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Protection techniques for DC microgrid- A review

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ABSTRACT

The proliferation of DC microgrid is a commendable stride for the future power system to match the load requirement precisely with the distributed generation. The potential benefits of DC system over AC technology have made DC microgrid as a competent solution for anonymously increasing DC applications and load demands. However, the thriving advantages of emerging DC microgrid system are undermined due to the substantial challenges associated with its protection. Chronologically changing DC microgrid architectures decisively affects the existing protection schemes. Fault current nature and fault types further elevate this issue. Furthermore, due to the discharge of converter's DC link capacitor, the rapid rise of fault current in a short duration is a hindrance for the DC microgrid protection and thus decisively affects the safety layer for expensive loads and power converters. No zero crossing of DC fault current vehemently constrained the subroutine of DC circuit breakers. Conduction loss, operational speed requirement, fault current handling capability, and cost is the primary factors that inhibit the advancement of DCCB implementation. To address all those events regarding DC microgrid protection, this paper has explicitly reviewed the existing techniques along with the jurisdiction for the protection requirements towards the proclivity of future DC microgrid.

1. Introduction

In the trend of modern distributed power system, DC microgrid is an attractive technology due to its inherent ability to interface DERs, SST, ESS, and various types of electric loads such as residential and commercial DC loads, data center loads, EVC load. Also, DC microgrid technology is developing so rapidly as it offers several benefits over the AC system (voltage, frequency regulation, synchronization problems are diminished inherently), reliability, and also power quality of the system is extensively enhanced [1–6]. DC system reduces the power loss and allows $\sqrt{2}$ times more power flow than the AC system as skin effect and reactive power drop issues are inherently evanesced [7]. Reduction in power conversion stages and easier integration of DERs and loads have primarily increased the system efficiency and provide excellent operational flexibility [8]. These aforementioned benefits emerge DC microgrid as a substantial solution for several types of applications, such as propulsion system, telecommunication systems, traction applications, electric shipboards applications, etc. [9–11]. However, the promising resilience provided by the DC microgrids has degraded as its protection is again challenging due to the presence of multiple sources and due to the installed ESS, which feeds fault current [12,13]. The approach of curtailment of fault current by the fully controlled power

Abbreviations: AIE, Active impedance estimation; CB, Circuit breaker; MCB, Mechanical CB; SSCB, Solid-state CB; HCB, Hybrid CB; ZSCB, Z-source CB; CIT, Current injection technique; CMV, Common mode voltage; CPL, Constant power load; DAB, Dual-active bridge; MMDAB, Modular multilevel DAB; DG, Distributed generations; DER, Distributed energy resource; DS, Distribution system; ESS, Energy storage system; BESS, Battary energy storage system; ETSI, European telecommunications standard institute; EVC, Electrical vehicle charging; F2F, Front-to-Front; FT, Fourier Transform; FTC, Fault-tolerant capability; FFT, Fast Fourier Transform; STFT, Short time Fourier Transform; GPS, Global positioning system; GTO, Gate turn-off thyristors; HIF, High impedance fault; HRF, High resistance fault; HVDC, High voltage DC; IED, Intelligent electronics device; INR, Incremental negative resistance; IGBT, Insulated gate bipolar transistor; IGCT, Insulated-gate commutated thyristors; I/O, Input/Output; IEMS, Intelligent energy management system; JFET, Junction field-effect transistor; LIF, Low impedance fault; LVDC, Low voltage DC; MMC, Modular multilevel converter; MMF, Mathematical morphology filters; MRA, Multi resolution analysis; MOSFET, Metal oxide semiconductor field-effect transistor; MTDC, Multiterminal DC; MVDC, Mid voltage DC; OCR, Overcurrent relay; OCF, Open circuit fault; DOCR, Directional overcurrent relaying; PD, Protection device; PE, Power electronics; PP, Pole to Pole; PG, Pole to Ground; PI, Proportional Integral; RCD, Residual current device; SCF, Short circuit fault; SCADA, Supervisory control and data acquisition; SiC, Silicon carbide; SST, Solid state transformer; TCC, Time-current curve; TLC, Two-level converters; TW, Travelling wave; WAMPS, Wide-area monitoring and protection system; WAN, Wide-area network; WBG, Wide bandgap; WiMAX, Worldwide interoperability for microwave access; WT, Wavelet Transform; CWT, Continuous WT; DWT, Discrete WT; SWT, Stationary WT; FDWT, Fast dyadic WT

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converter for their safety is one of the suggested current interruption techniques; however, generic OCRs are failed to identify the occurrence of fault due to low magnitude of fault current [14,15]. Apart from this, one of the major challenges is the stringent rise of initial DC fault current within a very small duration due to the rapid discharge of DC-link capacitors. The low impedance of line further augments this phenomenon [16]. Therefore, the fault must be located and cleared as fast as possible for equipment safety. To resolve the issue, fast-acting PDs are solely being required. Natural zero crossings in AC fault current effectively help the ACCBs to extinguish the fault current at the zero-crossing. On the contrary, the absence of natural zero-crossings point of DC fault current hinders to augment the application of DCCBs [13,17–19].

Nonetheless, in DC microgrid system, several voltage levels and different configurations exist and predominantly applied according to the system requirements. The lake of comprehensiveness in regulation and standardization is a non-negligible obstacle for the implementation of DC microgrid system.Thus, while DC microgrid provides significant advantages in terms of flexibility and survivability, the implementation of DC microgrid is undermined due to the inevitable challenges that arise due to protection. Lack of availability of viable protection philosophies is a substantial hindrance to the widespread adoption of DC technology. Therefore, this survey has comprehensively reviewed all the protection techniques deployed for DC microgrids. From this in-depth analysis, this can be concluded that the protection subroutine for DC microgrid can be evaluated based on the following main features such as speed, selectivity, sensitivity, dependability, reliability of the deployed strategies. Before employing any protection scheme, it is essential to substantiate the performance of that strategy by the technicalities mentioned above and has to be verified by different fault scenarios. The merits and demerits of all these protection schemes are identified to foresight the visible scope of advanced and fast protection schemes that may be suitable for the reliable protection of DC microgrid systems.

The content of this paper will substantially help the researchers to alleviate the shortcomings and excavate new techniques to augment the application of DC technology in the future.

2. DC microgrid architecture

Before progressing towards the protection challenges, the architecture of DC microgrid should be understood. This is annotated in tabulation form for better realization with their pros and cons. Table 1 illustrates the used supply polarities for the loads, where DC microgrid topologies are described in Table 2. Due to the intermittent nature of renewable generation, the potential benefits of DC microgrid will be optimized only when the individual DC distributed generations will be interfaced with a common DC grid. Further, the reliability, availability, and accessibility of the supply will be revamped when DC grid will be interlinked with an AC grid. Different type of DC microgrid interfacing with AC utility is detailed in Table3.

3. DC fault current analysis

Analysis of fault current in DC microgrid is essential to design an appropriate protection scheme. Faults associated with DC microgrid are of two types, PP and PG, as shown inFig. 2. PP type fault is generally LIF as the phase conductors are directly in contact with each other, where PG fault is a HIF as both or one of the conductors fall to the ground. Faults can be possibly located either in buses or in feeders. Internal fault inside the VSCs and batteries can also be occurred [16]. Bus fault directly affects converters and batteries, where feeder fault is a hindrance to the supply continuation of un-faulted lines [35,36]. Fault current consists of two different characteristics; transient and steady-state [37]. Transient current is injected from cable discharge of converters and DC-link capacitor, whereas the steady-state part is due to power resources. Converter fault current is stringent due to capacitor-discharge; however, it sustained for a small duration and can be expressed as,

$$i_{cap}(t) = \frac{v_{dc}}{2R_{cap}} e^{-t/\tau_{cap}} \tag{1}$$

where, $\tau_{cap} = R_{cap}C_{cap}$ is the effective time constant of converter. R_{cap}, C_{cap} are the series resistance and capacitance of the capacitor circuit. The battery fault current consists of cable impedance and also its own internal impedance term, expressed as,

$$i_{batt} = \frac{v_{batt}}{R_{batt} + R_{LB}}\left(1 - e^{-t/\tau_{batt}}\right) \tag{2}$$

where, $\tau_{batt} = \frac{L_{batt} + L_{cable}}{R_{batt} + R_{cable}}$ is the time constant of battery system and line cable. L_{cable}, R_{cable} are line inductance and resistance of the cable respectively, where L_{batt}, R_{batt} are the inductance and resistance of battery, respectively. Hence, the total fault current is the sum of the converter current and battery discharge current. A brief explanation is made to realize the VSC fault response. When the fault is initiated, IGBTs will go to cut-off region for self-protection, and body diodes face significant overcurrent. As shown in Fig. 3, a basic converter structure is selected to understand the consequences of VSC fault response. Fault current and DC link voltage expression have been established for three stages of VSC operation[16, 38–40].

3.1. Stage-1: Capacitor discharge

Capacitor discharge current of VSC primarily commences the fault current in DC side. The equivalent circuit of capacitor discharge is shown in Fig. 3(b). Before deriving voltage and current expression of the capacitor, some initial condition has been assumed, $R < 2\sqrt{L/C}$ under the natural response and fault has occurred at $t_0$where, $v_C(t_0) = V_0$, and $i_{cable}(t_0) = I_0$. Thus the expression yields [16].

$$v_C = \frac{V_0\,\omega_0}{\omega} e^{-\delta t}\sin(\omega t + \beta) - \frac{I_0}{\omega C} e^{-\delta t}\sin\omega t \tag{3}$$

Table 1
DC microgrid supply polarities.

Polarities	Description	Merits	Demerits
i. Unipolar [20–22] Illustrated in Fig. 1(a).	• Sources and customer loads are connected between the positive and the negative pole of the DC bus. • Power is transmitted at one voltage level. • Effectively utilized for remote areas to power off-grid houses due to the nonavailability of grid infrastructure.	• No asymmetry exists between the DC poles. • Simple and flexible structure.	• System redundancy is relinquished and any fault in the system leads to entire system shutdown. • Limited application for appliances. • Implementation for high voltage level introduces extra cost for converters and also increase safety risk.
ii. Bipolar [9,21] Illustrated in Fig. 1(b).	• Introduces three different voltage possibilities for the customer loads +Vdc, −Vdc, and 2Vdc, which provides more flexibility to connect the loads. •. High life-cycle costs of customer end inverter due to the higher voltage rating requirement.	• By switching the load to the healthy pole during a fault it increases the reliability.	• Due to unequal load distribution, it exhibits system unbalancing. • Extra voltage balancer circuit and adequate converter controlling is necessitated.

Table 2
Comparison of different DC microgrid topologies.

Topologies	Description	Merits	Demerits
i. Single-bus DC Microgrid [9,23]	• Mainly used to increase operationa flexibility of the DC system • Enhance DC grid voltage regulation. • Used in telecommunication applications. • If ESS is connected to the LVDC bus through appropriate converter, it allows multiple bus connections.	• Inherently substantiate dynamic stability to the system. • Helps to increase system reliability by connecting multiple battery units.	• Suffers from unregulated battery charging and uncontrollable DC grid voltage. • The parallel operation of converters exhibits uneven loading and circulating current.
ii. Multi-bus DC Microgrid [24–27]	• Uses series or parallel connected microgrids to enable the power-sharing capability between individual microgrids to provide higher reliability. • Under fault, it is facilitated with the provision of DG disconnection. • Communication infrastructure enhances DC microgrid performance. • LVDC distribution systems can be interfaced with MVAC utility mains through SST.	• This multiple cluster configuration enables each microgrid to absorb or inject power from its neighboring microgrid when there is a shortage or surplus of power.	• Based on the microgrids connected configuration some corrupted buses can be isolated automatically during a fault, which may erode the system resilience.
iii. Reconfigurable Topology	✓ To increase the operational flexibility and reliability during contingencies or periodic maintenance of the equipment, a reconfigurable type DC microgrid configuration is employed with IEDs.		
(a) Ring bus-type [7]	• The substitute power flow path is facilitated with ring bus-based reconfigurable topology during the faulty condition.	• Loads can be fed bidirectionally as they are connected to the common DC bus.	• Though it provides good reliability, voltage and power limitation is one of the hindrances for augmenting this application.
(b) Multi-terminal type [28,29]	• Provide multiple power flow paths, which manifests more reliable than the other aforementioned reconfigurable topologies.	• It can provide an alternative path during a fault. • More flexible as it provides multiple power flow paths. for the system. • Provide high reliability and redundant operation.	• Compared to conventional radial configuration, power flow in mesh configuration is more complicated.

Table 3
Different configurations of DC microgrid interfacing with AC grid.

Type	Description	Merits	Demerits
i. Radial configuration [21,24]	• DC bus is connected with AC grid at one end. •Allows single power flow path towards the loads. • Depending on the requirement, this bus can be unipolar or bipolar.	• Widely used for LVDC residential loads. • Reduce extra DC-DC converter stage. • Enables power-sharing between neighboring buses. • Reduces losses by locating loads close to AC interfacing. • In a multi-bus system, it isolates only the faulty bus during fault, while assures uninterrupted supply from healthy buses to improve reliability.	• Due to the radial structure, a single fault affect the customers connected to single bus system. • Not flexible to handle the fault condition.
ii. Ring or loop configuration [7,30]	• AC grid interfacing enables two or more paths to the loads. • IEDs monitor each bus and also the interfacing with other buses.	• Fast-acting DC switches, offer enough flexibility by isolating the faulty bus. • IEDs ensure suppy continuation through an alternative path when faulty bus is isolated. • More reliable than the radial configuration.	• Highly depends on AC grid supply. • For AC feeder fault, DC microgrid supply from the utility is interrupted.
iii. Interconnected configuration	✓ To prevent the risk of a power outage of the DC microgrid system during a failure of more than one feeder, more than one supply from the AC grid is provided. Two different architectures are mentioned.		
(a) Mesh Type DC Microgrid System [31,32]	• Consist of more than one AC grid interfacing. • Provide scope to implement different control strategies for the converters.	• Assures more reliability than radial or the ring-type configuration. • Used mainly for HVDC system in off-shore wind farms, underground urban sub-transmission, and distribution applications.	• Require different coupling interface. • Complex designing.
(b) Zonal Type DC Microgrid System [27,33,34]	• Improve system reliability by sub-dividing DS into several zones. • Each zone contains two redundant DC buses powered by the utility AC mains and DERs.	• Provide superior reliability. • Provide flexibility due to use of more switches. • Cascaded system exhibits symmetrical configuration and contains ESS, converters, switchgear, etc. to supply a group of loads. • Allow more than one islanding operation during multiple faults. • Fault isolation is possible within each divided unit without hampering the operation of the other units.	• Power supply from multiple buses complicates the design and operation of the DS. • Appropriate bus selection is mandated.

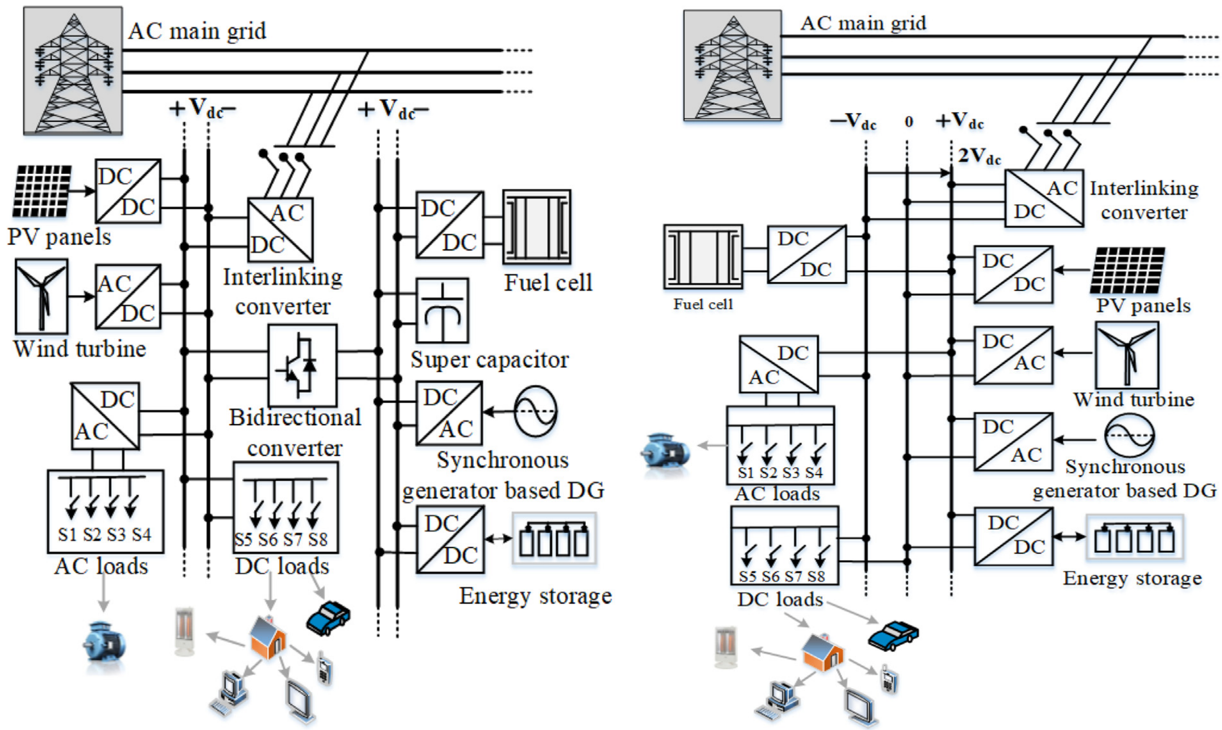
$$i_{cable} = C\frac{dv_C}{dt} = -\frac{I_0\omega_0}{\omega}e^{-\delta t}\sin(\omega t - \beta) - \frac{V_0}{\omega L}e^{-\delta t}\sin\omega t \tag{4}$$

where $\delta = R/2L$, $\omega = \sqrt{1/LC - (R/2L)^2}$, $\omega_0 = \sqrt{\delta^2 + \omega^2}$ and, $\beta = arctan(\omega/\delta)$.

The time taken by the capacitor voltage to drop down to zero is given by,

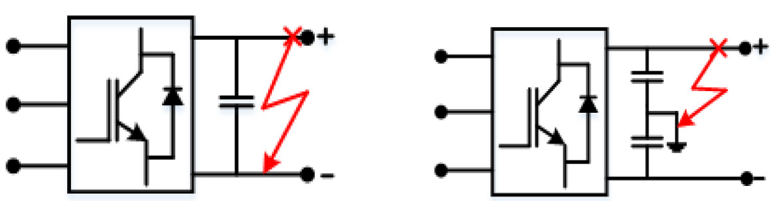
$$t_1 = t_0 + (\pi - \gamma)/\omega \tag{5}$$

where $\gamma = arctan[(V_0\,\omega_0 C\sin\beta / V_0\,\omega_0 C\cos\beta - I_0)]$.



a b

Fig. 1. DC microgrid polarity (a) Unipolar, (b) Bipolar.



a b

Fig. 2. DC microgrid fault (a) PP fault (b) PG fault.

3.2. Stage-2: Diode freewheeling

When capacitor is entirely discharged and $v_C = 0$; cable inductance drive circulating cable current, which commutates by natural freewheeling through the diodes, as shown in the Fig. 3(c). This stage is very crucial for the diodes to handle this sudden high magnitude overcurrent. Here also the prior assumption is taken as initial cable current is $i_{cable}(t_1) = I_0'$. The instantaneous cable current and diode current in each phase leg is expressed as,

$$i_{cable} = I_0' \, e^{-(R/L)t}, \; i_{D1} = i_{cable}/3, \tag{6}$$

3.3. Stage-3: AC grid side current feeding

In this stage, when IGBT switches are turned off, and DC-link capacitor voltage is not necessarily zero, a forced current is encountered from AC side as shown in Fig. 3(d). To explore the fault contribution from AC side, only phase ‘a’ is considered from a three-phase fault analysis, and fault expression has been formulated.

$$v_{ga} = V_g \, \sin(\omega_s t + \alpha) \tag{7}$$

where v_{ga} and V_g is the post fault a phase grid voltage and grid voltage magnitude, respectively. ω_s denotes the synchronous angular frequency, α is the phase-a voltage angle at t_1. Further, the current equation of phase-a is expressed as,

$$\begin{aligned} i_{ga} &= I_g \, \sin(\omega_s t + \alpha - \varphi) + [I_{g|0|} \sin(\alpha - \varphi_0) - I_g \sin(\alpha - \varphi) \,] \\ &= I_g \sin(\omega_s t + \alpha - \varphi) + I_{gn} e^{-t/\tau} \end{aligned} \tag{8}$$

where $\varphi = arctan\,[\omega_s(L_{ac} + L)/R]$, $\tau = (L_{ac} + L)/R$, and L_{ac} is the grid side line inductance and, $I_{g|0|}$ and φ_0 denote the initial grid current magnitude and phase angle, respectively. Here only the fault contribution from phase-a of the AC grid side is shown; however, the total contributed current is the sum of all the three phases current shown as,

$$i_{VSI} = i_{D1} + i_{D2} + i_{D3} = \; i_{ga}, (>0) + i_{gb}, (>0) + i_{gc}, (>0) \tag{9}$$

Furthermore, VSC DC ground fault also can be analyzed similarly [16]. Also, to investigate the DC series arc fault, several approaches are mentioned in [41–44]. A study has also addressed the HIF detection in DC microgrid [45].

4. Impact of the grounding system on DC microgrid protection

Grounding is necessary to accomplish the design of microgrid with the main prospectives of facilitating fault detection, protection requirements, safety for equipment, and individuals (reduce touch voltage), minimize stray currents (earth current from the conductor) and reduction in CMV level. IEC 60364 has developed three types of earthing configurations, namely TN, TT and IT. For TT earthing system, (shown in Fig 4(a)), the significantly high fault impedance in the current loop restricts the fault current to circulate between customer

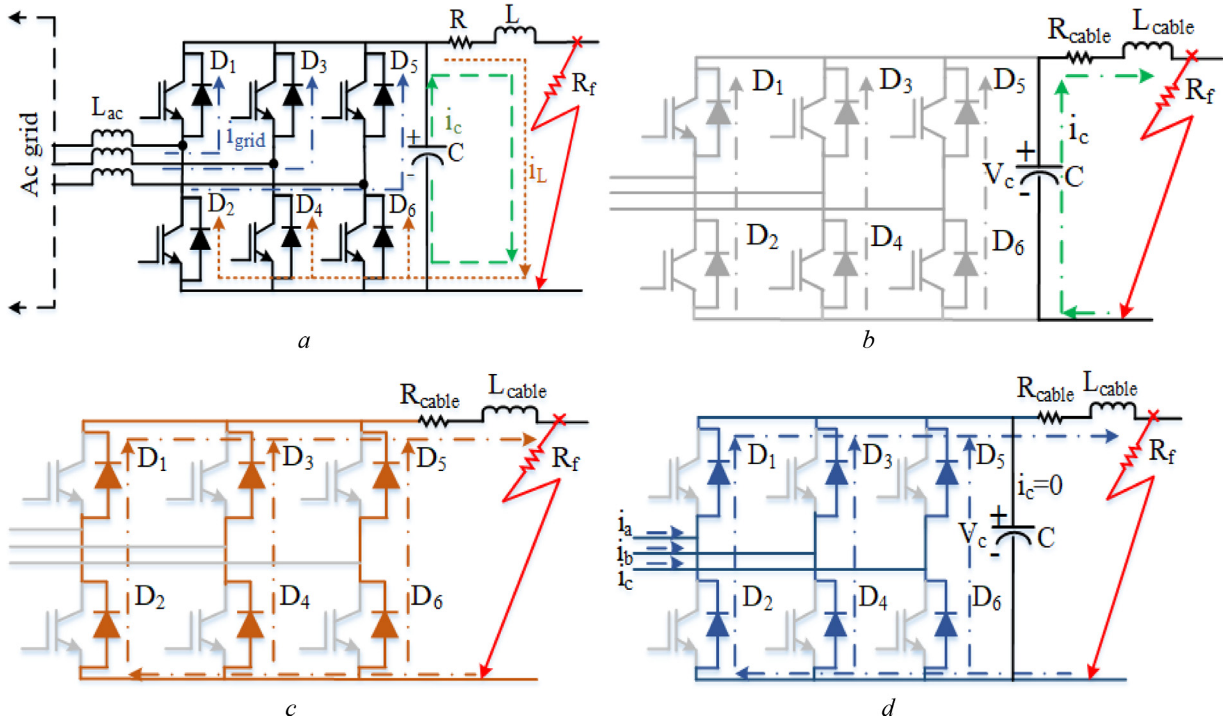


Fig. 3. DC fault current (a) DC cable fault in VSC, (b) stage-1:Capacitor discharge (c) stage-2:Diode freewheeling, (d) stage-3: AC grid feeding the fault.

installation and supply [46]. This grounding system may contain multiple grounding points. In case of IT system, the conducting parts are earthed either on the positive or negative pole, while power line is earthed with very high resistance or unearthed; which, substantially reduces the touch voltage, but due to high resistance, fault magnitude become very less, which imposes an elusive challenge for fault detection [46]. For single-pole IT grounding, the grounding resistance control both fault and body current, however for double pole IT grounding, both the pole consists of high resistances and acts as a voltage divider, but this does not help to reduce the touch voltage and fault or body current [47].

For TN system, conducting parts and power line is generally earthed via their respective midpoints. The fault resistance associated with TN system is less; thus, it exhibits detectable fault current. However, the touch voltage threshold limit can be exceeded. Besides all the shortfalls, the compatibility, and superior fault detectable current assign TN system as a promising choice for DC microgrid [9]. TN system further allows the use of RCDs to confirm safety for the individuals. It is further sub-divided into TN-C, TN-S, and TN-C-S, based on connection orientation as shown in Fig 4(c-e). TN-S system separates PE and N conductors and ensures safety and highest EMC, whereas TN-C combines PE and N to PEN conductor to substantiate a cost-effective grounding configuration. However, to obtain maximum benefits, TN-C-S grounding topology is made by combining TN-C and TN-S system. The pros and cons of these three grounding configurations are presented in Table 4. Besides grounding configurations, the grounding devices (ungrounded, solidly grounded, resistance grounded, diode-grounded, thyristor-grounded) substantially affect the fault response. In [48], the

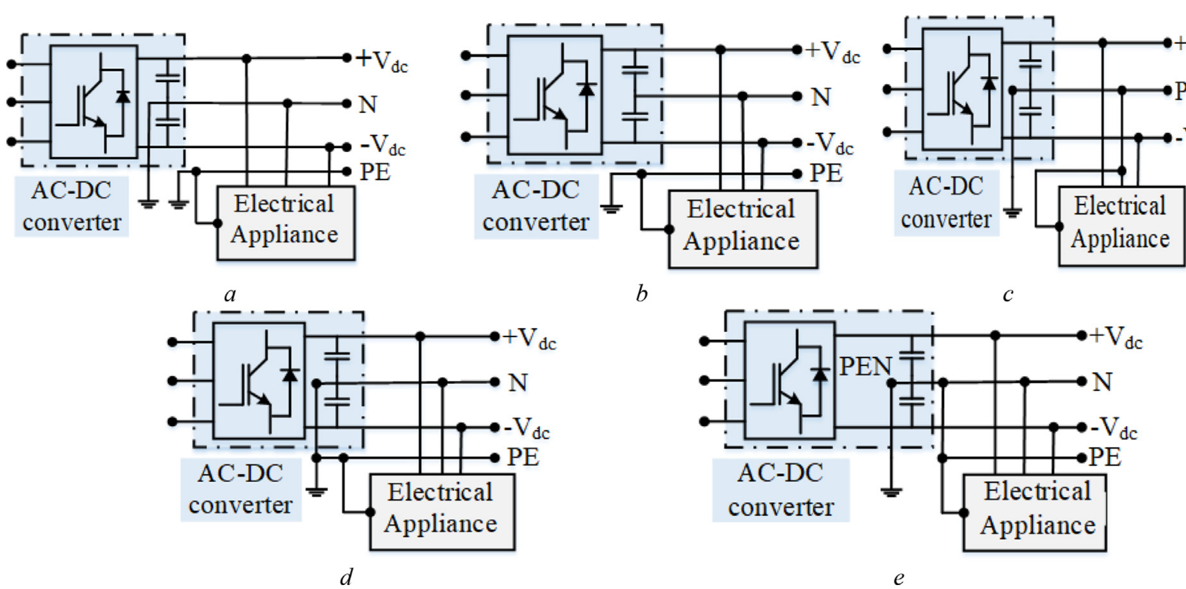


Fig. 4. Grounding system of DC microgrid (a) TT, (b) IT, (c) TN-C, (d) TN-S, (e) TN-C-S.

Table 4
Comparison of different DC microgrid grounding Configurations [46,47,49–51].

Type	Merits	De-merits	Application
TT	• Provide reliable and adequate protection against P-G faults. • Simple installation.	• Exhibit circulating currents. • Possibility of high voltage stress.	✓LVDC
IT	• Exhibit lower current and voltage transients for PG faults. • Provides stable operation of loads under PG faults.	• Low fault current magnitude obstructs fault detection. • Require insulation monitoring.	✓Telecommunication power systems
TN	• Provide sufficiently large fault current, which helps to detect the fault. • Overvoltage stress on equipment insulation is significantly reduced. • Provide the provision to reduce the magnitude of fault current by introducing ground resistance at the converter midpoint. • Allow the use of RCDs to confirm safety for the individuals.	• Exhibit substantial current transients for low resistance LG fault.	✓ LVDC, ✓ Information technology, ✓Communication networks

fault response, relay protection, safety measure, service continuation, and system reliability are considered to analyze the effect of grounding devices in unipolar or bipolar topologies.

5. Technical challenges of DC microgrid protection

The proliferation of DC technology is facing some unavoidable difficulties during its operation and protection. Initially the stringent rise of DC fault current in a short duration makes the protection strategy more complicated and also increase the breaker size and capacity. Moreover, lack of regulations and comprehensiveness in standards for different voltage levels on grounding is a non-negligible obstacle for its hastening future. Recently, various organizations such as EMerge Alliance, ETSI, IEC, IEEE, etc. are actively working to develop comprehensive standards for DC microgrid. Here some of the main protection challenges are elaborated for better realization.

5.1. Protection challenges due to DC fault current characteristics

5.1.1. Dynamic fault current magnitude

Different fault types (PP, PG) create distinct fault current magnitude. The fixed setting of OCR for a particular fault condition creates mal-operation in other fault types. Conventional OCRs in DC microgrid suffer from dynamic fault currents due to interlinking with the AC utility grid. As under fault situation, infeed from AC grid side effectively changes the short circuit level. Furthermore, The remote operation of DC microgrid in autonomous mode has a different fault level than the grid-connected mode. Nevertheless, the converters primarily truncate the fault current for their safety, which also impedes overcurrent based protection due to low magnitude of fault current [14,15]. To overcome this, an adaptive setting is necessitated for OCRs.

5.1.2. Bi-directional fault current

DC microgrids are interfaced with AC grid through bi-directional converters that allow power flow from both directions. The location of DGs also exhibits fault current from both the direction. Topological changes also promote bi-directional fault current, which undermines nondirectional relay operation. To enhance selectivity, the directional feature must be incorporated into the protection philosophies.

5.1.3. Dynamic current due to CPL

The loads and converters installed at the load ends with closed-loop control behave as CPL together [56]. Under fault condition, voltage decreases rapidly, CPLs draw massive current to maintain the power constant, which accelerates the fault current, and substantially introduces INR. Under stand-alone mode of operation of DC microgrid, CPL elevates voltage and current oscillation, which again creates ambiguity for PDs to discriminate between the fault situation and system oscillation [57–59].

5.2. Effect of grounding

Grounding configurations decisively influence the fault current for a ground fault (PG). The fault current magnitude is profoundly affected by the grounding resistance, fault type, and devices used in the grounding system, which may create a major fault detection problem for OCRs. Grounding configurations also influence the transient overvoltage, CMV, which are the predominant factors for designing a DC protection system (detailed in Section 3).

5.3. Fault interruption problem due to the absence of natural zero-crossing current

Interruption of DC fault current is a big obstacle as it does not contain natural zero crossings. Fuse can be implemented to chop the fault current for a low impedance system if the time constant of dc circuit is low (less than 2.5ms), a large time constant (more than 6ms) increase fuse operating time; thus, extinguishing arc is not possible [60,61]. Transient overvoltage is also a hindrance to fuse operation.

Discharge of converter capacitors (DC-link), line filter capacitors, creates a rapid current surge up to 50 KA for a very short time [62]. This much amount of current is a threat to PDs. Even though the fault current magnitude is large, less sustainability of that high magnitude often fails to initiate DCCB operation. Further, arcing results in contact erosion of DCCBs and reduces their lifetime. Also, traditional DCCBs have less FRT capability, which leads to inappropriate time-trip coordination of traditional DCCBs. To alleviate that, low voltage power CBs are suggested to ride through initial capacitor discharge and to augment the current interruption process proficiently [1,63,64].

Table 5
Comparison of different DC microgrid grounding devices [48,52–55].

Type	PG fault current	Transient overvoltage	CMV	Insulation level	Service Interruption	Leakage current	System reliability
Ungrounded	Reduced	High	High	High	No	Low	Low
Solidly grounded	High	Low	Low	Low	Yes	High	Low
High resistance grounding	Reduced	High	High	High	No	Low/ Moderate	High
Low resistance grounding	Moderate	Moderate	Low	Low	No	Moderate/ High	High
Diode Grounding	Moderate	Moderate	Low/Moderate	Moderate	Yes	Moderate/ High	High
Thyristor grounding	Moderate	Moderate	Moderate/ High	Moderate	Yes	Low/ Moderate	High

Table 6
Comparison of different DC microgrid protection techniques

Protection Scheme	Speed	Sensitivity	Selectivity	Reliability	Dependability	Cost
• Current based						
✓ Overcurrent Protection	Moderate	Low	Moderate	High	Low	Reasonable
✓ Current Derivative	High	High	Low	Moderate	High	Low
✓ Current differential	High	High	High	Moderate	High	High
• Voltage based	Moderate	Low	Moderate	Low	Low	Low
• Impedance based	Moderate	Moderate	High	High	High	Reasonable
• Travelling Wave	High	Moderate	High	Moderate	Moderate	Reasonable
• Time-frequency transform and algorithm techniques	High	High	High	Very high	High	Reasonable
• Converter control action	Moderate	High	High	Moderate	High	Low
• Others protection strategies (PPU)	High	Moderate	Moderate	Moderate	Moderate	Reasonable

5.4. *Less virtual inertia and low stability*

Interlinked DC microgrid suffers from virulent power instability and oscillation problems due to AC side disturbance, which causes momentary faults in DC side. Also, instability and power oscillation hinders the process of distinguishing power swing event and fault occurrence. Fault restoration process is also affected by low stability and low inertia of DC microgrid. To overcome this, protection strategies should consider virtual inertia and impedance in their protection paradigm [56,65].

5.5. *DC microgrid protection*

Before inaugurating the protection strategies for DC microgrid, the idea of the unit and non-unit type protection has to be clarified. Unit protection schemes are specifically implemented to protect fixed zones of a DC microgrid and used to protect DC bus, converters, energy storage devices, loads, etc. They are unable to provide backup protection. Current differential protection is the most commonly implemented unit protection. On the other hand, non-unit protection relies on predefined threshold settings of electrical quantities for operation. It provides substantially large protection coverage area and free operation for PDs for neighboring zone (if needed). Non-unit protection includes overcurrent, under/over-voltage, current and voltage derivative schemes, AIE, etc. The unit protection accomplishes the speed and accuracy unless the event of severe communication outage undermines its effectiveness, where non-unit protection potentially assures protection reliability and necessary discrimination [66,67]. Another concept beholds single-ended and double-ended protection [68]. Single-ended protection includes current derivative, TW based schemes, etc. and relies on local measurement of voltage and current signals for fault detection. Double-ended protection scheme incorporates communication assisted advance sensing devices and IEDs. It includes longitudinal DC line current differential schemes [68]. All the possible protection schemes employed for DC microgrid have been detailed comprehensively in this section.

5.6. *Current based protection*

5.6.1. *Overcurrent protection*

Any fundamental protection strategy still majorly relies on ubiquitous overcurrent protection unless any factor influences the current magnitude or changes the short circuit level stochastically. The most common and pervasive PD for LVDC or MVDC system is OCR [69]. Due to rapid transients nature of DC fault current, TCC setting and appropriate coordination of OCRs becomes challenging. The upstream and downstream OCRs must follow a specific time delay margin to ensure selectivity. As an integral part of protection, modern converters equipped with OCRs can behave as a fast-acting current limiting CB for fast fault current interruption [70]. Relays can be embedded into the converters to achieve rapid fault identification within a few milliseconds.

For HRF in DC microgrid, the fault current magnitude being very low; thus, fault identification becomes a very strenuous job, whereas LIF exhibits a very high fault current magnitude. In [71], a hybrid passive OCR equipped with an inductor and a capacitor detect high current magnitude for LIF. On the other hand, to detect HRF, the voltage transient of a specific known damped frequency generated by the inductor and capacitor equipped in OCR is evaluated by employing real-time DWT technique. Looped DC configuration seamlessly promotes bidirectional fault current, to ensure appropriate relay selection and coordination, a communication assisted DOCR is proposed in [72]. A novel evolution strategy is used in every line section to decide which relays are to be set for grid-connected and for stand-alone operation. Moreover, relay setting up-gradation is assisted by communication. Directional blocking feature also improves relay selectivity, and intertripping enables relays of one end to send a trip signal to the CBs of both end of a protected line section. Also, a protection algorithm is established based on the change in fault current direction to detect and locate the fault System [73]. Directional overcurrent based strategy also increases the protection redundancy.Therefore, overcurrent protection approaches with different features have accomplished the necessary protection requirements except for the event of rapid transient DC fault current that creates current measurement error due to stray inductance of DCCB [74]. An improved fault current measurement can potentially reduce the current measurement error [75].

5.6.2. *Current derivative-based protection*

The feature of rapid rate of rise of current in a short time duration ensures a fault occurrence. Current derivative scheme has utilized the rate of change of current for fault detection and location. It operates when the calculated current differential exceeds a preset threshold value [76]. However, line length, line loading, and fault impedance have a direct impact on fault current derivative. Selecting an

Table 7
Comparison of different types of DCCBs.

DCCB	Reaction speed	Voltage blocking capability	Current interruption capability	On-state power loss	Arcing and fire hazards	Structure	Cost
MCB	Low	Moderate	Moderate	Very low	Yes	Less complex	Low
SSCB	High	High	High	Low	No	Complex	High
HBCB	High	High	High	Low	No	Complex	Very High
ZSCB	High	High	High	Low	No	Complex	Reasonable

Table 8
Standard for DC microgrid.

Standard	Title/Description	Scope/application	Current Status
IEEE P2030.10	Standard for DC Microgrids for Rural and Remote Electricity Access Applications.	• Cover the design, operations, and maintenance of DC microgrid for rural or remote applications. The standard further provides requirements for low voltage DC and AC power to off-grid loads.	✓Active
IEEE 1547-2018	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.	• Characterizing various DERs interconnection issues, technical requirements, penetration level, etc.	✓Active
IEEE 946-2004	Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Systems.	• Guidance for the design of the DC auxiliary power systems for nuclear and non-nuclear power generating stations. Also provide guidance for ESS, equipment ratings, interconnections, instrumentation, and protection.	✓Active
IEEE DC@ Home	DC-Powered House.	• Standard for residential application of LVDC microgrid.	✓Active
IEC SEG 4	**Low Voltage Direct Current Applications, Distribution, and Safety for use in Developed and Developing Economies.**	• Low voltage direct current applications (up to 1500V), focuses on energy efficiency, EMC reduction, protection, and grounding issues.	✓Active
IEC SEG 6	**Non-conventional Distribution Networks / Microgrids.**	**• Evaluate the usage of LVDC in different integration environments to increase energy efficiency and to establish new ideas for optimal use of LVDC power.**	✓Active
IEC SEG 9	**Smart Home/Office Building Systems.**	• Standardization, gaps related to electrical installations and communication technologies for Smart Home/Office building System.	✓Active
IEC 62040-X X:1, 2, 3, 4, 5-3	**Uninterruptible power systems (UPS).**	• Safety requirements (1), Electromagnetic compatibility (EMC) requirements (2), Method of specifying the performance and test requirements (3), Environmental aspects - Requirements and reporting (4), DC output UPS - Performance and test requirements (5-3).	✓Active
IEC 60364-4-XX XX:41, 43, 44	Low-voltage electrical installations.	• Cover general requirements for safety services against electric shock (4-41), protection against overcurrent (4-43), safety and protection against voltage, and electromagnetic disturbances (4-44).	✓Active
IEC 60479-X X:1, 2, 4, 5	Effects of current on human beings and livestock.	**• General aspects(1),Special aspects(2), Effects of lightning strokes (4),Touch voltage threshold values for physiological effects(5)**	✓Active

appropriate threshold is also challenging for changeable operating conditions.

The first-order and second-order derivatives of DC fault current can be calculated by using a backward finite difference approximation method [66].

$$\frac{di}{dt} = \lim_{\Delta t \to 0} \frac{i(t_0 + \Delta t) - i(t_0)}{\Delta t} = \frac{\Delta i}{\Delta t} \quad (10)$$

$\Delta i = i_k - i_{k-1}$ and, $\Delta^2 i = \Delta i_k - \Delta i_{k-1}$, further $\Delta^2 i$ can be written as

$$\Delta^2 i = i_k - 2i_{k-1} + i_{k-2} \quad (11)$$

where, k is the sampling instant, and i_k, i_{k-1} and i_{k-2} are the present and previously sampled line currents, respectively. It is considered that the fault has occurred at $k=0$, and the value of k is increased at every instant of time. Under fault condition, the fault current nature is studied to calculate the time during which the fault current reaches its peak value for different fault locations. To evaluate the sampling period, approximately 1/10 of the minimum time to reach the peak value of fault current is selected [77]. Further to determine the tripping signal, the value of $\Delta^2 i$ is compared with the threshold value and when it exceeds the preset threshold; a trip signal is sent to respective protective relay. Despite the effectiveness of this technique, the high sampling rate of sensors to measure the current derivative, amplify the noise and often promotes false tripping. To eliminate this, proper filtering is necessary with noise cancellation capability. However, *di/dt* based protection is relatively faster than threshold-based overcurrent protection [78]. Another method has shown its credibility on fault detection and location by using rate of change of current (*di/dt*) and voltage *dv/dt* both [79]. Under the limiting and blocking operation of converters, fault detection becomes an elusive challenge due to low fault current. Thus, this method utilizes *dv/dt* for detecting the fault, and *di/dt* address the fault location; while, the product of *di/dt* and *dv/dt* is used to ensure protection coordination between relays. Fault location and fault distance estimation by current derivation method is further rejuvenated when a small inductor has essentially been employed at each end of the network to obtain *di/dt* instead of using current difference value [80]. During fault in a DC loop microgrid system, *di/dt* is estimated by means of voltage drop in the inductor, which has potentially increased the accuracy than other conventional approaches.

5.6.3. *Differential current protection*

Fault response of DC network is highly sensitive to fault impedance. Most of the deployed non-unit protection techniques have eventually overlooked this fact, which decisively erodes their application by sub-optimal fault discrimination for more complex network configurations [36,70]. Non-unit protection sometimes results in relatively more area disconnection and take longer time for fault clearing; thus, unit protection is recommended to ensure better fault discrimination within the network [67]. High selectivity and fast operation envisage current differential protection is a viable protection solution for complex DC microgrid; however, it imposes an elusive challenge due to additional cost of communication and advanced relay technology (IEDs) [81]. For AC system, the need for individual phase current measurement and phasor comparison increases the operating time (around 20 ms), whereas, for DC system, only the current magnitude is needed to be compared, which effectively improves the response time (approximately 2 ms) [36]. Measuring the DC fault current using current transducer helped to facilitate the transducer output to integrate easily with digital processing devices [82]. Under high *di/dt* conditions, problem associated with the synchronization of current measurements and generating trip signal within a definite time frame from the comparison of current measurements are two substantial issues. A legitimate solution for the aforementioned issues is obtained with significant reduction in fault detection time in [82].

Non-iterative differential current method substantially supports fast reaction of PDs when implemented in low voltage MTDC system

[83,84]. It has used cumulative sum average approach to identify the fault, and fault distance is obtained by adaptive Moore-Penrose pseudo-inverse solution As a cost-effective communication solution for a small coverage area, Ethernet cable is employed, which ensures a communication delay less than the propagation velocity of the DC cable and sampling time [85]. However, synchronizing relay operation through communication necessitate the employment of GPS transducers with optimal accuracy. Failure in GPS can be detrimental and may cause severe communication outage. Thus, GPS signal failure detector is also required [86]. Current differential protection can further be reinforced by an overcurrent protection as a backup for load and source protection of an islanded MVDC system to clinch superior reliability [87].

5.7. Voltage based protection

The phenomena of extensive system voltage drop, voltage variation, and rate of change of voltage during fault are utilized to establish voltage based protection strategy. To substantiate better protection sensitivity, the fault location point and microgrid state of operation can be made independent, while pick-up setting of the threshold is formulated [88]. Voltage based protection scheme is a single-ended, local measurement-based scheme, which does not need any communication infrastructure. As voltage based protection technique is entirely depending on voltage magnitude, it is relatively a fast protection scheme. However, the inability to discriminate against temporary and permanent faults undermines its widespread application. Also, the nature of fault resistance is one of the constraints for voltage based protection for DC microgrid.

5.8. Impedance based protection

The scenario of distance protection for DC system is different from AC as the inductance of DC cable is quite less, and the predefined fundamental frequency is absent. The design impedance of PE infrastructure satisfies their design specification under normal operating conditions [89]. By checking the impedance of any interfaced PE module (if it differs from the specification), disturbance can be identified. Primarily the I/O impedance is checked against their specification to determine the faulted module. DC bus stability has a direct dependency on impedance characteristics; hence, insufficient stability margin also alarms disturbance in the system. However, checking the impedance of individual modules to match with the I/O specification is tedious work. An approx estimation of impedance is sufficient for relay operation, instead of emphasizing on complete accuracy from time-consuming iterative methods. Thus, noniterative techniques show more proficiency due to fast response. AIE technique provides information about the severity of fault and also helps to locate the fault such that the system can be reconfigured accordingly [90,91]. It locates the bus fault by measuring impedance of the bus. A positive and negative voltage pulse (V_{inj}) is generated to apply on a coupled inductor as shown in Fig. 5, which creates a triangular-shaped current (I_{inj}) that is injected into the DC bus. The value of injected transient current and bus transient voltage is recorded and impedance is evaluated by using the equation depicted in (12).

$$Z = \frac{F(V_{trans})}{F(I_{trans})} \tag{12}$$

where $F(V_{trans})$, $F(I_{trans})$ are the bus transient voltages and transient currents in the frequency domain, respectively. The real part of the measured impedance by AIE technique essentially used to represent the fault severity, where the imaginary term is designated for the location of fault. Moreover, the authors have suggested the thriving effectiveness of AIE technique when it is used in conjunction with "foldback" control action of the main converter to ensure fast and accurate fault location (< 100ms). Also, it provides communication less fault detection, which gives freedom to PDs to detect the fault autonomously and allow the network to reconfigure during fault if needed.

5.9. Traveling wave-based protection

After the occurrence of fault, initiated current and voltage TW propagates through the line until the circuit has been interrupted. Determining the fault location by analyzing the features of high-frequency TW such as magnitude, polarity, and time intervals between the arriving waves are implemented for both AC and DC systems [80,92,93]. To consolidate TW based technique widely spread GPS signals (to ensure superior time synchronization accuracy) and WT (as an effective tool for detecting the rapid signal changes) are effectively incorporated. Protection schemes for fault identification based on initial fault induced current TW assisted by WT has been implemented for parallel transmission lines [94]. Furthermore, by using MMF for extracting the information from TW is substantially applied for AC microgrid protection [95]. TW based protection is also explicitly conducted in bipolar HVDC system [93]. By analyzing symmetrical components taken from the initial TW characteristics, this scheme affirms rapid fault detection, classification, and faulty pole identification. Fault location of a relatively wide area MTDC system is presented by analyzing online and offline stages in [96]. The offline analysis is performed to develop the graph of current network topology, then two graph theory-based lemmas are deployed to sectionalize that obtained graph so that minimum path from fault point to different fault detector can be specified. On the other hand, the faulted section of the graph is then determined by using the arrival time of surge. In [97], the authors have focused mainly on surge arrival time and emphasis on wave shape feature and polarity of the generated TW and not constrained by the voltage level of the system.The optimum accuracy of TW based scheme depends on accurate detection time calculation and performance of the employed data acquisition tools.

5.10. Time-frequency transform and algorithm techniques

Transient DC fault current predominantly contains high-frequency components, which decisively helps as an indicator for fault estimation. Frequency and time-domain information of a signal can be analyzed simultaneously by utilizing strong signal processing tools like WT, FT, etc. Especially STFT provides precise frequency information, being operated based on specified window size. Window length selection is a viable factor and mainly selected by considering DC fault current ripple

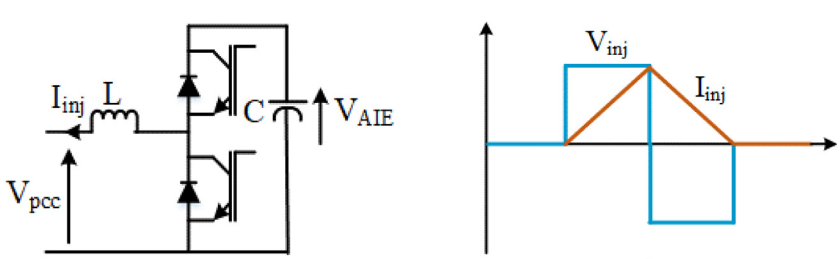


Fig. 5. Active impedance estimation technique [90] (a) Signal injector circuit, (b) Injected signal to the dc bus.

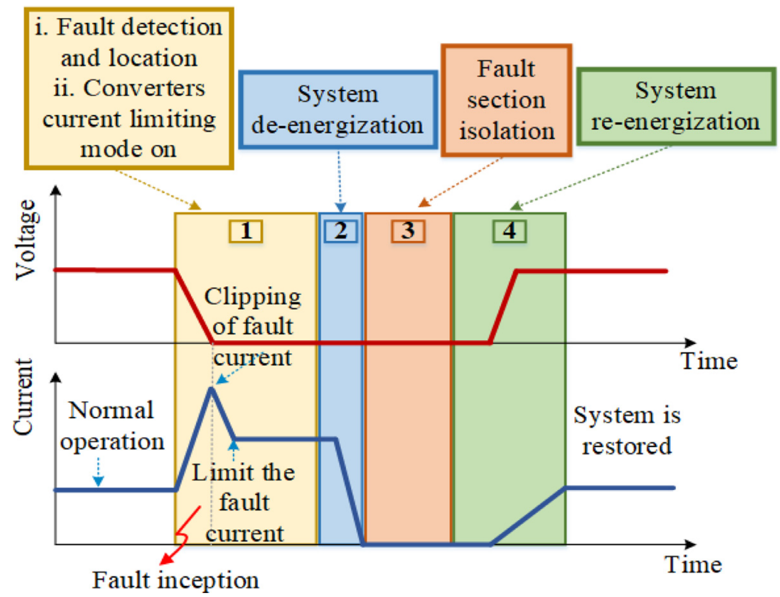


Fig. 6. Converter control action for fault mitigation [118].

content. Frequency resolution again ameliorated with larger window size; this helps to facilitate STFT for quantitative analysis of frequency components for nonstationary transient signals [98]. Further, to explore the principal advantages of STFT, a directional zonal interlocking technique and STFT is implemented for a DC marine power system [99]. This technique has envisaged the advantages of frequency domain-based directional protection over time-domain based overcurrent approach. This inherently eliminates the need for a tripping set point. However, STFT based method is principally constrained by the window's size. Wide window size ensure supreme frequency, but time resolution is compromised, while a narrow window size improves time resolution, but reduces the frequency. WT is a linear transform similar to FT unless it yields the advantages of time localization of different frequency components of a signal that consists of transients and discontinuities [100]. For the multi-terminal VSC-driven HVDC system, WT based frequency analysis is potentially executed for rapid fault detection [101–103]. While addressing the event of fast clearance of DC fault, a significant reduction of processing time is obtained by FDWT technique, which is a translation-invariant wavelet representation [101].

Further to avoid the multiple wavelet coefficient and vigorous calculation process of CWT, DWT is proactively used to filter out the superimposed transient frequency component from DC fault current along with the fast fault detection [102]. Nonetheless, by introducing the degree of correlation to fault pattern and time delay, the mother wavelets are chosen adequately for fault detection by DWT in [103]. The extension of DWT has been proved effective for MVDC and LVDC microgrid applications when the wavelet features have been extracted from the second derivative of DC fault current to identify and locate the fault [104,105]. WT has further ameliorated this fault detection process when wavelet multiresolution analysis has been incorporated [106]. In case of fault diagnosis, a direct adaptation of WT coefficients requires large memory space and more computational time. To address that, reduced amount of feature vectors (unfaltering) from the original signal is required to be selected. In [107], the wavelet coefficient energy variation is considered as the feature vector to execute the WT-based MRA technique. Also, the most crucial event like HIF is identified by DWT based MRA, which is performed on the local measurement of current signal [45]. Some other significant application of WT based MRA is a multi-resolution PI controller under severe disturbance in hybrid AC-DC microgrid [108]. The culmination of frequency transform-based techniques and evolutionary change in DC microgrid protection is obtained when neural networks and WT have been established cumulatively [109,110]. In this paper, the feature vector is constructed from the variation of relative wavelet energy within the frequency band, and subsequently, ANN is implemented as the classifier ensuring smart fault detection. Less time consumption feature of ANN radically accelerate the fault diagnostic process, when equipped with WT. Nevertheless, some individual implementation of different classical approaches like machine learning, SVM, fuzzy logic, also ANN has further consolidated the protection system of LVDC, MVDC microgrids [111–116]. Due to the presence of actively commutated converters in DC microgrid, DC power flow perceive an effect of high-frequency content. Thus not only for the transient evolution but during system modeling, it helps to execute the frequency-based analysis. Besides, under real load power situation, the high-frequency component present in DC link voltage and current decisively assists in designing microgrid electrical subsystems and their controllers [117].

5.11. Protection based on converter control action

Power converters interface DERs with adequate controllability. Under fault conditions, the converter either can palliate the fault by truncating the fault current and participate in protection subroutine to prevent catastrophic damage of the system or can lose controllability and needs to secure its own protection by employing fast-acting CBs and current limiters. Back-to-back VSCs, buck-type isolated converters, Full Bridge MMCs and similar types converters are capable of controlling the fault current magnitude and provide excellent resilience and survivability [14]. The ubiquitous power sharing control, i.e., droop control method, is extended to control the fault current by a fictitious adaptive resistance [15]. Under the fault condition, it reduces the source current flow from a particular converter, which directly affects the fault clearing time. But unfortunately, no natural zero-crossing point, cost, size, and other issues encountered the use of DCCBs (detailed in section 7). Therefore, as an alternative “breaker less” architecture for protection by controlling the converter operation during contingencies is presented in [118]. The autonomous operation of fully controlled converters for fault isolation decisively reduces the power loss for un-faulted lines, especially when system restoration requires time. This proposed scheme is accomplished with four subsequent stages, as shown in Fig. 6 [118].

I When the fault is detected, the converter activates the current limiting mode instantly, and an appropriate algorithm allegedly locates the fault.

II By converter control action, the excessive fault current is initially limited and made zero such that the system can be de-energized.

III Appropriate coordination of converters substantiate the opening of contractors and isolate the faulty segment.

IV After the disconnection of faulty section, the converters re-energize the system and return to regular operation.

Although this approach secures its potential effectiveness without any DCCBs, the current limiting capability of converters is a big concern. Also, all the converters are not capable of controlling its action adequately [119,120].

5.11.1. Handshaking method

A cost-effective DCCB less solution for VSC-driven MTDC microgrid fault is obtained by fast-acting DC switches and through the operation of ACCBs (already equipped in AC side). Under a fault condition, the DC-link capacitor discharges and voltage is gradually decreased (no reverse bias thus exists anymore for anti-parallel diodes), which allows the AC power to infeed DC fault through diode rectifier bridge formed by anti-parallel diodes. A cumulative and sequential operation have been carried out by ACCBs and fast-acting DC switches to handle the fault scenario. Though DC switches are not capable of current breaking, but can effectively isolate the faulted DC line when ACCBs confirm fault clearing and subsequently before restoration of the line (for a permanent fault). A novel communication less fault identification strategy called "handshaking" method detects and isolates the faulted line of MTDC system by using fault current direction [121]. As depicted in Fig.7, VSC stations are dedicatedly monitoring all the three DC lines. Every VSC station is capable of selecting only one DC switch that is emerging from it to perform the opening operation. The selection of DC switch opening depends on which DC switch is carrying the largest amount of positive DC fault current. This method executes a few specific and subsequent operation stages to ensure significant protection reliability. First the faulted line is selected, and DC switch corresponding to that faulted line is opened. After isolation of DC fault, ACCBs can be reclosed, which allows the DC capacitors to start recharging through anti-parallel diodes of VSC from 3-phase AC supply. Finally, the DC switch is allowed to be reclosed only if other side voltage of DC switch reaches up to DC voltage level of the VSC terminals. Though the handshaking method initially requires fault inception detection technique, the restoration time does not change if the size of MTDC increases.

5.11.2. Fault isolation and network reconfiguration

To maintain supply continuation, the provision of current limiting by reconfiguring the DC system is another approach presented in [34,119,120]. Current limiting, fault isolation, and to provide supply continuation by least affecting the healthy section have effectively been obtained by cumulative operation of PCR and no-load switches [122]. To ensure fast fault interruption, static switch assembly is utilized. The local control processor is equipped with static switches for controlling the open and close operation. It also shares the operational status of the network with PCRs and converters. For this fault isolation and reconfiguration technique, the initiated fault is first detected at PCR output, and immediately it holds-back the power conversion. PCRs and switch assembly proactively analyze the current vector for subsequent actions. A definite time is allocated for the switch operation, then PCRs restores supply for the non-isolated zones. This scheme also assists system resilience, when AC side is isolated, PCR effectively detects the loss of AC utility mains and inhibits the power exchange between AC and DC. However, communication between system components have necessitated for adequate operation.

5.11.3. DG interfaced DC-DC converter protection

In power conversion stages of DG integration, isolated and non-isolated DC-DC converters are essentially used as an integral part of DC technology, especially in DG integrated HVDC and MVDC systems [123–126]. While VSCs are dedicated to DC microgrid interconnection with utility mains, the DC-DC converters are employed in intermediate stages to connect solar PV, BESS, etc. to the DC grid.

Similar to VSCs, DC-DC converters also exhibit a distinctive fault behavior for PP and PG faults; thus, they need to be considered separately [39,127]. Besides, the external system faults, DC-DC converters also can exhibit internal SCFs and OCFs in its switches and/or gate

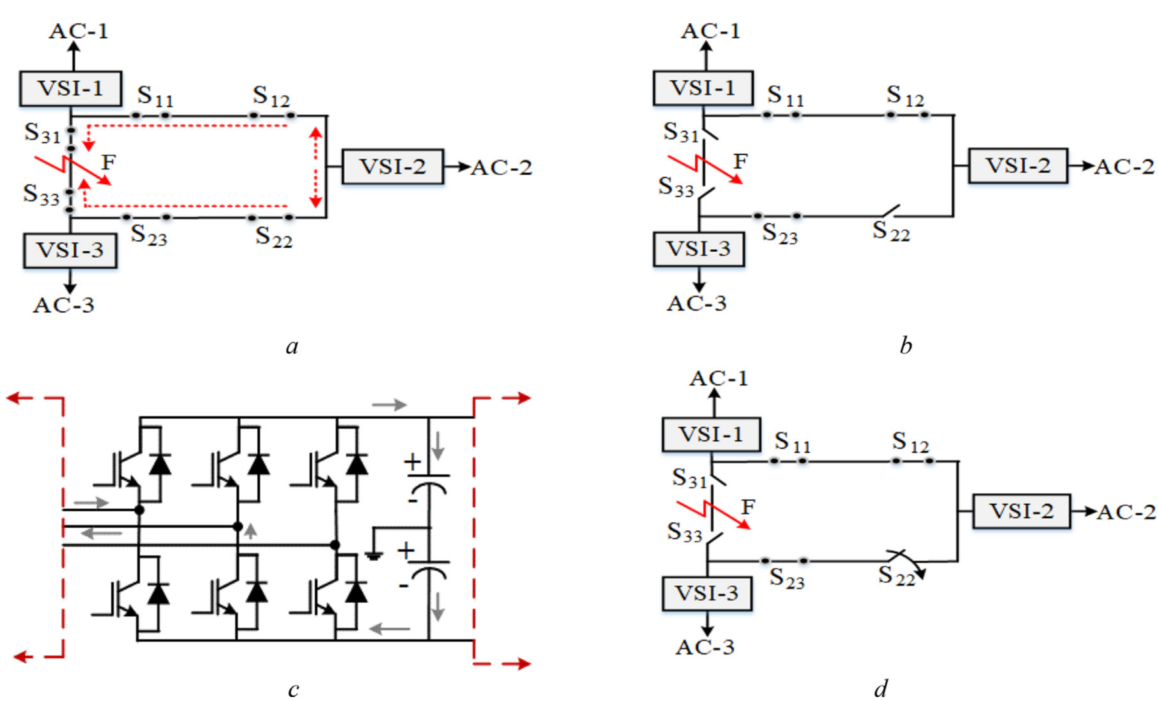


Fig. 7. Illustration of handshaking method [121], (a) Identification of the faulted line, (b) Opening of the faulted line, (c) Recharging of DC capacitors, (d) Reclosing of fast dc switch..

drivers. Converter internal OCFs and SCFs detection methods (signal processing and model-based fault diagnosis algorithms) are a separate area of research, and a considerable number of fruitful publications have already been proposed in the literature for several DC-DC converters [128–133]. However, the response of DC-DC converters for external faults is subject of concern. The choice of DC-DC converter from the protection point of view, isolated converters provide perceptible advantages over non-isolated converters by dint of safety and grounding. It provides galvanic separation and inhibits high voltage appearance on LV side, and also yields DC fault blocking capability inherently [123]. Additionally, by utilizing the transformation ratio, voltage adaptation can also be performed. The viability of galvanic separation, high efficiency, voltage level transformation, bidirectional power flow capability, and FTC make DAB converter as a legitimate solution for the DG grid interfacing technology [134,135]. Further, the refurbishment of DAB converter yields MMDAB converter, with an inherent current limiting capability during short-circuit situations; thus, substantially proved as a competent solution for shipboard MVDC system (as zonal DC-DC converter), BESS in MVDC applications [136,137]. Further modification of DAB converter divulges as fault-tolerant multiple active-bridge converters, which is used in smart transformers [138].

Though the primary need to interface the converters is to control the power flow and voltage conversion (up /down) to match different grid voltage levels, the additional benefit of security can be achieved if the converters are inherently enabled with FTC [14,139]. Fault-tolerance implies the continuation of post-fault power conversion and can be implemented to the converters either by incorporating additional hardware components or by adjusting the phase-shift, by bypassing the faulted module(s), by thrusting changes in gate pulses of the healthy semiconductor switches, or by employing redundant module into operation [131,140–143].

As the PV generation, in particular, gets more attention in the emerging DC technology due to its inherently DC power generation capability, several DC-DC converters are implemented to the PV system for reliability improvement [129,144]. Besides, due to the benefits of high efficiency, output current ripple cancelation, modularity, interleaved DC-DC converters (buck, boost, bidirectional buck-boost) are decisively interfaced with the PV system [140].

In HVDC applications, fault current interruption and limiting by a resonant DC-DC converter has been elucidated in [145]. During a fault, the converter reduces the power flow internally, which keeps the fault variables (voltage, current) approximately to the rated value. This concept yields continuous operation of the converter even under fault conditions. A different idea incorporates F2F converter, which is built by the sets of MMCs and effectively implemented as HVDC-DC converter to eradicate the fault [146]. F2F based HVDC-DC converter has the ability to subdue the fault current, when the converter current exceeds its nominal current. Furthermore, to ensure more robust protection for interconnected MVDC-HVDC grid, a redundant fault-tolerant TLC-MMC hybrid converter structure is suggested in [126]. Fault-tolerant Z-source DC-DC converter based scheme, flyback-forward converter based modular DC-DC converter structure with FTC, full-bridge DC-DC converter module are also envisaged as competent solution for converter interfaced high power wind systems [147–149]. Fault current limiting can be retrofitted by implementing fault-tolerant converters or by employing external protection through DCCBs in current-conducting parts of the constituent converters. However, it has been investigated experimentally that fault-tolerant DC-DC converter based protection exhibits a higher failure rate than DCCB based protection; hereafter, reliability can be a concern [127,150].

5.12. Others protection strategies

5.12.1. Probe power unit (PPU) and Current injection technique (CIT)

If DC bus is shut down completely due to any fault, then it is very difficult to locate the fault. Due to this, without de-energizing the multiple sources of DC microgrid system, only isolating the faulty section is a practical approach to exploit the benefits of connected resources for maximizing the service continuity and reliability (reduce power outage stages) [151]. For a ring-type LVDC microgrid structure with a non-iterative deterministic fault location scheme, proposed PPU locates the faulted zone while rest of the system remains energized [7]. The ring-bus structure can be divided into several zones equipped with multiple IEDs and PPUs. IEDs are capable of detecting fault current and enabled with the feature of isolating faulty sections to prevent the whole system from being shut down. PPUs are installed at each node to locate the fault and to monitor the bus for reclosing after fault clearance. For permanent fault, if fault is not cleared, the reclosing of CBs causes severe damage to the system. To handle this, PPUs are implemented for a pilot test to identify the fault type (temporary or permanent). PPU works based on the assumption that the damped resonant frequency of probe current is equal to the natural system frequency, which creates erroneous fault location calculation. To eliminate that error, fault location is obtained by damping frequency and attenuation constant, where the damping coefficient is made as a function of fault resistance [152].

Further progression on this idea is accomplished by introducing both fault segment identification and fault distance location by rolling mean technique, where system bus voltages are also considered [153]. Where IEDs isolate the faulted zone, and PPU is employed for fault location. Therefore, PPU based protection scheme for LVDC system also attains good reliability by reducing power outage stages besides protection, unlike it imposes a high implementation cost.

Being addressed the shortfall of PPU system, CIT based fault location scheme has claimed to be a more proficient fault location scheme [154]. The inaccurate presumptions of PPU technique and neglecting the impact of fault resistance on damping coefficient upraise more errors in fault distance calculation. To subdue this, attenuation constant in damped injected current response and the obtained damped resonant frequency of current sample data from FFT is effectively used in CIT to locate the DC line fault accurately.

6. Protection devices (PDs) for DC microgrid

Fuse is the most primitive and simplest protective unit used in DC system. Though the high initial DC fault current transient helps to attain melting point of the fuse faster, the application is restricted up to 4200 volts [69]. Slow response, replacement after each successful operation, and inability to discriminate momentary and permanent fault inhibit the use of fuse in the modern DC microgrid system. For adapting a more reliable, cost-effective protection solution, DCCBs are introduced, as shown in Fig. 8. They are structurally categorized as MCBs (operated by traditional mechanical switches), SSCB (encompasses PE solid-state switches), and rapid DC technological growth has gradually incorporated HBCBs (combination of MCB and SSCB) and ZSCBs (for more complex DC applications)[64,127,155–167]. The design specification of DCCBs should encompass the features of compact size, low cost, low on-state conduction loss,etc. To withstand the initial high inrush fault current (twenty times the maximum operating current), the current rating of DCCB is very important. Power converters stop operation (for its safety) if the CB takes a longer time to react, which leads the entire system to shut down. To preclude this, the operating time of CB is potentially selected in μs range when it includes grid-level service. During fault, voltage quality can be improved by limiting the voltage distortion within 100 μs [168]. Though MCBs have the maximum short-circuit current rating, the arcing occurs at its mechanical contacts opening. The passive and active commutated MCB is shown in Fig. 8(a) and 8(b) respectively [167]. Despite the advantages of low on-state power loss and low cost, slow response and requirement of frequent maintenance restricts the application of passive and active commutated MCB. To address this, an operating mechanism uses a repulsion coil,

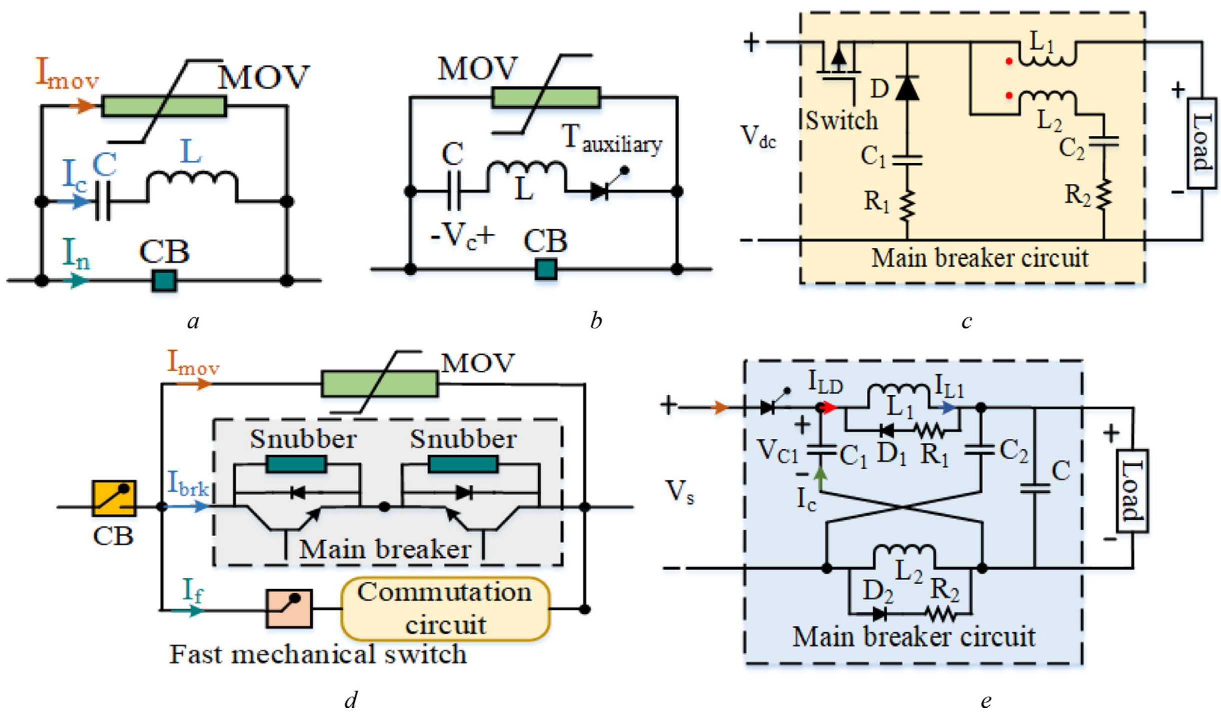


Fig. 8. DCCBs [18,19,35,74,162]. (a) MCB with passive commutation, (b) MCB with active commutation (c) SSCB, (d) HCB, (e) ZSCB.

which reduces the operating time to 1-3ms [161,169]. The proclivity of SSCB is to overcome the slow response problem associated with MCB. Fast switching (within few µs) of SSCBs allows the peak current to rise only up to two times the maximum normal operating current [161]. Fast switching and high current rating semiconductor devices such as IGBT, GTO, IGCT are integrated to increase the current handling/limiting capability of SSCBs [165,170]. However, by using SCR instead of gate commutated turn-off thyristors, the on-state losses, short-circuit level and also the cost of triggering circuit can be significantly reduced with an enhanced current-limiting feature for MVDC system [159]. For WBG semiconductors, such as SiC MOSFETS and JFETs are also fitted in the SSCBs circuit to augment its reaction time without requiring any external power supply [163]. JFET fabricated ultrafast SSCBs have ameliorated the response time approximately ten times faster than other SSCBs and several thousand times than traditional MCBs [168,170].

DC reactors used in current-limiting strategies encounter DCCBs operation. To alleviate the issue, a new SSCB enabled with self-adaptive fault current limiting capability is proposed for a low-voltage MTDC system [64]. Furthermore, for loop DC microgrid system, to deal with bi-directional power flow, bidirectional DCCBs are also developed 166, [171–174]. The requirement of high current handling during on state with nominal conduction loss, the fast transition from operating mode to blocking mode during fault and large insulation level to withstand system voltage, evolutionary changes in breaker structure are made to invent HCB [74,160]. Fabricating multiple switching devices into the main CB structure reduce the arcing issue during current interruption [156]. However, fast current commutation from mechanical switch brunch to solid-state circuit is required to minimize the contact erosion [157]. Although a significantly fast operation can also be achieved with low conduction losses, the operation complexity has simultaneously increased. To handle the momentary faults in DC microgrid, bi-directional ZSCB is enabled with re-breaking and reclosing capability [175]. Also, for discrimination between load steps and fault scenarios, a modified series ZSCB is proposed in [176]. Moreover, ZSCBs legitimate significant advantages over other DCCBs by allowing the provision of incorporating bi-directional devices, provide more fault tolerance capability (limiting fault current by introducing impedance), and can be equipped with PE converter to enhance the fault handling capability [158,162]. However, ZSCBs are incapable of providing prolonged protection, and large transient fault is required for activation.

Therefore, it can be concluded that DC microgrid protection based on DCCBs is more feasible than the converter-based protection, majorly due to its more fault handling capability, selectivity, and reliability [127]. Moreover, during contingency, transferring sources and loads using solid-state transfer switches, can further consolidate the protection system [177].

7. Current industrial practice and future trends for DC microgrid protection

The recent trend of automated smart microgrid operation potentially depends on smart information metering, intelligent computer-based monitoring, and measurement. To improve system operation by increasing the usage of micro sources, to match customer power demand, grid-status monitoring, up-gradation of IED's operation status during system reconfiguration and contingencies, the substation units (smart sensors, power measurement units, power management controllers, manual/automated control units) are tied together with strong communication infrastructure for interoperability of data exchanges. Smart protection technologies have incorporated communication assisted multi-agent-based centralized protection unit to supervise the PDs. Real-time analysis is performed to provide adaptability for different operating conditions of the microgrid. During utility side incipient faults, islanding operation (even zonal sub-microgrid) can be contrived.

Furthermore, future DC microgrid protection technology emerges towards WAMPS; however, this requires more efficient interoperability and faster-operating speed than that of the existing SCADA system, which is not designed to exchange extensive data for supporting more IEDs. Thus, WAN would consolidate the future high-speed communication requirements for the DC microgrid, supported by Fiber Optics and WiMAX technologies. However, the impediments to reliable protection of DC microgrids can be due to the lack of modernization of PDs. Thus, the use of modern multifunctional devices can only exaggerate the automated smart protection system. SST is one of the promising candidates to be considered as a multi-purpose device (AC and DC interfacing, power flow control, limiting fault current, microgrid operation state transition, compensation for voltage sag, etc.) to be incorporated into the smart DC microgrid system. Also, towards the proclivity of the efficient energy management system, an IEMS maximizes the energy usage of each source and profoundly support static and dynamic power requirement. IEDs are essentially deployed in IEMS to perform dynamic adjustment of energy flow, communication between power devices, and storage of data of different operations. As an extension of this, the deployment of this advanced infrastructure, the communication system, further promotes the opportunity to expand the use of unit protection schemes within microgrids.

8. Discussion

Protection is the last unavoidable obstacle that jeopardizes the actual objectives of DGs. To enliven DC microgrid as a legitimate solution for the future DC load requirements and several DC applications, the protection subroutine should prudent to ensure supreme reliability. This paper has sought out the elusive protection challenges associated with DC microgrid, and has comprehensively reviewed, analysed to endeavour the pros and cons of every protection strategies, and the essential factors have been tabulated precisely. This section elucidated the crucial factors for DC microgrid protection, which will decisively help in decision making before implementing the new protection subroutines.

- Protection strategy must accommodate system operation state (grid-connected, islanding), also support system reconfiguration (separate zone /sub-microgrid). To increase sufficient operation redundancy and reliability, a meshed MTDC structure is recommended.
- Before designing a protection strategy, the factors that must be considered are different types of faults (external system PP and PG faults, arc faults, converter-internal OCFs and SCFs), fault positions (DC feeder, DC bus, AC side, internal) and grounding system (fault detection, safety against touch voltage) to analyze their impacts on protection precisely.
- The rapid rise of initial transient DC fault current within a short duration of fault inception put the system under high mechanical and thermal stress, and the absence of natural zero-crossing point inhibits natural arc extinction. To prevent any damage to the equipment, fault clearing by the deployed DCCBs within a scheduled time frame is necessitated. DCCBs should be capable of handling high fault current with minimum on-state conduction loss, however high transient current leads to an increase in the size and cost of DCCBs.
- Low virtual inertial, dynamic, bidirectional fault current, and also CPL has lessened the effectiveness of conventional overcurrent and under-voltage protection schemes. To address that, current and voltage derivative, AIE, etc. are effectively implemented to assure reliability. On the contrary, unit protection (current differential) accomplishes high-speed operation and accuracy unless severe communication outage impedes its effectiveness.
- The use of algorithm techniques along with frequency analysis methods (STFT, DWT) has significantly improved the accuracy in detection and identification of faults. Besides transient evolution, the high-frequency component present in the system decisively helps to execute the frequency-based analysis and also assists in system modeling.
- While designing the protective system, the advantage of protective abilities (FTC, current limiting, rapid post-fault recovery) of different interconnected DC-DC converters must be contemplated; however, this should not impede the primary protection strategy.
- Some power converters can inhibit the fault severity by truncating the fault current and can participate in protection subroutine to prevent catastrophic damage of the system, but this also promotes fault detection issue and paralyzes the overcurrent protection. By activating the handshaking method, accurate detection of fault line and clearance can be provided, but extra fault detector is required. Furthermore, the coordination between control and protection should be made more effective to assist protection subroutine.
- To attain maximum service continuity, non-iterative deterministic fault location scheme (PPU) primarily prohibits the process of de-energizing the multiple sources, rather isolate the affected zone and generations.
- Applied protection topology must be capable of adopting further penetration of DGs and a significant amount of extra loads without re-programming the existing PDs. It should anticipate system disturbance and would be capable of resolving those issues very quickly to improve resilience.
- Lack of comprehensiveness in practical standardization, guideline, and regulations on grounding systems for different voltage levels, cyber-security issues restrict its widespread application. Henceforth, a legitimate protection solution for the future DC smart microgrid can be accomplished, if a secured communication assisted, automated wide-area monitored centralized protection system equipped with intelligent multi-functional PDs would be implemented.

9. Conclusion

Protection is the inevitable challenge that precludes the thriving benefits of DC microgrid and its applications. This paper aims first to shed light on the protection challenges that are associated with DC microgrid. To seek out a viable solution, later sections are contrived to delineate pros and cons of all the protection philosophies. A convenient protection paradigm can only be accomplished if a step by step systematic consideration of DC topology, utility grid interconnection, grounding system, converter operation followed by the fault type and fault current behavior have seamlessly solicited. As the converters are primarily responsible for fault current behavior, consideration of converter interfacing and its control should be an integral part of the protection solution. To interrupt the fast-growing fault current transient, chronological changes on DCCBs have been performed to assists the primary protection. Different DCCBs topologies are briefly discussed and tabulated based on the feasible operating parameters. In this paper, successive refurbishment of different protection techniques is explained in such a way that it can be more informative for realizing the facts regarding protection. This article also addresses the guidelines of the DC microgrid precisely, which will help proper designing of the protection instruments. Finally, the protection strategies are tabulated based on the main fundamental parameters that are substantial for the implementation of any protection scheme. Therefore, it can be concluded that anticipating the system disturbances accurately and immediate action making within a scheduled time frame to locate and isolate the fault will only preserve the effectiveness of the suggested protection strategy. The deployment of IEDs into an automated power system further emerges towards more reliable and accurate power flow measurement, fault protection, energy management by the concept aimed to supervise a potentially large zone by WAMPS. The invention of a novel protection strategy is still in demand to substantiate fast, accurate fault inception and isolation.

Declaration of Competing Interest

None.

References

[1] D. Keshavarzi, E. Farjah, T. Ghanbari, Hybrid DC circuit breaker and fault current limiter with optional interruption capability, IEEE Trans. Power Electron 33 (2018) 2330–2338 https://doi.org/10.1109/TPEL.2017.2690960.

[2] T. Dragicevic, J. Vasquez, J. Guerrero, D. Škrlec, Advanced LVDC electrical power

architectures and microgrids, IEEE Electrif. Mag. 2 (2014) 54–65 https://doi.org/10.1109/MELE.2013.2297033.

[3] M. Starke, F. Li, L.M. Tolbert, B. Ozpineci, AC vs. DC distribution, Maximum transfer capability, IEEE Power Energy Soc. 2008 Gen. Meet. Convers. Deliv. Electr. Energy 21st Century, PES. 2008 https://doi.org/10.1109/PES.2008.4596730.

[4] J.J. Justo, F. Mwasilu, J. Lee, J.W. Jung, AC-microgrids versus DC-microgrids with distributed energy resources: a review, Renew. Sustain. Energy Rev. 24 (2013) 387–405 https://doi.org/10.1016/j.rser.2013.03.067.

[5] P. Fairley, DC versus AC: The second war of currents has already begun [in my view], IEEE Power Energy Mag. 10 (2012) 103–104 https://doi.org/10.1109/MPE.2012.2212617.

[6] T. Shah, Z.A. Ansari, An overview of intelligent energy management system for DC microgrid: system and communication architecture and application in power distribution system, 2018 13th Int. Conf. Ind. Inf. Syst. ICIIS 2018 - Proc. 2018, pp. 339–342 https://doi.org/10.1109/ICIINFS.2018.8721384.

[7] J. Do Park, J. Candelaria, L. Ma, K. Dunn, DC ring-bus microgrid fault protection and identification of fault location, IEEE Trans. Power Deliv. 28 (2013) 2574–2584 https://doi.org/10.1109/TPWRD.2013.2267750.

[8] K. Shenai, K. Shah, Smart DC micro-grid for efficient utilization of distributed renewable energy, IEEE 2011 EnergyTech, ENERGYTECH 2011, 2011 https://doi.org/10.1109/EnergyTech.2011.5948505.

[9] H. Kakigano, Y. Miura, T. Ise, Low-voltage bipolar-type dc microgrid for super high quality distribution, IEEE Trans. Power Electron 25 (2010) 3066–3075 https://doi.org/10.1109/TPEL.2010.2077682.

[10] A. Pratt, P. Kumar, T.V. Aldridge, Evaluation of 400V DC distribution in telco and data centers to improve energy efficiency, INTELEC, Int. Telecommun. Energy Conf. 2007, pp. 32–39 https://doi.org/10.1109/INTLEC.2007.4448733.

[11] A. Kwasinski, Quantitative evaluation of DC microgrids availability: Effects of system architecture and converter topology design choices, IEEE Trans. Power Electron 26 (2011) 835–851 https://doi.org/10.1109/TPEL.2010.2102774.

[12] J. Wang, B. Berggren, K. Linden, J. Pan, R. Nuqui, Multi-terminal DC system line protection requirement and high speed protection solutions, Cigré Int. Symp. - Across Borders - HVDC Syst. Mark. Integr. 2015, pp. 1–9.

[13] S. Augustine, J.E. Quiroz, M.J. Reno, S. Brahma, DC Microgrid Protection: Review and Challenges, Researchgate.Net, 2018, https://www.researchgate.net/profile/Matthew_Reno/publication/326957897_DC_Microgrid_Protection_Review_and_Challenges/links/5b6db1bfa6fdcc87df7112d2/DC-Microgrid-Protection-Review-and-Challenges.pdf.

[14] P. Cairoli, R. Rodrigues, H. Zheng, Fault current limiting power converters for protection of DC microgrids, Conf. Proc. - IEEE SOUTHEASTCON, 2017, pp. 1–7 https://doi.org/10.1109/SECON.2017.7925392.

[15] S. Augustine, S.M. Brahma, M.J. Reno, Fault current control for DC microgrid protection using an adaptive droop, 2019 IEEE 28th Int. Symp. Ind. Electron. 2019, pp. 2591–2596 https://doi.org/10.1109/isie.2019.8781462.

[16] J. Yang, J.E. Fletcher, J. O'Reilly, Short-circuit and ground fault analyses and location in VSC-based DC network cables, IEEE Trans. Ind. Electron 59 (2012) 3827–3837 https://doi.org/10.1109/TIE.2011.2162712.

[17] S. Beheshtaein, R. Cuzner, M. Savaghebi, J.M. Guerrero, Review on microgrids protection, IET Gener. Transm. Distrib. 13 (2019) 743–759 https://doi.org/10.1049/iet-gtd.2018.5212.

[18] A. Mokhberdoran, A. Carvalho, H. Leite, N. Silva, A review on HVDC circuit breakers, IET Conf. Publ. 2014, 2014, pp. 1–6 https://doi.org/10.1049/cp.2014.0859.

[19] S. Beheshtaein, R.M. Cuzner, M. Forouzesh, M. Savaghebi, J.M. Guerrero, DC microgrid protection: a comprehensive review, IEEE J. Emerg. Sel. Top. Power Electron (2019) 1 -1 https://doi.org/10.1109/jestpe.2019.2904588.

[20] E. Rodriguez-Diaz, M. Savaghebi, J.C. Vasquez, J.M. Guerrero, An overview of low voltage DC distribution systems for residential applications, 5th IEEE Int. Conf. Consum. Electron. - Berlin, ICCE-Berlin 2015, 2016, pp. 318–322 https://doi.org/10.1109/ICCE-Berlin.2015.7391268.

[21] D. Kumar, F. Zare, A. Ghosh, DC microgrid technology: system architectures, AC grid interfaces, grounding schemes, power quality, communication networks, applications, and standardizations aspects, IEEE Access 5 (2017) 12230–12256 https://doi.org/10.1109/ACCESS.2017.2705914.

[22] J. Karppanen, T. Kaipia, P. Nuutinen, A. Lana, P. Peltoniemi, A. Pinomaa, A. Mattsson, J. Partanen, J. Cho, J. Kim, Effect of voltage level selection on earthing and protection of LVDC distribution systems, IET Semin. Dig. 2015, 2015, pp. 1–8 https://doi.org/10.1049/cp.2015.0057.

[23] S.J. Chiang, H.J. Shieh, M.C. Chen, Modeling and control of PV charger system with SEPIC converter, IEEE Trans. Ind. Electron 56 (2009) 4344–4353 https://doi.org/10.1109/TIE.2008.2005144.

[24] T. Dragičević, J.C. Vasquez, J.M. Guerrero, D. Škrlec, Advanced LVDC electrical power architectures and microgrids: a step toward a new generation of power distribution networks, IEEE Electrif. Mag. 2 (2014) 54–65 https://doi.org/10.1109/MELE.2013.2297033.

[25] Q. Shafiee, T. Dragicevic, J.C. Vasquez, J.M. Guerrero, Modeling, stability analysis and active stabilization of multiple DC-microgrid clusters, ENERGYCON 2014 - IEEE Int. Energy Conf. 2014, pp. 1284–1290 https://doi.org/10.1109/ENERGYCON.2014.6850588.

[26] Q. Shafiee, T. Dragičević, J.C. Vasquez, J.M. Guerrero, Hierarchical control for multiple DC-microgrids clusters, IEEE Trans. Energy Convers 29 (2014) 922–933 https://doi.org/10.1109/TEC.2014.2362191.

[27] R.S. Balog, P.T. Krein, Bus selection in multibus DC microgrids, IEEE Trans. Power Electron 26 (2011) 860–867 https://doi.org/10.1109/TPEL.2010.2094208.

[28] N.R. Chaudhuri, R. Majumder, B. Chaudhuri, System frequency support through multi-terminal DC (MTDC) grids, IEEE Trans. Power Syst. 28 (2013) 347–356 https://doi.org/10.1109/TPWRS.2012.2196805.

[29] R. Teixeira Pinto, P. Bauer, S.F. Rodrigues, E.J. Wiggelinkhuizen, J. Pierik, B. Ferreira, A novel distributed direct-voltage control strategy for grid integration of offshore wind energy systems through MTDC network, IEEE Trans. Ind. Electron 60 (2013) 2429–2441 https://doi.org/10.1109/TIE.2012.2216239.

[30] T. Dragičević, X. Lu, J.C. Vasquez, J.M. Guerrero, DC microgrids - Part II: a review of power architectures, applications, and standardization issues, IEEE Trans. Power Electron 31 (2016) 3528–3549 https://doi.org/10.1109/TPEL.2015.2464277.

[31] W. Lu, B.T. Ooi, Multiterminal LVDC system for optimal acquisition of power in wind-farm using induction generators, IEEE Trans. Power Electron 17 (2002) 558–563 https://doi.org/10.1109/TPEL.2002.800995.

[32] W. Lu, B.T. Ooi, Optimal acquisition and aggregation of offshore wind power by multiterminal voltage-source HVDC, IEEE Trans. Power Deliv. 18 (2003) 201–206 https://doi.org/10.1109/TPWRD.2002.803826.

[33] J.G. Ciezki, R.W. Ashton, Selection and stability issues associated with a navy shipboard DC zonal electric distribution system, IEEE Trans. Power Deliv. 15 (2000) 665–669 https://doi.org/10.1109/61.853002.

[34] M.E. Baran, N. Mahajan, System reconfiguration on shipboard DC zonal electrical system, 2005 IEEE Electr. Sh. Technol. Symp. 2005, 2005, pp. 86–92 https://doi.org/10.1109/ESTS.2005.1524658.

[35] J. Do Park, J. Candelaria, Fault detection and isolation in low-voltage dc-bus microgrid system, IEEE Trans. Power Deliv. 28 (2013) 779–787 https://doi.org/10.1109/TPWRD.2013.2243478.

[36] D. Salomonsson, L. Söder, A. Sannino, Protection of low-voltage DC microgrids, IEEE Trans. Power Deliv. 24 (2009) 1045–1053 https://doi.org/10.1109/TPWRD.2009.2016622.

[37] A. Berizzi, A. Silvestri, D. Zaninelli, S. Massucco, Short-circuit current calcultions for DC systems, IEEE Trans. Ind. Appl. 32 (1996) 990–997.

[38] Z. Shuai, D. He, Z. Xiong, Z. Lei, Z. John Shen, Comparative study of short-circuit fault characteristics for VSC-based DC distribution networks with different distributed generators, IEEE J. Emerg. Sel. Top. Power Electron 7 (2019) 528–540 https://doi.org/10.1109/JESTPE.2018.2834542.

[39] A. Meghwani, S. Chakrabarti, S.C. Srivastava, S. Anand, Analysis of fault characteristics in DC microgrids for various converter topologies, 2017 IEEE Innov. Smart Grid Technol. - Asia Smart Grid Smart Community, ISGT-Asia 2017, 2018, pp. 1–6 https://doi.org/10.1109/ISGT-Asia.2017.8378426.

[40] W. Javed, D. Chen, M.E. Farrag, Y. Xu, System configuration, fault detection, location, isolation and restoration: a review on LVDC microgrid protections, Energies (2019) 12 https://doi.org/10.3390/en12061001.

[41] R.D. Telford, S. Galloway, B. Stephen, I. Elders, Diagnosis of series DC arc faults - a machine learning approach, IEEE Trans. Ind. Inform. 13 (2017) 1598–1609 https://doi.org/10.1109/TII.2016.2633335.

[42] Z. Shuangle, Z. Yanfeng, Z. Yuan, W. Yao, L. Kui, Measurement and analysis method of electromagnetic signals for DC arcing fault, ICEPE-ST 2017 - 4th Int. Conf. Electr. Power Equipment- Switch. Technol. 2017-Decem, 2017, pp. 833–836 https://doi.org/10.1109/ICEPE-ST.2017.8188975.

[43] F.M. Uriarte, A.L. Gattozzi, J.D. Herbst, H.B. Estes, T.J. Hotz, A. Kwasinski, R.E. Hebner, A DC arc model for series faults in low voltage microgrids, IEEE Trans. Smart Grid. 3 (2012) 2063–2070 https://doi.org/10.1109/TSG.2012.2201757.

[44] S. McCalmonit, Low cost arc fault detection and protection for PV systems, Contract 303 (2013) 275–3000.

[45] K. Subramaniam, M.S. Illindala, High impedance fault detection and isolation in DC microgrids, Conf. Rec. - Ind. Commer. Power Syst. Tech. Conf. 2019-May, 2019, pp. 1–8 https://doi.org/10.1109/ICPS.2019.8733334.

[46] A. Makkieh, A. Emhemed, D. Wang, A. Junyent-Ferre, G. Burt, Investigation of different system earthing schemes for protection of low-voltage DC microgrids, J. Eng. (2019) 5129–5133 2019 https://doi.org/10.1049/joe.2018.9365.

[47] T.R. De Oliveira, A.S. Bolzon, P.F. Donoso-Garcia, Grounding and safety considerations for residential DC microgrids, IECON Proc. (Industrial Electron. Conf. 2014, pp. 5526–5532 https://doi.org/10.1109/IECON.2014.7049345.

[48] J. Mohammadi, S. Member, F.B. Ajaei, G. Stevens, Grounding the DC microgrid, IEEE Trans. Ind. Appl. 55 (2019) 4490–4499 https://doi.org/10.1109/TIA.2019.2928278.

[49] J. Mohammadi, F. Badrkhani Ajaei, G. Stevens, Grounding the AC microgrid, IEEE Trans. Ind. Appl. 55 (2019) 98–105 https://doi.org/10.1109/TIA.2018.2864106.

[50] D.K.J.S. Jayamaha, N.W.A. Lidula, A.D. Rajapakse, Ground fault analysis and grounding design considerations in DC microgrids, 2018 IEEE 4th South. Power Electron. Conf. SPEC 2018, 2019, pp. 1–8 https://doi.org/10.1109/SPEC.2018.8636090.

[51] M. Mobarrez, D. Fregosi, S. Bhattacharya, M.A. Bahmani, Grounding architectures for enabling ground fault ride-through capability in DC microgrids, 2017 IEEE 2nd Int. Conf. Direct Curr. Microgrids, ICDCM 2017, 2017, pp. 81–87 https://doi.org/10.1109/ICDCM.2017.8001026.

[52] D. Paul, DC traction power system grounding, IEEE Trans. Ind. Appl. 38 (2002) 818–824 https://doi.org/10.1109/TIA.2002.1003435.

[53] M.K. Bucher, C.M. Franck, Comparison of fault currents in multiterminal HVDC grids with different grounding schemes, IEEE Power Energy Soc. Gen. Meet. 2014-Octob, 2014, pp. 1–5 https://doi.org/10.1109/PESGM.2014.6938990.

[54] M. Carminati, E. Ragaini, Considerations on DC side grounding configurations of LVDC microgrids, IYCE 2015 - Proc. 2015 5th Int. Youth Conf. Energy. 20133, 2015, pp. 1–6 https://doi.org/10.1109/IYCE.2015.7180739.

[55] M. Farhadi, O.A. Mohammed, Protection of multi-terminal and distributed DC systems: Design challenges and techniques, Electr. Power Syst. Res. 143 (2017)

715–727 https://doi.org/10.1016/j.epsr.2016.10.038.

[56] X. Lu, K. Sun, J.M. Guerrero, J.C. Vasquez, L. Huang, J. Wang, Stability Enhancement based on virtual impedance for DC microgrids with constant power loads, IEEE Trans. Smart Grid. 6 (2015) 2770–2783 https://doi.org/10.1109/TSG.2015.2455017.

[57] R.M. Kamel, K. Nagasaka, Effect of load type on standalone micro grid fault performance, Appl. Energy 160 (2015) 532–540 https://doi.org/10.1016/j.apenergy.2015.09.044.

[58] L. Meng, Q. Shafiee, G.F. Trecate, H. Karimi, D. Fulwani, X. Lu, J.M. Guerrero, Review on control of DC microgrids and multiple microgrid clusters, IEEE J. Emerg. Sel. Top. Power Electron 5 (2017) 928–948 https://doi.org/10.1109/JESTPE.2017.2690219.

[59] P. Magne, B. Nahid-Mobarakeh, S. Pierfederici, Dynamic consideration of DC microgrids with constant power loads and active damping system—a design method for fault-tolerant stabilizing system, IEEE J. Emerg. Sel. Top. Power Electron 2 (2014) 562–570 https://doi.org/10.1109/jestpe.2014.2305979.

[60] S. Mirsaeidi, X. Dong, D.M. Said, Towards hybrid AC/DC microgrids: Critical analysis and classification of protection strategies, Renew. Sustain. Energy Rev. 90 (2018) 97–103 https://doi.org/10.1016/j.rser.2018.03.046.

[61] H. Sun, M. Rong, Z. Chen, C. Hou, Y. Sun, Investigation on the arc phenomenon of air DC circuit breaker, IEEE Trans. Plasma Sci. 42 (2014) 2706–2707 https://doi.org/10.1109/TPS.2014.2343257.

[62] R.M. Cuzner, G. Venkataramanan, The status of DC micro-grid protection, Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc. 2008, pp. 1–8 https://doi.org/10.1109/08IAS.2008.382.

[63] W. Liu, F. Liu, X. Zha, M. Huang, C. Chen, Y. Zhuang, An improved SSCB combining fault interruption and fault location functions for DC line short-circuit fault protection, IEEE Trans. Power Deliv. 34 (2019) 858–868 https://doi.org/10.1109/TPWRD.2018.2882497.

[64] B. Li, J. He, Y. Li, R. Li, A novel solid-state circuit breaker with self-adapt fault current limiting capability for LVDC distribution network, IEEE Trans. Power Electron 34 (2019) 3516–3529 https://doi.org/10.1109/TPEL.2018.2850441.

[65] W. Wu, Y. Chen, A. Luo, L. Zhou, X. Zhou, L. Yang, Y. Dong, J.M. Guerrero, A virtual inertia control strategy for DC microgrids analogized with virtual synchronous machines, IEEE Trans. Ind. Electron 64 (2017) 6005–6016 https://doi.org/10.1109/TIE.2016.2645898.

[66] A. Meghwani, S.C. Srivastava, S. Chakrabarti, A non-unit protection scheme for DC microgrid based on local measurements, IEEE Trans. Power Deliv. 32 (2017) 172–181 https://doi.org/10.1109/TPWRD.2016.2555844.

[67] S.D.A. Fletcher, P.J. Norman, S.J. Galloway, P. Crolla, G.M. Burt, Optimizing the roles of unit and non-unit protection methods within DC microgrids, IEEE Trans. Smart Grid 3 (2012) 2079–2087 https://doi.org/10.1109/TSG.2012.2198499.

[68] I. Jahn, N. Johannesson, S. Norrga, Survey of methods for selective DC fault detection in MTDC grids, IET Conf. Publ. 2017, 2017, pp. 1–7 https://doi.org/10.1049/cp.2017.0041.

[69] J.P. Brozek, DC overcurrent protection - where we stand, Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc. 1992-Janua, 1992, pp. 1306–1310 https://doi.org/10.1109/IAS.1992.244268.

[70] M.E. Baran, N.R. Mahajan, Overcurrent protection on voltage-source-converter-based multiterminal DC distribution systems, IEEE Trans. Power Deliv. 22 (2007) 406–412 https://doi.org/10.1109/TPWRD.2006.877086.

[71] K.A. Saleh, A. Hooshyar, E.F. El-Saadany, Hybrid passive-overcurrent relay for detection of faults in low-voltage DC grids, IEEE Trans. Smart Grid 8 (2017) 1129–1138 https://doi.org/10.1109/TSG.2015.2477482.

[72] A. Shabani, K. Mazlumi, Evaluation of a communication-assisted overcurrent protection scheme for photovoltaic based DC microgrid, IEEE Trans. Smart Grid (2019) 1 -1 https://doi.org/10.1109/tsg.2019.2923769.

[73] K. Satpathi, N. Thukral, A. Ukil, M.A. Zagrodnik, Directional protection scheme for MVDC shipboard power system, IECON Proc. (Industrial Electron. Conf. 2016, pp. 3840–3847 https://doi.org/10.1109/IECON.2016.7793893.

[74] A. Shukla, G.D. Demetriades, A survey on hybrid circuit-breaker topologies, IEEE Trans. Power Deliv. 30 (2015) 627–641 https://doi.org/10.1109/TPWRD.2014.2331696.

[75] H. Li, M. Chen, B. Yang, F. Blaabjerg, D. Xu, Fast fault protection based on direction of fault current for the high-surety power-supply system, IEEE Trans. Power Electron 34 (2019) 5787–5802 https://doi.org/10.1109/TPEL.2018.2870982.

[76] A. Meghwani, S.C. Srivastava, S. Chakrabarti, A new protection scheme for DC microgrid using line current derivative, IEEE Power Energy Soc. Gen. Meet. 2015-Septe, 2015, pp. 1–5 https://doi.org/10.1109/PESGM.2015.7286041.

[77] P.B. Petrovic, M.R. Stevanovic, Digital Processing and Reconstruction of Complex AC Signals, Springer Science and Business Media, New York, USA, 2009.

[78] C. Li, P. Rakhra, P. Norman, P. Niewczas, G. Burt, P. Clarkson, Practical computation of di/dt for high-speed protection of DC microgrids, 2017 IEEE 2nd Int. Conf. Direct Curr. Microgrids, ICDCM 2017, 2017, pp. 153–159 https://doi.org/10.1109/ICDCM.2017.8001037.

[79] D. Wang, A. Emhemed, G. Burt, A novel protection scheme for an LVDC distribution network with reduced fault levels, 2017 IEEE 2nd Int. Conf. Direct Curr. Microgrids, ICDCM 2017, 2017, pp. 69–75 https://doi.org/10.1109/ICDCM.2017.8001024.

[80] Y. Chen, D. Liu, B. Xu, Wide-area traveling wave fault location system based on IEC61850, IEEE Trans. Smart Grid 4 (2013) 1207–1215 https://doi.org/10.1109/TSG.2012.2233767.

[81] A. Prasai, Y. Du, A. Paquette, E. Buck, R. Harley, D. Divan, Protection of meshed microgrids with communication overlay, 2010 IEEE Energy Convers. Congr. Expo. ECCE 2010 - Proc. 2010, pp. 64–71 https://doi.org/10.1109/ECCE.2010.5618074.

[82] S.D.A. Fletcher, P.J. Norman, K. Fong, S.J. Galloway, G.M. Burt, High-speed differential protection for smart DC distribution systems, IEEE Trans. Smart Grid 5 (2014) 2610–2617 https://doi.org/10.1109/TSG.2014.2306064.

[83] S. Dhar, P.K. Dash, Differential current-based fault protection with adaptive threshold for multiple PV-based DC microgrid, IET Renew. Power Gener. 11 (2017) 778–790 https://doi.org/10.1049/iet-rpg.2016.0577.

[84] S. Dhar, R.K. Patnaik, P.K. Dash, Fault detection and location of photovoltaic based DC microgrid using differential protection strategy, IEEE Trans. Smart Grid 9 (2018) 4303–4312 https://doi.org/10.1109/TSG.2017.2654267.

[85] S. Azizi, S. Afsharnia, M. Sanaye-Pasand, Fault location on multi-terminal DC systems using synchronized current measurements, Int. J. Electr. Power Energy Syst. 63 (2014) 779–786 https://doi.org/10.1016/j.ijepes.2014.06.040.

[86] N. Villamagna, P.A. Crossley, A symmetrical component-based GPS signal failure-detection algorithm for use in feeder current differential protection, IEEE Trans. Power Deliv. 23 (2008) 1821–1828 https://doi.org/10.1109/TPWRD.2008.919035.

[87] C. Yuan, M.A. Haj-Ahmed, M.S. Illindala, Protection strategies for medium-voltage direct-current microgrid at a remote area mine site, IEEE Trans. Ind. Appl 51 (2015) 2846–2853 https://doi.org/10.1109/TIA.2015.2391441.

[88] A. Meghwani, S. Chakrabarti, S.C. Srivastava, A fast scheme for fault detection in DC microgrid based on voltage prediction, 2016 Natl. Power Syst. Conf. NPSC 2016, 2017, pp. 1–6 https://doi.org/10.1109/NPSC.2016.7858867.

[89] X. Feng, Z. Ye, C. Liu, R. Zhang, F.C. Lee, D. Boroyevich, Fault detection in DC distributed power systems based on impedance characteristics of modules, Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc. 4 2000, pp. 2455–2462 https://doi.org/10.1109/ias.2000.883167.

[90] E. Christopher, M. Sumner, D.W.P. Thomas, X. Wang, F. De Wildt, Fault location in a zonal DC marine power system using active impedance estimation, IEEE Trans. Ind. Appl. 49 (2013) 860–865 https://doi.org/10.1109/TIA.2013.2243391.

[91] E. Christopher, M. Sumner, D. Thomas, F. De Wildt, Fault location for a DC zonal electrical distribution systems using active impedance estimation, 2011 IEEE Electr. Sh. Technol. Symp. ESTS 2011, 2011, pp. 310–314 https://doi.org/10.1109/ESTS.2011.5770888.

[92] Z. Galijasevic, A. Abur, Fault area estimation via intelligent processing of fault-induced transients, IEEE Trans. Power Syst. 18 (2003) 1241–1247 https://doi.org/10.1109/TPWRS.2003.814854.

[93] Y. Zhang, N. Tai, B. Xu, Fault analysis and traveling-wave protection scheme for bipolar HVDC lines, IEEE Trans. Power Deliv. 27 (2012) 1583–1591 https://doi.org/10.1109/TPWRD.2012.2190528.

[94] A. Sharafi, M. Sanaye-Pasand, P. Jafarian, Ultra-high-speed protection of parallel transmission lines using current travelling waves, IET Gener. Transm. Distrib. 5 (2011) 656–666 https://doi.org/10.1049/iet-gtd.2010.0767.

[95] X. Li, A. Dysko, G.M. Burt, Traveling wave-based protection scheme for inverter-dominated microgrid using mathematical morphology, IEEE Trans. Smart Grid 5 (2014) 2211–2218 https://doi.org/10.1109/TSG.2014.2320365.

[96] S. Azizi, M. Sanaye-Pasand, M. Abedini, A. Hassani, A traveling-wave-based methodology for wide-area fault location in multiterminal DC systems, IEEE Trans. Power Deliv. 29 (2014) 2552–2560 https://doi.org/10.1109/TPWRD.2014.2323356.

[97] K.A. Saleh, A. Hooshyar, E.F. El-Saadany, Ultra-high-speed traveling-wave-based protection scheme for medium-voltage DC microgrids, IEEE Trans. Smart Grid 10 (2019) 1440–1451 https://doi.org/10.1109/TSG.2017.2767552.

[98] K. Satpathi, Y.M. Yeap, A. Ukil, N. Geddada, Short-time fourier transform based transient analysis of VSC interfaced point-to-point DC system, IEEE Trans. Ind. Electron. 65 (2018) 4080–4091 https://doi.org/10.1109/TIE.2017.2758745.

[99] K. Satpathi, A. Ukil, S.S. Nag, J. Pou, M.A. Zagrodnik, DC marine power system: transient behavior and fault management aspects, IEEE Trans. Ind. Informatics. 15 (2019) 1911–1925 https://doi.org/10.1109/TII.2018.2864598.

[100] S.C. Shekar, G.R. Kumar, S. Lalitha, Wavelet based transient fault detection and analysis of microgrid connected power system, Iaras.Org 1 (2016), pp. 46–52 http://www.iaras.org/iaras/filedownloads/ijps/2016/010-0007.pdf.

[101] K. De Kerf, K. Srivastava, M. Reza, D. Bekaert, S. Cole, D. Van Hertem, R. Belmans, Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems, IET Gener. Transm. Distrib. 5 (2011) 496–503 https://doi.org/10.1049/iet-gtd.2010.0587.

[102] A.E.B. Abu-Elanien, A.A. Elserougi, A.S. Abdel-Khalik, A.M. Massoud, S. Ahmed, A differential protection technique for multi-terminal HVDC, Electr. Power Syst. Res. 130 (2016) 78–88 https://doi.org/10.1016/j.epsr.2015.08.021.

[103] Y.M. Yeap, N. Geddada, A. Ukil, Analysis and validation of wavelet transform based DC fault detection in HVDC system, Appl. Soft Comput. J. 61 (2017) 17–29 https://doi.org/10.1016/j.asoc.2017.07.039.

[104] S. Som, S.R. Samantaray, Efficient protection scheme for low-voltage DC micro-grid, IET Gener. Transm. Distrib. 12 (2018) 3322–3329 https://doi.org/10.1049/iet-gtd.2017.1533.

[105] S. Som, S.R. Samantaray, Wavelet based fast fault detection in LVDC micro-grid, 2017 7th Int. Conf. Power Syst. ICPS 2017, 2018, pp. 87–92 https://doi.org/10.1109/ICPES.2017.8387273.

[106] J. Liang, S. Elangovan, J.B.X. Devotta, A wavelet multiresolution analysis approach to fault detection and classification in transmission lines, Int. J. Electr. Power Energy Syst. 20 (1998) 327–332 https://doi.org/10.1016/s0142-0615(97)00076-8.

[107] W. Li, M. Luo, A. Monti, F. Ponci, Wavelet based method for fault detection in *medium voltage* DC shipboard power systems, 2012 IEEE I2MTC - Int. Instrum. Meas. Technol. Conf. Proc. 2012, pp. 2155–2160 https://doi.org/10.1109/I2MTC.2012.6229382.

[108] M. Akbari, S.M. Moghaddas-Tafreshi, M. Aliakbar Golkar, Wavelet-based multi-resolution voltage controller in a hybrid AC/DC microgrid, Prz. Elektrotech. 88 (2012) 197–204.
[109] W. Li, A. Monti, F. Ponci, Fault detection and classification in medium voltage dc shipboard power systems with wavelets and artificial neural networks, IEEE Trans. Instrum. Meas. 63 (2014) 2651–2665 https://doi.org/10.1109/TIM.2014.2313035.
[110] C.S. Chang, S. Kumar, B. Liu, A. Khambadkone, Real-time detection using wavelet transform and neural network of short-circuit faults within a train in DC transit systems, IEE Proc. Electr. Power Appl. 148 (2001) 251–256 https://doi.org/10.1049/ip-epa:20010350.
[111] A.J. Mair, E.M. Davidson, S.D.J. McArthur, S.K. Srivastava, K. Schoder, D.A. Cartes, Machine learning techniques for diagnosing and locating faults through the automated monitoring of power electronic components in shipboard power systems, IEEE Electr. Ship Technol. Symp. ESTS 2009 (2009) 469–476 https://doi.org/10.1109/ESTS.2009.4906553.
[112] I. Almutairy, M. Alluhaidan, Fault Diagnosis based approach to protecting DC microgrid using machine learning technique, Procedia Comput. Sci. 114 (2017) 449–456 https://doi.org/10.1016/j.procs.2017.09.019.
[113] A. Abdali, K. Mazlumi, R. Noroozian, Fast fault detection and isolation in low-voltage DC microgrids using fuzzy inference system, 5th Iran. Jt. Congr. Fuzzy Intell. Syst. - 16th Conf. Fuzzy Syst. 14th Conf. Intell. Syst. CFIS 2017, 2017, pp. 172–177 https://doi.org/10.1109/CFIS.2017.8003678.
[114] J. Aswani, P. Kanakasabapathy, Protection of a low-voltage DC ring microgrid system, 2016 Int. Conf. Energy Effic. Technol. Sustain. ICEETS 2016, 2016, pp. 17–22 https://doi.org/10.1109/ICEETS.2016.7582892.
[115] N.K. Chanda, Y. Fu, ANN-based fault classification and location in MVDC shipboard power systems, NAPS 2011 - 43rd North Am. Power Symp. 2011, pp. 1–7 https://doi.org/10.1109/NAPS.2011.6025172.
[116] Q. Yang, J. Li, S. Le Blond, C. Wang, Artificial neural network based fault detection and fault location in the DC microgrid, Energy Procedia 103 (2016) 129–134 https://doi.org/10.1016/j.egypro.2016.11.261.
[117] A. Senfelds, A. Avotins, P. Apse-Apsitis, E. Grinfogels, L. Ribickis, Investigation on power quality parameters of industrial 600V DC microgrid hardware, 2018 20th Eur. Conf. Power Electron. Appl. EPE 2018 ECCE Eur. 2018, pp. P.1–P.6.
[118] D. Soto, M. Sloderbeck, H. Ravindra, M. Steurer, Advances to megawatt scale demonstrations of high speed fault clearing and power restoration in breakerless MVDC shipboard power systems, 2017 IEEE Electr. Sh. Technol. Symp. ESTS 2017, 2017, pp. 312–315 https://doi.org/10.1109/ESTS.2017.8069299.
[119] P. Cairoli, I. Kondratiev, R.A. Dougal, Coordinated control of the bus tie switches and power supply converters for fault protection in DC microgrids, IEEE Trans. Power Electron 28 (2013) 2037–2047 https://doi.org/10.1109/TPEL.2012.2214790.
[120] W. Choi, B.H. Cho, Topology and control design of converters for short-circuit fault protection in DC microgrids, IECON Proc. (Industrial Electron. Conf. 2013, pp. 1386–1391 https://doi.org/10.1109/IECON.2013.6699335.
[121] L. Tang, B.T. Ooi, Locating and isolating DC faults in multi-terminal DC systems, IEEE Trans. Power Deliv. 22 (2007) 1877–1884 https://doi.org/10.1109/TPWRD.2007.899276.
[122] R. Cuzner, A. Jeutter, DC zonal electrical system fault isolation and re-configuration, IEEE Electr. Sh. Technol. Symp. ESTS 2009, 2009, pp. 227–234 https://doi.org/10.1109/ESTS.2009.4906520.
[123] J.D. Paez, D. Frey, J. Maneiro, S. Bacha, P. Dworakowski, Overview of DC-DC converters dedicated to HVdc grids, IEEE Trans. Power Deliv. 34 (2019) 119–128 https://doi.org/10.1109/TPWRD.2018.2846408.
[124] G. Yang, F. Xiao, X. Fan, R. Wang, J. Liu, Three-phase three-level phase-shifted PWM DC-DC converter for electric ship MVDC application, IEEE J. Emerg. Sel. Top. Power Electron 5 (2017) 162–170 https://doi.org/10.1109/JESTPE.2016.2620282.
[125] G.P. Adam, I.A. Gowaid, S.J. Finney, D. Holliday, B.W. Williams, Review of dc-dc converters for multi-terminal HVDC transmission networks, IET Power Electron 9 (2016) 281–296 https://doi.org/10.1049/iet-pel.2015.0530.
[126] S. Cui, J. Hu, R. De Doncker, Fault-tolerant operation of a TLC-MMC Hybrid DC-DC converter for interconnection of MVDC and HVdc Grids, IEEE Trans. Power Electron 35 (2020) 83–93 https://doi.org/10.1109/TPEL.2019.2911853.
[127] L. Qi, A. Antoniazzi, L. Raciti, DC distribution fault analysis, protection solutions, and example implementations, IEEE Trans. Ind. Appl. 54 (2018) 3179–3186 https://doi.org/10.1109/TIA.2018.2825437.
[128] Z. Xiao, An instantaneously triggered short-circuit protection architecture for boost switching DC/DC converters, IEEE Trans. Power Electron 33 (2018) 5677–5685 https://doi.org/10.1109/TPEL.2017.2743170.
[129] E. Jamshidpour, P. Poure, S. Saadate, Photovoltaic systems reliability improvement by real-time FPGA-based switch failure diagnosis and fault-tolerant DC-DC converter, IEEE Trans. Ind. Electron. 62 (2015) 7247–7255 https://doi.org/10.1109/TIE.2015.2421880.
[130] E. Pazouki, Y. Sozer, J.A. De Abreu-Garcia, Fault diagnosis and fault-tolerant control operation of nonisolated DC-DC converters, IEEE Trans. Ind. Appl. 54 (2018) 310–320 https://doi.org/10.1109/TIA.2017.2751547.
[131] E. Jamshidpour, P. Poure, E. Gholipour, S. Saadate, Single-switch DC–DC converter with fault-tolerant capability under open- and short-circuit switch failures, IEEE Trans. Power Electron 30 (2015) 2703–2712.
[132] M. Berger, I. Kocar, H. Fortin-Blanchette, C. Lavertu, Open-phase fault-tolerant operation of the three-phase dual active bridge converter, IEEE Trans. Power Electron 35 (2020) 3651–3662 https://doi.org/10.1109/TPEL.2019.2933487.
[133] F. Bento, A.J.M. Cardoso, Open-circuit fault diagnosis and fault tolerant operation of interleaved DC-DC boost converters for homes and offices, IEEE Trans. Ind. Appl 55 (2019) 4855–4864 https://doi.org/10.1109/TIA.2019.2916825.
[134] Y.A. Harrye, K.H. Ahmed, A.A. Aboushady, DC fault isolation study of bidirectional dual active bridge DC/DC converter for DC transmission grid application, IECON 2015 - 41st Annu. Conf. IEEE Ind. Electron. Soc. 2015, pp. 3193–3198 https://doi.org/10.1109/IECON.2015.7392592.
[135] M.I. Rahman, K.H. Ahmed, D. Jovcic, Analysis of DC fault for dual-active bridge DC/DC converter including prototype verification, IEEE J. Emerg. Sel. Top. Power Electron 7 (2019) 1107–1115 https://doi.org/10.1109/JESTPE.2018.2856759.
[136] R. Xie, Y. Shi, H. Li, Modular multilevel DAB (M2DAB) converter for shipboard MVDC system with fault protection and ride-through capability, 2015 IEEE Electr. Sh. Technol. Symp. ESTS 2015, 2015, pp. 427–432 https://doi.org/10.1109/ESTS.2015.7157930.
[137] Y. Shi, R. Li, H. Li, Modular multilevel dual active bridge DC-DC converter with ZVS and fast DC fault recovery for battery energy storage systems, Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC. 2016-May, 2016, pp. 1675–1681 https://doi.org/10.1109/APEC.2016.7468092.
[138] V. Ferreira, G. Buticchi, B. Cardoso, M. Liserre, Fault tolerance in multiple-active bridge converters applied in smart transformers, 2019 21st Eur. Conf. Power Electron. Appl. EPE 2019 ECCE Eur. 2019, pp. P.1–P.10 https://doi.org/10.23919/EPE.2019.8915477.
[139] F. Bento, A.J. Marques Cardoso, Fault tolerant DC-DC converters in DC microgrids, 2017 IEEE 2nd Int. Conf. Direct Curr. Microgrids, ICDCM 2017, 2017, pp. 484–490 https://doi.org/10.1109/ICDCM.2017.8001090.
[140] E. Ribeiro, A.J.M. Cardoso, C. Boccaletti, Open-circuit fault diagnosis in interleaved Dc-DC converters, IEEE Trans. Power Electron 29 (2014) 3091–3102 https://doi.org/10.1109/TPEL.2013.2272381.
[141] M. Gleissner, M.M. Bakran, Design and control of fault-tolerant nonisolated multiphase multilevel DC-DC converters for automotive power systems, IEEE Trans. Ind. Appl. 52 (2016) 1785–1795 https://doi.org/10.1109/TIA.2015.2497218.
[142] F. Bento, A.J. Marques Cardoso, A comprehensive survey on fault diagnosis and fault tolerance of DC-DC converters, Chin. J. Electr. Eng. 4 (2018) 1–12 https://ieeexplore.ieee.org/abstract/document/8471284.
[143] G.K. Kumar, D. Elangovan, Review on fault-diagnosis and fault-tolerance for DC-DC converters, IET Power Electron 13 (2020) 1–13 https://doi.org/10.1049/iet-pel.2019.0672.
[144] E. Ribeiro, A.J.M. Cardoso, C. Boccaletti, Fault-tolerant strategy for a photovoltaic DC-DC converter, IEEE Trans. Power Electron 28 (2013) 3008–3018 https://doi.org/10.1109/TPEL.2012.2226059.
[145] D. Jovcic, B.T. Ooi, Theoretical aspects of fault isolation on high-power direct current lines using resonant direct current/direct current converters, IET Gener. Transm. Distrib. 5 (2011) 153–160 https://doi.org/10.1049/iet-gtd.2010.0274.
[146] A. Schon, M.M. Bakran, A new HVDC-DC converter with inherent fault clearing capability, 2013 15th Eur. Conf. Power Electron. Appl. EPE 2013, 2013 https://doi.org/10.1109/EPE.2013.6631739.
[147] R.T. Naayagi, S.K. Panda, Fault-tolerant converter for future offshore wind farm HVDC networks, 2017 IEEE Innov. Smart Grid Technol. - Asia Smart Grid Smart Community, ISGT-Asia 2017, 2018, pp. 1–5 https://doi.org/10.1109/ISGT-Asia.2017.8378453.
[148] Y. Hu, G. Chen, Y. Liu, L. Jiang, P. Li, S.J. Finney, W. Cao, H. Chen, Fault-Tolerant converter with a modular structure for HVDC power transmitting applications, IEEE Trans. Ind. Appl. 53 (2017) 2245–2256 https://doi.org/10.1109/TIA.2017.2657480.
[149] T. Li, L. Parsa, Design, control, and analysis of a fault-tolerant soft-switching DC – DC converter for high-power, 33 (2018) 1094–1104.
[150] J. Ma, M. Zhu, X. Cai, Y.W. Li, DC substation for DC grid - Part I: comparative evaluation of DC substation configurations, IEEE Trans. Power Electron 34 (2019) 9719–9731 https://doi.org/10.1109/TPEL.2019.2895043.
[151] J. Do Park, J. Candelaria, Fault detection and isolation in low-voltage dc-bus microgrid system, IEEE Trans. Power Deliv. 28 (2013) 779–787 https://doi.org/10.1109/TPWRD.2013.2243478.
[152] R. Mohanty, U.S.M. Balaji, A.K. Pradhan, An accurate noniterative fault-location technique for low-voltage DC microgrid, IEEE Trans. Power Deliv. 31 (2016) 475–481 https://doi.org/10.1109/TPWRD.2015.2456934.
[153] V. Nougain, V. Nougain, S. Mishra, Low-voltage DC ring-bus microgrid protection with rolling mean technique, 2018 IEEMA Eng. Infin. Conf. ETechNxT 2018, 2018, pp. 1–6 https://doi.org/10.1109/ETECHNXT.2018.8385341.
[154] R. Mohanty, S. Member, A.K. Pradhan, S. Member, Cable fault location in a DC microgrid, IEEE Conf. 2016, 2016.
[155] W. Song, N. An, Y. Wang, A novel bidirectional solid-state circuit breaker for DC microgrid, IEEE Trans. Ind. Electron 66 (2019) 1540–1545 https://doi.org/10.1109/ICIEA.2019.8833694.
[156] C. Peng, X. Song, A.Q. Huang, I. Husain, A medium-voltage hybrid DC circuit breaker - Part II: ultrafast mechanical switch, IEEE J. Emerg. Sel. Top. Power Electron. 5 (2017) 289–296 https://doi.org/10.1109/JESTPE.2016.2609391.
[157] W. Wen, Y. Huang, Y. Sun, J. Wu, M. Al-Dweikat, W. Liu, Research on current commutation measures for hybrid DC circuit breakers, IEEE Trans. Power Deliv. 31 (2016) 1456–1463 https://doi.org/10.1109/TPWRD.2016.2535397.
[158] A. Maqsood, A. Overstreet, K.A. Corzine, Modified Z-source DC circuit breaker topologies, IEEE Trans. Power Electron 31 (2016) 7394–7403 https://doi.org/10.1109/TPEL.2015.2511588.
[159] C. Meyer, M. Höing, R.W. De Doncker, Solid-state circuit breaker based on active thyristor topologies, PESC Rec. - IEEE Annu. Power Electron. Spec. Conf. 4 2004, pp. 2559–2564 https://doi.org/10.1109/PESC.2004.1355232.
[160] J.M. Meyer, A. Rufer, A DC hybrid circuit breaker with ultra-fast contact opening and integrated gate-commutated thyristors (IGCTs), IEEE Trans. Power Deliv. 21 (2006) 646–651 https://doi.org/10.1109/TPWRD.2006.870981.

[161] C. Meyer, S. Schröder, R.W. De Doncker, Solid-state circuit breakers and current limiters for medium-voltage systems having distributed power systems, IEEE Trans. Power Electron 19 (2004) 1333–1340 https://doi.org/10.1109/TPEL.2004.833454.

[162] K.A. Corzine, R.W. Ashton, A new Z-source DC circuit breaker, IEEE Trans. Power Electron. 27 (2012) 2796–2804 https://doi.org/10.1109/TPEL.2011.2178125.

[163] Z.J. Shen, G. Sabui, Z. Miao, Z. Shuai, Wide-bandgap solid-state circuit breakers for DC power systems: device and circuit considerations, IEEE Trans. Electron Devices 62 (2015) 294–300 https://doi.org/10.1109/TED.2014.2384204.

[164] A.H. Chang, B.R. Sennett, A.T. Avestruz, S.B. Leeb, J.L. Kirtley, Analysis and design of DC system protection using Z-source circuit breaker, IEEE Trans. Power Electron 31 (2016) 1036–1049 https://doi.org/10.1109/TPEL.2015.2415775.

[165] L.L. Qi, A. Antoniazzi, L. Raciti, D. Leoni, Design of solid-state circuit breaker-based protection for DC shipboard power systems, IEEE J. Emerg. Sel. Top. Power Electron 5 (2017) 260–268 https://doi.org/10.1109/JESTPE.2016.2633223.

[166] D.J. Ryan, H.D. Torresan, B. Bahrani, A bidirectional series Z-source circuit breaker, IEEE Trans. Power Electron. 33 (2018) 7609–7621 https://doi.org/10.1109/TPEL.2017.2764903.

[167] K. Tahata, S. El Oukaili, K. Kamei, D. Yoshida, Y. Kono, R. Yamamoto, H. Ito, HVDC circuit breakers for HVDC grid applications, IET Semin. Dig. (2015) 1–9 2015 https://doi.org/10.1049/cp.2015.0018.

[168] Z.J. Shen, Ultrafast solid-state circuit breakers: protecting converter-based AC and DC microgrids against short circuit faults [Technology Leaders], IEEE Electrif. Mag. (2016) 4 https://doi.org/10.1109/MELE.2016.2544058.

[169] F. Wang, Z. Zhang, T. Ericsen, R. Raju, R. Burgos, D. Boroyevich, Advances in power conversion and drives for shipboard systems, Proc. IEEE 103 (2015) 2285–2311 https://doi.org/10.1109/JPROC.2015.2495331.

[170] I. Almutairy, Solid state circuit breaker protection devices for DC microgrid in review, 2016 5th Int. Conf. Electron. Devices, Syst. Appl. 2017, pp. 1–3 https://doi.org/10.1109/icedsa.2016.7818478.

[171] Y. Wang, W. Li, X. Wu, A novel bidirectional solid-state circuit breaker for DC microgrid, IEEE Trans. Ind. Electron. 66 (2019) 5707–5714 https://doi.org/10.1109/ICIEA.2019.8833694.

[172] A. Maqsood, K.A. Corzine, The Z-source breaker for ship power system protection, 2015 IEEE Electr. Sh. Technol. Symp. ESTS 2015, 2015, pp. 293–298 https://doi.org/10.1109/ESTS.2015.7157907.

[173] S. Savaliya, S. Singh, B.G. Fernandes, Protection of DC system using bi-directional Z-source circuit breaker, IECON Proc. (Industrial Electron. Conf. 2016, pp. 4217–4222 https://doi.org/10.1109/IECON.2016.7793084.

[174] A. Maqsood, K. Corzine, The Z-source breaker for fault protection in ship power systems, 2014 Int. Symp. Power Electron. Electr. Drives, Autom. Motion, SPEEDAM 2014, 2014, pp. 307–312 https://doi.org/10.1109/SPEEDAM.2014.6872131.

[175] S. Savaliya, B.G. Fernandes, Comparative analysis and coordination study of Bi-directional Z-source breaker with reclosing capabilities, 2017 19th Eur. Conf. Power Electron. Appl. EPE 2017 ECCE Eur. 2017-Janua, 2017, pp. 1–10 https://doi.org/10.23919/EPE17ECCEEurope.2017.8099221.

[176] A. Maqsood, K. Corzine, Z-source Dc circuit breakers with coupled inductors, 2015 IEEE Energy Convers. Congr. Expo. ECCE 2015, 2015, pp. 1905–1909 https://doi.org/10.1109/ECCE.2015.7309928.

[177] J. Commerton, M. Zahzah, Y. Khersonsky, Solid state transfer switches and current interruptors for mission-critical shipboard power systems, 2005 IEEE Electr. Sh. Technol. Symp. 2005, 2005, pp. 298–305 https://doi.org/10.1109/ESTS.2005.1524692.</bib.