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Protection in DC microgrids: a comparative review

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Abstract: A direct current (DC) microgrid has become a superior power system in recent years due to the development of DC loads and higher efficiency of DC systems. One of the challenging problems on DC microgrids operation is protection, and it is still a particular concern associated with the challenges of developing a proper protection scheme owing to its characteristics and lack of standards in DC protection. Due to the significant increasing interest on DC microgrid; this study investigates protection problems and schemes that need to be addressed in modern power systems involving DC microgrids. This study analyses and presents a comprehensive review of the most recent growth in the DC microgrids protection. Additionally, the fault characteristics of DC microgrids, the impact of constant power loads, the protection devices and several proposed methods to overcome the protection problems are discussed. The differences between the proposed protection methods for the DC microgrids are also discussed.

1 Introduction

Direct current (DC) microgrids have the wide potential for different power applications, such as small-scale generation, backup of energy storages, data centres, marine and other sensitive loads and industrial applications [1, 2]. DC microgrids have several advantages over traditional alternating current (AC) power systems when they are compared based on their power density and efficiency [3]. On the other hand, the lack of an effective protection scheme for DC microgrids represents a significant obstacle to more adoption of DC systems. The particular challenges associated with DC microgrids include protection against short circuit (SC) faults. Therefore, there has been considerable attention to developing a protection method for DC microgrids.

Protection plays a crucial role in the power systems, and one of the main purposes of introducing microgrids is increasing the reliability. Hence, one of the main problems of using microgrids is related to protection issues, because the protection of microgrids may not be solved by conventional methods for several reasons [4] such as bidirectional power flow of microgrids, dynamic characteristics of renewable resources, changing the fault current during islanded mode, number, and types of resources. Therefore, proposing a reliable protection method is essential for the microgrids in both grid and islanded mode.

Since loads and power resources can connect to a common DC bus with a fewer power conversion stages, the result is less waste heat and potentially lower cost than AC systems. Moreover, DC transmission lines can flow more power than AC. The positive aspects of using DC microgrids are that loads, distribution energy resources (DERs) and storage equipment can be interfaced simpler and more efficiently. DC microgrids provide great advantages in terms of resilience, efficiency, reliability, and flexibility [5]. In addition, the DC microgrids have the following advantages:

- Most residential loads are DC or can operate with DC voltage.
- AC microgrids only need six current leads, as against two for DC microgrids that can reduce losses in DC microgrids, and thus lower need for the refrigeration and cost-effective [6].
- Skin effect cannot occur in DC cables, consequently, the cable losses can decrease by 15–20% [7].
- DC systems are safer for human bodies, the damages to the human body in the DC system discharges is lower than AC [8].
- High power transfer capacity [8].

- Fewer redundant stages of converters can reduce the losses and heat, as both loads and resources are DC [1].
- Multiple resources can connect to a bus; therefore, power flow is more robust [1].
- Most of the storage devices such as battery and ultra-capacitors are DC [9].
- Synchronisation problems are eliminated in DC microgrids [10].

DC microgrids are being considered in several applications, and they are divided into two voltage levels: medium-voltage DC (MVDC) and low-voltage DC (LVDC). MVDC microgrids are of wide interest for marine and shipboard power systems, because this will be able to prepare the power and energy density of marine systems [11, 12], and MVDC systems are rated from 1500 V to 22 kV [13]. Also, the different applications of MVDC systems are introduced in [14–18]. On the other hand, LVDC microgrids are suitable to use because most loads in the low-voltage rate are DC. LVDC microgrids can be used in the wide applications such as telecom power systems, power system controls, protection systems and residential [19]. LVDC microgrids must connect to the AC power system using converters, and power flow of the system will be bi-directional and therefore a different protection scheme is required for the DC microgrid [20]. Fig. 1 shows a typical DC microgrid.

On the other hand, due to the differences between the protection methods of DC microgrids and AC, fault location, classification

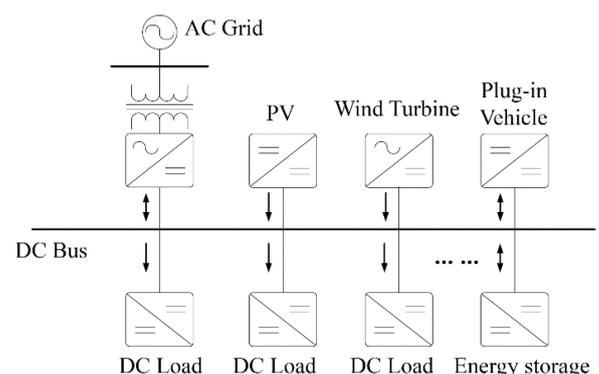


Fig. 1 Diagram of a DC microgrid

and detection are the protection challenges in these systems. Therefore, the DC system must be effectively protected against faults. A protection method must propose a sensitive, reliable and selective protection in the DC microgrids. Batteries, loads and PVs can be easily connected to the DC microgrids without extra inversion stages [21], which can reduce the probability of internal faults. On the other hand, in the AC microgrids, the voltage can be changed by transformers, but in the DC microgrids, converters need more complex protection because of the sensitivity of converters to fault and control systems.

Moreover, protection systems require a protection device (PD) and actuators to clear the fault current. In the DC microgrids, due to the differences of characteristics of DC and AC currents, AC PDs and actuators cannot be used in the DC microgrids. Hence, typically the DC PDs and actuators are fuses, relays, DC CBs, and switches. During the fault in the DC microgrid, if the contribution of the main grid is limited by the limiting devices and methods, the power quality of the DC microgrid will be reduced. Also, in high impedance fault, voltage dip will be reduced by fault injection of the main grid [22].

In addition, DC microgrids typically have several load converters, which behave as constant power loads (CPLs) [23]. CPLs introduce an undesirable effect on the protection system after voltage drop, and due to the negative incremental impedance of them [24]. The growing use of DC loads which behave as a CPL make their study more important and practical. In this study, the impact of CPLs on the DC microgrid protection system is studied.

This study presents a comprehensive and comparative review of the protection methods proposed in DC microgrids. The proposed study identifies the differences between methods and also it introduces their benefits and drawbacks as well. The rest of the paper is organised as follows: Section 2 discusses their types of faults and characteristics. Section 3 focuses on the impact of CPLs on DC microgrid protection. The issues faced by the DC microgrids protection are overviewed in Section 4. The proposed methods for DC microgrids are explained in Section 5, and Section 6 presents a comprehensive discussion about PDs in the DC microgrids. Also, in Section 7, protection of different parts of DC microgrids is discussed. Finally, Section 8 discusses future trends and conclusion.

2 Faults in DC microgrids

The knowledge and analysis of fault currents are an essential part of designing an appropriate protection scheme. Moreover, coordination of PDs such as relays requires knowing the fault current characteristics. Also, the fault current can damage microgrid components. Therefore, converters can lose the voltage and current control, converters need higher power rating that increases the cost, and cascade tripping in the other protection zones [25].

In the DC microgrids, faults occur in two different ways, pole to pole (PP) and pole to ground (PG). In the PG faults, one or both of the conductors are connected to the ground. Hence, the PG faults are high-impedance faults. In the PP faults, the conductors are directly connected to each other. Hence, the PP faults are low-impedance faults and these faults are more detectable and dangerous [26–28].

All systems can be modelled by a Thevenin DC and AC equivalent circuit, as shown in Fig. 2.

On the other hand, the response characteristics of faults in the DC systems are divided into two different cases: transient and steady state. The transient part of fault injected from DC-link capacitors and cable discharge of converters, and the steady state party injected from power resources [29]. The DC-link capacitor SC obtained by the following equation:

$$\frac{d^2 i_c}{dt^2} + \frac{R}{L} \frac{di_c}{dt} + \frac{1}{LC} i_c = 0, \quad (1)$$

where C is the capacitance of the DC-link capacitor, L is the inductance of the line, R is the resistance of line and i_c is the fault current. Moreover, after faults and switching of the converters, the

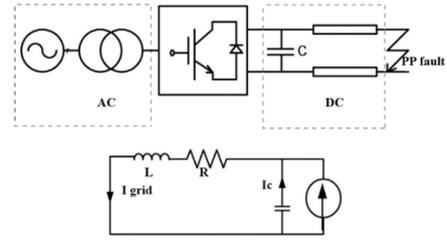


Fig. 2 Equivalent circuit of a DC system

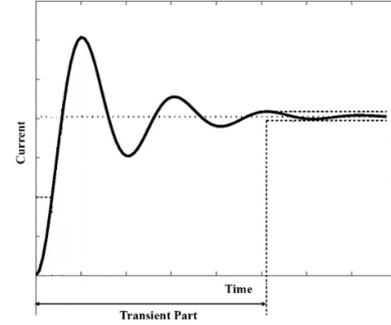


Fig. 3 SC current in the DC system

energy in the cable inductance is discharged. The cable discharge current is obtained by the following equation:

$$L \frac{di_L}{dt} + i_L R = 0. \quad (2)$$

Therefore, the transient current of the fault is made by i_L and i_C , this part is shown in Fig. 3.

In addition, the transient part of the fault currents is divided into slow, medium and fast front transient. Voltage-dependent loads, converter control and batteries cause slow front transients. Surge current in the capacitors of the filter causes medium front transient, and transient recovery voltage at the opening of the PDs cause fast front transient [30–34].

In the steady state part, the fault current injected from the AC grid, hence, it generated from three phase of the AC side. The steady state fault current is obtained by the following equation [14]:

$$i_{\text{Grid}} = i_{\text{phase-a}} + i_{\text{phase-b}} + i_{\text{phase-c}}, \quad (3)$$

where the fault current is calculated by adding the positive value of the SC current to other phases. The current of each phase is calculated by [14]

$$i(t) = A \sin(\omega_s t + \gamma) + B e^{-(R/L_T)t} + \frac{C}{\omega_d} \omega_0 e^{-(R/L_T)t} \sin(\omega_d t + \beta) + \frac{D}{\omega_d} \omega_0 e^{-(R/L_T)t} \sin(\omega_d t), \quad (4)$$

where,

$$A = I_g \sqrt{[(1 - \omega_s^2 LC)^2 + (RC\omega_s)^2]}, \quad C = -(A \sin \gamma + B),$$

$$B = I_{gn} [\tau^2 / (\tau^2 - RC\tau + LC)], \quad L_T = L + L_{\text{Reactor}},$$

$$D = (BL_T/R) - \omega_s A \cos \gamma, \quad \gamma = \alpha - \arctan((RC\omega_s)/(1 - \omega_s^2 LC)) - \arctan((\omega_s L_T)/R),$$

I_g is the maximum current of phase, ω_s is the frequency of the system and α is the phase of the phase.

According to Fig. 3, fault current in DC microgrid does not have a zero cross point, therefore, AC CBs cannot be applied to the DC microgrids (Table 1). In addition, the value of reactance is negligible in DC systems, hence, the peak value of DC fault is higher than the one for AC systems, and also it gives a higher rate of change in the DC microgrids [35]. Due to this high raising rate of fault, faults in DC microgrids develop with more speed than AC microgrids [36, 37]. Moreover, DC microgrids typically use

Table 1 Summarises the main characteristics of faults in the DC microgrid

	Feature
PP fault	low-impedance, detectable, dangerous for system
PG	occur because of insulation degradation, high-impedance, not critical PP faults
transient part of faults	<ul style="list-style-type: none"> • DC-link capacitor • Cable discharge • Slow, medium and fast front transient
steady state part of faults	Equation (4)

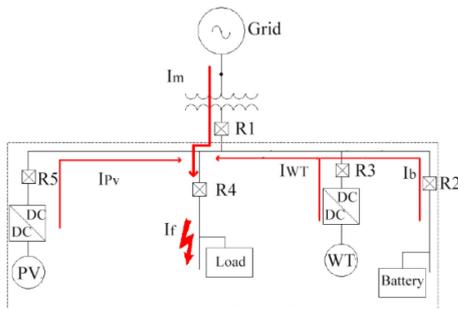


Fig. 4 Example of fault protection

voltage source converters (VSCs), whose withstand rating is lower than devices in AC systems [28]. Therefore, the protection systems for DC microgrids must be faster than AC systems to prevent damage to converters.

Moreover, the upstream grid can have an impact on the protection system. For example, in Fig. 4, a DC microgrid is connected to the grid, and a fault occurs in the load. In a passive system, the R4 must clear the injected fault current from the main grid, I_m . However, in DC microgrids, the fault is injected also from photovoltaic (PV), wavelet-transform (WT) and battery. Then, the settings of the R4 must be modified based on all faults. Hence, when the number and size of resources increase, the contribution of the main grid will decrease. If the fault occurs at the main grid, the R1 islands the DC microgrid. Therefore, relays must be bi-directional operation [38].

In the grid connected operation mode of the microgrids, the fault current is more than the islanded mode. Also, the contribution of fault current is different according to the type of resource, which synchronous type of power resource inject SC current 5 times of the rated current and inverter base resource inject 1.5 times of the rated current [39].

3 Impact of CPLs on the DC microgrid protection

In the DC microgrid, several converters implemented in the load's sides, and when they are tightly or closed-loop controlled, converters and loads act as a CPL. The CPL means that the output power of the converter, on the load side, is constant. Therefore, after a voltage drop, the current of loads must increase. Hence, the mathematical model of CPL can be obtained by the following equations [40]:

$$p_{out} = \text{constant}. \quad (5)$$

The $V-I$ curve is shown in Fig. 5. The behaviour of the CPL can be shown by the following model:

$$R = \frac{dv}{di} = -\frac{v}{i}. \quad (6)$$

This negative sign can be introduced by the $V-I$ curve and this is known as incremental negative resistance (INR). The problem of the INR appears during the fault in the DC bus. If there is a fault situation, the voltage of the system will drop, and then all CPLs

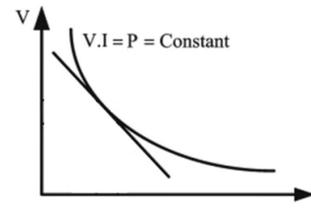


Fig. 5 $V-I$ curve of CPLs

will need more current to maintain the constant power. This trend can continue and accelerate the fault current [41]. On the other hand, CPLs can make an oscillation in voltage and current, and due to the low value of fault current in the islanded mode of DC microgrids, it will be difficult to distinguish between the oscillation of current and fault situation of PDs [42]. Thus, one of the solutions is to limit faults at the input of loads to alter the INR during the voltage drop [43]. The other protection methods will be explained in Section 5.

4 DC microgrid protection challenges

Faults in the DC systems faced with the unique challenges and short-circuit current in the DC bus can quickly increase to a high level. Also, due to the differences in the characteristics of traditional and DC microgrids, the protection schemes are designed for traditional power systems and DC microgrids have fundamental differences. In this section, the main issues associated with the protection challenges of DC microgrids are discussed.

4.1 Direction of fault current

Traditional power systems are normally radial, and because of the unidirectional behaviour of current, they are protected by current-based relays [44, 45]. Hence, the protection schemes of these systems are designed for unidirectional fault current. Conversely, due to the connection of power resources in different locations, fault current in the microgrids are bidirectional, and the traditional protection schemes cannot be implemented in the microgrids [45]. In other words, in the ring systems, all DERs can contribute to faults, and change the fault direction. Therefore, the non-directional relays cannot protect the system, and this reduces the reliability of the microgrids.

On the other hand, the topology of DC microgrids may regularly change, thus, the direction of fault will change. Hence, this needs an adaptive protection method to provide the protection scheme for the new topology.

4.2 Coordination problem of current-based relay

Due to the low value of line resistance and the high value of fault rising rate in the DC microgrids, coordination of current-based relays is a challenge [46, 47]. Therefore, all series current-based relays sense a high-value fault current, and it causes a discoordination between relays. On the other hand, as mentioned before, faults in DC microgrids are PP and PG. Hence, relays must coordinate in both faults. However, because of the differences of fault currents in PP and PG, if the relay settings set for one of them, in another case a discoordination will happen. According to [9], due to the lack of selectivity, typical overcurrent relays cannot be implemented in the DC microgrids. Thus, several protection methods for current-based relays are proposed and discussed in Section 5.

4.3 Non-suitability of AC circuit breakers (CBs)

CBs interrupt fault currents in power systems by a mechanical mechanism, and AC CBs interrupt the fault current in the cross zero point at every half period. However, due to the lack of cross zero point in the DC microgrids, the conventional CBs cannot be implemented in these systems. In addition, DC microgrids require faster fault current interrupters to prevent damage to the VSCs [14, 26, 48]. On the other hand, DC CBs can be made by magnetic arc

blowers and arc chutes [49] to force the fault current to zero. However, this method is expensive and slow, and cannot be implemented in all DC microgrids. Therefore, the best solution to this problem is using power electronic devices such as Insulated gate bipolar transistor (IGBT) and integrated gate-commutated thyristor (IGCT).

4.4 Change in the SC level

In the AC power systems, SC faults are typically 10 times greater than the rated current of the system, and this greater fault current assists protection schemes to easily detect faults. Nevertheless, fault currents in DC microgrids may be limited by the converters, and currents may be smaller than the threshold of fault detection schemes and make the fault detection more difficult. On the other hand, the operation modes of DC microgrids impact the SC level and direction. In the grid connected mode, grid and DERs contribute to the fault current, 20–50 times greater than the nominal rated current, while in the islanded mode, only DERs generate fault current, 5 times greater than the nominal rated current [50]. Therefore, the level of the fault in grid connected mode is higher than the islanded mode, and the direction of this current may be different in each mode. Thus, to overcome this problem, the settings of relays must be set according to the variations of fault current levels, or an adaptive protection scheme must be implemented in the DC microgrids [51].

4.5 Low fault current capacity of inverters

The fault current capacity of inverters inside the microgrids is normally less than half of the fault current which they are designed [52]. Hence, during the faults, if the penetration of DERs is low in the microgrid, the operation mode of DC microgrid can change to islanded mode to reduce the fault current level. Consequently, the coordination and sensitivity of current based relays will be affected, and it may make a delay or discoordination between relays [45]. In addition, the inverter between the grid and DC microgrid is the main inverter which can have a limiting role. This inverter has the most fault current; hence, they need most fault tolerance. Moreover, these inverters can limit the fault with a high flexibility [53].

4.6 Grounding

One of the main settings of current-based relays is fault current amplitude, and in the PG faults, it is affected by the grounding system [54]. On the other hand, the grounding system helps detection of PGs by providing a path for fault current circling. Hence, designing a proper grounding system is vital for a reliable protection of DC microgrids.

5 Protection methods in the DC microgrids

In the conventional power systems, the topology of the system is radial [55], and the protection of these systems designed based on unidirectional power flows. On the other hand, increasing the penetration of the distributed generations (DGs) in the system, make the protection of the systems more challenging. DGs cause increasing the fault current level and changing the power flow direction of the system. Therefore, it can impact on the coordination of the PDs.

In addition to the common issues related to the both AC and DC protection, due to the nature of DC power systems, such as large DC capacitors, low impedance of DC cables, high transient current and voltage, several challenges are only related to the DC protection [8].

One of the fault current interrupters is CB, which interrupt the fault current in the AC networks using zero crossing. However, due to the lack of zero crossing in the DC systems, conventional CBs cannot be used in the DC systems. On the other hand, DC systems need a faster protection scheme, because of the prevention of any damages to the voltage-source inverters (VSIs).

Also, grounding in the DC microgrids must be designed properly to detect the faults [51]. Hence, a grounding system must minimise the DC stray current and common mode voltage [56].

In recent years, several protection methods have been reported to protect the DC microgrid. In the AC systems, distance protection uses the analysis of the symmetrical component to avoid the impact of fault resistance on the protection method. However, in the DC systems, these are not possible.

5.1 Current- and voltage-based methods

The impedance and travelling wave methods have been accepted as an industry standard for AC power systems, however, it is difficult to directly implement these methods to the DC microgrids due to the lack of phasor parameters [26]. In AC microgrids, by changing the voltage angles, the magnitude of the travelling waves will change. Thus, this is a problem for travelling wave protection methods. On the other hand, there are no such problems for DC microgrids [57]. High transient faults cause a voltage collapse within 5 ms during the fault. Therefore, the protection methods required for the DC microgrids must be much faster than the AC power systems [58]. A method proposed in [28] was used to calculate the amplitude of the DC link voltage along with the fault in order to locate and detect the fault in LVDC microgrids. Another structure which is proposed in [59] is event-based protection. In this method, the variables, such as voltage and current of the bus, are classified at each protection unit locally, and then only the class of the fault is distributed between the protection units, instead of sending and receiving the actual data. The handshaking protection scheme has been studied in [60], this method is a protection scheme that can be applied for detection and isolation of various lines to line and line to ground faults in a multi-terminal DC power system. In other words, when a positive line to ground fault occurs on the one line of a DC bus in a multi-terminal system, the current direction of the faulted line always flows from the bus to the fault location, while the current flows in the negative direction on the other healthy lines of the DC bus.

5.2 Impedance based methods

In [14], a distance protection is proposed for DC systems, the difference between this method and the conventional methods is an estimation of the fault location. To design a fast fault detection method, this study presents a simple algorithm by using only two DC measuring units on the transmission line. In the mentioned paper, a scheme using one more reference voltage to avoid communication requirements is discussed. Two voltage dividers are used for distance measurement and representation in the DC side. Also, locating a SC by measuring the reference voltages is easier than to specify the location of a ground fault which may have relatively large impedance. Yet, the problem of this method is the high sensitivity of this type of relay to fault impedance. Differential protection is very useful for fault detection and protection in the DC networks.

Therefore, most of the research studies in fault detection depend on fault resistance. For instance, in [61], a protection scheme is proposed based on the differential protection strategy for DC microgrids. The amount of error in the proposed method depends on the fault resistance. Hence, eliminating the impact of the fault resistance on the fault protection methods is very important. In addition, a new distance protection method is proposed in [58], this method uses different distance calculations to set relay settings to distinguish between the main and backup relays.

5.3 Communication-based methods

Differential protection is a common protection method for units, which protect the system by using and comparing the current amplitudes and directions at the boundaries of a specified unit within a network [62].

In [63], a differential-based method is applied for fault protection in a DC network; differential protection has an accurate protection system. First, the relay calculates the current difference between these two currents and if this differential between currents

is greater than a threshold, it sends a trip signal to the breakers. The fault level, DGs, and fault resistance have low influence on the differential protection. The result shows that differential protection can detect DC faults very fast and accurate. Yet, due to the communication requirements, this protection relays are expensive [27].

5.4 Local protection methods

In [58], a protection scheme was proposed for fault detection in DC microgrid based on the local measurement units. It uses first- and second-order derivative for detecting faults. Yet, the problem with this method is depending on the system topology. In this method, the settings of the PDs are calculated based on the system topology and different locations of faults. The intermittence and uncertainty of renewable energy sources may further bring variable infeed currents on the feeder; therefore, the protection system may lose the sensitivity and selectivity during the fault [64]. Another applicable solution for microgrid is adaptive protection that can modify the protective settings response to a change in system conditions or requirements [65]. Hence, because of variation in real power systems, an adaptive protection scheme is essential for power systems. Hence, in DC microgrids defining an adaptive protection method is very important.

5.5 Wave and intelligent methods

A WT fault protection method is proposed in [66]. The WT demonstrates signals in the time frequency and provides the signal time localisation. The WT is an efficient method for calculation of transient signals as the frequency value of a transient signal modifies during a specific time. On the other hand, the WT can provide both time and frequency information, hence, it can extract transient information from the fault current. The method which is provided in [66] is based on the factors of voltage and current,

amplitude and derivative of the voltage. The wavelet methods can be linked with intelligent approaches for the protection of DC microgrids. The intelligent methods are widely used in AC power systems. This method needs fast Fourier transform, hence, it cannot be used in DC systems, yet, in [67], the sampled magnitude of the voltage and current is sent to artificial neural networks (ANNs). Typically, the input data of the ANN is taken from the post fault waveform information.

As mentioned, one of the main challenges in the DC microgrid protections is to select a fast and cost-effective fault interrupting method [68]. Hence, in summary, the protection scheme must include:

- Detect high resistance faults
- Fast protection method
- Isolate fault section
- Cost-effective
- Adaptive in changing of topology
- Considering the dynamics of renewable resources

In Table 2, the advantages and disadvantages of the mentioned methods have been introduced. Table 3 compares speed, selectivity, reliability, and price of DC microgrid protection methods.

6 DC microgrid PDs

Typically, after detection of the fault, a protection device is required to isolate the fault section. Furthermore, based on the nature of the DC fault current and lack of cross zero points, the AC equipment cannot be used in the DC systems. Typically, DC microgrids use PDs such as fuses [69], relays, and actuators such as DC CBs [70] and switches [71]. Also, this device is optimised for applying to DC systems by considering the differences in inductance and capacitance of lines.

Table 2 Comparison of protection methods according to their advantages and disadvantages

Protection method	Advantages	Disadvantages
distance protection	<ul style="list-style-type: none"> • simple algorithm 	<ul style="list-style-type: none"> • more sensitivity to fault resistance • usually needs a back-up unit • limited accuracy in short lines
differential protection	<ul style="list-style-type: none"> • better sensitivity • lower dependency to fault impedance • independent of the current direction • independent of high raising rate of DC currents and fault resistance 	<ul style="list-style-type: none"> • need of high bandwidth communication link • does not work satisfactorily with noisy measurements • needs fast and accurate data synchronisation
over-current protection	<ul style="list-style-type: none"> • simple algorithm • applicable in fault interrupt methods 	<ul style="list-style-type: none"> • only low- and medium-voltage • Should be used with other schemes or used by communication links to provide selectivity • require accurate and fast methods for detecting the current direction • cannot detect high-impedance faults
event-based protection method	<ul style="list-style-type: none"> • scheme does not require high-speed communication and synchronisation • transfers less data • needs less measurement equipment 	<ul style="list-style-type: none"> • accurate fault classification in high-resistance fault • increase the possibility of the protection failure
handshaking protection	<ul style="list-style-type: none"> • reliable in HVDC and MVDC • localised • affordable 	<ul style="list-style-type: none"> • shutdown the network • not suitable for networks with a large number of resources
wavelet	<ul style="list-style-type: none"> • effective in fault detection • can be used as a hybrid method with other methods 	<ul style="list-style-type: none"> • needs global positioning system • require data acquisition elements with a high-sampling rate
ANN	<ul style="list-style-type: none"> • can be easily linked to other methods • accurate and robustness 	<ul style="list-style-type: none"> • the trained network is only specific to the system studied case.
communication based	<ul style="list-style-type: none"> • accurate • can be applicable for coordination relays • does not need any complex algorithm 	<ul style="list-style-type: none"> • delay in the communication line • lack of the standard protocols for the DC networks • require a backup protection during the communication failures • can be impacted by noise

Table 3 Comparison of protection methods according to speed selectivity, reliability, and price

Method	Speed	Selectivity	Reliability	Price
distance protection	H	M	M	M
differential protection	VH	H	H	H
over-current protection	M	L	H	M
event-based protection method	H	M	M	L
handshaking protection	M	L	M	L
wavelet	H	H	VH	M
ANN	M	H	H	L
communication based	VH	H	L	H

H: high; VH: very high; M: moderate; L: low.

6.1 Fuses

A fuse is applied to the power system to protect the system during the fault. The main part of the fuse is a copper or silver which is used in series with the power line for protecting the system, and during the fault, and increasing the current, heat of fault current melt the fuse. Therefore, its fuse will be an open circuit device in the system [72]. Fuses are divided into two types, fast-acting and time-delay fuses [73]. The time-delay fuses are used in higher inrush and surge current applications, but fast-acting fuses are suitable for applying in series with converters for their protection. In [74], a fuse is used to protect a DC motor in a DC power system, and the impact of the DC power system parameters on the fuse operation is investigated. Hence, the clearing time depends on the motor time constant, supply impedance, and number of fuses. If the several fuses are used in the system, due to the sharing the energy between them, the clearing time of all fuses will change. In networks equipped with relays and fuses, relays and fuses need to coordinate with each other. In AC microgrids, fuse selecting needs between 10 and 100 ms [48] to interrupt the faults, but, due to the nature of DC microgrids, DC ones need almost 0.5 ms.

On the other hand, AC fuses may be too slow to isolate fault section, hence, in [75] a hybrid fuse for applying in the DC power systems. A pyro-switch and fuse are linked to each other, and the pyro-switch makes the conduction path and fuse clears the fault. Also, this method only can be applied to the LVDC systems. In addition, selecting a fuse rating is a challenging task in DC systems. The fuse rating is selected from [76] for protecting a DC/DC converter. It is mentioned that the fuse rating must be lower than the other protection systems, and if the nominal melting value of the fuse was higher than the suitable value, the fuse will not remove the fault soon, then the converters will be damaged.

6.2 DC CBs

One of the most important devices for the isolating system after faults is the DC CB, various DC CBs have been proposed in [77, 78]. The mechanical DC CBs are made up of a conventional AC CB with a parallel resonant circuit [79–81], but their clearing time is between 30 and 100 ms, which is not suitable for the DC microgrids. On the other hand, solid-state DC CBs are suitable for MVDC and high-voltage DC (HVDC) systems. If the CB interrupts the fault immediately, the system can be faced with the surge in voltage and large energy absorption in the CB [82]; moreover, molded-case circuit breakers (MCCBs) and vacuum CBs can reduce and limit the SC currents in the DC microgrids [83].

A DC CB was proposed in [82], and many valve devices and snubber circuits are connected to each other in series to increase the blocking voltage, and the fault bypassed by a freewheeling diode. This scheme can remove faults fast, but this scheme can be applied only in HVDC systems. Moreover, a hybrid DC CB proposed in [84] consists of reactors for current limiting, mechanical contactor, and a converter. This method is fast for LVDC and can be applied to the higher voltages, and also the steady state loss of this method is zero. In addition, recently, the Z-source DC CBs have been proposed to interrupt fault quickly in the DC microgrids. This CB operates based on the natural commutation for critical faults [85]. During the large fault currents,

the Z-source CB makes a fraction of the current during the fault through the capacitors and forces a current zero crossing point in the controlled rectifier. After reaching fault to zero in the rectifier, the faulty section will be isolated. The problem with this method is that the Z-source CBs only can isolate components against large fault currents, and cannot be used for overload protection. In [86], a Z-source DC CB was applied to the DC microgrid, which isolated the faulty section quickly, and can clear the fault in LVDC and MVDC microgrids.

6.3 Switches

Compared with the CBs, switches can interrupt the fault within several microseconds, and they can detect over current and limit the current to a constant value or force the current to zero immediately. Switches have a wide range of applications, such as shipboard, residential and other LVDC and MVDC applications. In [87], high-speed AC switches were converted for LVDC microgrids, and it can clear the 500 A fault current and suppress energy and voltage of the fault. Based on the differences and limitations of the different types of switches, a new power switch was developed in the recent years.

In the LVDC systems, the most common solid state CBs or switches are IGBTs and metal oxide semiconductor field effect transistors (MOSFETs). MOSFETs applied to the DC systems was within the range of <1200 V, but their speed is high and due to the high on-state resistance, MOSFETs have a high-voltage drop, and consequently, high loss under high current conditions. In [88], a converter was integrated with a voltage cell in the DC microgrid to provide a higher voltage gain, moreover, an auxiliary switch for the converter turn-on the MOSFET for protection of the system. In addition, for improving the reliability of the system, a MOSFET-based DC CB was proposed in [89], and the clearing delay time changes based on the transient behaviour of the protection device, this variable time makes the protection actuator more reliable under different fault conditions.

On the other hand, IGBTs improved many characteristics of the MOSFETs, such as gain and speed, than the other solid states CBs, IGBTs produces fewer harmonics, and cheaper than other devices [90, 91]. However, the disadvantage of the IGBTs is that they are unidirectional protection actuators, hence, IGBTs only can clear faults in the DC line and cannot have an impact on the fault on the converter side [92]. In summary, IGBTs provide a fast clearing time but the losses of the IGBTs are high [93–95].

Furthermore, the emitter turn off (ETO) is a high power switch which is proper for high frequency, high power, and high speed faults [96]. An ETO consists of a gate-turn-off (GTO) and an emitter switch, and during the faults, the mechanism of the GTO causes the clearing of the fault by ETO. This device is really fast and can clear the faults in DC microgrids in 10 μ s. In [97], a MVDC system was protected by an ETO and the faults cleared in the <4 ms. However, the ETO may cause a loss in the system [98]. Accordingly, the applications of the ETO on the grid are discussed in [99].

For improving the IGBT disadvantages, IGCT device is proposed. The losses of the IGCTs are lower than IGBTs and suitable for MVDC microgrids [100]. In [101], an IGCT-based protection system was applied to a DC microgrid and used as an reverse blocking IGCT (RB-IGCT). Therefore, the protection method can clear the fault by considering the bidirectional behaviour of the current. In addition, due to the increasing speed of the IGCT, a hybrid protection method was proposed in [102] for DC protection. This method includes a mechanical switch, two parallel IGCTs, four diodes, and a metal oxide varistor (MOV). The diodes can make the device capable of clearing faults in both directions.

6.4 Breaker-less

Another approach for clearing faults is a breaker-less method, which uses converters as fault clearing equipment [103]. Coordinating converters and mechanical contactors can make a fast DC fault clearing method without using conventional CBs [104]. A breaker-less approach was proposed for MVDC marine systems in

Table 4 Advantages and disadvantages of PDs and actuators in DC microgrids

Device	Advantages	Disadvantages
fuses	<ul style="list-style-type: none"> • cheap • can be applied in the DC systems • clearing inrush and surge current applications • can be used as a hybrid protection 	<ul style="list-style-type: none"> • slow • small time constant in the SCs with a high rate of increase • difficulty in the choosing a suitable fuse and coordinate with other devices
CBs	<ul style="list-style-type: none"> • high speed CBs are fast for DC systems • suitable for HVDC systems • MCCBs can limit the fault current 	<ul style="list-style-type: none"> • cannot use AC CBs in the DC systems • needs a recovery time • cannot protect systems in the high-inductive systems • cannot clear faults in sensitive LVDC systems
switches	<ul style="list-style-type: none"> • can be used in DC microgrids • applicable in both LVDC and MVDC microgrids • they solve the limitations of CBs and fuses • the switches are fast enough for DC microgrids • IGBTs can withstand in high SC currents • IGCTs have low losses and suitable for MVDC microgrids • ETO causes a loss in the normal operation of the system 	<ul style="list-style-type: none"> • IGBTs have high losses • IGBTs are unidirectional • MOSFETs have a high-voltage drop • ETOs are really fast and applicable in both LVDC and MVDC microgrids, but faster in the LVDC systems
breaker-less	<ul style="list-style-type: none"> • uses converters for clearing faults • best application is for DC/DC converters • it can be a localised method 	<ul style="list-style-type: none"> • cannot be applied in all DC microgrids • may cause cascading faults

[105]. In these methods, a converter can control the DC fault current and generate uninterrupted power to loads by using a DC fault ride-through method [106]. In [3], a breaker-less method was applied for protecting a system. This method detects low- and high-impedance faults by using local information. Emphasising that breaker-less DC systems are desired for DC/DC converters.

Despite its benefits, this method has some disadvantages. All DC microgrids cannot be protected by this method, because this method needs some specific paths for fault current [107]. In addition, this method has difficulties in series devices, i.e. it may cause a cascading fault.

In conclusion, a brief comparison between PDs and actuators is presented in Table 4.

7 Protection of different parts of DC microgrids

DC microgrids have several parts, which have different behaviours during faults. Therefore, considering all the characteristics of PV, WT, battery and loads are really important for proposing a comprehensive protection method. Therefore, in this section, protection methods or specific behaviour of each part are introduced.

7.1 PV protection methods

During the fault, the PV injects a fault current to the faulty section which depends on the inverter design [108]. The majority of inverters have fault current limiters, and when the current becomes more than the maximum current rate of the inverter, it limits the current to twice the rated current [109]. Hence, the protection systems assume this limitation for the design of the inverter for PVs. On the other hand, because of the voltage-dependent behaviour of PVs, the same as the CPLs in Fig. 4, the protection system must consider the behaviour of PVs, because in the systems with high penetration of PVs, it is possible to have different PVs with different voltage values, which can have an impact on the time of disconnection of PVs.

In [110], an adaptive threshold based protection method was proposed for the PV-based microgrids. In this method, according to the penetration of the PV on the microgrid, a piecewise cubic Hermite polynomial is used to detect islanding for the converter of a PV. In addition, a differential current-based fault protection for PV-based DC microgrids is presented in [111], based in the Moore Penrose pseudo-inverse and Cusum method. This method applied to the PVs of a LVDC microgrid, due to the high frequency of converters, as it is a fast detection method, with <100 ms in fault detection.

7.2 WT protection methods

In a DC microgrid, due to the lower contribution in the supply, usually, WT is a secondary resource. WT systems are equipped with the full power rating of converters, therefore, they have a high fault ride through during faults. During a fault, the voltage of the WT terminal will drop and then the output power of the WT is also decreased [112].

One of the protection methods of WTs is crowbar protection [113], it can limit over voltage in the DC part of the microgrid. During the fault, crowbar protection makes a SC in the rotor and it can make another current path in the rotor. In a WT, this protection method protects the rotor and WT against over current and over voltage [114].

Each variation in wind speed and voltage of WT can have an impact on the DC side of the microgrid [115]. In addition, during a fault in the DC side, the mechanical speed increases and the torque of the WT becomes zero [116]. Hence, in [117] a control strategy was proposed to limit the DC side voltage during the fault.

7.3 Battery protection methods

One of the main parts of the DC microgrid is the battery and due to the dependency of batteries on voltage, a protection method is needed. During a fault, the voltage of the system can drop, and consequently, batteries are over discharged and injects more current into the system. In addition, energy storage systems can cause a protection blinding that affects the protection method [118]. In [119], the main characteristics of energy storage systems, which can have an impact on the protection blinding, are identified. This study indicates that fault impedance is higher than a critical level will decrease the overcurrent protection units. In addition, a solution to minimise the protection blinding was proposed in [119].

8 Conclusion

In this study, the introspective review of the DC microgrids protection and problems that are available in recent literature was presented. The key requirements for their protection in terms of fault detection, location, and classification capabilities were discussed. This study also presented a detailed fault analysis and impact of CPLs on DC microgrids. The presented methods provide the essential guidelines for the proper design of the protective devices and methods for DC microgrids, and they have been compared with the conventional and AC protection methods, it shows that they must be modified to provide a proper protection system for the DC microgrids. Due to the lack of standards and guidance for the DC system protection, further researches must study these systems. This study shows that the fault detection and

location of AC systems cannot be applied to the DC microgrids, and relay PDs must be modified for use in the DC microgrids. Moreover, the CBs cannot use directly in the DC systems; therefore further studies are required for this area.

On the other hand, due to the challenges and difficulties in the present protection schemes, the DC microgrids require future works in the following topics:

- AC CBs and protection methods cannot be implemented in DC microgrids; hence, protection methods must be designed based on the nature of DC faults and systems.
- Protection schemes must provide an adaptive fault protection algorithm to solve protection problems considering variation of topologies.
- Develop a method for fault detection in DC microgrids which is independent of fault impedance.
- Considering the dynamic behaviour of renewable energy resources to increase the accuracy of models.
- Current-based relays cannot be implemented in DC microgrids directly; hence, these types of relays must develop for DC microgrids.

9 References

- [1] Cuzner, R., Venkataramanan, G.: 'The status of DC micro-grid protection'. Proc. IEEE Industry Applications Society Annual Meeting (IAS), Edmonton, AB, Canada, October 2008, pp. 1–8
- [2] George, K., EPRI Solutions, Inc.: 'DC power production, delivery and utilization: an EPRI white paper', 2006
- [3] Deng, Q.: 'Fault protection in DC microgrids based on autonomous operation of all components'. Dissertation, University of South Carolina, 2017
- [4] Brearley, B.J., Raja Prabu, R.: 'A review on issues and approaches for microgrid protection', *Renew. Sustain. Energy Rev.*, 2017, **67**, pp. 988–997
- [5] Cairoli, P., Rodrigues, R., Zheng, H.: 'Fault current limiting power converters for protection of DC microgrids'. SoutheastCon, 2017, Charlotte, NC, USA, 2017
- [6] Manohar, P., Ahmed, W.: 'Superconducting fault current limiter to mitigate the effect of DC line fault in VSC-HVDC system'. 2012 Int. Conf. on Power, Signals, Controls and Computation (EPSCICON), Thrissur, Kerala, India, 2012
- [7] de Oliveira, T.R., Bolzon, A.S., Donoso-Garcia, P.F.: 'Grounding and safety considerations for residential DC microgrids'. IECON 2014 – 40th Annual Conf. of the IEEE Industrial Electronics Society, Dallas, TX, USA, 2014
- [8] Amamra, S.-A., Ahmed, H., El-Sehiemy, R.A.: 'Firefly algorithm optimized robust protection scheme for DC microgrid', *Electr. Power Compon. Syst.*, 2017, **45**, (10), pp. 1141–1151
- [9] Elsayed, A.T., Mohamed, A.A., Mohammed, O.A.: 'DC microgrids and distribution systems: an overview', *Electr. Power Syst. Res.*, 2015, **119**, pp. 407–417
- [10] Jin, Z., Savaghebi, M., Vasquez, J.C., et al.: 'Maritime DC microgrids—a combination of microgrid technologies and maritime onboard power system for future ships'. 2016 IEEE Eighth Int. Power Electronics and Motion Control Conf. (IPEMC-ECCE Asia), Hefei, China, 2016
- [11] Mirzaee, H., Bhattacharya, S., Bala, S.: 'A high power medium-voltage DC amplifier system'. 2011 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 17–22 September 2011, pp. 4043–4050
- [12] Schulz, N.N., Hebner, R.E., Dale, S., et al.: 'The U.S. ESRDC advances power system research for 107 shipboard systems'. 43rd Int. Universities Power Engineering Conf. (UPEC 2008), Padova, Italy, 1–4 September 2008, pp. 1–4
- [13] Lee, K.C., Ukil, A., Yeap, Y.M.: 'Short-circuit protection for MV & LVDC grid'. 2014 IEEE PES Asia-Pacific Power and Energy Engineering Conf. (APPEEC), Hong Kong, China, 7–10 December 2014, pp. 1–6
- [14] Yang, J., Fletcher, J.E., O'Reilly, J.: 'Short-circuit and ground fault analyses and location in VSC-based DC network cables', *IEEE Trans. Ind. Electron.*, 2012, **59**, pp. 3827–3837
- [15] De Doncker, R.W., Meyer, C., Lenke, R.U., et al.: 'Power electronics for future utility applications'. Seventh Int. Conf. on Power Electronics and Drive Systems, Bangkok, Thailand, 2007, pp. K-1–K-8
- [16] Majumder, R.: 'Aggregation of microgrids with DC system', *Electr. Power Syst. Res.*, 2014, **108**, pp. 134–143
- [17] Larruskain, D.M., Zamora, I., Abarrategui, O., et al.: 'Conversion of AC distribution lines into DC lines to upgrade transmission capacity', *Electr. Power Syst. Res.*, 2011, **81**, pp. 1341–1348
- [18] Baran, M.E., Mahajan, N.R.: 'DC distribution for industrial systems: opportunities and challenges', *IEEE Trans. Ind. Appl.*, 2003, **39**, pp. 1596–1601
- [19] IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations, IEEE Std. 946-2004, 2004
- [20] Salomonsson, D.: 'Modeling, control and protection of low-voltage DC microgrids'. Dissertation, KTH, 2008
- [21] Planas, E., Gil-de-Muro, A., Andreu, J., et al.: 'General aspects, hierarchical controls and droop methods in microgrids: a review', *Renew. Sustain. Energy Rev.*, 2013, **17**, pp. 147–159
- [22] Ghanbari, T., Farjah, E.: 'Unidirectional fault current limiter: an efficient interface between the microgrid and main network', *IEEE Trans. Power Syst.*, 2013, **28**, (2), pp. 1591–1598
- [23] AL-Nussairi, M.K., Bayindir, R., Padmanaban, S., et al.: 'Constant power loads (CPL) with microgrids: problem definition, stability analysis and compensation techniques', *Energies*, 2017, **10**, (10), p. 1656
- [24] Ghisla, U., Kondratiev, I., Dougal, R.: 'Protection of medium voltage DC power systems against ground faults and negative incremental impedances'. Proc. IEEE SoutheastCon 2010 (SoutheastCon), Concord, NC, USA, 2010
- [25] Satpathi, K., Thukral, N., Ukil, A., et al.: 'Directional protection scheme for MVDC shipboard power system'. IECON 2016 – 42nd Annual Conf. of the IEEE Industrial Electronics Society, Florence, Italy, 2016
- [26] Monadi, M., Zamani, M.A., Candela, J.I., et al.: 'Protection of AC and DC distribution systems embedding distributed energy resources: a comparative review and analysis', *Renew. Sustain. Energy Rev.*, 2015, **51**, pp. 1578–1593
- [27] Park, J.-D., Candelaria, J.: 'Fault detection and isolation in low-voltage DC-bus microgrid system', *IEEE Trans. Power Deliv.*, 2013, **28**, (2), pp. 779–787
- [28] Li, X., Song, Q., Liu, W., et al.: 'Protection of nonpermanent faults on DC overhead lines in MMC-based HVDC systems', *IEEE Trans. Power Deliv.*, 2013, **28**, (1), pp. 483–490
- [29] Salomonsson, D., Soder, L., Sannino, A.: 'Protection of low-voltage DC microgrids', *IEEE Trans. Power Deliv.*, 2009, **24**, (3), pp. 1045–1053
- [30] Cuzner, R., MacFarlin, D., Clinger, D., et al.: 'Circuit breaker protection consideration in power converter-fed DC systems'. IEEE Electric Ship Technologies Symp., Baltimore, MD, USA, April 2009, pp. 360–367
- [31] Fletcher, S.D.A., Norman, P.J., Galloway, S.J., et al.: 'Determination of protection system requirements for DC unmanned aerial vehicle electrical power networks for enhanced capability and survivability', *IET Electr. Syst. Transp.*, 2011, **1**, (4), pp. 137–147
- [32] Fletcher, S.D.A., Norman, P.J., Galloway, S.J., et al.: 'Mitigation against overvoltages on a DC marine electrical system'. Electric Ship Technologies Symp. (ESTS 2009), Baltimore, MD, USA, April 2009, pp. 420–427
- [33] Morel, R.: 'Schneider Cahier technique no154 – LV circuit breaker breaking technique', 2000, pp. 1–29
- [34] Doan, D.R.: 'Arc flash calculations for exposures to DC systems', *IEEE Trans. Ind. Appl.*, 2010, **46**, (6), pp. 2299–2302
- [35] Jin, C., Dougal, R.A., Liu, S.: 'Solid-state over-current protection for industrial DC distribution systems'. Proc. Fourth Int. Energy Conversion Engineering Conf. and Exhibit (IECEC), San Diego, California, 2006, pp. 26–29
- [36] De Kerf, K., Srivastava, K., Reza, M., et al.: 'Wavelet-based protection strategy for DC faults in multi terminal VSC HVDC systems', *IET. Gener. Transm. Distrib.*, 2011, **5**, pp. 496–503
- [37] Peng, C., Huang, A.Q.: 'A protection scheme against DC faults VSC based DC systems with bus capacitors'. Proc. 29th Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), Fort Worth, TX, USA, 2014, pp. 3423–3428
- [38] Ustun, T.S., Ozansoy, C., Zayegh, A.: 'A microgrid protection system with central protection unit and extensive communication'. 2011 10th Int. Conf. on Environment and Electrical Engineering (EEEIC), Rome, Italy, 2011
- [39] Selim Taha, U.: 'Design and development of a communication assisted microgrid protection system'. Ph.D. thesis, School of Engineering and Science, Faculty of Health, Engineering and Science, Victoria University, 2013
- [40] Kwasinski, A., Onwuchekwa, C.N.: 'Dynamic behavior and stabilization of DC microgrids with instantaneous constant-power loads', *IEEE Trans. Power Electron.*, 2011, **26**, (3), pp. 822–834
- [41] Magne, P., Nahid-Mobarakkeh, B., Pierfederici, S.: 'Dynamic consideration of DC microgrids with constant power loads and active damping system – a design method for fault-tolerant stabilizing system', *IEEE J. Emerging Sel. Top. Power Electron.*, 2014, **2**, (3), pp. 562–570
- [42] Kamel, R.M., Nagasaka, K.: 'Effect of load type on standalone micro grid fault performance', *Appl. Energy*, 2015, **160**, pp. 532–540
- [43] Prempraneerach, P., Karniadakis, G., Chrysosostomidis, C.: 'Technical Report DC protection'. ESRDC Technical Report, December 2011
- [44] Kamel, R.M., Chaouachi, A., Nagasaka, K.: 'Comparison the performances of three earthing systems for micro-grid protection during the grid connected mode', *Smart Grid Renew. Energy*, 2011, **2**, (03), p. 206
- [45] Mirsaedi, S., Said, D.M., Mustafa, M.W., et al.: 'Progress and problems in micro-grid protection schemes', *Renew. Sustain. Energy Rev.*, 2014, **37**, pp. 834–839
- [46] Girgis, A., Brahma, S.: 'Effect of distributed generation on protective device coordination in distribution system'. LESCOPE'01. 2001 Large Engineering Systems Conf. on Power Engineering, 2001, Halifax, NS, Canada, 2001
- [47] Li, W., Monti, A., Ponci, F.: 'Fault detection and classification in medium voltage DC shipboard power systems with wavelets and artificial neural networks', *IEEE Trans. Instrum. Meas.*, 2014, **63**, (11), pp. 2651–2665
- [48] Baran, M.E., Mahajan, N.R.: 'Overcurrent protection on voltage-source-converter-based multiterminal DC distribution systems', *IEEE Trans. Power Deliv.*, 2007, **22**, (1), pp. 406–412
- [49] Cairoli, P., Dougal, R.A.: 'New horizons in DC shipboard power systems: new fault protection strategies are essential to the adoption of dc power systems', *IEEE Electr. Mag.*, 2013, **1**, (2), pp. 38–45
- [50] Swathika, O.V.G., Hemamalini, S.: 'Prims-Aided Dijkstra algorithm for adaptive protection in microgrids', *IEEE J. Emerging Sel. Top. Power Electron.*, 2016, **4**, (4), pp. 1279–1286
- [51] Beheshtaein, S., Savaghebi, M., Vasquez, J.C., et al.: 'Protection of AC and DC microgrids: challenges, solutions and future trends'. 41st Annual Conf. of the IEEE Industrial Electronics Society (IECON 2015), Yokohama, Japan, 2015
- [52] Malekpour, A.R., Niknam, T., Pahwa, A., et al.: 'Multi-objective stochastic distribution feeder reconfiguration in systems with wind power generators and

- fuel cells using the point estimate method', *IEEE Trans. Power Syst.*, 2013, **28**, (2), pp. 1483–1492
- [53] Kou, W., Wei, D.: 'Fault ride through strategy of inverter-interfaced microgrids embedded in distributed network considering fault current management', *Sustain. Energy Grids Netw.*, 2017, in press
- [54] Teimourzadeh, S., Aminifar, F., Davarpanah, M., et al.: 'Macro protections for micro grids', *IEEE Ind. Electron. Mag.*, 2016, **10**, (3), pp. 6–18
- [55] Kermani, M.: 'Transient voltage and frequency stability of an isolated microgrid based on energy storage systems'. 2016 IEEE 16th Int. Conf. on Environment and Electrical Engineering (EEEIC), Florence, Italy, 2016
- [56] Paul, D.: 'DC traction power system grounding', *IEEE Trans. Ind. Appl.*, 2002, **38**, (3), pp. 818–824
- [57] Shang, L., Herold, G., Jaeger, J., et al.: 'High-speed fault identification and protection for HVDC line using wavelet technique'. 2001 IEEE Porto Power Tech Proc., Porto, Portugal, 2001, vol. 3
- [58] Meghwhani, A., Srivastava, S.C., Chakrabarti, S.: 'A non-unit protection scheme for DC-microgrid based on local measurements', *IEEE Trans. Power Deliv.*, 2017, **32**, (1), pp. 172–181
- [59] Farhadi, M., Mohammed, O.: 'A new protection scheme for multi-bus DC power systems using an event classification approach'. 50th IEEE IAS Annual Meeting, Dallas, Texas, 18–22 October 2015
- [60] Tang, L., Ooi, B.T.: 'Locating and isolating DC faults in multi-terminal DC system', *IEEE Trans. Power Deliv.*, 2007, **22**, (3), pp. 1877–1884
- [61] Dhar, S., Patnaik, R.K., Dash, P.K.: 'Fault detection and location of photovoltaic based DC-microgrid using differential protection strategy', *IEEE Trans. Smart Grid*, 2017
- [62] Aly, M.M.A.M., El-Sayed, M.A.H.: 'Enhanced fault location algorithm for smart grid containing wind farm using wireless communication facilities', *IET Gener. Transm. Distrib.*, 2016, **10**, (9), pp. 2231–2239
- [63] Fletcher, S.D.A., Norman, P.J., Fong, K., et al.: 'High-speed differential protection for smart DC distribution systems', *IEEE Trans. Smart Grid*, 2014, **5**, (5), pp. 2610–2617
- [64] Lin, H., Guerrero, J.M., Jia, C., et al.: 'Adaptive overcurrent protection for microgrids in extensive distribution systems'. 42nd Annual Conf. of the IEEE Industrial Electronics Society (IECON 2016), Florence, Italy, 2016
- [65] Rockefeller, G.D., Wagner, C.L., Linders, J.R., et al.: 'Adaptive transmission relaying concepts for improved performance', *IEEE Trans. Power Delivery*, 1988, **3**, pp. 1446–1458
- [66] Li, W., Luo, M., Monti, A., et al.: 'Wavelet based method for fault detection in medium voltage DC shipboard power systems'. 2012 IEEE Int. Instrumentation and Measurement Technology Conf. (I2MTC), Graz, Austria, 2012
- [67] De Kerf, K., Srivastava, K., Reza, M., et al.: 'Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems', *IET Gener. Transm. Distrib.*, 2011, **5**, (4), pp. 496–503
- [68] Baran, , Mahajan, : 'PEBB based DC system protection: opportunities and challenges'. Proc. IEEE Transmission and Distribution Conf. and Exhibition, Dallas, TX, USA, 2006, pp. 705–707
- [69] Brozek, J.P.: 'DC overcurrent protection – where we stand', *IEEE Trans. Ind. Appl.*, 1993, **29**, (5), pp. 1029–1032
- [70] Gregory, G.D.: 'Applying low voltage circuit breakers in direct-current systems', *IEEE Trans. Ind. Appl.*, 1995, **31**, (4), pp. 650–657
- [71] Tennakoon, S., McEwan, P.: 'Short-circuit interruption performance of thyristor circuit breakers'. Proc. IEEE Applied Power Electronics Conf. and Exposition (APEC), Orlando, FL, 13–17 February 1994, vol. 2, pp. 832–838
- [72] Devarajan, B.: 'Modeling of a DC fuse for protection of semiconductor devices using PSCAD/EMTDC'. Dissertation, 2010
- [73] Sadiq, N., Noor, T.: 'Selecting fuses: simple procedures to get the right overcurrent protection for DC-DC converters', August 2010
- [74] Qader, M.R., Al-Asooly, H., Qamber, I.S.: 'Influence of system parameters on fuse protection use in regenerative DC drives', *Energies*, 2009, **2**, (2), pp. 411–426
- [75] Ouaida, R., De Palma, J.F., Gonther, G.: 'Hybrid protection based on pyroswitch and fuse technologies for DC applications'. Symp. Genie Electrique, Grenoble, France, 2016
- [76] Soon, J.L., Lu, D.D.-C.: 'Design of fuse-MOSFET pair for fault-tolerant DC/DC converters', *IEEE Trans. Power Electron.*, 2016, **31**, (9), pp. 6069–6074
- [77] Candelaria, J., Park, J.-D.: 'VSC-HVDC system protection: a review of current methods'. Proc. IEEE PSCE, Phoenix, AZ, USA, March 2011, pp. 1–7
- [78] Franck, C.M.: 'HVDC circuit breakers: a review identifying future research needs', *IEEE Trans. Power Deliv.*, 2011, **26**, (2), pp. 998–1007
- [79] Bachmann, B., Mauthe, G., Ruoss, E., et al.: 'Development of a 500 kV airblast HVDC circuit breaker', *IEEE Trans. Power Appar. Syst.*, 1985, **PAS-104**, (9), pp. 2460–2466
- [80] Senda, T., Tamagawa, T., Higuchi, K., et al.: 'Development of HVDC circuit breaker based on hybrid interruption scheme', *IEEE Trans. Power Appar. Syst.*, 1984, **PAS-103**, (3), pp. 545–552
- [81] Pauli, B., Mauthe, G., Ruoss, E., et al.: 'Development of a high current HVDC circuit breaker with fast fault clearing capability', *IEEE Trans. Power Deliv.*, 1988, **3**, (4), pp. 2072–2080
- [82] Sano, K., Takasaki, M.: 'A surgeless solid-state DC circuit breaker for voltage-source-converter-based HVDC systems', *IEEE Trans. Ind. Appl.*, 2014, **50**, (4), pp. 2690–2699
- [83] Genji, T., Nakamura, O., Isozaki, M., et al.: '400 V class high-speed current limiting circuit breaker for electric power system', *IEEE Trans. Power Deliv.*, 1994, **9**, (3), pp. 1428–1435
- [84] Oishi, M., Suzuki, A., Hagiwara, M., et al.: 'A hybrid DC circuit breaker combining a multilevel converter and mechanical contactors: verification of the principles of operation by experiment and simulation', *Electr. Eng. Jpn.*, 2017, **200**, (3), pp. 13–22
- [85] Chang, A.H., Sennett, B.R., Avestruz, A.T., et al.: 'Analysis and design of DC system protection using z-source circuit breaker', *IEEE Trans. Power Electron.*, 2016, **31**, (2), pp. 1036–1049
- [86] Corzine, K.: 'DC micro grid protection with the z-source breaker'. IECON 2013-39th Annual Conf. of the IEEE Industrial Electronics Society, Vienna, Austria, 2013
- [87] Commerton, J., Zahzah, M., Khersonsky, Y.: 'Solid state transfer switches and current interrupters for mission-critical shipboard power systems'. IEEE Electric Ship Technologies Symp., Philadelphia, PA, USA, 2005, pp. 298–305
- [88] Sathyan, S., Sennett, B.R., Avestruz, A.T., et al.: 'ZVS-ZCS high voltage gain integrated boost converter for DC microgrid', *IEEE Trans. Ind. Electron.*, 2016, **63**, (11), pp. 6898–6908
- [89] Zhang, Y., Liang, Y.C.: 'Over-current protection scheme for SiC power MOSFET DC circuit breaker'. 2014 IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh, PA, USA, 2014
- [90] Mohan, N., Undeland, T.M.: 'Power electronics: converters, applications and design' (John Wiley and Sons, Inc., 1989), pp. 161–187
- [91] Wellner, E.L., Bendre, A.R.: 'IGCTs vs. IGBTs for circuit breakers in advanced ship electrical systems'. 2009 IEEE Electric Ship Technologies Symp. (ESTS 2009), Baltimore, MD, USA, 2009
- [92] Flourentzou, V.A., Demetriades, G.: 'VSC-based HVDC power transmission systems: an overview', *Power Electron. Trans.*, 2009, **24**, (3), pp. 592–602
- [93] Iwamoto, H., Satoh, K., Yamamoto, M., et al.: 'High power semiconductor device: a symmetric gate commutated turn-off thyristor', *IEEE Proc., Electr. Power Appl.*, 2001, **148**, (4), pp. 363–368
- [94] ABB: 'Section on hiPak IGBT & diode modules'. Available at <http://www.abb.com/semiconductors>
- [95] Schmerda, R., Krstic, S., Wellner, E., et al.: 'IGCTs vs. IGBTs for circuit breakers in advanced ship electrical systems', 2009 IEEE Electric Ship Technologies Symposium, Baltimore, MD, USA, April 2009, pp. 400–405
- [96] Xu, Z., Zhang, B., Sirisukprasert, S., et al.: 'The emitter turn-off thyristor-based DC circuit breaker'. 2002 IEEE Power Engineering Society Winter Meeting, New York, NY, USA, 2002, vol. 1
- [97] Peng, C., Huang, A.Q., Song, X.: 'Current commutation in a medium voltage hybrid DC circuit breaker using 15 kV vacuum switch and SiC devices'. 2015 IEEE Applied Power Electronics Conf. and Exposition (APEC), Charlotte, NC, USA, 2015
- [98] Peng, C., Song, X., Rezaei, M.A., et al.: 'Development of medium voltage solid-state fault isolation devices for ultra-fast protection of distribution systems'. 40th Annual Conf. of the IEEE Industrial Electronics Society (IECON 2014), Dallas, TX, USA, 2014
- [99] Huang, A., Liu, Y., Chen, Q., et al.: 'Emitter turn-off (ETO) thyristor, ETO light converter and their grid applications'. 2009 IEEE Power & Energy Society General Meeting (PES'09), Calgary, AB, Canada, 2009
- [100] Park, J.-D., Candelaria, J., Ma, L., et al.: 'DC ring-bus microgrid fault protection and identification of fault location', *IEEE Trans. Power Deliv.*, 2013, **28**, (4), pp. 2574–2584
- [101] Munasib, S., Balda, J.C.: 'Short-circuit protection for low-voltage DC microgrids based on solid-state circuit breakers'. 2016 IEEE 7th Int. Symp. on Power Electronics for Distributed Generation Systems (PEDG), Vancouver, BC, Canada, 2016
- [102] Meyer, J.-M., Rufer, A.: 'A DC hybrid circuit breaker with ultra-fast contact opening and integrated gate-commutated thyristors (IGCTs)', *IEEE Trans. Power Deliv.*, 2006, **21**, (2), pp. 646–651
- [103] Satpathi, K., Ukil, A., Pou, J.: 'Short-circuit fault management in DC electric ship propulsion system: protection requirements, review of existing technologies and future research trends', *IEEE Trans. Transp. Electrification*, 2018, **4**, (1), pp. 272–291
- [104] Cairoli, P., Kondratiev, I., Dougal, R.A.: 'Coordinated control of the bus tie switches and power supply converters for fault protection in DC microgrids', *IEEE Trans. Power Electron.*, 2013, **28**, (4), pp. 2037–2047
- [105] Soto, D., Sloderbeck, M., Ravindra, H., et al.: 'Advances to megawatt scale demonstrations of high speed fault clearing and power restoration in breakerless MVDC shipboard power systems'. 2017 IEEE Electric Ship Technologies Symp. (ESTS), Arlington, VA, USA, 2017
- [106] Shi, Y., Li, H.: 'Isolated modular multilevel DC-DC converter with DC fault current control capability based on current-fed dual active bridge for MVDC application', *IEEE Trans. Power Electron.*, 2018, **33**, (3), pp. 2145–2161
- [107] Babaei, M., Shi, J., Abdelwahed, S.: 'A survey on fault detection, isolation, and reconfiguration methods in electric ship power systems', *IEEE Access*, 2018, **6**, pp. 9430–9441
- [108] Hooshyar, H., Baran, M.E.: 'Fault analysis on distribution feeders with high penetration of PV systems', *IEEE Trans. Power Syst.*, 2013, **28**, (3), pp. 2890–2896
- [109] Draft Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection, IEEE.7/D4.0
- [110] Dhar, S., Dash, P.K.: 'Adaptive threshold based new active islanding protection scheme for multiple PV based microgrid application', *IET Gener. Transm. Distrib.*, 2017, **11**, (1), pp. 118–132
- [111] Dhar, S., Dash, P.K.: 'Differential current-based fault protection with adaptive threshold for multiple PV-based DC microgrid', *IET Renew. Power Gener.*, 2017, **11**, (6), pp. 778–790
- [112] Sartika, L., Rosyadi, M., Umemura, A., et al.: 'Stabilization of PMSG based wind turbine under network disturbance by using new buck controller system for DC-link protection'. 5th IET Int. Conf. on Renewable Power Generation (RPG) 2016, London, UK, 2016, 9, (5), pp. 4303–4312
- [113] Sava, G.N., Costinas, S., Golovanov, N., et al.: 'Comparison of active crowbar protection schemes for DFIGs wind turbines'. 2014 IEEE 16th Int. Conf. on Harmonics and Quality of Power (ICHQP), Bucharest, Romania, 2014
- [114] Abad, G., Lopez, J., Rodriguez, M.A., et al.: 'Double fed induction machine' (John Wiley & Sons, New Jersey, 2011), pp. 479–499

- [115] Yang, J., Fletcher, J.E., O'Reilly, J.: 'A series dynamic resistor based converter protection scheme for doubly-fed induction generator during various fault conditions', *IEEE Trans. Energy Convers.*, 2010, **25**, (2), pp. 422–432
- [116] Yunus, M.S., Siada, A.A., Masoum, M.A.S.: 'Impact of DC-link fault'. IEEE General Meeting Power and Energy Society, San Diego, CA, 22–26 July 2012
- [117] Yao, J., Li, H., Liao, Y., *et al.*: 'An improved control strategy of limiting the DC-link voltage fluctuation for a doubly fed induction wind generator', *IEEE Trans. Power Electron.*, 2008, **23**, (3), pp. 1205–1213
- [118] Coffele, F., Booth, C., Dysko, A., *et al.*: 'Quantitative analysis of network protection blinding for systems incorporating distributed generation', *IET Gener. Transm. Distrib.*, 2012, **6**, pp. 1218–1224
- [119] Rakhra, P., Norman, P.J., Fletcher, S.D., *et al.*: 'Evaluation of the impact of high-bandwidth energy-storage systems on DC protection', *IEEE Trans. Power Deliv.*, 2016, **31**, (2), pp. 586–595