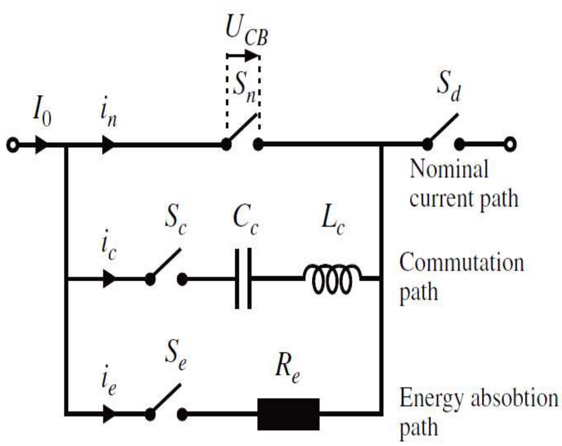


Figure 3.2: Structure of an electromechanical circuit breaker

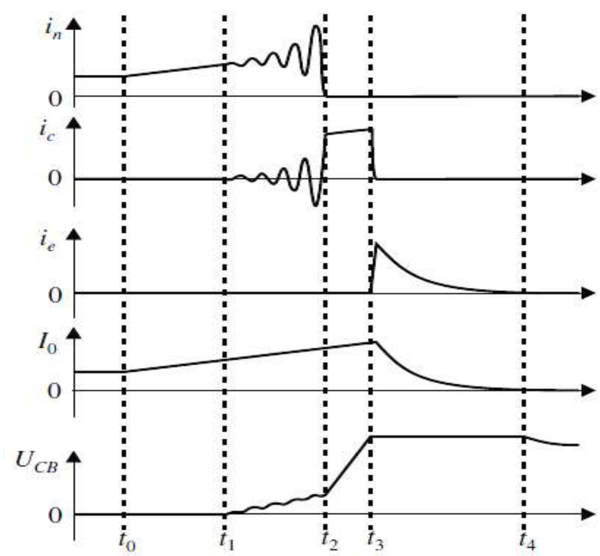


Figure 3.3: Voltage and current expansion during interruptions

This circuit breaker scheme's operation in time is summarized as follows:

- Period t_0 to t_1: A DC fault develops at moment t_0, and the DC current begins to grow. At t_1, the interrupter terminals of nominal current route segregate.
- Period t_1 to t_2: During moment t_1, the commutation route becomes inserted into the circuit, and the current begins to oscillate with growing amplitude due to a normal transformation inside the arc voltage.
- Period t_2 to t_3: Whenever the intensity of the oscillatory current becomes greater than the systemic DC current I_0, at instant t_2, a current zero crossing happens in the conventional channel and Sn interrupts the current. In the commutation route, current I0 continues to flow, charging capacitor C_c.

- Period t_3 to t_4: During moment t_3, whenever the capacitor voltage surpasses a predetermined value, that's either the voltage capabilities of the CB or the insulation coordinate of the network, the energy absorbing route activates, prompting the systemic current I_0 to drop. The voltage UCB being capped with the components of the absorption path, current flowing exclusively through the energy absorption route as well as the system's current I_0 stops.

To minimize the cost of this design, improvement of the pricey elements is necessary. Furthermore, the optimal capacitance values might shorten the breaker's interrupting duration thus increases overall disruption performance. Simultaneously, a high C/L proportion may assist optimizes the break's interrupting functionality.

3.3 Passive resonance circuit breakers

Resonance that is passive DC circuit breakers employ inductance & capacitance self oscillation for the mechanical switch as it provides a current zero-crossing. The primary interrupter branches consisting a mechanical switch. The commutation path having inductor & capacitor in series. The energy absorbing branch that dissipates the network energy contained in the line inductance [22]. Figure 3.4 depicted Passive resonance CB.

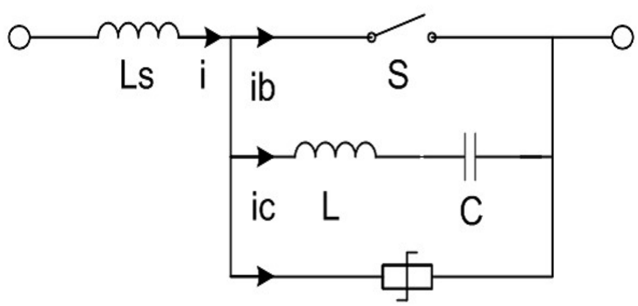


Figure 3.4: Passive resonance CB

Because of the mechanical switch's low contact resistance, electricity flows through it during normal operation. The capacitor has no voltage across it. When a problem has been detected, the mechanical switch becomes open, causing an arc voltage to be introduced that commutates current through mechanical switch along with commuting branch. Current oscillations are produced by inductance and capacitance in an exponentially growing manner. The arc is extinguished when the oscillation can totally resist the current passing via the mechanical switch. The fault current has been transmitted via the inductor & capacitor, charging the capacitor towards the systems voltage. While the mechanical switch's dielectric strength recovers and it can tolerate the systems voltage. Whenever the voltage exceeds the varistors knee position, the varistor begins to participate and consumes the leftover energy contained along with line inductance. The problem is totally isolated when the current inside the varistor decreases to zero.

This resonant DC circuit breaker seems to be a straight forward passive design that allows an AC mechanical switch to function like a DCCB. Regarding the time required to build up the oscillatory current to a point in which it surpasses the fault current as well as insures arc destruction, the fault interrupting duration is rather lengthy, on the range of numerous tens of milliseconds. For restrict the level of expansion of such fault current, a large inductance seems to be important.

3.4 Active resonance circuit breakers

To achieve speedier functioning, the active resonance DCCB has been created. This is identical to the passive resonance CB, as illustrated in Figure 3.5, however the capacitor is pre-charged & an injecting switch has used to stimulate the resonator [7]. Whenever a problem occurs, the mechanical switch gets activated as well as the injection switch gets deactivated.

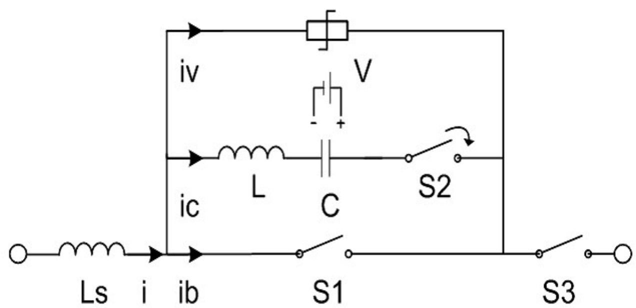


Figure 3.5: Active resonance CB

The current inside the inductance & capacitance begins to fluctuate at this point. If the oscillation is properly engineered, a zero current crossing will attain for mechanical switch. This current being commutated towards the varistor after the interruption, and the energy accumulated in network inductances is wasted as the current decomposes to zero. When residual current detaching CB is activated, as well as the system gets turned off by 5 ms [7], such an active injecting resonance DCCB effectively stopped up to 10.5 kA. Because there seems to be no time latency required to create the oscillations, the process is quicker than with an active resonance DCCB. This construction, however, necessitates reliable injection switch solutions as well as a mechanism to charge the capacitor.

3.5 Mechanical CB with turn-off snubber

Integrated mechanical CB cannot switch off a direct current and does not have any cooling device to eliminate arc. As a result, an extra circuit seems to be required to switch off a DC current. A circuit for a quick mechanical circuit breaker was created depending on renowned turn-off snubber for power electronics equipment. Figure 3.6 displays the essential topology.

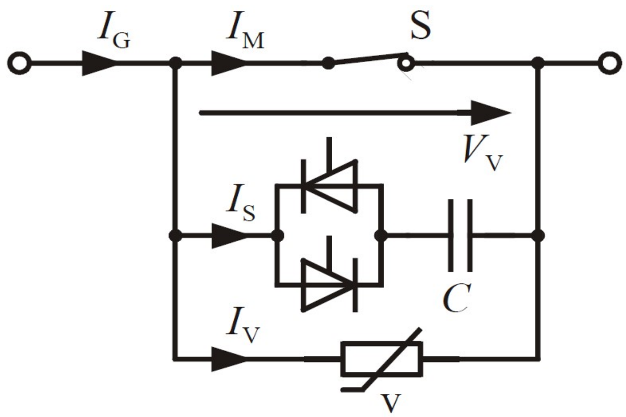


Figure 3.6: Mechanical CB with turn-off snubber

Under regular functioning, current propagates via the circuit breakers mechanical component. Whenever a fault has been discovered, the circuit breaker trips as well as the current being shifted towards the parallel line. Because of the capacitor, current may continue to flow while the voltage steadily rises. As a consequence, the arc gets quenched, therefore the circuit might be managed to open without worrying about the air separation shrinking. The charge of the capacitor reduces voltage throughout the grid inductance therefore increases of current. The voltage increases up to 30 kV depending on the maximum current as well as grid inductance has been demagnetized through varistor. Additional thyristors are employed, as opposed to a normal turn-off snubber. The main factor for this is because the varistor would demagnetize the inductance as well as with a decreasing current, voltage may also decrease. The above causes the current to commutate back to the capacitor, resulting in a negative voltage along the inductance & negative current. As a result, there seems to be an oscillations as well as the malfunction cannot be switched off. That consequence is prevented by utilizing thyristors, which cut off once the current being reduced to zero by the capacitor, preventing a change in current gesture. Firstly, the snubber capacitor must be appropriately constructed. As per the previously described mechanical CB standards, the voltage dispersion rates should be restricted to 80 V/µs. The following differential equation may be written using a basic equivalent grid circuit with V_n as grid voltage & L_{grid} as line inductance [23].

$$V_N = L_{grid} C \frac{d^2 v_c(t)}{dt^2} + v_c(t) \qquad (7)$$

Taking into account the starting parameters for both the current & voltage at the start of the turn-off procedure, required capacitance may be determined to be roughly 58 µF. Figure 3.7 depicts all voltages to demonstrate the functioning of this approach. In addition, the inverting voltage along the mechanical switch also indicated [23].

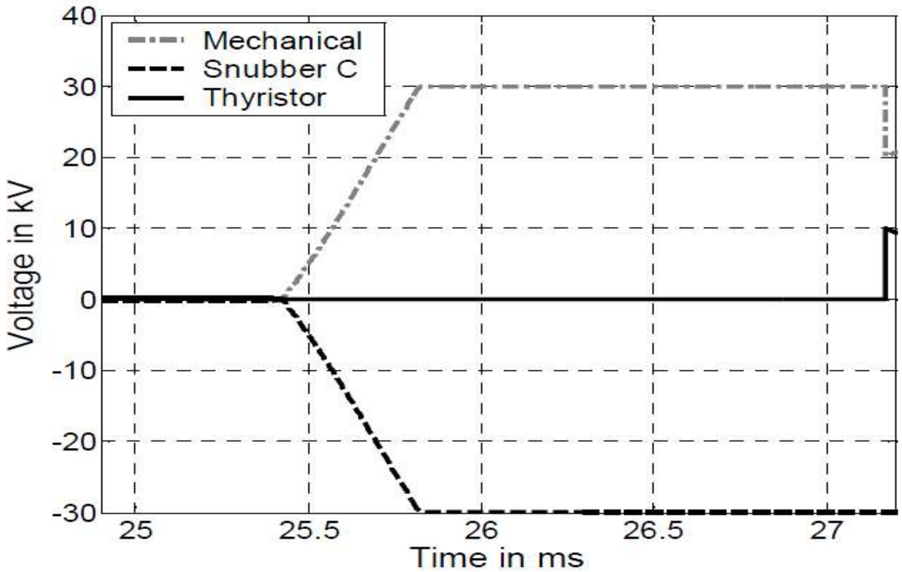


Figure 3.7: Voltages along the mechanical CB

Initially, voltage steadily rises over capacitor & hence over mechanical breakers, staying considerably under 80 V/µs breakage limit. When the maximal voltage of 30 kV has been achieved, the current is lowered till reaches zero during 26.5 ms. These thyristors now can restrict the voltage at that point. Because the capacitor seems to be charged up to 30 kV, the thyristor would suppress the voltage differential among this value as well as the 20 kV grid voltages. The capacitor would be drained while the off-state by using a big resistor. Figure 3.8 depicts the current flow during the power-off operation. It is clear that the varistor, not the capacitor, is accountable for the demagnetization of line inductance [23].

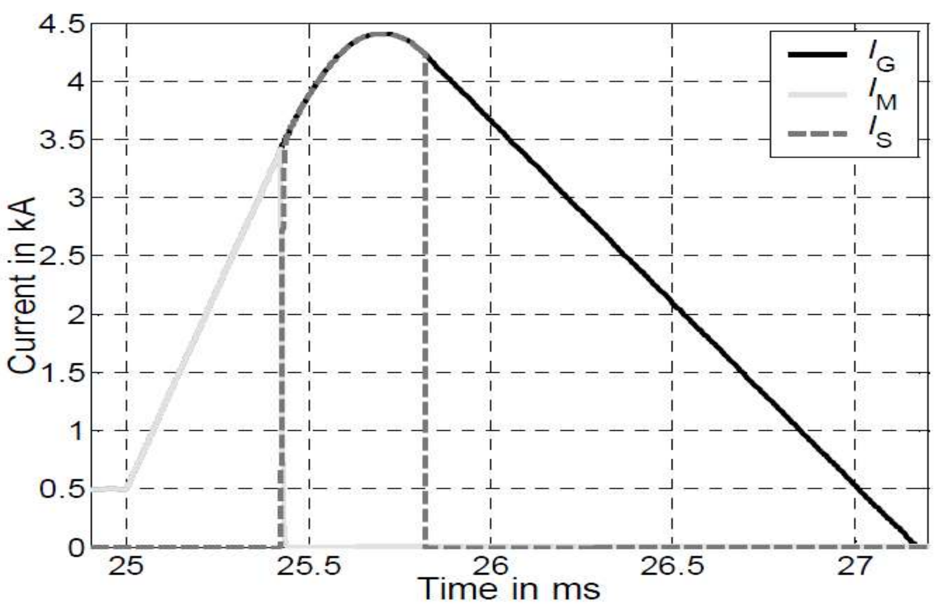


Figure 3.8: Current waveform.

In comparison to the previous configurations, no active semiconductor component being required. Therefore, this configuration comprises just of a mechanical circuit breaker, identical towards the previously mentioned hybrid remedies as well as several thyristors in the commutation route. Furthermore, several varistors & commutation capacitors have been required, which are highly dependent upon its maximal turn-off current.

Chapter 4

Solid State Circuit Breakers (SSCB)

4.1 Principle of SSCB

The following major determinants make up a general SSCB: Power semiconductors devices, a gate driver, a cooling mechanism, a voltage clamping circuit, a leakage sensor devices, sensing and trip electronics, and an additional power source. Several examples include the Z source solid-state circuit breakers [24], the SiC JFET premised self-powered SSCB [25] etc. The gate driver module supplies the required biased voltage or current to keep the power semiconductors gate terminals in a steady, low-resistance on-state. The number of power semiconductors required is determined by the application's voltage and current ratings, as well as power semiconductor systems & the breaker's architecture. Figure 4.1 is a fictitious block schematic of a SSCB. The waveform of a semiconductor-based circuit breakers switching operation is depicted in Figure 4.2. Throughout regular functioning, the power semiconductors device being always on.

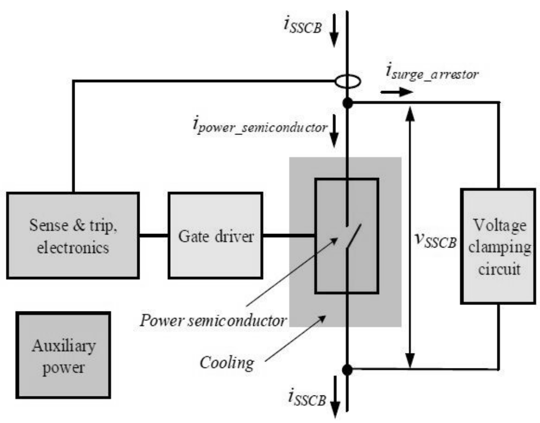


Figure 4.1: Key components of SSCB

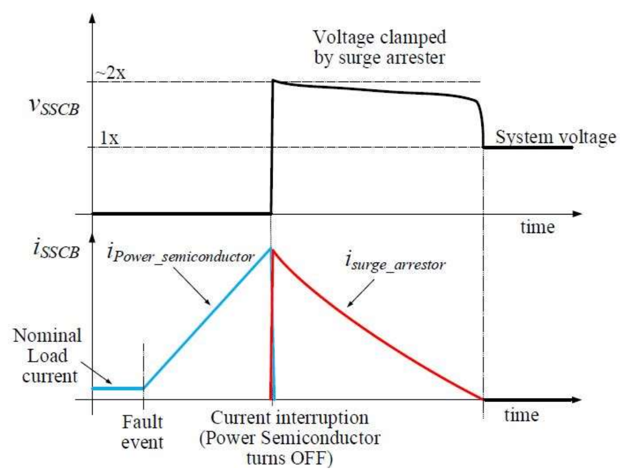


Figure 4.2: Conventional switching pattern SSCB

Both the power semiconductors and the voltage clamping circuit consumes devices leftover energy and force the current to zero. The circuit has a large impedance, and the voltage across it is low. Whenever those voltage hits a specific threshold, the voltage clamping circuit is triggered, clamping the voltage to a comfortable limit for the power semiconductors. If a fault is recognized, the sensor and tripping electronics remove the power semiconductors by a gate driver or a commutation circuit. Whenever the power semiconductors have been switched off, the leftover energy in the systems inductance develops voltage on it. The circuit breaker is set to the system's voltage.

4.2 Review of SSCB Systems

The paragraph summarizes the literature on many aspects of SSCB, as an example power semiconductors technologies, power circuit architectures, voltage clamping circuits, gate drivers, leakage detection techniques & tripping electronic systems. A classification tree will be shown for each main topic area, with descriptive numbers for key concepts and a categorization tree to describe major patterns.

4.2.1 Power semiconductor systems (SSCB)

Whereas there are several methods to construct one, the architecture of power semiconductors defines the layout, which is either commercially accessible or custom-made. Varied power semiconductors technologies have specific qualities, and these attributes will dictate whether a device may be used with others. Various gadgets can only carry current in one direction or limit voltage in Some other illustration is the capability of a system when subjected to excessive current, or currents that are much more than the minimum conduction current. For the purposes of this examination, we will simply deal with the essential properties shown in Figure 4.3.Furthermore, especially in the thyristor family, these offer good overcharging and short-circuit capacity. Because of these considerations, several researchers have suggested Si bipolar devices as CB for medium voltage distribution network. MVCV built on Si IGBT, Gate Commutated Thyristor, and Gate Commutated Thyristor has been suggested for MVAC distribution networks up to 4.5 kV and 4 kA [26]. The classification of power semiconductors devices utilized in the power circuit of SSCB is shown in Figure 4.3. The contrast among bipolar and unipolar semiconductor devices is the first and most important differentiation. Si devices have matured to the point that they can now be purchased commercially in a wide range of voltage and current requirements.

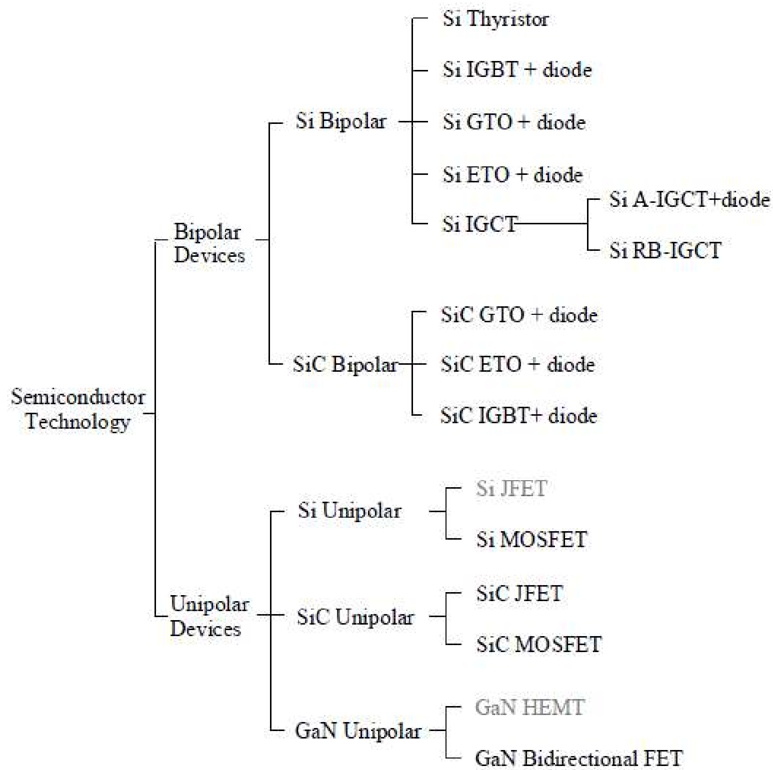


Figure 4.3: Tree of power semiconductor systems

In the implementation of MVDC Bus tie SSCB for electric ships, IGBTs with a blocking voltage of 4.5 kV are employed. The RB-IGCT was developed in response to the IGBT and other standard IGCT, GTO, and other tests. For MV applications, IGCTs with blockage voltages up to 10 kV have also been shown [27]. Low voltage, low power applications are found in silicon unipolar devices. SiC JFETs proposed as a possible suitable fit for SSCB applicant. SiC unipolar devices were the first WBG devices to reach maturity, with specific on-resistances as low as 0.9 m.cm2 for a blocking voltage of 650 V and 1.2 kV [28]. The turn-on feature of such gadgets demands no energy to keep them running. Certain SiC MOSF implementations additionally offer optically triggered fault identification owing to light emission at high current. Multiple SiC MOSFET based breakers supporting system voltages of 270, 380, and 850 V have been built and tested [29-32]. A power switch for solid state circuit breaker applications was assessed using monolithic bidirectional GaN Field Effect Transistors with a blockage voltage of 650 V. Bipolar devices relying on Wide – band gap semiconductors typically suitable for the high voltage application areas because to the inherent high knee voltage penalties, which creates considerable particular conduction losses in lower voltage applications category. In the literature, the IV map of power semiconductor used in SSCBs has been summarized (see Figure 4.4).

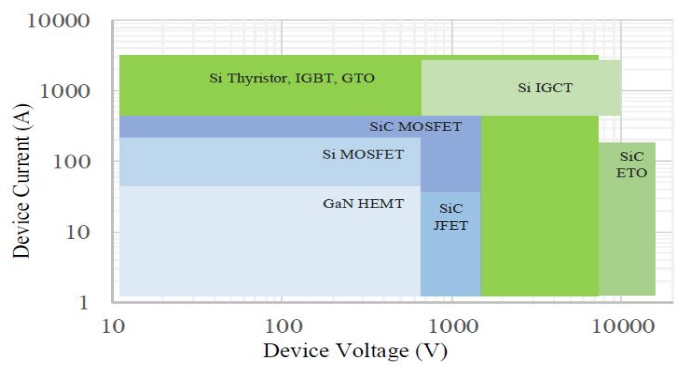


Figure 4.4: V-I diagram of power semiconductor devices

4.2.2 Circuit topology for implementing SSCB

In this section, we look at the many topologies addressed in the paragraph for SSCB. The properties of power semiconductor switches & the application prerequisites have a big impact on the circuit topologies that support them. The power characteristics of power symmetrically semiconductors are of particular importance; other characteristics include loss, expense, size, interruption speed, and others. The principal solid-state circuit breaker devices found in the paragraph are summarized in Figure 4.5.

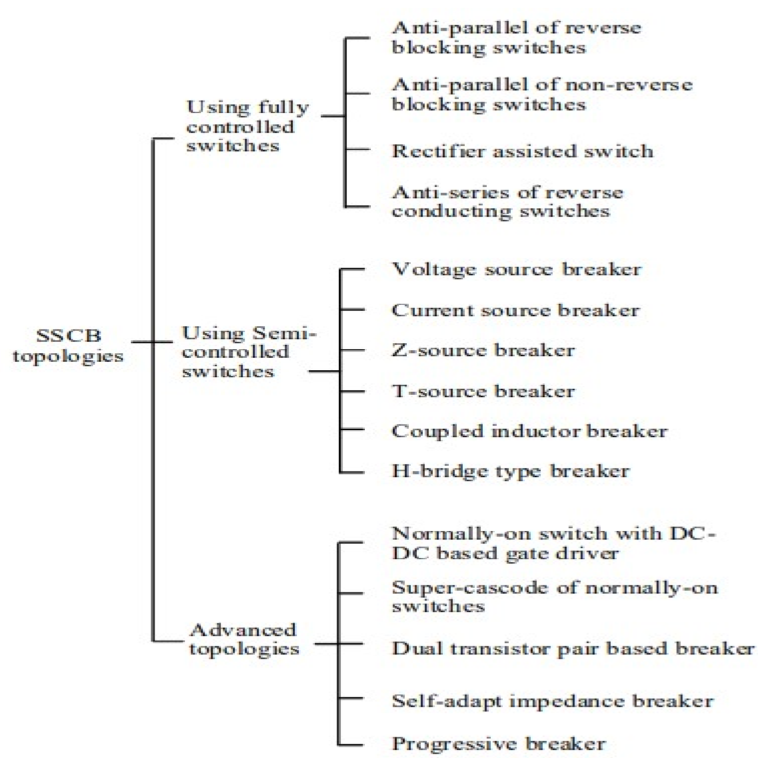


Figure 4.5: Tree of Circuit topologies

Whenever supplemented by a complete bridge rectifier made up of four diodes (e.g. IGBT), just one fully programmable power semiconductor transition may be used [23]. It's possible to utilize a symmetrical, asymmetrical, or reverse conducting switch. Two asymmetrical IGCTs or GTOs can also be used to construct an anti-parallel topology [26]. At lower currents, unipolar FETs exhibit lower conduction loss than bipolar equipments [33]. A SSCB is one that does not have any moving parts. It has a low conduction loss, is cheap, and may be used in rising applications. The fault current is not routed through the system power supply; therefore Z-source breakers enable a speedy turn-off and simple control. In the third point of SSCB systems, more sophisticated power semiconductor devices or supplementary circuits seems to be engaged. For higher voltage applications, the super-cascade layout of typically switches might be used [34-35]. Topology allows for the use of smaller, fewer costly in the design of a rated power circuit breaker, such as low power MOSFETs.

4.2.3 Voltage clamping (SSCB)

In most applications, a SSCB is series devices that must withstand electrically isolated inductive swapping when the breaker shuts off the current. Thus an incident might simply result in a considerable power overvoltage, resulting in the semiconductor device's irreversible breakdown. This may be prevented by using a snubber. The clamped circuit has a one-of-a-kind design. An suitable clamping voltage is frequently used to drive energy. Clamping can be accomplished with a single energy source absorbent element or a combination of energy sources absorbent elements. Solid-state circuit breakers cannot be designed using traditional converter snubber techniques.

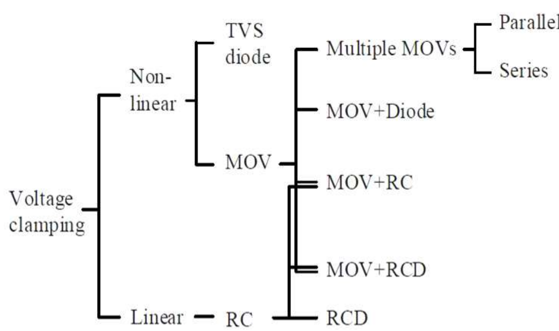


Figure 4.6: Segmentation of voltage clamping methods

At turn-off, the potential drop along a resistor being mirrored on the power semiconductors. The RC snubber approach is inefficient and difficult to apply in solid-state circuit breaker applications [36]. A RCD Snubber is a more upgraded version that adds a diode in parallel with the resistor. This arrangement reduces voltage oscillations during turn-offs while also avoiding an extra voltage drop across the resistor [36-39]. One more variation of clamping mechanism includes the Metal Oxide Varistor (MOV). SiO, ZnO, silicon carbide, and other materials can be used to make MOVs [40]. The essential working concept of the MOV is the variation in resistance being a function of input voltage, as shown in Fig. 4.7. The variation in resistance seems to be inversely proportional to voltage; therefore it has the highest resistance when no voltage is applied and the lowest resistance when the input voltage exceeds clamping voltage.

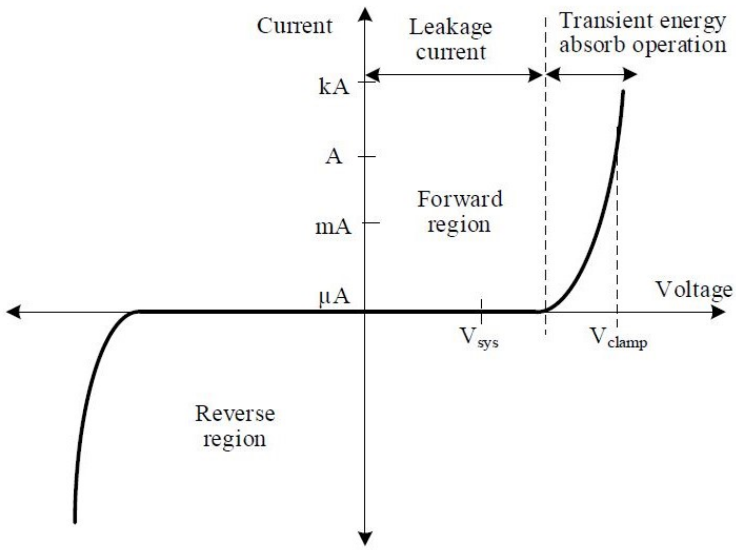


Figure 4.7: V-I diagram of Metal Oxide Varistor

One of the fundamental features of MOVs is that the variation in resistance being a strongly non-linear consequence of the input load. The use of a TVS diode to clamp the turn-off voltage is a more rare approach. TVS diodes are solid-state devices that clamp the voltage while absorbs the inductance's leftover energy in avalanche mode. Both TVS diodes & MOVs have a fast reaction duration; moreover, TVS diodes seem to be costlier than MOVs for equal power and clamping voltage needs. To separate voltage clamping as well as energy absorption, some researchers propose using two separate MOVs at important spots in the circuit. In UPS applications, a combination of MOV and RCD circuits minimizes voltage stress on power semiconductors [41-43].

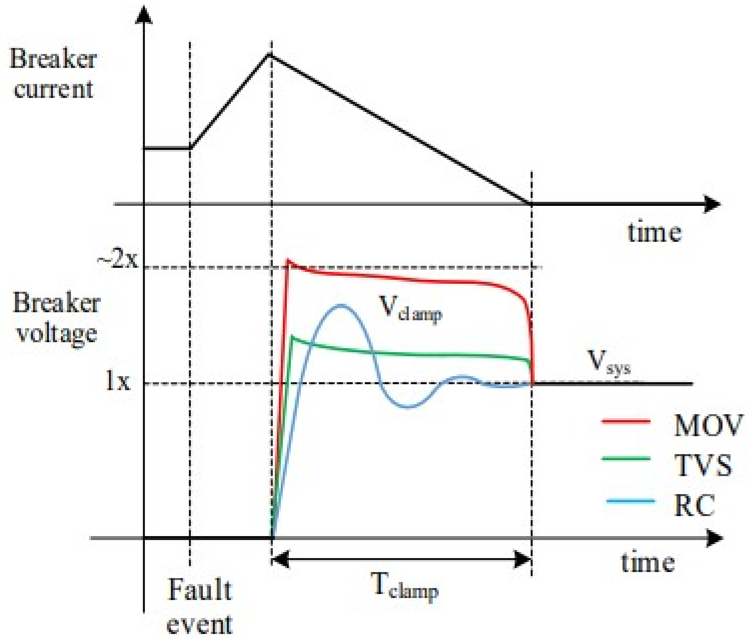


Figure 4.8: Different voltage clamping events

Table 4.1 comparison of different voltage clamping approaches (pros & cons)

Clamping type	Pros	Cons
C	Simple; lower Vclamp & dv/dt	Oscillations; High discharge current
RC	lower oscillations	Higher Vclamp and dv/dt
RCD	Lower oscillations; Lower Vclamp & dv/dt	More components
MOV	Better clamping than RCD	Limited lifetime; No dv/dt control,
MOV+RCD	Advantages of MOV and RCD	More components and cost
Multiple MOVs	Scalability	Voltage and current balancing
TVS diode	Better clamping than MOV	Higher cost

Setting a clamping voltage more than the device voltage is the most important prerequisite for driving the systems current towards zero. Increasing the clamping voltage reduces the voltage clamping duration in MOVs and TVS diodes. Thus, a larger clamping voltage reduces device current to zero rapidly, but it also stresses the power semiconductor by increasing voltage stress. A higher clamping voltage may cause unwanted over voltage’s in sensitive downstream equipment. Clamping voltages closer to the system voltage, on the other hand, would take longer to reduce the device current to zero, requiring the clamping devices to misuse more energy. A exchange between the leakage current elimination time and the permissible clamping voltage must be achieved for premium and excellent performances of the SSCB [31,44]. Depending on predetermined specifications of voltage clamping devices in the field [36], (8) may be used to derive a commonly recognized maximum clamping voltage range,

$$1.5 \text{ p.u.} < V_{clamp} < 2.5 \text{ p.u.} \qquad (8)$$

Where, 1 p.u. is nominal voltage of breaker.

4.2.4 Gate driver

The primary purpose of gate driver seems to be to regulate the conduction, blockage & switching states of the power semiconductor. In power converters, the gate driver requires extra power proportionate to the operating frequency. SSCB rarely have on/off switches. It is possible to use a more complex gate driver with additional capabilities such as damage detection and progress monitoring. The gate drivers of SSCBs are auxiliary supplied by a power source at ground level. They must maintain a steady gate bias for the power semiconductor's on and off states. Other structure constraints, such as dead time, phase leg crosstalk, and so on, must be taken into account by gate drivers for converters. Such criteria do not present in breaker applications.

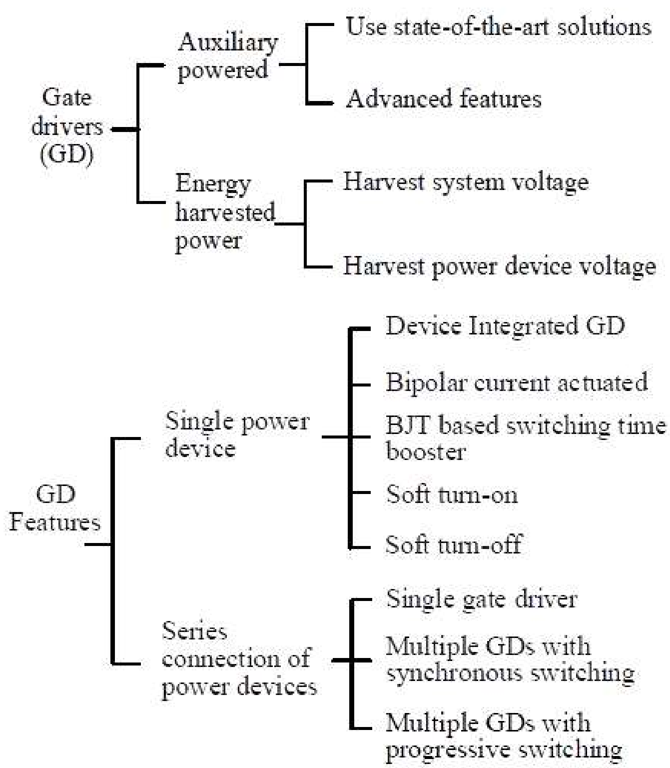
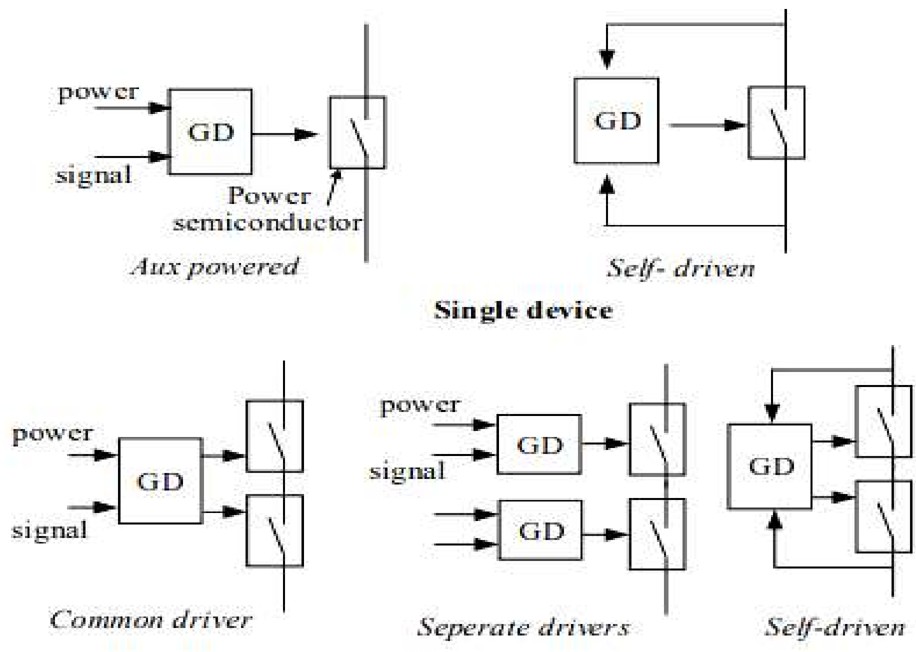


Figure 4.9: Segmentation of gate driver approaches

Energy is required to maintain the SiC JFET during off in solid-state circuit breakers that don't really require using a constant supplemental power supply for execution process. Breakdown energy recovery technologies are being investigated by several researchers in order to turn off power semiconductors during overload failures [25,45]. Figure 4.10 depicts a variety of gate driver design strategies for individual and sequence linked power semiconductor found in the literature. Custom gate drivers are used to maintain the on-state or off-state of power semiconductors such as Si/SiC MOSFETs and IGBTs. The terminal voltage is normally about +20 V, while the voltage stress is typically between -5 V and -20 V, depending on the kind of device [41,46].To obtain the greatest performance out of extremely high semiconductor, including IGCT, ETO, GTO, and so on, a bespoke gate driver is created [47-49].



Series connected devices

Figure 4.10: Various types of gate drivers

4.2.5 Fault sense and trip systems

A breaker's principal function is to prevent or restrict current flow during an overload event. It is commonly accomplished using a direct or indirect method to detect fault current. The fault's most important requirements High-bandwidth sensors are currently available for a quick response, reduced losses, and a small and appropriate interface with circuits for control this section examines many ways. Utilized in the literature for current sensing and tripping, as well as ways for altering the breaker's tripping characteristics. The system inductance might vary a lot depending on the application (from a few H to several mH). As a result, the pace at which current changes during a short-circuit failure might vary greatly. As a result, it's critical to have a sensor design that works well over a large scope of di/dt and present values. Aside from fast broadband and rapid reaction times, the sensor ought to have better efficiency than the primary power semiconductor for keeping the breaker effectiveness as high as feasible. In the journals, researchers have looked at a variety of current detecting and breaking techniques, as shown in Figure 4.11.

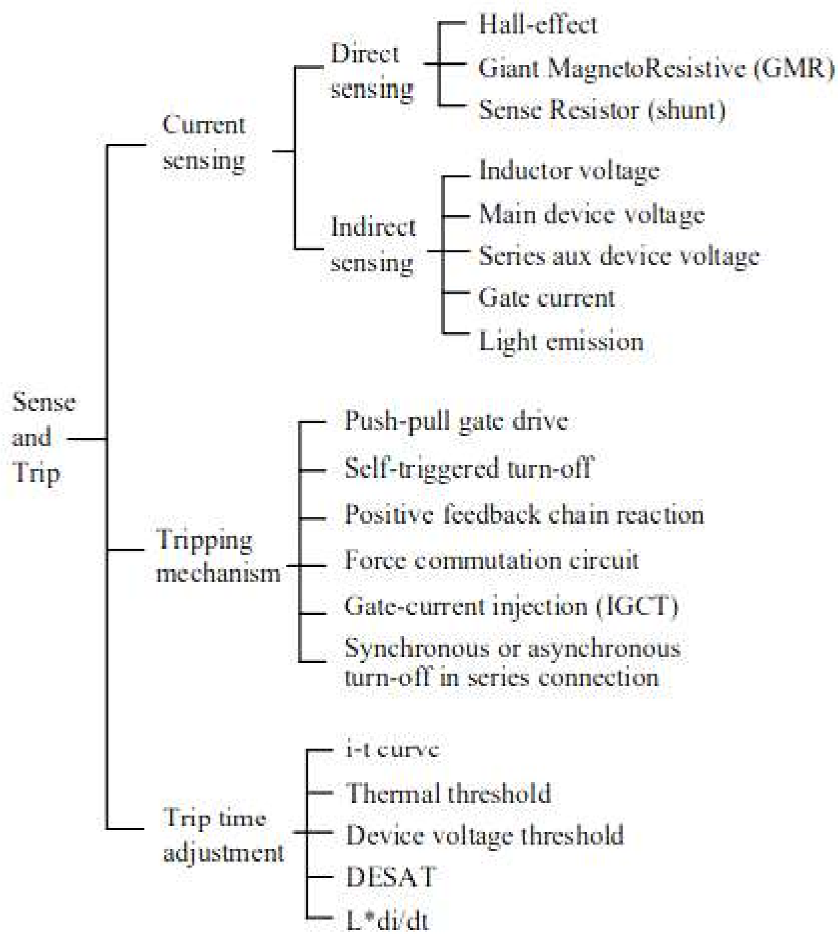


Figure 4.11: Segmentation of Fault sense and trip systems

(a) Current Sensing

By detecting the load current, the presence of a problem can be recognized directly or indirectly. Direct current sensing entails continually measuring and monitoring the current with a dedicated current sensor. Indirect current detecting employs system characteristics that are based on the current's instantaneous and rate of change. The voltage through the primary power semiconductor devices, for example, utilized to detect a fault [35,45].

(b) Tripping process

The Tripping process of SSCBs differs varies based on the type of power semiconductors employed. A classic push-pull kind of gate driver can handle devices like MOSFETs and IGBTs if an auxiliary power supply is supplied. Force commutation circuits are commonly used to turn off power devices such as thyristors. These devices' turn-off currents can be extremely high because they're built for high-power applications .That indicates their gate drivers must be capable of carrying such a higher current for such a short time throughout the turn-off transition [47,48,50].

Chapter 5

Hybrid Circuit Breakers

5.1 Conventional Hybrid CB

A hybrid circuit breaker is often made up of at least two distinct switching technologies. The majority of the time, it is made up of a mechanical and semiconductor device. Figure 5.1 depicts the technique.

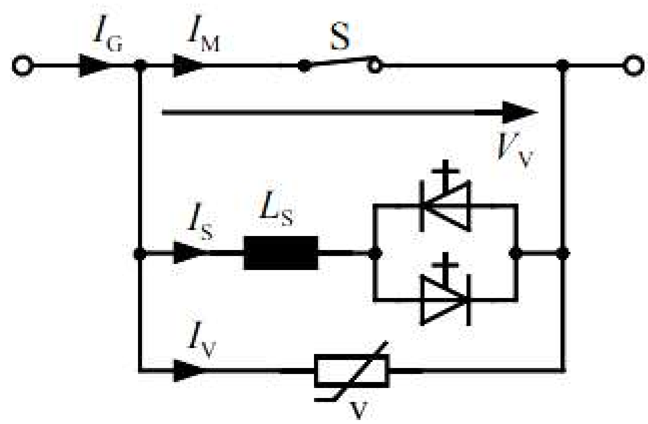


Figure 5.1: Conventional Hybrid CB

While on technique, the mechanical breaker (S) organizes the current. When a crisis strikes the current being commutated to the semiconductor through opening the mechanical CB (S). As one result, there are no pieces required in the structural segment to quench the arc that results. The current is then carried via the semiconductors till the mechanical breaker can prevent the entire voltage. Here, the semiconductors have been powered off. Because to energy retained in the line inductance, the voltage will climb swiftly till the varistors current and cap the voltages. The blow voltage ought to be greater than the grids voltage to demagnetize the grids inductance. Additionally, the current may be switched off without causing a spontaneous zero crossovers. On the other hand, the switching frequency is strongly reliant on the mechanical devices. As a result, due to its slow speed, a typical mechanical circuit breaker cannot be employed. The commuting duration from the mechanical portion to the semiconductor as well as subsequently to the varistor, may be ignored. The initial commutation is limited by the maximal di/dt of the chosen semiconductors. The conduction may last only few seconds because current electronics can handle absolute values of approximately 1 kA/s. In this circumstance, both the hardening of the air gap and the rapidity of the quick mechanical switch's contact separation are critical. Despite the fact that the arc that occurs is quickly extinguished owing to commutation, deionization takes time. As a result, the maximum voltage rise during this section is limited to 80 V/s. As a result, the semiconductors must wait 375 seconds before the turn-off operation may begin. The current will raise throughout this period. In addition, a 60-second sensing delay is taken into account. When all of these considerations are taken into account, the semiconductors are turned off once the current exceeds the threshold, which takes around 440 seconds. Figure 5.2 depicts the current throughout a short circuit switch off using a typical hybrid circuit breaker.

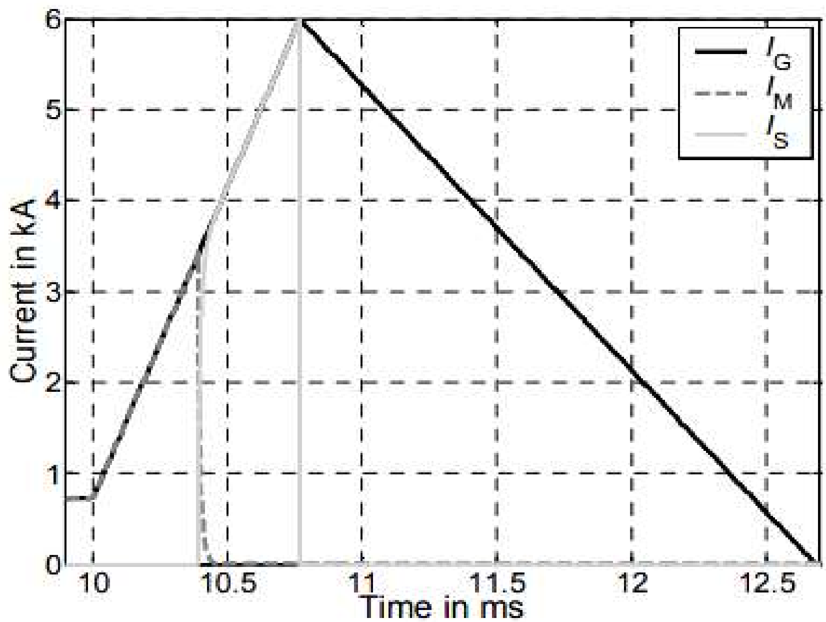


Figure 5.2: Current throughout turn off operation

The output current is initially routed throughout the mechanical CB. A short circuit is employed after 10 milliseconds, resulting in an increase in current. The sensing level is set at 3 kA, and the current is commutating to the semiconductor parts by enacting the mechanical breaker after detection duration of 60 seconds. It is clear from Figure 3 that the commutating time may ignore. After 375 seconds, the mechanical portion is capable to blockage the entire voltage, turning off the semiconductor and demagnetizing the inductance. Before the current is eventually brought to zero, this process takes around 1 ms. The current grows dramatically due to the extended delay period, reaching 6.5 kA, which is more than double the detection limit. Because the whole grid, particularly the semiconductors utilized, must be constructed for this high value, a way to decrease the delay time must be discovered. This problem will be exacerbated with greater grid voltages. This design necessitates the use of a fast responding mechanical CB with a maximal blockage voltage of higher than 30 kV and a notional at above of 2 kA. A number of semiconductors make up the second component. At this case, a 4.5 kV/4 kA GCT was utilized. As a result, the maximal switching off current requires two GCTs in parallel, whereas the maximum blocking voltage necessitates seven GCTs in series.

5.2 CB with Forced Commutation

When looking at the turning-off procedure of a traditional hybrid CB, It does become clear that the time lag between current commutation & semiconductor turning-off is the major cause of the excessive current. As a result, minimizing the delay time is one a method of lowering the maximal current. One option is to enhance the circuit breakers opening speed. Furthermore, if a faster speed is used, mechanical issues may arise. As a result, we must presume that raising the opening speed is not a possibility at this time. The tolerated blockage voltage ripple rate may be enhanced from 80 V/s to 300 V/s by considering simply the rapidity of the mechanical CB as well as the crucial electric field strengthening of air. When the arc upon commutating that causes plasma among the contacts does not exist [51], this improvement can be accomplished. As a result, the plasma ought to vanish before the breaker can block a high voltage. As a result, avoiding the arc within the mechanical CB is one efficient technique to lessen the delay time. As a result, a forced commutation circuit was designed for mechanical CB that commutating the current towards the parallel line once the mechanical CB gets triggered. The mechanical connections can thus be severed without the need of an arc. A topology like this is shown in Figure 5.3.

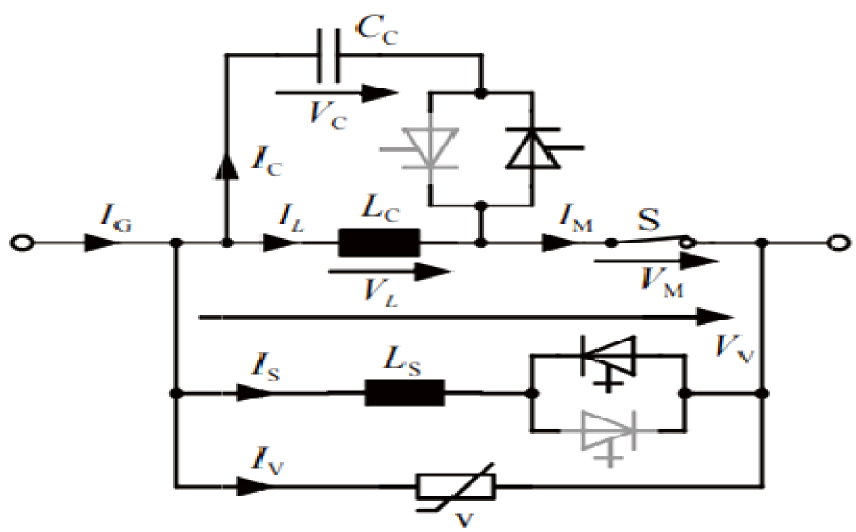


Figure 5.3: CB with Forced Commutation

Several more components are required in comparison to a traditional hybrid system. The commutation requires the LC inductor, as well as the capacitor and extra thyristors. The parallel semiconductors are burned to produce commutation, and the inductor is demagnetized by draining the commutating capacitor. To reduce the amount of energy required for the commutation process, the inductance LC is set to a low value (20 H).The commutation time can be set based on the capacitor's pre-charged voltage. 20 seconds was selected as a suitable trade-off for the commutating time in order to minimize excessive voltage at the capacitor while yet increasing switching performance. The required capacitance and pre-charged voltage may be estimated using these assumptions. The current at the start of the commutation is roughly 3.4 kA, depending on a line inductance of 3 mH and a sensing level of 3 kA. Equations (9) and (10) can be used to calculate the required pre-charge voltage.

$$\frac{diM}{dt} \approx \frac{3362\ A}{20\ \mu s} = 170\,\frac{A}{\mu s} \qquad (9)$$

$$V_{Co} = L_{Tot} \cdot \frac{diM}{dt} \qquad (10)$$

Figure 5.4 describes the present waveform throughout the commutation operation. At first, the current flows continuously between the commutation inductance & the mechanical CB. As a result, the commutation circuit being turned on and current is flowing across the inductor to the capacitor. The current via the mechanical component will stay steady till the capacitor voltage changes signs and actual commutation starts. The mechanical circuit breaker can now be activated because the full current has been commutated to the line drawn.

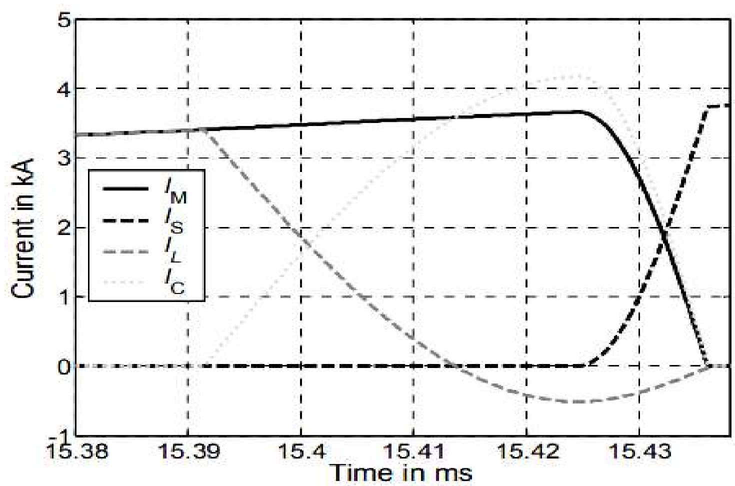


Figure 5.4: Current throughout the commutation

The whole turn-off process is represented in Figure 5.5 below. It is clear that the maximal current might be cut by 30%, resulting in a limiting in the parallel path's required switching power. Furthermore, the overall turn-off time is shortened. The major cause for this is that the current peak has been lowered, resulting in a shorter demagnetization period.

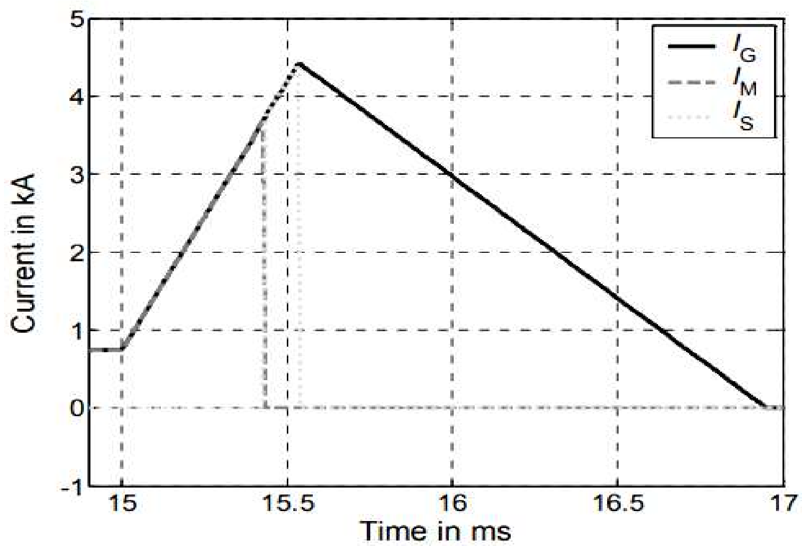


Figure 5.5: Turn-Off process

Because a parallel connection of GCT is not required, unlike the traditional hybrid circuit breaker, just 14 devices are required. This topology, however, necessitates the use of multiple thyristors and a modest commutation capacitor. At the end of this article, there is an economic comparison of these two conceptions.

5.3 Latest MVDC CB Innovations

This section discusses new hybrid technologies with assisted commutation, as well as techniques to reduce operating times. It's worth noting that while certain circuit breaker technologies were created for HVDC networks, the functioning concept can be used to MVDC systems as well.

5.3.1 Generic HVDC CB

Figure 5.6 provides an overall framework for hybrid CB layouts with assisted commutation. A hybrid CB is making up of three parallel branches each linked to an isolated switch. All through normal system operation, current is flowing via the primary branch because to its low conduction resistance. Whenever a failure occurred, the semiconductor branch and the commutating part are activated. The inductance's energy is absorbed by the semiconductors branch, while the isolating switch keeps the system voltage off. A transient restoration voltage arises all throughout the hybrid DCCB. When the voltage is over the knee position of energy absorbing, it starts to conducts and absorb the energy accumulated by the induction.

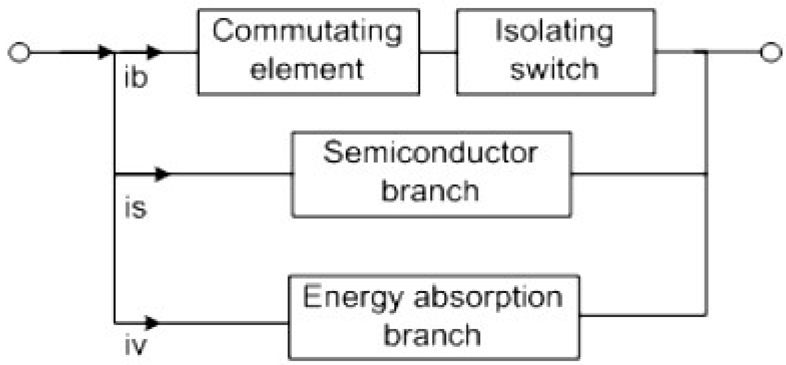


Figure 5.6: Generic HVDC CB

5.3.2 Proactive HVDC CB

Figure 5.7 depicts the proactive hybrid CB suggested and produced by ABB [52]. There are two parallel branches on this circuit breaker. A mechanical separator and a LCS coupled in series form the conventional current path. The LSC is a commutating element made up of a tiny group of semiconductors switches. The primary DC breaker is located on the secondary branch and is made up of a series of semiconductor switches linked by parallel sections along the varistors.

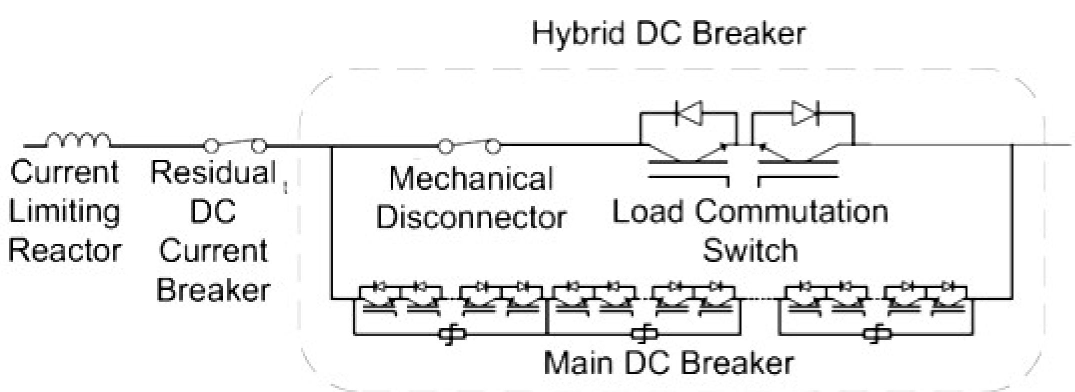


Figure 5.7: Proactive HVDC CB

The mechanical disconnector seems to be closed & the main breaker being turned off while normal operation. When the auxiliary branch is first turned on, just a little amount of current goes between the main circuit breakers semiconductor switches. The varistors limit the transient recovery voltage that occurs over the circuit breaker. The conduction loss via the primary breaker and accompanying components is broken by the series leftover current extracting circuit breaker. This hybrid CB enables proactive current commutation into the semiconductor branch to accommodate for the quick mechanical disconnectors lag time & to work using any selected protection system [52]. An 80 kV module disrupting 16 kA in 5 ms was used to show a proactive hybrid circuit breaker. The LCS is a small set of semiconductor switches that produces on-state losses that are much lower than those of a solid state circuit breaker.

5.3.3 Commutation Booster HVDC CB

The arc voltage being employed to commutate current in a traditional hybrid CB. The commutation booster is a novel idea that using an inductively linked inductor to enhance commutation [53-54]. The hybrid CB with the commutation booster is shown in Figure 5.8. The main branch is a mechanical switch with one inductively coupled inductor, the auxiliary branch is a semiconductor elements with the other inductively coupled inductor & the another branch has a varistor. The primary branch inductance L1 must be greater than the auxiliary branch inductance L2 as a result whenever the current raises, all of it flowing in the auxiliary branch.

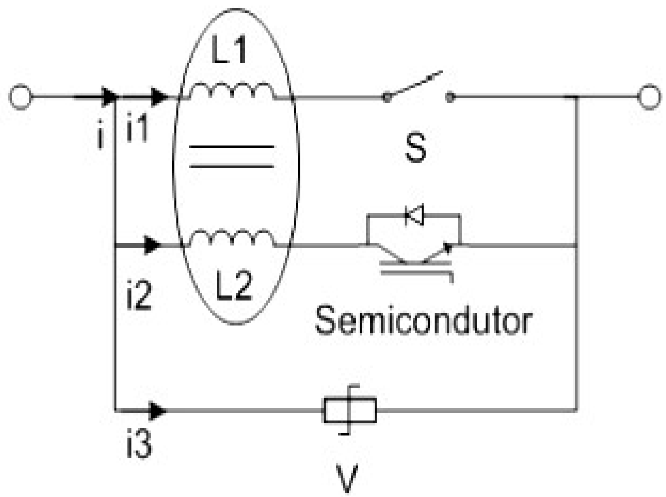


Figure 5.8: Commutation Booster HVDC CB

Due to the inductive connection produced when a semiconductor switch is turned on, and a fault arises in an electrical circuit, the fault begins to reduce. This causes the mechanical switch to experience a current zero-crossing, allowing it to interrupt the current in a similar manner as an AC breaker. After the semiconductor is turned off, the varistor restricts the voltage across the CB. The mechanical switch is not required to generate a higher arc voltage because the commutation booster reduces the demand for an arc voltage. The inductance is utilized to execute the commutation in a hybrid breaker with a commutation booster. By inductively linking the mechanical switch and the semiconductors, the rising fault current is employed to improve commutation. The inductively driven current commutation is also accelerated by the rate of rise of the fault current. For system efficiency, losses in the winding of inductor L1 must be meticulously examined.

5.3.4 Superconducting Hybrid DCCB

A patented superconducting hybrid DCCB [57] is seen in Figure 5.10. The primary branch of this superconducting hybrid DCCB comprises of a superconductor coil connected to the mechanical switch; the auxiliary branch being the semiconductor branch & the another branch is the varistor. The superconducting coil, indicated as Rsc in Figure 35, serves as the commutating element in this configuration. IGBTs coupled in a bidirectional current flow from the semiconductor branch. All of these elements are connected by a residual breaker.

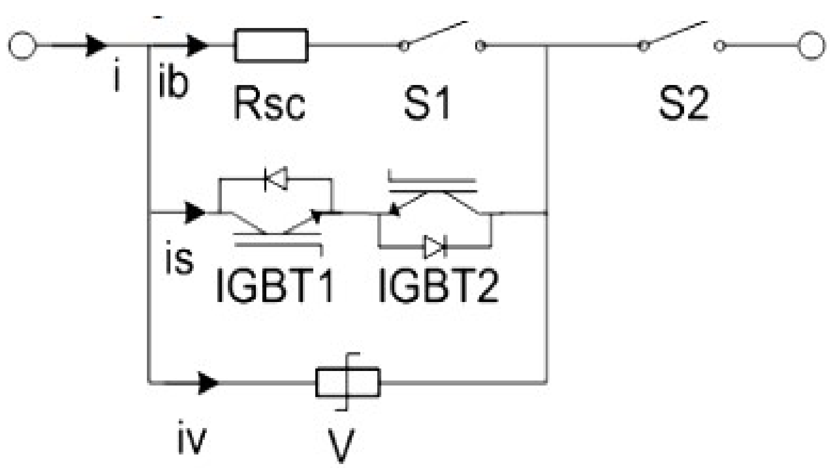


Figure 5.9: Superconducting Hybrid DCCB

The semiconductor branch is switched on during normal operation, yet current flowing via the superconductor as well as mechanical switch owing to their lower resistance. Whenever a defect develops, the current begins to build, and whenever the fault current exceeded the superconducting coil's troublesome current, the superconducting coil quenches & becomes resistive. As the resistance rises, current is forced into the semiconductor branch. When the current in the mechanical switch S1 has dropped to a safe level, the mechanical switch could be opened. The semiconductor branch can be switched off after the mechanical switch is completely open, clearing the error. Within the varistor, the line energy is wasted, limiting the transient recovery voltage. S2 is a mechanical switch that stops any leftover current. A low-voltage superconducting hybrid DCCB has been created, with a 500 A DC current interruption time of 4.5 milliseconds. This is owing to the semiconductor switches is isolated from normal current flowing and the superconductor's low resistance. Other systems, which need active monitoring and control to execute the commutation, are less robust and thus more susceptible to internal defects.

Chapter 6

Comparison and Tech Giants

6.1 Technology comparison

Various methods being contrasted in this section in basis of interruption duration, power dissipation, voltage & current ratings.

6.1.1 Interruption Duration

Electro-mechanical circuit breakers are projected to offer the fastest switching reaction up to 60ms, whereas circuit breakers based on semiconductor are anticipated may have interruption durations below 1ms. Among the two schemes, hybrid circuit breakers featuring disconnecting times of 2 to 30ms are also appealing for usage in high power applications [58-64].

6.1.2 Power dissipation

Electromechanical circuit breakers & hybrid circuit breakers having none semiconductor components in the primary current channel provide the smallest power dissipation of any arrangement. This is due to a relatively modest voltage fluctuation upon this metal contacts in the primary circuit breaker. The power dissipation for such systems are just under 0.001 percent of the power dissipation for VSC stations. Furthermore, hybrid networks with small ratings semiconductor switching devices inside the primary current route exhibit moderate power inefficiencies. The power losses inside this sort of circuit breaker typically just under 0.1 percent of the power dissipation in a VSC scheme. Alternatively, solid-state designs have significant power dissipation. The cumulative voltage loss of the circuit breaker seems rather substantial in these systems as there are multiple IGBT or other semiconductor components inside the primary channel of current. When compared to a VSC station, the power losses for this technique might exceed 30 % [58-64].

6.1.3 Voltage Rating

Electromechanical dc breakers with voltage ratings of 550 kV are conceivable, and hybrid circuit breakers have been demonstrated empirically for 120 kV. Furthermore, solid-state CBs are not accessible towards high voltage systems; they have conceived and implemented within moderate voltage ranges. Yet, considering the advancements in semiconductor devices, an SSCB with a voltage rating of 800 kV is possible [58-64].

6.1.4 Current rating

Electromechanical HVDC circuit breakers may disrupt current flow up to 4kA utilizing a passive resonance system & up to 8kA utilizing an active resonance circuit. Experimentally, a current disruption intensity of 9kA was already demonstrated for hybrid circuit breaker setups, while theoretically values up to 16kA are feasible [23]. Given the projected high voltage ratings of semiconductor CBs, a current interrupting value of 5kA seems appropriate. A summary of the various HVDC breaker technologies is provided in this table [22]:

Table 6.1: Summary of the several HVDC breaker systems

Types of CB	Interruption Time	Power Losses	Voltage Rating	Current Rating	Cost	Maintenance	Life Span
Electro–mechanical	-60 ms	0.001%	Max. 550 kV	Up to 4–8 kA	High	Required—High	Longest
Solid state	<1 ms	30%	120–320 kV	16 kA	Low	Required—Low	Long
Hybrid	2-30 ms	0.1%	800 kV exp.	9–16 kA	Medium	Required—Medium	Longer

6.2 Circuit Breakers from Technology Giants

6.2.1 Hybrid HVDC Circuit Breaker (ABB)

As illustrated in Figure 6.1, ABB designed a Hybrid HVDC CB with a primary branch as well as an additional branch. Fig 6.2 depicts the control technique enabling fault current disruption of that kind of breaker [65-67]. Ultra–fast mechanical disconnector linked series while a load commutation switch based on semiconductor creates a shunt route. The above semiconductor based breaker being separated among multiple sections, each having its own arrester bank intended for specified current and voltage interrupting. Meanwhile the load commutation switch correlates the energy capabilities as well as lower voltage. After the fault is cleared, an isolating breaker interrupts residual current, while the arrester bank of Hybrid circuit breaker seems guarded against thermal overloading by separating the problematic line from the grid [68]

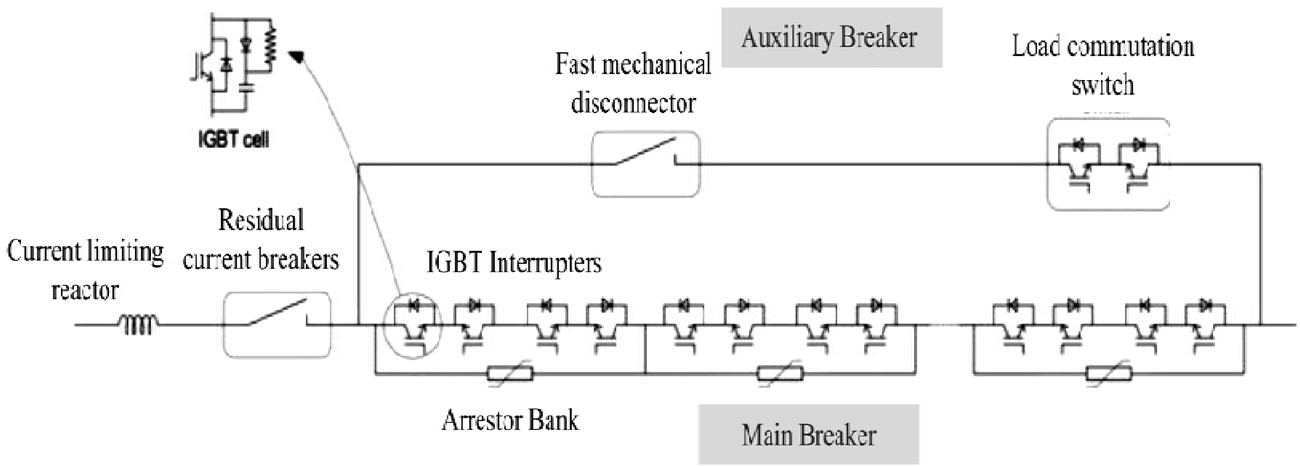


Figure 6.1: Hybrid HVDC circuit breaker (ABB)

The current inside the primary breaker being zero during steady–state and normal operation, yet the sole channel for current will be through the shunt. Throughout the event of a dc failure, load commutation switch instantly transfers the current towards the principal breaker & the ultra fast mechanical disconnector operates and opens. In an open state, the primary breaker terminates the current via mechanical disconnector.

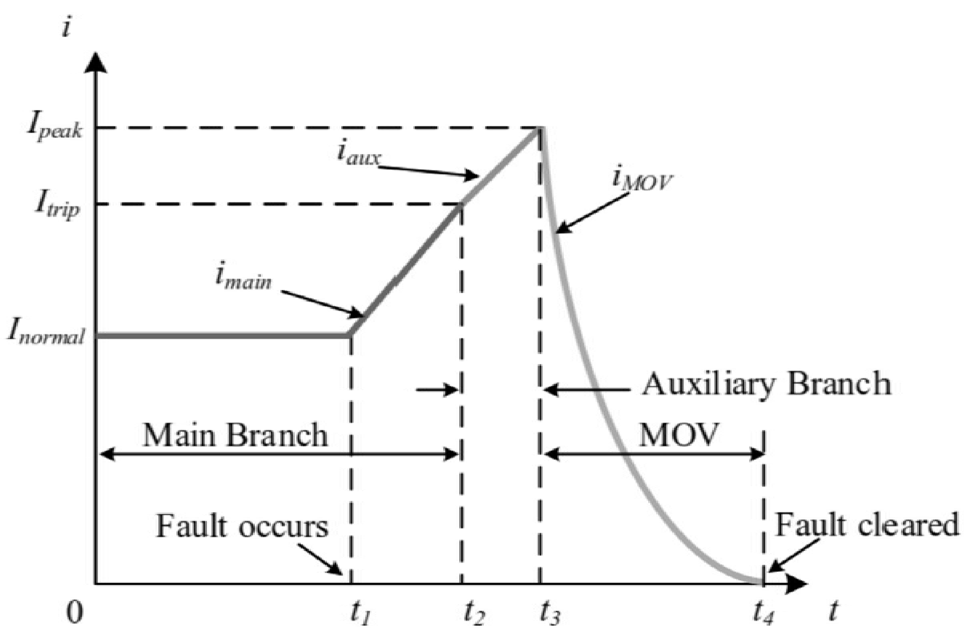


Figure 6.2: Control technique for hybrid HVDC Breaker fault current interruption, ABB

6.2.2 Hybrid HVDC Circuit Breaker (Alstom)

Alstom Grid Hybrid HVDC circuit breaker features a hybrid of HVDC semiconductor & mechanical switch. Construction of that kind of CB is seen in Figure 6.3. A low voltage switch is also included in the core branch, in addition to mechanical contact. Alstom dc breakers include two additional branches: energy absorbent & commutation branch. Figure 6.4 depicts the control approach regarding fault current disruption for that type Circuit breaker [69].

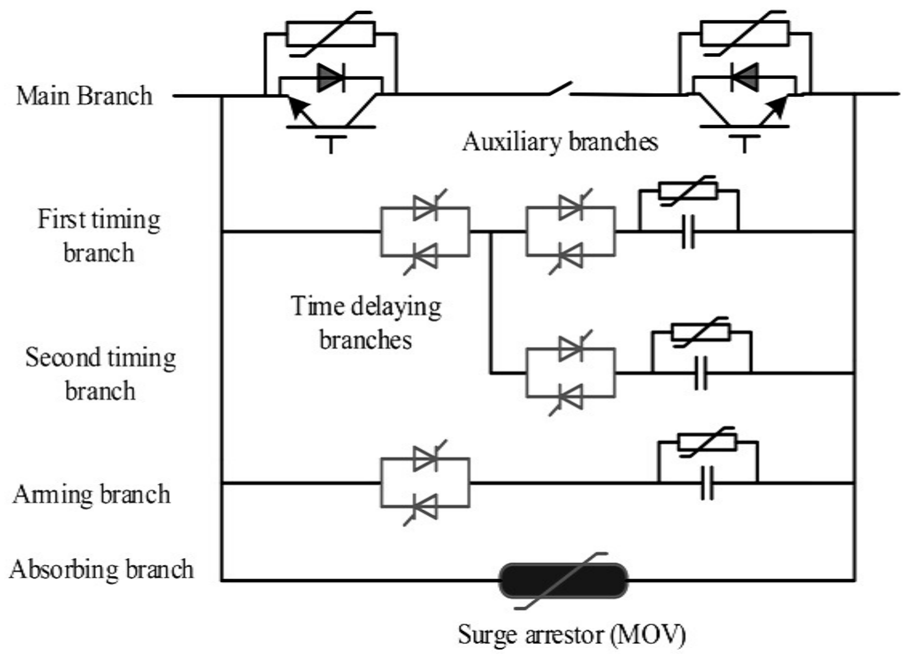


Figure 6.3: Hybrid HVDC circuit breaker (Alstom)

The current is flowing through the primary branch under steady–state & typical functioning. The reduced voltage switch has negligible power inefficiencies as well as a zero contact voltage. For current rating, many elements typically linked through parallel,, and for voltage rating, several components are linked in series. When there is a problem, a large quantity of fault current flows across the primary branch. When a defect is identified, the commutation branch is blocked as well as the low voltage switch being activated and open. At this time, the majority of the fault current would commutate along commutation branch. The mechanical switch might operate with no arcing throughout its terminals till the fault current flowing across the primary branch being practically zero. Whenever the commutation branch gets disabled, the fault current being compelled to travel via the energy absorbent unit. To lower the fault current and the mechanical switch's breakdown voltage, the voltage created along the energy absorption element has to be greater than the supply voltage. Inside an inductive circuit, the variation in voltage created across the energy absorption unit as well as the source determines the overall duration to current elimination & the rate of fault current [69].

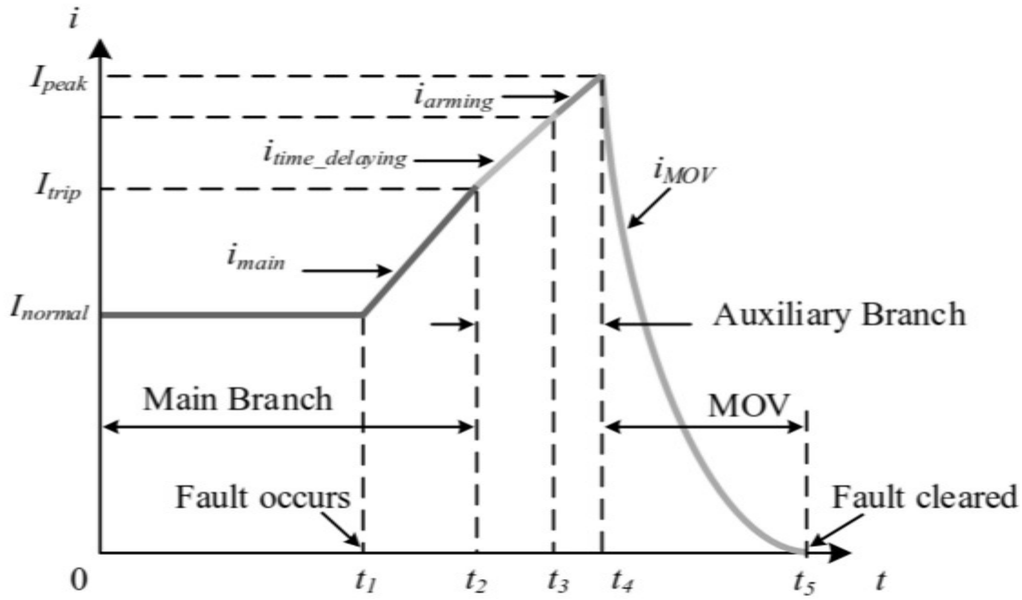


Figure 6.4: Control technique for hybrid HVDC Breaker fault current interruption, Alstom grid

6.2.3 Superfast Medium Voltage Circuit Breaker (General Electric)

Conventional dc circuit breaker designed for point–to–point purposes seem to be too expensive, too large & too slow to employment in MVDC distribution system. The energy division of the United States 'Advanced Research Projects Agency–Energy' granted a $5.8 million research funding to a team of engineers at General Electric to construct a superfast circuit breaker [70-71]. The General Electric researchers group intends to build a quicker switch out of gas plasma. According to Timothy Sommerer, the ARPA–E grant main investigator, a conventional HVDC circuit breaker demands an air–conditioned structure, dimensions 10x10x25 feet & prices among $5 M to $10 M. A HVDC circuit breaker consisting of power semiconductor switches which commutates the current in milliseconds, allowing duration to function a primary mechanical breaker. Setting up an MVDC grid with such a topology would be prohibitively costly. The researcher group involves developing a breaker which operates between two electrodes using plasma or charged gas. The switch is activated by a tiny current passing via a mesh cable embedded between its two electrodes. Their objective would be to develop a 100 kV dc breaker within next 3 years, which will serve as a barrier among high & medium dc voltage. Plasma switch provide the benefit of being lighter in dimension. Semiconductor switches may also run quickly, however the cooling requirements necessitate larger area between the switches for keeping them cool. As a result, the size of the equipment grows. Because plasma switches typically function at extremely higher temperatures & they may be operated in close proximity and modified in limited spaces with lower footprints.

Chapter 7

Conclusion and Future Research Needs

7.1 Conclusion

Currently, the primary impediment to the use of HVDC systems seems to be a deficiency of established HVDC fault current breaking technology. The current advancements of HVDC circuit breakers have been encapsulated and contrasted in this paper. Over the previous two decades, this issue has evolved fast. Also with expansion of real–life multi–terminal HVDC grids, researches and improvements in HVDC breaker systems are undoubtedly increasing. After obtaining the specified performance level, the ideal HVDC breaker contender might have a minimal price. All of the breaking strategies described possess limited functionality in interrupting persistent fault current that could be considerably upgraded. Mechanical circuit breakers being the basic equipment providing fault current termination would be optimized in terms of the dimensions of the resonance circuit's components. In order to get a better current rating, the arc chamber's behavior must also be modified. Because hybrid circuit breakers provide greater efficiencies & optimum interruption speed, the advancement of speedier mechanical switches having strong surge voltage resist & lower concoction losses may result in further advancements in this field. In the case of solid state circuit breakers, the use of novel wideband-gap semiconductor materials such as SiC or GaN focused switches must be researched. Active gates programming methods, on the other hand, can increase the perform of semiconductor switches into solid-state circuit breakers. Furthermore, correct static formulations for semiconductor switches having applicability in high voltage and high currents must be constructed for usage in prototypes & simulation. Utilization of DC fault current attenuators in HVDC systems may be of interest to explore in order to differentiate persistent faults from transient grid occurrences.

7.2 Future Research Needs

Various technical aspects in which research & advancement are necessary to enhance or allow HVDC circuit breakers have been discovered and described in previous portions of the article. The following sections provide a summary of the discussed literature as well as prospective research directions [4]:

- Through minimizing the sizes of elements like the inductors, capacitors, varistors, and so on, advancements in the existing dc breaker architecture could be obtained. The objective would be to limit interruption duration, size, and expense.

- By strengthening the technology, making series connection or spreading dc breaker throughout the medium-voltage stages in multilayer converter configurations, medium–voltage dc breakers may be used for high-voltage ranges.
- Both oscillation development and interruption capabilities of the switching arc may be improved by thoroughly researching the arc characteristics with numerous vacuum & gas breaker settings. The restrictions are verified and deduced using mathematical arc models.
- It is advised that hybrid dc breakers be used. Because it may have properties from both mechanical and solid–state breakers while having lower switch ratings. As a result, size, cost, and interruption duration have been minimized.
- For strong oscillating current and during the disruption, Comsol Multiphysics simulations of dc arcs have been recommended.
- Active gate driving methods that have the potential to increase the efficiency of semiconductor switching inside a genuine solid circuit breaker are advocated.
- Speedy mechanical disconnectors having minimal on–state losses & strong sustain voltage restoration have enough arcing voltage for quick commutation. For rapid actions, those switches could be used in hybrid dc breakers.
- New wide–band gap power semiconductor equipment (SiC or GaN) are advised for achieving the minimum on–state losses.
- It is necessary to develop new proceedings procedures regarding the dc breaker with any of its parts. Because dc breakers interact heavily with the network, Approaches that use powerful hardware-in-the-loop devices might be helpful.
- To meet the requirements of breaker–control protection, the whole multi–terminal HVDC system should be integrated optimized.
- For medium dc voltage, GE Plasma switches that can work at excessive temperatures are relatively inexpensive, as well as can be changed in limited spaces with lower footprints are recommended.
- To establish effective dc–grid protection, criteria and rules for the functioning of multi–terminal HVDC networks should be specified.

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