

*Research article*

## **Interconnected standalone DC microgrid fault protection based on Self-Adaptive DC fault current limiter with hybrid solid state circuit breaker**

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**Abstract:** DC system has the potential of vast and rapid fault current generation due to multiple (line and converters) discharge capacitors and small impedance of DC lines. DC fault current spreads through the system exponentially compared to AC. Such an unexpected huge current causes a voltage drop, impacts the normal operation of system components and exposes the system to a great challenge for fault detection and interruption. For prevention of system destruction during the fault, multiple approaches such as application of Mechanical Circuit Breakers (MCBs), fuses, Solid State Circuit Breaker (SSCB), and Hybrid Solid-State Circuit Breaker (HSSCB) have been proposed and applied. In DC fault applications, fast fault detection and interruption without any interference to the other components are quite important. Therefore, semiconductor breakers have been implemented to meet the DC fault protection requirements with a high-speed operation where traditional MBs have failed. Due to the high conduction loss and low efficiency of semiconductor switches, for fast and efficient DC fault interruption, different Fault Current Limiter (FCL) types are suggested. Although a high impedance FCL can prevent the voltage fluctuations due to the current decline, it can cause operation speed issues, coordination troubles, overheat, and malfunction of protective components in a fault situation.

This paper focused on a combination of two-way HSSCB with a self-adapt DC short current limiter, ultra-fast switch, and power electronic switch to overcome the above challenges. It can efficiently

and fast fault current limiting response with low conducting loss and appropriate cooperation among protective components in a low voltage DC system. The MATLAB/Simulink is used to analyze the effectiveness and consistency of the proposed FCL-HSSCB in 400 V interconnected standalone DC microgrids.

**Keywords:** standalone DC microgrids; PV array; converters; battery; DC short circuit protection; Self-adapt FCL; HSSCB

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## 1. Introduction

The combination of renewable energy resources has paved the way for sustainable DC distribution networks. Power converters are extensively applied for the integration of different components in an interconnected LV DC distribution system. It will cause multidirectional fault current to follow and increase exponentially the fault current [1,2]. A huge DC short circuit current interruption is challenging for traditional Circuit Breakers (CBs), and it will damage system components and cause system instability. Depending on the system structure and components situations, the reconnection of protective devices may not be feasible in short circuit situations. The next challenge for a multisource LV DC system during a short circuit is the inverse time over-current of presumed short current in coordinated relays [3,4]. It is suggested that the short circuit protective system in an interconnected DC distribution network needs to work based on the direction of current flow. For a two-way short circuit current protection, the fast-acting protective relays and breakers are required to be coordinated. With the various structural configuration and activity mode of multisource DC microgrids, fault current limiting technique and interruption time has also changed to an important topic [5]. To enhance operation stability and security of multisource LV DC microgrid, it is suggested to apply fault current limiting strategies and coordination among protective devices to achieve appropriate fault clearing techniques. Thus, it is important to suppress DC fault current to less than breakers interruption capacity to maintain the system safety and stability. Compared to a single source LV DC network, a multisource DC system can be exposed to the most complicated fault topology. DC short circuit can be pole-to-pole and pole-to-ground short circuit. Due to the low impedance in a pole-to-pole DC short circuit, a huge current will follow through converters valve and other devices. The system will be destroyed if the short current is not suppressed and removed quickly [6–8].

Furthermore, LV DC microgrids rely on power electronic technologies for stable operation. They can not sustain a huge fault current without a fast protective device. Unlike AC short circuit, it is complicated and stressful for MCBs and fuses to interrupt a high DC short current with no zero-crossing point [9–11]. The size and strength of the arc between breaker contactors is another challenge for DC breakers. It is highly required to reduce interruption time in DC applications to prevent huge arc creation. The quickest clearing time for SSCBs has confirmed tens of  $\mu s$ , where it is hundreds of  $ms$  for traditional MBs [12]. Although due to high operation speed, the SSCB technologies have been considered an ideal fault interruption solution in the DC system [13]. For DC fault protection purposes, still it has safety and efficiency concerns during normal operation. To provide a high operation speed and maximize the normal operation efficiency, HSSCB is considered the most appropriate technique for DC fault application [14]. Additionally, besides HSSCB an accurate detection system is required to

identify the faulted area and disconnect the related breaker within a specified time to maintain power stability to the rest of the system. Therefore, an investigation of appropriate protective technology is required to ensure safety for the system during fault conditions and assure human safety and power system equipment. In an interconnected DC system, the converters and line capacitors discharge through short-circuits point, causing a huge current flow and leaving an essential demand for FCL strategy. The capacitors will be discharged and it will be stored as electromagnetic energy in inductors. That will cause a reverse current to follow through the commuting diode of each converter. Also, due to the transient response of power electronic converters to short circuit conditions, it cause a poor overload strength and stability of the converters [15,16]. It will keep remaining the components in operation even the current goes beyond the rated value in fault situations. In a normal operation period, the FCL circuit is expecting to have the minimum impedance to enhance efficiency and component's reactivity. While in a short circuit situation it is required to maximize the impedance to reduce the short current, particularly fast quenching and recovery after DC short circuit interruption. Therefore, a current limiting circuit with a high-speed breaker will decrease voltage dip and maintain the power supply stability. Additionally, the structure, components, effective deployment of FCLs is a contemporary topic for fault protection purposes. Recently for softening DC short current extension, the DC FCL techniques change to a crucial topic in DC electrical system and various types of FCL have been applied [17,18].

Currently, the most well-known current limiting methods are reactive current limiter and Superconducting Fault Current Limiter (SFCL) [19,20]. In [21–23] the resistive and inductive FCL is investigated for high voltage DC system applications. Both superconductive resistive and reactive FCL can extinguish and limit the DC short circuit current to an acceptable level and maintain a safe operation for protective devices. Although the larger reactive FCL capable of appropriate short current limiting, a suitable size of the reactor is quite important for power system safety and clearing time. Therefore, technically, a large reactor is not permitted to install in the DC electrical network due to undesirable consequences [24,25].

- FCL with a large reactor slows down the detection and operation speed of sensors and breakers. After breakers disconnect the circuit with a large current, the accumulated short circuit energy will be extinguished by parallel MOV in a DC fault situation. In a large inductor FCL circuit, considerable energy will be charged in the reactor. It may take a long time to dissipate the accumulated energy. Consequently, it will take a longer time for fault clearance and system recovery.
- Magnify breaker size: A larger reactor will cause a bigger breaker; it may increase the cost and need more space and maintenance cost.
- Impacting on normal condition of DC network: In a healthy situation, it is required to unplug the large DC reactor because of the rate of direct current change restriction and system efficiency. Subsequently, with a large reactive FCL, the system will be faced with stability and power flow issues.

The main purpose of this research is fast and efficient fault clearance using HSSCB with a self-adapt FCL circuit. It will improve DC fault clearing time and may not hurt a normal situation of the LV DC system. Using a DC limiting method in this paper, the operation circumstances for system components in a normal condition can be enhanced. In abnormal situations, the FCL circuit will be

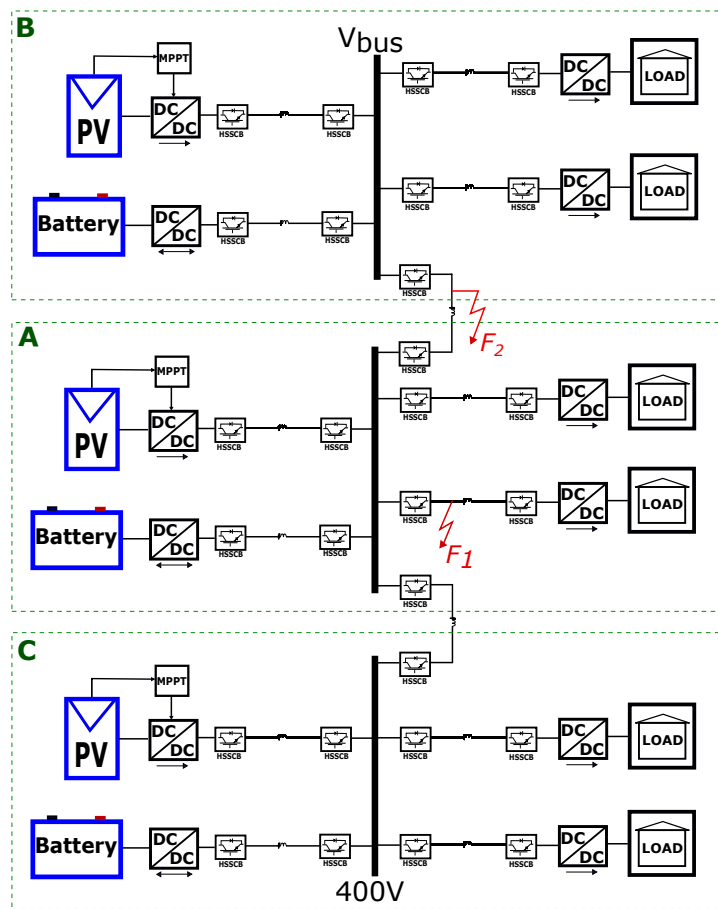
connected instantly to the system and help the breakers operate appropriately without any electrical or thermal stresses. Regarding the DC short circuit current transient features, the initial high current is supplied by line and converters capacitors. Subsequently, if the proposed FCL-HSSCB is applied with each converter, the current will be limited to the desired value in each part of the DC system. The rest of the paper is arranged as follows; Section II discussed the desired interconnected small-scale DC microgrid configuration and related elements with parameters. In section III, the DC short circuit current features and characteristics is studied. Section IV discusses the FCL circuit and high-speed HSSCB performance methods. Simulation outcomes and performance is depicted and described in Sections V. The paper is ended with a conclusion and summary in section VI.

## 2. Interconnected standalone DC microgrids structure and components

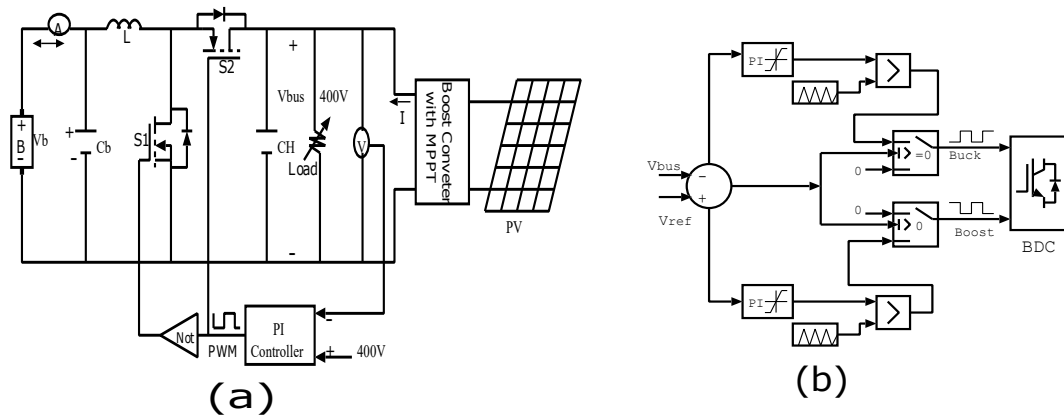
LV DC system with modern power electronic devices has the capabilities to mitigate a significant amount of conversion loss during power conversion steps in the system with renewable resources and DC load. The structure and main components of the desired interconnected standalone DC microgrids are depicted in Figures 1–3 and Table 1. It has three small independent parts (A, B, C) which are interconnected through distribution feeders and power electronic elements. The solar panels, battery arrays, and load are connected to the DC bus via power electronic converters and self-adapt FCL-HSSCBs. Feedback PI regulator is applied to control DC bus voltage ( $V_{bus}$ ) and the charge and discharge of the battery in different environmental and operational conditions. For the PV and boost converter, the MPPT-IC algorithm is used to maximize and boost PV power and voltage. Each feeder is equipped with a two-way FCL-HSSCBs at both ends to protect the fault current follow in both directions. Based on the power and load demand in each small area, the controller is capable to share power among A, B, and C to maintain the entire power stability. A two line-to-line DC short circuits ( $F_1, F_2$ ) are applied at two different points and at a different time to analyze the performance of the suggested DC short circuit protection techniques.

**Table 1.** System components and computed values.

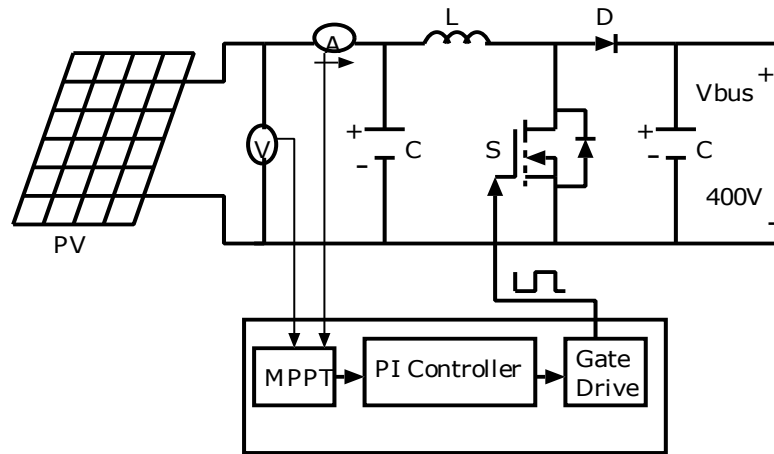
Parameter	Value	Symbol
Rated $P_{PV-A}$	26 kW	$P_{PV-A}$
Rated $P_{PV-B}$	30 kW	$P_{PV-B}$
Rated $P_{PV-C}$	45 kW	$P_{PV-C}$
Rated DC Load <sub>A</sub>	20 kW	$L_A$
Rated DC Load <sub>B</sub>	28 kW	$L_B$
Rated DC Load <sub>C</sub>	34 kW	$L_C$
Battery Capacity	50 kWh	$B$
DC Bus Voltage	400 V	$V_{bus}$
DC Feeder Length	1.5 km	
Switching Frequency	5 kHz	$F$
Line Resistance	0.14 $\Omega/km$	$R$
Line Inductance	0.24 mH/km	$L$



**Figure 1.** Interconnected standalone DC microgrid structure and configuration.



**Figure 2.** Battery array as the main storage device for this study: (a) Battery and bidirectional converter system (b) Detailed description of the two way PI controller structure.



**Figure 3.** PV array and boost converter with MPPT-IC algorithm structure.

### 3. DC short circuit characteristics

DC system comes with the main barrier, which is extremely vulnerable to DC short circuit situations. The structure of interconnected converters support the fault current through its freewheeling diodes. The operation speed of the MB breaker is slow and due to the absence of inductance in the DC line, the fault current growth is 5–10 times faster than AC. Also due to the absence of zero-crossing point and abrupt increase of DC fault current, DC fault protection can not be achieved by traditional AC breakers. The major issue with SSCB and HSSCB for DC fault protection is it's immature to the huge current during DC fault conditions and a high conduction loss due to the presence of multiple power electronic switches. The DC fault protection can be achieved by integration of full-bridge multi-modular converter stations, but it will cause a low system efficiency and increase the normal operation loss (30–35% total loss) and initial cost [26]. Whereas, in HSSCB there are parallel auxiliary paths with the mechanical switch to reduced the conduction loss during normal situations.

Although using a large capacitor bank in an LV DC system is the easiest way to limit voltage fluctuation caused by power converters switching. It will cause over current and create the most critical situation for power electronic converters. Also, in a critical situation, the IGBT switches will be blocked automatically due to self-protection characteristics [27]. There are two main types of DC short circuits ( pole-to-pole and pole-to-ground faults). In line-to-line short circuit conditions, the line's electrical parameters are small compared to a line-to-ground fault. They are causing a huge short current jump and an underdamped transient approach according to the following equation.

$$\frac{C(R_c + R_{fault})^2}{4L_c} < 1 \quad (3.1)$$

Additionally, due to huge current jump causing by discharging of line and converter capacitors, the size of the capacitor is required to decrease to satisfy Eq 3.2:

$$\frac{C(R_c + R_{fault})^2}{4L_c} > 1 \quad (3.2)$$

It will facilitate the protection operation in the overdamping state to protect sensitive power electronic devices and other components [28].

To know the DC fault ride-through in abnormal situations, the reduction and time delay criteria of the current rising are requiring to be considered in the initial stage of the fault circuit. It also minimizes the frequent disturbance and component damage during fault response. That will be feasible by extending the discharging time constant capacity of the capacitors and short circuit resistance during fault conditions. According to  $e^{-\frac{t}{\tau}}$  where  $\tau = \frac{L}{R}$ , the inductor discharge rate and time constant can increase by a higher inductor for a faulted circuit. Therefore, by integration of series inductors, the rate of discharge time of capacitors will be extended, and a complete discharge of capacitors will take a longer time. Consequently, postponing the raising of faulted current to critical value can be achievable.

#### 4. Self-Adapt FCL circuit and High-Speed HSSCB performance

FCL is working as a series impedance with DC distribution line. Theoretically, it is considered a normally closed switch with a parallel resistor. It is required to have a high operation speed and automatically return to normal and recovery state after the fault clearance. Therefore, an appropriate FCL circuit with DC breaker needs to have: (a) Fast fault current restriction capability; (b) Insignificant impact on the normal operation of the system; (c) High efficiency; (d) Low price and maintenance cost [29,30]. It can help to prolong the life span of system components, reduce high voltage fluctuation, and obtain lower mechanical and electrical pressures.

The proposed self-adapt FCL-HSSCB in this study is suggested for an LV DC distribution system with small damping. It is capable of fault current restriction for two-way protection application shown in Figure 4. And it will act with the highest speed to maintain safety for the sensitive devices and enhance the fast recovery for the whole system. Comparatively with previous work, the breaker in this study achieved a higher operation speed, efficiency and configuration [31]. The FCL circuit is capable of efficient self-compatibility during different situations.

The stored energy in parasitic components will be quenched by MOV, and due to clamping characteristics of MOV the voltage on HSSCB clamps to  $V_{MOV}$ . The maximum current of HSSCB ( $I_{max}$ ) and voltage on inductor ( $V_L$ ) can be achieved by the following equations respectively [32]:

$$I_{max} = i_L + \frac{V_{MOV} - V_{DC}}{L} \quad (4.1)$$

$$V_L = V_{MOV} - V_{DC} \quad (4.2)$$

where,  $i_L$  and  $V_{DC}$  are inductor current and system rated voltage respectively. The FCL-HSSCB operation process in this paper has the following characteristics.

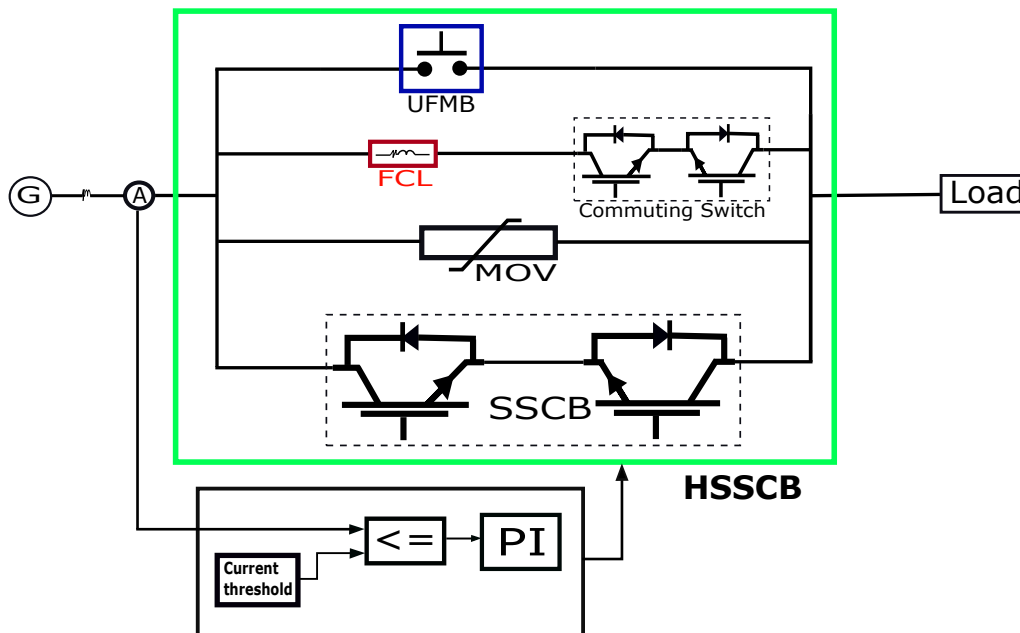
- In a normal situation, for stability and high-efficiency purposes, the FCL circuit will be disconnected automatically and the current will flowing through the ultra-fast MB.
- During a fault condition, the FCL will be connected instantly to restrict the fault current growth and propagation through the entire system and provides a safe operation and isolation for the protective devices.
- After the fault clearing the system is recovering fast and the protection system will be ready for the next unexpected short circuit occurrence.

- For the system fast recovery purposes and temporary fault situation, FCL will be disconnected.
- The stored energy in the inductors and accumulated DC fault energy will be quenched and dissipated by the parallel MOV.

After a DC short circuit occurring in any part of the system, the capacitor of all converters will be discharged along the faulted circuit that causes a large current follows through the short circuit point. Consequently, the DC short circuit current is the total of lines and power electronic converters discharge current. It is quite important to know that the system parameters calculation, transient feature, converter types are the most affecting factors during the fault condition. For a DC fault analysis, the type of DC distribution line, system configuration, capacity, feeder length, fault types, and location are the essential topics that need to be considered. Due to the direct effect of the fault position and feeder length on the current value, the equivalent fault impedance will not have the same value in a different location. It will affect the rate of current rise and peak value. Thereby, the desired FCL unit for each circuit is required to be arranged by DC circuit breaker interrupting current. And the restriction current of each FCL branch can be found by the following equation [33]:

$$I_L = \frac{1}{N} + I_M \quad (4.3)$$

where  $I_M$  is the maximum interrupting current of the DC breaker,  $N$  is the number of discharge circuits in a possible faulted branch and  $I_L$  is the desired limiting current of the FCL circuit. Regarding to equations 3.2, 4.1 and 4.3 the rated and maximum allowable current is considered to be 40 and 65 ampere respectively.



**Figure 4.** The desired self-adapt FLC-HSSCB with control system structure for the fast DC fault protection applications.



The high speed, self-adaptability, high-efficiency, fast recovery and multi-short fault current limiting makes it capable to handle the LV DC distribution during fault situations and giving a better system stability. Moreover, the configuration and technology enable it for more flexible and optimized integration of DGs and clean energy sources.

## 5. The main DC breakers characteristics and comparison

However, the demand for DC system technology keeps improving towards maturity, higher costs of DC breakers are anticipated to become comparable to AC components, while other remarkable advantages of DC breakers could lead to additional cost savings and security for the DC system. Easy and secured fault detection and interruption are quite important interactive factors for the maturity and adoption of DC power supply systems. Currently, the fault protection costs are higher for DC systems due to their immaturity and it has been decreasing by improving power electronic technologies [34].

In recent years different types of DC breakers have been proposed. But they are developed and proposed for current source or line-commuted power converter which is capable of fault protection within 30–100 *ms* [35,36]. For a voltage source converter-based DC system it is a long time for the short current to increase around 20 times and resulting in a cascading failure. Specifically, according to a techno-economic overview based on structure and feasible power electronic products, the breaker in this study is higher cost and efficiency. DC fault protection using HSSCB in [37] suggests an analysis of the operation speed and compares it with MB and Solid State Breakers (SSB). Although the HSSCB has a higher operation efficiency and speed than MB and SSB, still there is malfunctioning among controller and detection components.

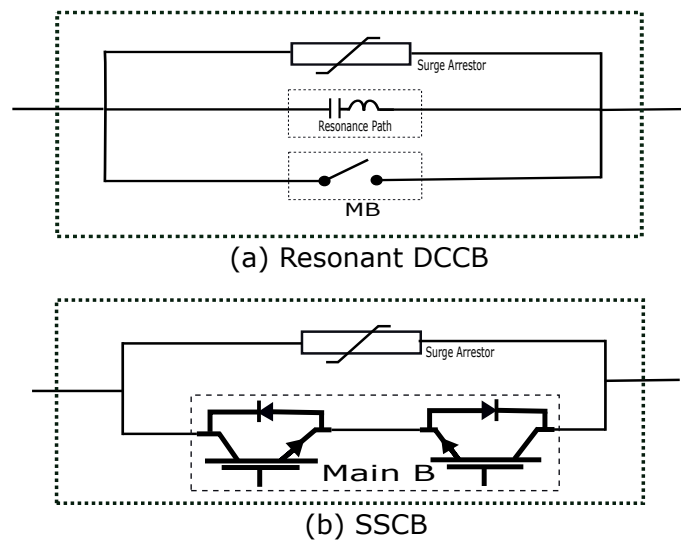
The analysis is performed for three typical available breakers (MB, SSCB, and FCL-HSSCB). Regrading breakers configuration and simulation results the FCL-HSSCB can be effective in all situations including normal and DC fault situations with a higher initial cost. Technically HSSCB and FCL-HSSCB have been touted as an opportunity to DC power systems with a high safety and stability, and communications capability. Because of the limited available DC component in the market that are comparatively more expensive than equivalent AC components. According to [38], despite the higher cost of available DC components, the overall DC network layout can be simpler and resulting in a lower cost because of the lower number of variables inspected in the AC distribution system. The self-adapt FCL circuit will decrease the voltage stress on the breaker and SSCB can smoothly interrupt a lower fault current and acting under a low DC short current to decrease the arcing and prolong the lifetime of breakers. Also, any malfunctions regarding fault detection and interaction can be prevented by the optimized size of the FCL circuit. Without FCL circuits, freewheeling diodes and IGBTs as important and expensive components of the breakers and converters will be destroyed due to low electrical withstanding and overheat under huge DC short circuit current. The individual control of the breaker is the other merit of the proposed breaker, and the malfunctioning of a single unit does not affect the functioning of the other components. Consequently, the initial high cost of self-adapt HSSCB will compensate in a long time stable system and requirement for breaker with a lower current rating.

### 5.1. Effectiveness of the proposed FCL-HSSCB

Different types of FCL breakers are discussed in [39]. Application of FCL arises various issue (communication disturbance with other components, disturbing normal operation, and conduction loss). Selecting desirable parameters, improving coordination among protective devices, feasibility analysis, and real operation in the power grid. By integration of self-adapt FCL-HSSCB for DC fault protection, the operation speed is increased to  $\mu s$  and the requirement of DC breaker interruption ability is reduced. A comparison is conducted in Table 2 among different types of DC breakers shown in Figure 5 and the proposed breaker in terms of speed, commutation, rated voltage, maximum fault current, and power loss. Due to high interruption speed, the peak fault current and the rated current of the breaker are decreased which contributes to decrease the cost and optimize coordination among protection components. The low impedance path during normal operation decreases the conduction loss and improving the dynamic operation of the low voltage DC system. The inductance of FCL is minimum in normal conditions and increases while the fault happens. Resulting in higher efficiency and lower cost compared to other FCL breakers.

**Table 2.** Comparative characteristics of the DC breakers [37].

	SSCB	Resonant	HSSCB	FCL-SSCB
Commutation	0.1 ms	breaker < 20 ms, Resonant < 30 ms	Switch 0.1 ms; breaker < 20 ms; UFD 1–4 ms	UFS 0.5–2 ms SSB 30 $\mu s$
Interruption	1 ms	60 ms	3–5 ms	50 $\mu s$
V <sub>max</sub>	800 V	550 V	750 V	450 V
I <sub>max</sub>	120 A	100 A	115 A	65 A
Loss	30–40%	Negligible	Negligible	Negligible



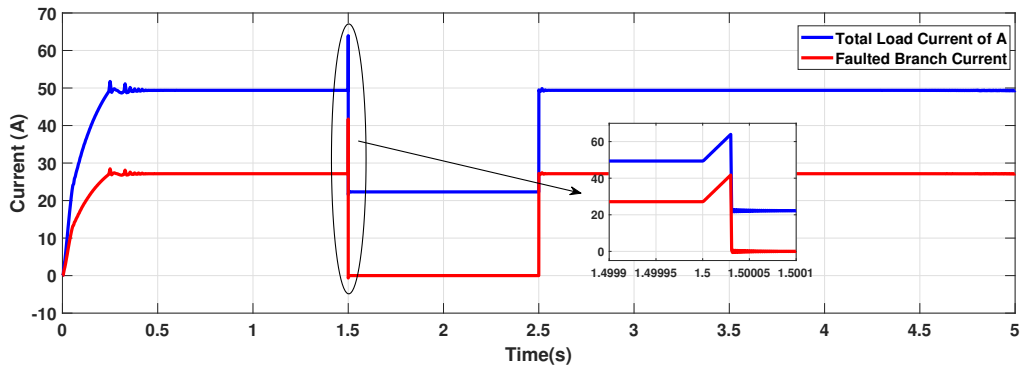
**Figure 5.** Comparison circuit diagram of Resonant DCCB and SSCB.

## 6. Simulation results and discussion

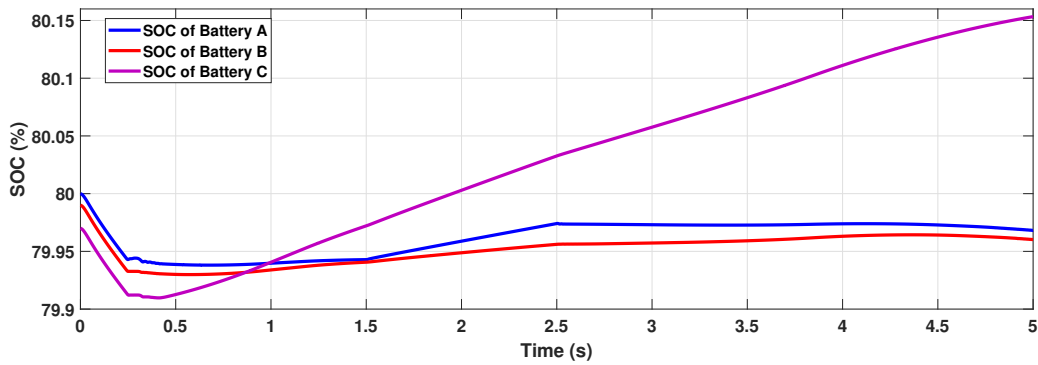
Two line-to-line faults ( $F_1, F_2$ ) are applied in different locations of the interconnected standalone DC microgrids to evaluate the performance of the proposed FCL-HSSCB and fault ride-through scheme. The output power of the PV array is variable according to environmental (solar radiation and temperature) conditions. In a normal situation, the current is flowing through parallel ultra-fast MB. When a fault occurs, the sensors and controller detect the high surge current and voltage dip. Consequently, the protective devices will act instantly to remove the fault. In case one, in time 1.5 s a line-to-line short circuit ( $F_1$ ) happens on an 11 kw load branch of the small area A. without an FCL circuit, the fault current has the potential to increase 3–5 times its normal value within 10 ms. As depicted in Figure 6, the discharged current follows through the faulted point. It is allowed to reach the considered threshold value for protective devices. After passing the threshold value, the circuit is immediately moved to the current limiting operation, and the nearest HSSCB operates to clear the fault within 50  $\mu$ s. During the fault  $F_1$ , the rate of battery charging in area A is increased and the extra power is sharing to neighbor areas (B, C) to maintain the stability of DC bus voltage, shown in Figures 7–10. In the second case, the interconnected line between A and B is shorted on 2 s and it is lasting for 1 s as shown in Figures 11–13. The same as case one, initially, the current is increased to a threshold value. While it passes the threshold value, the FCL circuit suppresses the current within permitted values and the two nearest HSSCBs disconnect A and B from the faulted point within 50  $\mu$ s. Figures 12 and 13 show the DC bus voltage and SoC of batteries, which are not affected by the short circuit situation due to the fast fault clearing. Here the self-adapt FCL circuit acts as a transferring path for the short current and allows the SSCB to operate in much lower current. Comparatively, the performance of HSSCB without FCL circuit is depicted in Figures 14 and 15 during  $F_2$ . The breaker interrupts the fault current within 3 ms and the fault current increases drastically (1500 A) and DC bus voltage collapse along this time. Resulting the requirement of protection devices with high current rating and sustainability to endure and interrupt the huge current.

Consequently, due to the high speed, low operation loss, configuration and fast recovery the proposed breaker can be an optimum fault protective device for the LV DC system. As depicted in simulation results, in both cases the fault is lasting for 1 s and the faulted circuit is isolating within 50  $\mu$ s and the power supply operation is maintained stable for the rest of the system. The excess power during the fault is shared with neighboring areas and storage devices to maintain the DC bus voltage stable. After the fault is removed, the circuit is recovered smoothly without any effect on system normal operation.

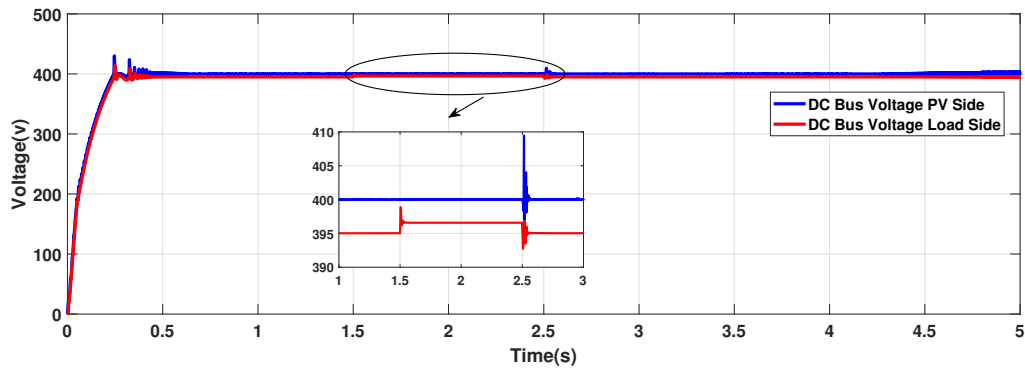
- Simulation results for  $F_1$ :



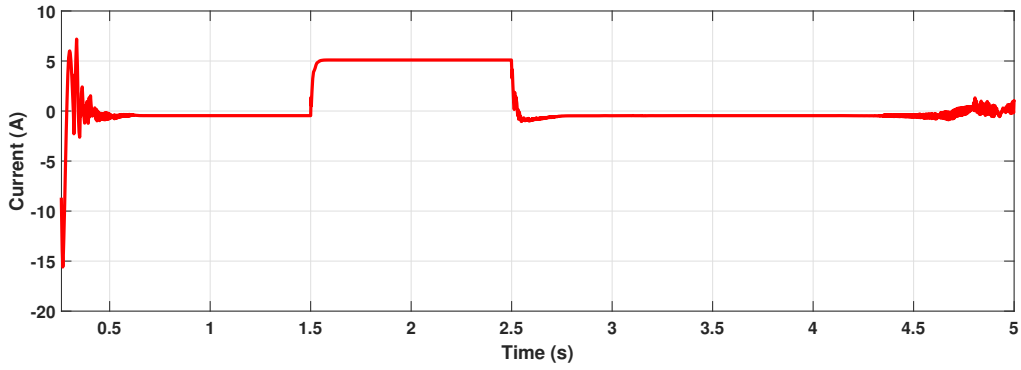
**Figure 6.** The total load current and fault interruption of 11 kW load branch of A.



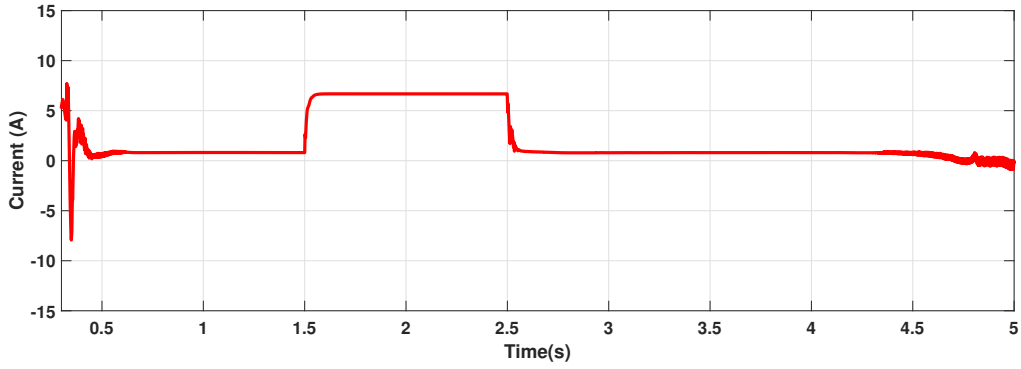
**Figure 7.** State of charge of the battery array in three areas.



**Figure 8.** DC bus voltage in both load and PV side during the fault  $F_1$ .

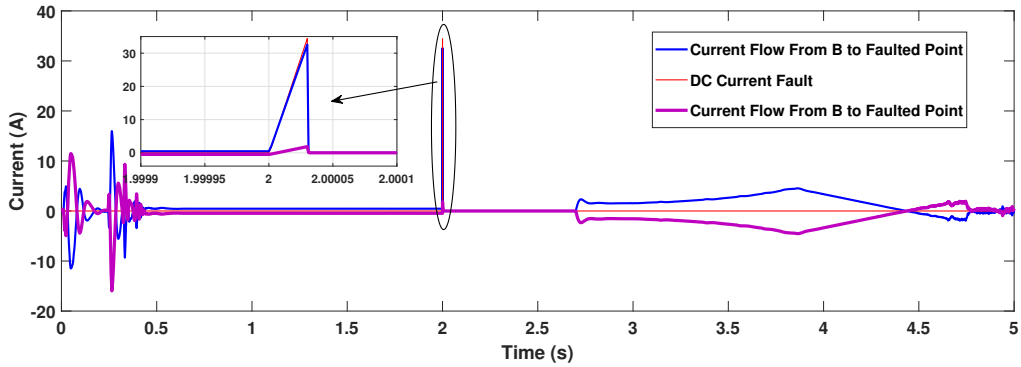


**Figure 9.** Current flow and the load sharing of A and B during  $F_1$ .

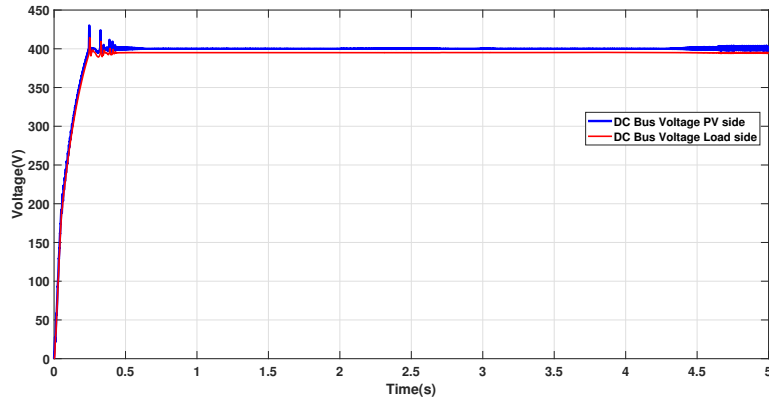


**Figure 10.** Current flow and the load sharing of A and C during  $F_1$ .

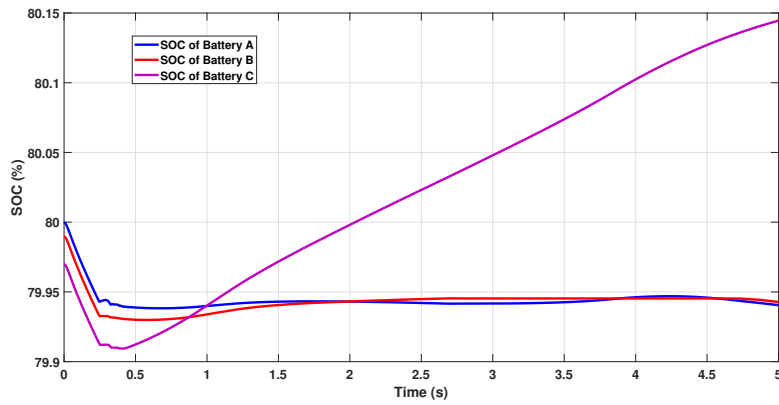
- Simulation results for  $F_2$ :



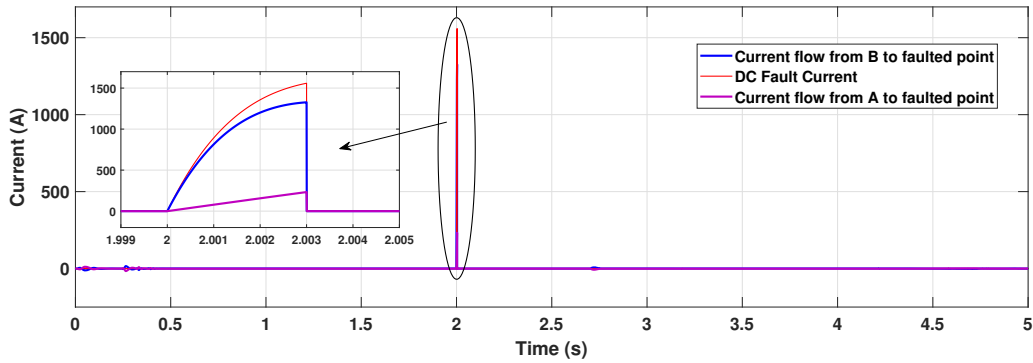
**Figure 11.** Fault current and the current flow from A to the faulted point.



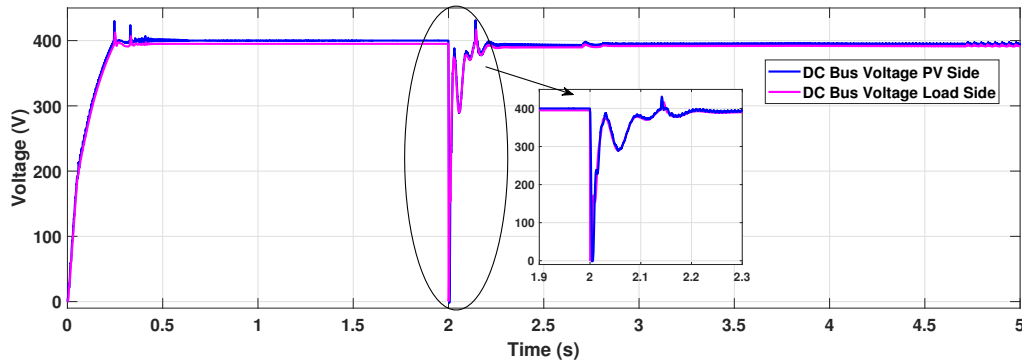
**Figure 12.** Current DC bus voltage in both load and PV side during the fault  $F_2$ .



**Figure 13.** State of charge of the battery array in three areas.



**Figure 14.** DC fault clearance using HSSCB without FCL circuit during  $F_2$ .



**Figure 15.** Bus voltage during  $F_2$  using HSSCB without FCL circuit.

## 7. Conclusions

The short circuit protection scheme in the LV DC network is a special topic. Particularly during an abnormal condition, it needs to have accurate detection capability, high speed, fast recovery, lower loss, and lower maintenance cost. Due to the mechanical action, traditional MBs and fuses have low operation speed and high maintenance cost. Additionally, a fault protection device with a high impedance FCL circuit will influence the regular operation of the system and prolong operation time. While a resistive FCL circuit has a suitable current restriction capability, it may cause a high-power loss in normal operation of the DC electrical system.

PV arrays and batteries supply the DC system in this study through power electronic converters. The desired FCL-HSSCB model is applied and developed in MATLAB/Simulink program to evaluate and improve the operation speed and reduce conduction loss. The system stability and protection performance of the proposed fault protection scheme are analyzed by applying DC short circuit actions on different locations of an LV DC system. From simulation results and system configuration analysis, it is concluded that the DC fault detection and interruption speed is depending on the type and configuration of protective devices. Fast fault detection and isolation can provide safety and power stability for the rest of the system.

Additionally, to protect and limit the current from different directions, the output side of converters is the most appropriate point to install the protection and FCL devices. Therefore, in this paper, a self-adapt FCL is considered for the outlet of each interconnected converters to restrict the discharge current of each device. Finally, as depicted in simulation results, the FCL circuit acting appropriately and suppress the DC fault current peak value and maintain a proper time for inspection, interruption, and recovery activities. After the fault isolation, the circuit will recover when there are no more fault condition issues in the system. As a future plan, this research will proceed with more detailed techno-economical characteristics for different level in DC fault protection application.

## Conflict of interest

All authors are agreed on the contents of this manuscript and declare that there is no conflict of interest.

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## References

1. Oh YS, Han J, Gwon G-H, et al. (2016) Detection of high-impedance fault in low-voltage DC distribution system via mathematical morphology. *J Int Counc Electr Eng* 6: 194–201.
2. Yang J, Fletcher JE, O'Reilly J (2012) Short-circuit and ground fault analyses and location in VSC-based DC network cables. *IEEE Trans Ind Electron* 59: 3827–3837.
3. Satpathi K, Ukil A, Pou J (2018) Short-Circuit fault management in DC electric ship propulsion system: Protection requirements, review of existing technologies and future research trends. *IEEE Trans Trans Electrif* 4: 272–291.
4. Kim S, Kim SN, Dujic D (2020) Extending protection selectivity in DC shipboard power systems by means of additional bus capacitance. *IEEE Trans Ind Electron Control Instrum* 67: 3673–3683.
5. Liu K, Yang X, Li Y, et al. (2018) Study of protection for serial multi-terminal DC grids. *J Int Counc Electr Eng* 8: 70–78.
6. Lacerda VA, Monaro RM, Peña-Alzola R, et al. (2020) Control-based fault current limiter for modular multilevel voltage-source converters. *Int J Electr Power Energy Syst* 118: 105–150.
7. Lee KH (2009) Prospect of DC distribution systems and safety issues. *J Korean Institute Power Electron* 14: 21–28.
8. Fletcher SDA, Norman PJ, Fong K, et al. (2014) High-Speed differential protection for smart DC distribution systems. *IEEE Trans Smart Grid* 5: 2610–2617.
9. Miao H, Sabui G, Roshandeh AM, et al. (2016) Design and analysis of DC Solid-State circuit breakers using SiC JFETs. *IEEE Emerging Sel Top Power Electron* 4: 863–873.
10. Salomonsson D, Sannino A (2007) Low-Voltage DC distribution system for commercial power systems with sensitive electronic loads. *IEEE Trans Power Delivery* 22: 1620–1627.
11. Liu YC, Chang EC, Lin YL, et al. (2018) A Novel online insulation fault detection circuit for DC power supply systems. *Int J Smart Grid Clean Energy* 7: 194–201.
12. Li LQ, Antonello A, Luca R (2017) Detection of high-impedance fault in low-voltage DC distribution system via mathematical morphology. *Design of solid-state circuit breaker-based protection for DC shipboard power systems* 5: 260–268.
13. Salato M, Zolj A, Becker D-J, et al. (2012) Power system architectures for 380 V dc distribution in telecom datacenters. *Proc IEEE Int* 23: 23–46.
14. Liu F, Liu W-J, Zha X-M, et al. (2017) Solid-state circuit breaker snubber design for transient overvoltage suppression at bus fault interruption in low-voltage dc microgrid. *IEEE Trans Power Electron* 32: 3007–3021.
15. Rashad M, Raoof U, Ashraf M, et al. (2018) Proportional load sharing and stability of DC microgrid with distributed architecture using SM controller. *Math Probl Eng* 3: 271–279.
16. Shuai Z, He N, Xiong Z, et al. (2018) Comparative study of Short-Circuit fault characteristics for VSC-Based DC distribution networks with different distributed generators. *IEEE J Emerging Sel Top Power Electron* 7: 528–540.



17. Jae S-H, Khan UA, Shin W-J, et al. (2016) Validity analysis on the positioning of superconducting fault current limiter in neighboring AC and DC microgrid. *IEEE Trans Appl Supercond* 23: 204–256.
18. Jovicic D, Zhang L, Hajian M (2013) LCL VSC converter for high-power applications. *IEEE Trans Power Delivery* 28: 137–144.
19. Nasereddine R, Amor I, Massoud A, et al. (2013) AC solid state circuit breakers for fault current limitation in distributed generation. *IEEE GCC Conference and Exhibition (GCC)* 7: 446–449.
20. Janowski T, Glowacki BA, Wojtasiewicz G, et al. (2011) Fault current limitation in power network by the superconducting transformers made of 2G HTS. *IEEE Trans Appl Supercond* 21: 1413–1416.
21. Chen L (2019) Application and design of a resistive-type superconducting fault current limiter for efficient protection of a DC microgrid. *IEEE Trans Appl Supercond* 29: 56–67.
22. Nair1 AA, Krishna KT (2016) Micogrid protection using superconducting fault current limiter. *Int Res J Eng Technol (IRJET)* 3: 72–95.
23. Xue S, Gao F, Sun W, et al. (2015) Protection principle for a DC distribution system with a resistive superconductive fault current limiter. *Energies* 8: 4839–4852.
24. Khan UA, Lee JG, Amir F, et al. (2015) A novel model of HVDC hybrid-type superconducting circuit breaker and its performance analysis for limiting and breaking dc fault currents. *IEEE Trans Appl Supercond* 25: 560–3009.
25. Xiaomin Q (2019) Analysis on characteristic of DC short-circuit fault in multi-terminal AC/DC hybrid distribution network. *J Eng* 16: 2051–3305.
26. Chaudhuri NR, Chaudhuri B, Majumder R, et al. (2014) Modeling, analysis, and simulation of AC–MTDC grids, in Multi-Terminal DC grids: Modeling, analysis, and control. *John Wiley and Sons, Inc* 33: 231–235.
27. Nag SS, Mishra S, Joshi S (2016) A passive filter building block for input or output current ripple cancellation in a power converter. *IEEE J Emerging Sel Top Power Electron* 4: 564–575.
28. Yeap YM, Geddada N, Ukil A (2017) Capacitive discharge based transient analysis with fault detection methodology in DC system. *Int J Electr Porwer Energy Syst* 97: 127–137.
29. Zhang J, Gao Y, Xiao F, et al. (2019) Study on DC breaker fault current and its limiting method of multiterminal flexible DC distribution system. *MDPI* 12: 840–859.
30. Huaren W, Ling Y, Lin S, et al. (2015) Modeling of Current-Limiting circuit breakers for the calculation of Short-Circuit current. *Power Del, IEEE Trans* 30: 652–656.
31. Li B, He J, Li Y, et al. (2019) A novel Solid-State circuit breaker with Self-Adapt fault current limiting capability for LVDC distribution network. *IEEE Trans Power Electron* 34: 3516 – 3529.
32. Li H, Yu R, Zhong Y, et al. (2019) Design of 400 V miniature DC solid state circuit breaker with SiC MOSFET. *Micromachines* 10: 314.
33. Yaqobi AM, Matayoshi H, Danish MSS, et al. (2019) Low-Voltage Solid-State DC breaker for fault protection applications in isolated DC microgrid cluster. *Appl Sci* 9: 723.

34. May-Ostendorp P, Porter SF, Denkenberger D, et al. (2014) Reviving the war of currents: Opportunities to save energy with DC distribution in commercial buildings. *ECOVA* 72: 342–365.
35. Sano K, Takasaki M (2014) Review of DC power distribution in buildings: A technology and market assessment. *IEEE Trans Ind Appl* 50: 2690–2699.
36. Andersson D, Henriksson A (2011) Passive and active DC breakers in the three gorges changahou hvdc project. *International Conference on Power System, Wuhan, China: CIGRE*: 391–395.
37. Mitra B, Chowdhury B (2017) Comparative analysis of hybrid DC breaker and assembly HVDC breaker. *IEEE Xplore*.
38. Planas E, Andreu J, Gárate JI, et al. (2015) AC and DC technology in microgrids: A review. *Renewable Sustainable Energy Rev* 43: 726–749.
39. Alam MS, Abido MAY, El-Amin I (2018) Fault current limiters in power systems: A comprehensive review. *MDPI Energies* 11: 1025.



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