

Review

DC Circuit Breaker Evolution, Design, and Analysis

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Abstract: While traditional AC mechanical circuit breakers have been competent for protecting AC circuits, high penetration of DC power distribution technologies like DC microgrids (MGs) obligate better disruption performance features such as quick and reliable switching speeds. However, a DC circuit breaker (DCCB) novel design is challenging due to the need to quickly break high currents within milliseconds, caused by the high fault current rise in DC grids compared to AC grids. In DC grids, the circuit breaker must provide zero current crossing and be designed for absorbing surges since the arc is not naturally extinguished by the system. Additionally, the DC breaker must mitigate the magnetic energy stored in the system inductance and withstand residual over-voltages after current interruption. These challenges require a fundamentally different topology for DCCBs, which are typically made using solid-state semiconductor technology, metal oxide varistors (MOV), and ultra-fast switches. This study aims to provide a comprehensive review on development, design, and performance description of DCCBs in parallel with a specific concentration on analysis of internal topology, energy absorption path and sub-circuits in Solid-State (SS)-based DCCBs. The research explores various novel designs that introduce different structures for energy dissipation solution. The classification of these designs is based on the fundamental principles of surge mitigation and a detailed analysis of the techniques employed in DCCBs. In addition, our framework offers an advantageous reference point for the future evolution of SS-circuit breakers in numerous developing power delivery systems.

Keywords: DC circuit breaker, Mechanical DCCB, Solid-state DCCB, Hybrid DCCB, DC Microgrids, DC circuit breaker topology, Metal oxide varistor, Surge absorption.

1. Introduction

DC microgrids (MGs) are a modern form of electricity distribution system that use DC instead of AC to transmit and distribute electrical energy. In a DC MG, various distributed energy resources (DERs) such as photovoltaic (PV) systems, wind turbines, and energy storage devices are connected to a common DC bus through power electronics interfaces. In recent years, DC MGs are becoming increasingly popular due to their numerous advantages over traditional AC grids, including improved energy efficiency, higher power quality, greater flexibility, and economical reasons in integrating renewable energy sources [1]–[3]. They are also considered to be an important solution for addressing the challenges of the increasing demand for electricity, energy security, and climate change mitigation.

However, the design and operation of DC MGs pose unique challenges, such as controlling power flow and maintaining stability and reliability, which require innovative solutions. As a result, research and development efforts in the field of DC MGs are ongoing, with the aim of improving their performance and expanding their application [4]–[6].

An overview of a typical DC MG is presented in Figure 1. DC circuit breakers are placed at various locations in the grid, near to the renewable energy resources, transmission line, main grid, battery bank, and load sides to ensure microgrid protection and maintenance. The DC circuit breaker (CB) types vary due to the presence of different levels of voltage and current paths within the

network, ranging from generation to load. The primary objective of having a DCCB in DC systems is to protect the system against intentional or unintentional faults and voltage or current switching surges [7]-[10]. Table 1 provides a brief comparison between DCCBs specification of some manufacturers [11]-[15]. The selection of DCCBs will be based on the working conditions, voltage and current level, and thermal capacity which is substantially affected by I^2t of the beaker. The AC system can endure the fault current for a little while longer when it is experiencing thermal overload or overcurrent since the fault current rise rate is comparatively slow. Due to the DC system's low short-circuit impedance and rapid rising time of the fault current, it must be stopped immediately [16]-[18].

Table 1. Comparison of different types of commercialized DCCB’s applications.

Description	Schneider Electric	Eaton	Siemens	ABB	LS
Model	Power PacT JDC	CJGPVS, CKDPV	HDGD	SACE Emax	Susol
Rated Current	30~1200 A	150~3000 A	50~1600 A	Up to5000 A	16~1600 A
Performance voltage	500 VDC	600~1000 VDC	600 VDC	250~1000 VDC	500-1500 VDC
Breaking Capacity	20 up to 50 KA	1.5 up to 42 KA	42 KA	65 KA	20 up to 50 KA
Ambient Conditions	-10 to 60 °C	-40 to 70 °C	-25 to 70 °C	-40 to 70 °C	-25 to 55 °C

Furthermore, DCCBs are also utilized for maintaining the devices within the DC system. When a component of the system requires maintenance, the DCCB can safely interrupt the circuit, allowing the maintenance work to be carried out without posing a risk to personnel or damaging the equipment.

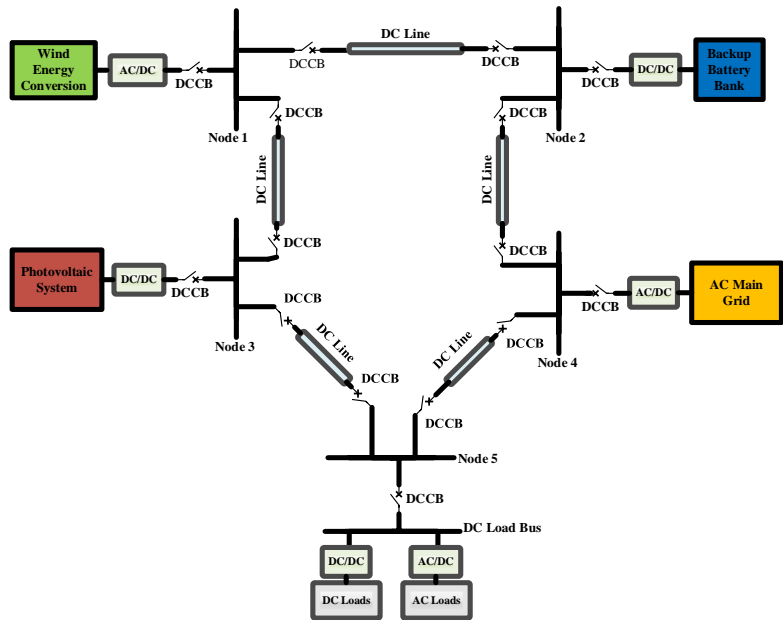


Figure 1. Overall topology of DC Microgrids

The DCCBs system makes it possible for some studies [19]-[21] to focus on DC MG fault current limiting, control, and clearing. These areas of study have been widened to include DC MG clusters.

2. Surge Absorption Design Principle for DC Circuits

Surge voltages are voltage increases that usually occur for a duration from approximately one signal cycle to 1.5 second. These overshoots are typically triggered by the switching of high range

loads and main grids. Although they are not as intense as sharp spikes, surges usually surpass the line voltage by around 20%, which can lead to data corruption of computers, harm of devices, and inaccurate readings in supervisions systems. If a surge persists for more than two seconds, it is generally known as an overvoltage. Therefore, to protect a circuit against transients, it is necessary to restrict the voltage amplitude of the surge at each part of the circuit and deviate the current and voltage of the surge through protection-specific components to absorb the released energy. The likelihood of experiencing damage from a power surge is typically associated with the size of the sudden increase and time span of the surge. Electric discharges and other transients in power systems exhibit rapid and intense properties in terms of both speed and magnitude (often several thousands of volts), hence, surge protection device (SPDs) needs to react promptly and manage considerable energy levels shortly to be effective. Typically, upstream circuit breakers or fuses cannot react quickly enough in response to the activation of the surge diverter because their reaction time is not fast as the span of the transient impulse [22], [23].

Essentially, all SPDs operate as voltage dividers [24]. Figure 2 demonstrates this concept with a series line impedance, Z_s , and a load impedance, Z_L . The source impedance, Z_s , is always present due to the impedance of system wiring and transient source. Without any protection, as shown in Figure 2a, the source voltage is divided between two series impedances. Since Z_L is significantly larger than Z_s , a greater voltage is generated across the load, which leads to detrimental consequences. When an impedance-blocking device like Metal-Oxide Varistor (MOV_{block}) is linked in series, as depicted in Figure 2b, its impedance rises in response to the surge's frequency components dependents. This causes a decrease in the load voltage. Thus, this type of series SPD topology is not conventional. When a shunt SPD element, such as MOV_{shunt} with impedance of Z_{MOV} in Figure 2c, is used, its impedance decreases during high-voltage surges, allowing a shunt current to flow through it and absorb the surge energy. If possible, components of Z_s should be selected to increase its value and mitigate the surge, thereby reducing the stress on the bypass device.

An optimal SPD should minimize the transmitted surge energy to the load to protect both the load and the SPD against any hazard. This transmitted energy can be determined by integrating the surge voltage and current over time, represented as $\int vi dt$. An effective SPD should achieve a lower voltage across the load (known as clamping voltage) to restrict the current flowing through the load. It should also possess characteristics such as low dynamic resistance and quick response time. Additionally, extra factors like longevity, repeatability, board size, cost, reliability, and a fail-safe mechanism are crucial considerations in the design of an SPD.

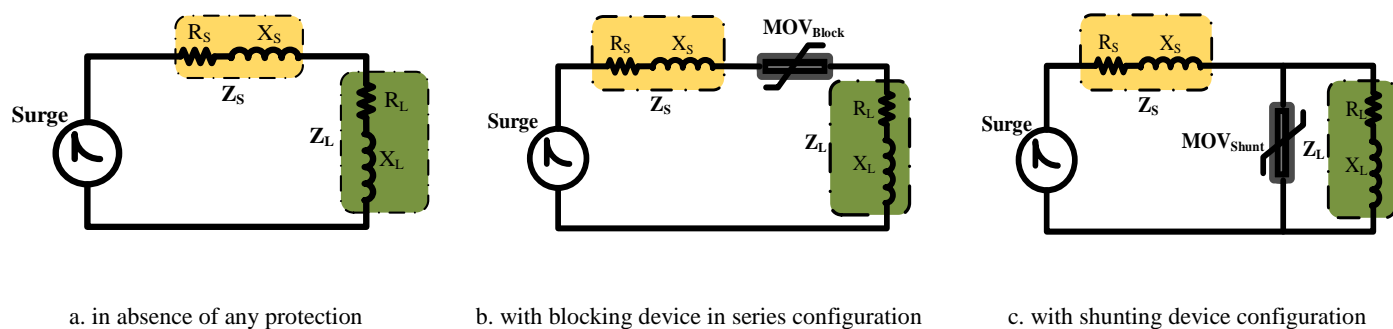


Figure 2. Voltage division methodology in transient surge protector design [22].

In DC calculations, due to zero frequency ($f=0$), impedance is considered as pure resistance. But, in case of high frequency surge occurrence, impedance behavior changes by created inherent inductance. Surge frequency for 20 μsec length time is 50 kHz, and for 50 μsec is 20 kHz. Thus, the impedance amount of the circuit ($Z = R + jX$) should be calculated if the inductance is negligible or not.

Since shunt structures are more suitable for SPD designs, the dissipated energy in MOV can be computed using the following method for estimation of voltage, V_{MOV} , and current, I_{MOV} of the MOV as expressed in Eqs. (1) and (2):

$$V_{MOV} = \frac{Z_{MOV}}{Z_{MOV} + Z_S} \times V_{Surge} \quad (1)$$

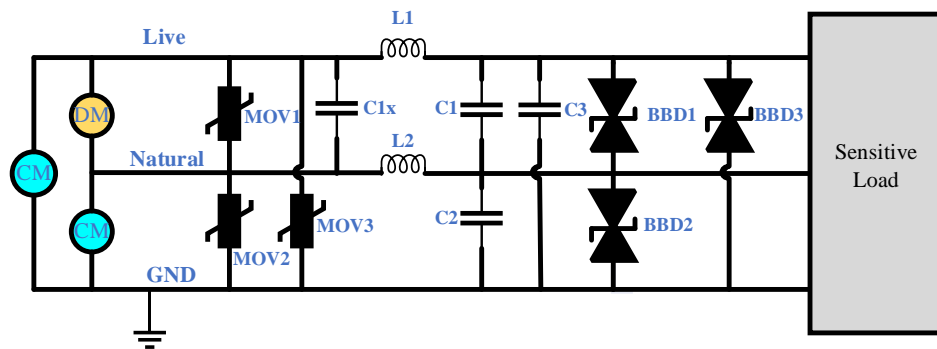
$$I_{MOV} = \frac{Z_L}{Z_L + Z_{MOV}} \times i_{Surge} \quad (2)$$

Therefore, the energy that is dissipated across the MOV, E_{MOV} , during the surge time denoted as t_{surge} , can be expressed in Eq. (3) as follows:

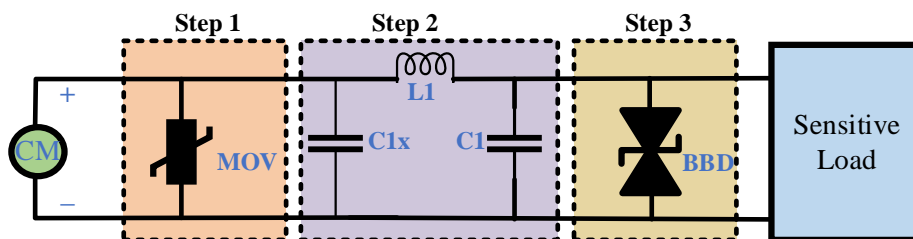
$$E_{MOV} = V_{MOV} I_{MOV} t_{surge} = \frac{Z_{MOV} Z_L}{(Z_{MOV} + Z_S)(Z_L + Z_{MOV})} V_{Surge} i_{Surge} t_{surge} \quad (3)$$

The above calculation could assist the designers in choosing the appropriate components for their SPD design.

A typical practical protector design with nonlinear devices such as MOV and bidirectional breakover devices (BBDs) for a three-wire DC system is illustrated in Figure 3. capacitors represent additional near short-circuit paths to the surges and offer exceptional protection as well. This technique also arranges protection against both common-mode and differential-mode surges [25]. If the maximum induced voltage is greater than the corresponding MOV's firing voltage, the MOV will activate and conduct a high current immediately. This causes a clamping voltage to form across the MOV terminals, and it absorbs the released energy over the surge duration. This protects the critical load from the surge voltage danger. Additionally, the surge energy is further filtered by the LC filters on the path. The series inductor's $L\omega$ impedance and the parallel capacitor's $\frac{1}{C\omega}$ impedance absorb more energy of the HV transient. If there is any residual HV transient, the BBDs at the end of the protection path will absorb it by firing, provided that the peak of the remaining surge surpasses the BBD's trigger voltage.



a. Three wire DC system surge protector topology [25]



b. surge protector topology against common mode surge

Figure 3. practical surge protector for a three-wire DC system.

Where total dissipated energy (E_D) in the system will be determined as the sum of the dissipated energy during the three steps of surge protection as expressed in Eq. (4).

$$E_D = E_{step1} + E_{step2} + E_{step3} \quad (4)$$

$$V_{MOV} = \frac{Z_{MOV}}{Z_S + Z_{MOV}} V_{Surge} \quad (5)$$

$$V_{C1} = \frac{Z_{C1}}{Z_{C1} + Z_{L1}} V_{MOV} \quad (6)$$

$$V_{SL} = V_{BBD} = V_{C1} = \frac{Z_{MOV} \times Z_{C1}}{(Z_S + Z_{MOV}) \times (Z_{C1} + Z_{L1})} \times V_{Surge} \quad (7)$$

$$i_{surge} = i_{MOV} + i_{C1x} + i_{L1} \quad (8)$$

$$i_{L1} = i_{C1} + i_{BBD} + i_{SL} \quad (9)$$

$$i_{MOV} = \frac{Z_S}{Z_S + Z_{MOV}} i_{surge} \quad (10)$$

$$i_{C1x} = \frac{Z_S}{Z_S + Z_{C1x}} i_{surge} \quad (11)$$

$$i_{C1} = \frac{Z_{L1}}{Z_{L1} + Z_{C1}} i_{L1} \quad (12)$$

$$i_{BBD} = \frac{Z_{L1}}{Z_{L1} + Z_{BBD}} i_{L1} \quad (13)$$

$$i_{L1} = \frac{(Z_{L1} + Z_{C1})(Z_{L1} + Z_{BBD})}{Z_{BBD}Z_{C1} - Z_{L1}^2} \times i_{SL} \quad (14)$$

$$i_{L1} = X i_{SL} \quad (15)$$

Given the component impedances and a constant value, X, the surge current can be calculated using the Eq. (14), which can then be used to determine the sensitive load current (Eq. (16)).

$$i_{SL} = Y \times i_{surge} \quad (16)$$

$$Y = \frac{Z_{BBD}Z_{C1} - Z_{L1}^2}{(Z_{L1} + Z_{C1})(Z_{L1} + Z_{BBD})} \times \frac{Z_{MOV}Z_{C1x} - Z_S^2 - Z_SZ_{C1x}}{(Z_S + Z_{MOV})(Z_S + Z_{C1x})} \quad (17)$$

Therefore, the amount of dissipated energy in each component in the circuit can be determined separately by considering the provided estimated values of voltage, and current of each component multiply with the time such as the formulation is Eq. (3).

3. DC Circuit Breaker Topologies

There are three fundamental topologies of DC circuit breakers [26]-[28]. Mostly, other researchers developed these designs. Although electromechanical based circuit breakers are not used in DC topology system designs anymore due to the significant disadvantage of their low-speed performance.

1. Mechanical (Resonance) DC circuit breakers (M-DCCB)

2. Solid state (Static) DC circuit breakers (SS-DCCB)

3. Hybrid DC circuit breakers (H-DCCB)

In the subsequent stage, there will be an examination and thorough discourse on the structure and efficiency of various topologies.

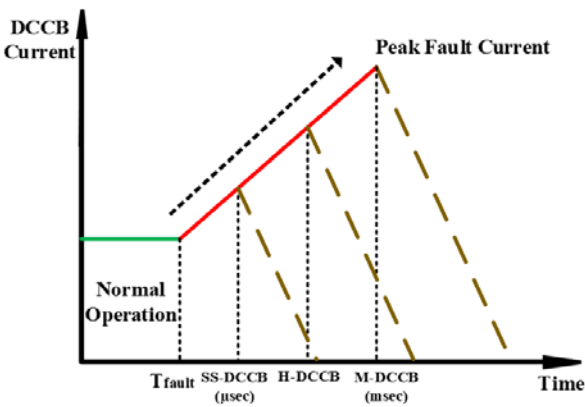


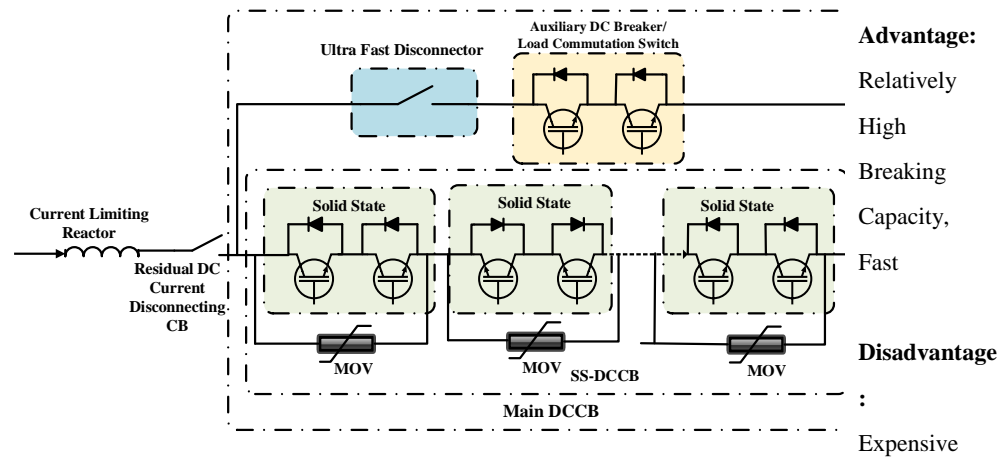
Figure 4. response time comparison between DCCBs in fault absorption.

The objective of Figure 4 is to demonstrate the significant contrast in both reaction time and current-limiting capacity between different topologies of DCCBs. Since control of semiconductor devices as active components is governed by a comparatively low-power external signal, the activation of SS-DCCB turn-off and current-limiting mechanism can take place in a matter of microseconds.

Table 2. Fundamental topology of DCCBs

<div>Topology 1, M-DCCB [16],[29]</div>			<div>Advantage: High breaking capacity</div> <div>Disadvantage: Low speed- Large size- Huge arc production</div>
<div>Topology 2, SS-DCCB [30],[31]</div>			<div>Advantage: Very fast- Small size- Low loss</div> <div>Disadvantage : Low Capacity</div>

Topology 3,
H- DCCB
[28],[32],[33
]



Efforts to develop DCCBs that utilize resonance began in the 1980s. Table 2, Topology 1 (M-DCCB) provides an overview of the topology, which involves mechanical switches that interrupt the current when a zero crossing is created through an LC path (known as forced current diverted commutation line) that runs in parallel with the main electromechanical breaker. The topology also comprises an energy absorption branch, which consists of MOVs. Although newer topologies mentioned in this section may have advantages over the resonance topology, such as lower resistive on-state loss, it may still have practical applications for load switching. The resonance DC breaker topology is comprised of three primary branches [34]:

1. The normal current flow line
2. The forced current diverted commutation line
3. The surge mitigation sub-circuit

During a typical operation, the current follows the intended line. However, if the breaker is instructed to interrupt the current, a mechanical switch will open, resulting in an arc and a change in current direction into a different path. This change generates current oscillations. The arc causes a voltage drop that contributes to these oscillations, which in turn help to extinguish the arc by crossing the zero current point. Afterward, the current flows into an absorption sub-circuit to dissipate any remaining induced energy of the system.

Internal structure of electrical contact in a Molded Case Circuit Breaker (MCCB) double break operating mechanism is presented in Table 2, Topology1. The double-breaking contact system is a highly advanced design for low voltage circuit breakers contacts and was patented by Siemens in 2007. The U-shaped contact points help to reduce the intensity of the shock caused by a surge in the breaker by producing a magnetic field that rotates 180 degrees in the opposite direction. This design simplifies the disconnection of the double-breaking mechanism [29,35].

To improve and supply the quick interruption during the fault or surges in DC systems, SS-DCCBs presented. The solid-state topology employs semiconductor devices such as IGBT, MOSFET, GTO, and Thyristor in conjunction with MOV and/or capacitor to interrupt the flow of electrical current. During regular operation, the current flows through the semiconductor devices. To halt the current, the devices are deactivated, and the current is rerouted into the paralleled sub-circuit, which acts as both the commutation and energy-absorbing path. The MOVs discharge the energy accumulated in the system, much like in the resonance topology. SS-DCCB topology illustrates a solid-state based configuration that employs IGBTs and diodes for bi-directional applications. The figure demonstrates a solid-state DC breaker for unidirectional configuration. The topology of bi-directional current interruption could be achieved by positioning the same range IGBT in anti-series with an anti-parallel diode. More breaker cells can be added in series to raise the rated voltage level [36]. Even though the SSCB can break the current swiftly enough for fault current disruption, the semiconductors conduct current during typical working conditions, causing high losses due to the voltage drop over the breaker, particularly in high voltage applications [31], [37].

A typical SSCB comprises several crucial elements, including power semiconductor devices, gate drivers, cooling mechanisms, voltage clamping circuits, fault detection systems, sense and trip

electronics, and an auxiliary power supply. In Table 2 a theoretical performance of a standard SSCB is depicted. The number of power semiconductors needed will vary depending on the application's voltage and current ratings, the power semiconductor technology, and the breaker's topology. Even though gate drivers with auxiliary power supply are already on the market, several researchers are investigating ways to enhance the gate driver's capabilities to create high-performance SSCBs and integrate multiple functions into a single unit [31].

Hybrid topologies combine both mechanical switches and semiconductor devices. Recent research papers suggest that ABB and ALSTOM have created DC circuit breaker prototypes using this approach, which show potential as promising technologies. H-DCCB topology provides an overview of the hybrid DC circuit breaker, which can be viewed as an extension of an IGBT-based solid-state topology. The utilization of thyristors in the design enables this topology to be appropriate for HVDC circuit breaker designs, as it can handle large voltage and current levels effectively [38]-[43]. The breaker includes an additional branch with a mechanical low resistance ultra-fast disconnecter (UFD) and a load commutation switch (LCS). The LCS, same as the solid-state DC breaker, is designed to interrupt current flow, but it has a limited number of breaker cells that can only transfer current to the main breaker. To address the issue of conduction losses in solid-state topology, hybrid topology allows for nominal current to flow through the LCS and a UFD under regular operation. When an interruption command is received, the LCS turns off and transfers current to the main breaker, same as the solid-state breaker. Following the commutation, the UFD opens to isolate and protect the LCS from voltage drops caused by the main breaker's interruption of current. The UFD is a crucial element in minimizing losses during regular operations and achieving rapid current interruption. It operates as an electromagnetic actuator, utilizing magnetic forces to achieve the fast-switching speed necessary for efficient circuit protection. According to ABB, their DC circuit breaker can eliminate faults within 5 milliseconds. The role of the current limiting reactor is to restrict the high slope of the fault current. In addition, a switch that operates in parallel with the hybrid DC breaker is also present to provide physical isolation following the clearance of the fault current. To determine the current and energy dissipation in these circuit breakers during a fault, certain circuit parameters must be considered. Following a circuit fault in a DC system, most of the fault current redirected through the H-DCCB is attributable to the IGBTs within the breaker [44]-[46]. The fault current can be denoted in Eq. (18) as follows:

$$i_f = I_{line} + \frac{V_{IGBT}}{L_{line} + L_{CLR}} \times (t - t_1) \quad (18)$$

Where I_{line} is the pre-fault current, L_{CLR} is current limiting reactor inductance, and t_1 is the fault time. And current of the IGBT switch will be calculated by Eq. (19) as:

$$i_{IGBT} = I_{line} + \frac{V_{IGBT}}{L_{line} + L_{CLR}} \times t_2 \quad (19)$$

Where t_2 is the performance time of the IGBT switch.

To calculate the dissipated energy of the MOV, the voltage at the protection level during t_3 (MOV performance time) is assumed to remain constant. The maximum amount of energy dissipated by the MOV in each series part is then determined by Eq. (20) as:

$$E_{MOV} = [I_{line} + \frac{V_{IGBT}}{L_{line} + L_{CLR}} \times t_2] \times V_{MOV} \times \frac{t_3}{2} \quad (20)$$

Thus, the dissipated energy between each individual series cell in H-DCCB could be calculated separately by the presented formula [47], [48].

4. Design Improvements of DCCBs for DC Microgrids Application

The upcoming section will examine three novel and distinct classifications of the DCCB's energy absorption techniques:

- 4.1. MOV-based DCCB
- 4.2. Capacitor-based DCCB
- 4.3. Hybrid MOV-Cap DCCB

The most crucial section in DCCBs for absorption of the released energy during switching and faults is the energy absorption part. In this Section, we compared a wide range of studies that suggested several designs to redirect the surge through solid state components to technically absorb the released energy. The constructed DCCB worked admirably in each of the approaches that were discussed, and the outcomes are pleasing. The difference is between their technology, performance voltage and current level, and the response time which is a key factor in DCCB designs.

4.1. MOV-Based DCCB

For DCCBs based on MOVs, the circuit breaker's embedded MOV completely handles surge absorption. Different designs define the strategy for absorbing the released energy [49]-[52].

Table 3. A comparative study on three conventional MOV-based design of DCCB's

Description	Topology 1 [53]	Topology 2 [54]	Topology 3 [55]
Proposed model			
Model verification			
Technique	Separated MOV	Ground Clamping	MC FCL
Technology	MOV- IGBT	MOV- MOSFET, IGBT	MOV- IGBT
V _{dc} /I _{dc}	30 v/ 2.5 A	400 v/4 A	500 v/ 380 A
Response Time	0.4 μsec	50 msec	1.8 ms
Number of Passive components	4	6	8
Number of Active components	1	2	≥4

The significant drawback of these designs is that the MOVs deteriorate over time when exposed to surges [22],[30].

The separated MOV technique in Table 3 has put forward an approach that involves using two distinct MOVs placed in specific locations within a circuit, to isolate the two functions of the MOV, namely voltage clamping and energy absorption. This proposed approach aims to separate the two

functions of MOVs, allowing them to operate independently and more efficiently. The result shows the successful test and surge absorption through paralleled MOV's circuit. But the test is restricted to a small range of voltage and current amplitudes.

Alongside, ground clamping strategy illustrates a new DCCB design that uses a current limiter to absorb the surge voltage [54]. This SSCB design consists of several components including a main switch (S_2) that conducts the line current and prevents source voltage before and after breaker operation. Additionally, the design includes a MOV to demagnetize the energy stored in the system inductor, a ground clamping switch (S_1) that bypasses the DC bus, and a current-limiting inductor (L_2) with its resistive energy absorber. In this design, Minimum current limiting inductance could be determined by Eq. (21) according to the bus voltage, V_{DC} , breaking time, T_{Break} , zero current detection time, T_{det} , saturation current of inductor, I_{Lsat} , and threshold current of I_0 :

$$L_s > \frac{V_{DC}(T_{Break} + T_{det})}{I_{Lsat} - I_0} \quad (21)$$

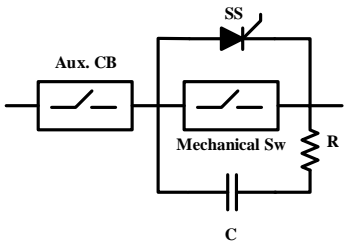
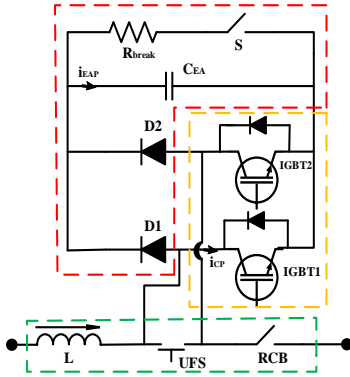
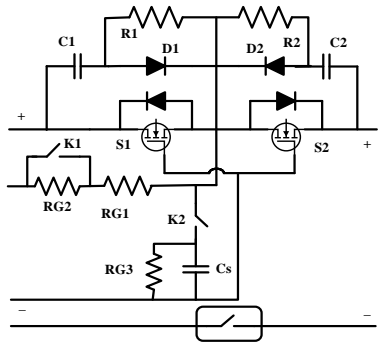
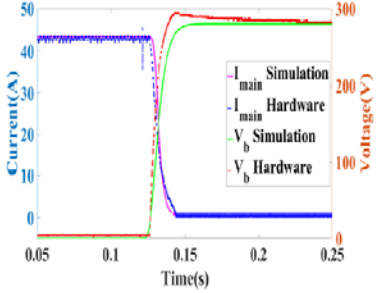
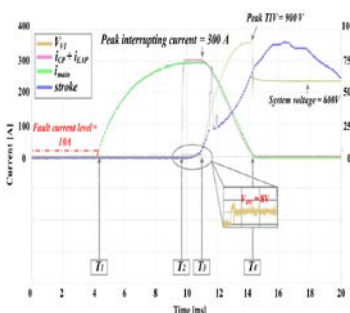
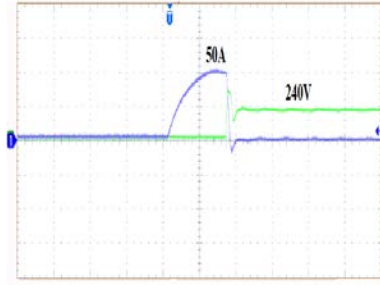
Furthermore, magnetic coupling fault current limiter (MC FCL) technique proposed a fault current limiting design with magnetic coupling auxiliary circuit in the input of the circuit breaker to limit the severity of the current shocks. In this study released energy is coordinated to be dissipated in both MOV and resistance in the secondary of the transformer.

Overall, while various techniques for surge absorption have been successful in damping surges and fault currents, there are design issues that need to be addressed. For example, many designs rely on metal oxide varistors (MOVs) for surge absorption, but often fail to consider the limitations of MOVs, which can weaken their ability to damp surges or will be degraded over time.

4.2. Capacitor-Based DCCB

To enhance the design of DCCBs, some studies have explored the use of capacitor-based technology for both commutating and surge absorption purposes. This approach involves a bridge-type capacitor-commutation unit that serves to buffer the device voltage and is considered an independent method for improving DCCB design [56], [57]. Table 4 provides a concise overview of the recent designs, highlighting their points of comparison.

Table 4. A comparative study on three conventional capacitor-based design of DCCB's

Description	Topology 1 [58]	Topology 2 [59]	Topology 3 [60]
Proposed Model			
Model Verification			

Technique	A/C Circuit	VI- PMA	Soft-switched
Technology	Cap- IGBT	Cap- IGBT	Cap- MOSFET
V_{dc}/I_{dc}	283 v/ 43.5 A	750 v/ 300 A	240 v/ 50 A
Response Time	15 msec	9.6 msec	20 msec
Number of	2	7	12
Passive components			
Number of	3	5	5
Active components			

All three-capacitor based DCCB designs mentioned in Table 4 redirect surges to a subcircuit to reduce the impact of energy released during DC system faults or surges. They effectively absorb energy using specific techniques. However, the designs differ in terms of their response time, voltage and current levels, and the components used in the circuit.

Other studies have followed unidirectional and bidirectional Z-source DCCB (Z-s DCCB) designs, which the strategy is focused on capacitor-based design [61]-[66]. Z-s DCCBs show potential as suitable options for protect low and medium-voltage distribution networks, along with DC equipment, among the various configurations available, because of their uncomplicated structure, control mechanism, and economical price [67]. As shown in Fig. 5 the general layout of bidirectional Z-s DCCB, where two sets of isolated thyristors are arranged in parallel to facilitate the flow of current in both directions.

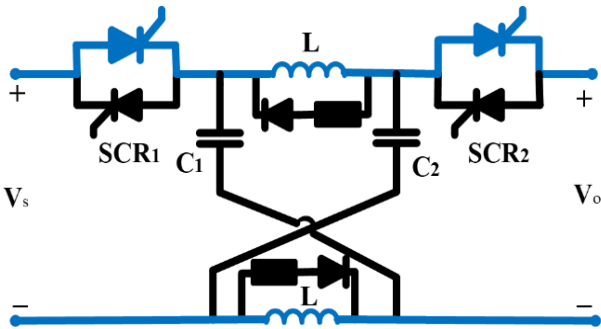


Figure 5. bidirectional Z-s DCCB [67]

In the mentioned designs electrolytic capacitors for surge absorption are utilized, but these components have limited capacity and cannot dissipate the energy released by high voltage longer duration faults, and have a limited lifespan due to their chemical structure.

4.3. Hybrid MOV-Cap. DCCB

Several studies have proposed novel designs of hybrid MOV-Cap DCCB to overcome the weakness of degradation of MOV and restricted capability of capacitors to absorb the energy [68]-[71].

In Table 5, all designs effectively performed fast through different techniques. capacitor discharge path is considered for all models and the level of voltage and current in the circuits are different.

In active thyristor CB (AT-CB) technique, bidirectional, low loss DCCB with a reliable opening process based on a simple hybrid design for capacitor and MOV is implemented. This technique is more suitable for medium voltage DC systems [72].

$$t_q = \frac{C_b V_n}{\alpha I_{fmax}} \tag{22}$$

$$C_b = \frac{\alpha t_q I_{fmax}}{V_n} \tag{23}$$

Therefore, the value of the bypass capacitor can be approximated using Eq. (23), which involves determining the recovery time, t_q , which will be calculated by Eq. (22), inserting the values for the maximum allowable fault, I_{fmax} , and the desired coefficient, α .

Table 5. A comparative study on three conventional hybrid MOV-Cap design of DCCB's

Description	Topology 1 [72], [73]	Topology 2 [74]	Topology 3 [75]
Proposed Model			
Model Verification			
Technique	AT CB-DCCB	TIM-Pack	LCC-AIC
Technology	MOV-Cap Thyristor	MOV-Cap Thyristor-IGBT	MOV-Cap SiC MOSFET
V _{dc} /I _{dc}	150 v/10 A	600 v/145 A	350 v /90 A
Response Time	1.6 msec	6 μsec	4 μsec
Number of Passive components	5	5	9
Number of Active components	4	4	2

Other techniques of Thyristor-IGBT-MOV (TIM-Pack) and inductor capacitor-capacitor based active injection circuit (LCC-AIC) in Table 5 switched fault currents into the designed sub-circuits within a couple of microseconds to improve the reliability.

5. Discussion on the Design Improvement

Various techniques of surge absorption have been discussed in the literature for designing DCCBs in nominal voltage ranges that span from a few hundred volts to tens of kV. The power rate, voltage, and flowing current level in a DC microgrid are directly linked to the semiconductor device utilized in its design. As a result, the design and techniques employed should be adapted for varying levels of power in the microgrid. During the DCCBs circuits design, the number of passive and active components used plays a crucial role in determining the most cost-effective topologies for the rate of DC system power. Additionally, it is important to consider the lifespan of the circuit components by assessing the weaknesses of each part during the design process. Regarding the reliability of the circuit, it has been mentioned that there is a lack of detailed comparison in literature, specifically in terms of the vulnerabilities of the components such as deterioration, chemical-based materials, and limited energy capacity.

This paper focuses on proposing new ideas to improve the design of the surge absorption sub-circuit in the evolution of DCCB designs. Table 3 concentrates on the performance of the circuit and the task of energy absorption, which currently relies on MOV-based subcircuits. However, the weakness in the performance of MOV degradation and protection is not taken into consideration. MOV alone is unable to protect the circuit against short circuits and overcurrent situations. Therefore, when designing a DCCB for DC protection with an MOV energy absorber, it is crucial to consider current limitations. This aspect is addressed in the designs presented by ground clamping strategy and MC FCL techniques.

Hybrid designs are typically employed to address the performance limitations of previous designs and enhance their features. A hybrid design in the energy absorber can mitigate the degradability and overcurrent and short circuit protection issues associated with MOV in Table 3, as well as the low capacity and chemical-based weaknesses of capacitors, in Table 4. In a hybrid design, the tension in the circuit is divided among various shock absorber components, effectively covering these weaknesses. This concept is most evident in the designs proposed by TIM-Pack and LCC-AIC techniques.

6. Prospective Future Advancement

Here are a few possible future advancements that have the potential for future research:

- Research on the surge absorption techniques and sub-circuits in DCCB design to cover the existing limitations.
- Integrated design of DCCBs in terms of performance, and higher breaking capacity against faults and switching of the DC circuits.
- Improve the reliability and lifetime of the DCCB's by using non-chemical, non-degradable components for surge, fault and switching effect absorption.
- Cost reduction by substituting minimal amount of the degradable components, and utilization of alternative components like resistance instead of expensive like MOV.
- Power loss can be minimized through design improvements, which involve reducing both switching power loss resulting from semiconductor switching and passive component loss from elements like current limiters and snubber resistors during regular system operation. This can lead to more efficient performance with reduced power dissipation.

7. Conclusion

DCCB as a significant part of the DC MG topology takes over the protection and improving the reliability of modern power systems. In this article, surge absorption principle in DC systems were reviewed to illustrate the process of limiting the voltage and current transients that occur in DC systems due to switching operations or lightning strikes. Furthermore, three level SP design estimations for sensitive load are determined, which ensure that sensitive loads are protected from transients.

Three main topologies of DCCB design evolution including M-DCCB, SS-DCCB, and H-DCCB topologies were investigated and reviewed. Each topology has its advantages and disadvantages,

and the choice of topology depends on the specific application requirements. Particularly, the energy absorption subcircuits of DCCBs were focused, which were separated into three sub-designs: MOV-based, capacitor-based, and hybrid MOV-Cap based designs. Then, various techniques were examined and discussed to identify the optimal design approach for different applications. Finally, design improvement factors and future development of DCCBs were discussed. These include the use of advanced materials, such as wide-bandgap semiconductors, and the integration of DCCBs with other protection devices to improve the overall system reliability.

Surge absorption technique and design plays a critical role in ensuring the reliable performance of DC MG and DCCB. The protection of modern power systems primarily depends on the employed techniques in DCCBs. Enhancing the subcircuit design responsible for energy absorption and considering design improvement factors will contribute to the advancement of DCCBs in the context of future power systems.

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