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IETE Technical Review

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/titr20

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Kamal Kant & Om Hari Gupta

To cite this article: Kamal Kant & Om Hari Gupta (2023) DC Microgrid: A Comprehensive Review on Protection Challenges and Schemes, IETE Technical Review, 40:4, 574-590, DOI: 10.1080/02564602.2022.2136271

To link to this article: https://doi.org/10.1080/02564602.2022.2136271

Published online: 03 Nov 2022.

IETE TECHNICAL REVIEW
2023, VOL. 40, NO. 4, 574–590
https://doi.org/10.1080/02564602.2022.2136271

REVIEW ARTICLE

DC Microgrid: A Comprehensive Review on Protection Challenges and Schemes

Kamal Kant and Om Hari Gupta

Electrical Engineering Department, National Institute of Technology, Jamshedpur 831 014, Jharkhand, India

ABSTRACT
The development of microgrids can prove to be a game changer in the realization of future smart grids. The increasing trends of automation in domestic loads and smart homes have increased the penetration of DC loads at the distribution level. Hence, the development of a low- or medium-voltage DC microgrid seems the need of the hour to match this changing scenario. Another point is that the various distributed generation (DG) sources like PV, batteries, fuel cells, *etc*., also provide energy in DC form. Hence, integrating these sources into the DC system also becomes convenient as the power conversion at each point of connection will no longer be needed. But, due to the lack of universally accepted standards and technological advancements, the implementation of DC microgrids is still limited to very small-scale usage. The unavailability of an efficient and reliable protection system is one such issue that is hindering the implementation of DC microgrids on a larger scale. Therefore, a thorough examination of the several DC microgrid protection difficulties and challenges is necessary. Thus the purpose of this article is to provide a comprehensive analysis of the protection challenges, and the currently available protection schemes for DC microgrids and to highlight the gaps for future research to enable the development of a more reliable and efficient protection system.

KEYWORDS
DC Microgrid; Fault Classification; Fault Detection; Low Voltage DC (LVDC) Microgrid; Protection Challenges; Protection Scheme

1. INTRODUCTION

Electrical energy continues to play a significant role in the economic growth of any country [1]. In fact, per capita energy consumption is among the significant indicators of the development of a country [2]. From industries to ordinary people, all depend on electricity for their well-being. With an increasing rate of urbanization and industrialization worldwide, the demand for electrical energy is increasing rapidly. The microgrid provides a very efficient, reliable, cost-effective, and in most cases pollution-free way to meet this increasing demand [3], and plays a very important role in the electrification of remote rural areas where grid integration is not economically feasible [4]. A microgrid can be defined as an active distribution network in which small-scale power generation facilities, mainly distributed energy sources like solar photovoltaics, wind, bio-mass energy, *etc*., are connected directly to the main grid at the distribution level near the load centers [5].

With distributed energy resources (DERs) like PV systems, fuel cells, storage devices, wind resources, and more, a microgrid can help make the smart grid of the future possible [6]. The microgrid can be characterized as an AC microgrid, DC microgrid (DCMG), or hybrid AC/DC microgrid, depending on the kind of source and load linked [7]. However, due to a lack of standards, technological innovation, and reliable protection mechanisms for the DC microgrid, the AC microgrid is continued to be favored [8].

With a large influx of electronic loads and smart appliances that mainly utilize DC power, along with the majority of DERs like PV, fuel cells, storage devices, *etc*., providing DC energy, the concept of a DC microgrid seems realistic in the near future [9]. A DC microgrid typically covers a small geographical region, such as a building or a colony. As a result, the length of the distribution line in a DC microgrid is shorter than in an AC microgrid [10].

The DC system has many advantages over its AC counterpart, such as no skin effect, no inductive reactance, no frequency mismatch issues, less losses, and many more. Another major advantage of DC microgrids is that the storage devices can easily be integrated into the DC system [11]. But just like every good thing comes at a cost, the DC system also has some major issues, particularly those related to the protection of the DC system. In the case of an AC system, current crosses the zero point twice in each cycle, and this property of AC current is very useful in isolating the faulty section at the natural current zero point. But this natural current zero point is not present in the case of DC, and for this particular reason, the mechanical circuit breakers, being used in the AC system, cannot be directly employed in the DC system [12]. In this case, we have to produce an artificial current zero point so that the faulty sections can be isolated using conventional mechanical breakers. This is one of the major challenges of DC microgrid protection. Some of the major differences between DC and AC systems from a protection point of view are: (1) in the case of a DC system, the frequency-dependent parameters, such as inductive reactance, phasor quantities, sequential components of current, *etc.*, are not available. These are the quantities that may be used for fault detection in AC systems. The parameters readily available for fault detection in DC microgrids are voltage, current, and resistances only [13]. (2) The physical inertia imposed by the DC system is generally very less compared to that of the AC system. Due to this reason, DC systems are more sensitive to transient disturbances or temporary faults [14]. (3) Due to less physical inertia and the capacitive nature of the circuit, the fault currents in the DC system increase very rapidly. Hence the protection systems used in DC microgrids should be very fast in detecting and isolating the faults [15].

Therefore, to provide a comprehensive analysis this paper presents a complete literature review of the DCMG protection challenges, protection schemes and standards available till date. The major highlights/contributions of this paper are as discussed below:

- It provides a complete overview of the different topologies of DCMG and discusses their effects on protection methodologies.
- It provides a complete discussion of the issues and challenges in the protection of DC microgrid.
- It provides a comprehensive analysis of the already existing protection schemes for DCMG protection.
- It provides the research gaps for further improvement in existing protection strategies.

The organization of the rest of the paper is as follows: Section 2 provides a review of the DCMG architecture; Section 3 discusses different types of faults in DCMG; Section 4 presents the protection challenges in DC microgrid; and Section 5 provides a detailed review of DC microgrid protection schemes, the research gaps identified are presented in Section 6 followed by a conclusion in Section 7.

2. DC MICROGRID ARCHITECTURE

The structure of the microgrid, like any other factor, must be taken into consideration while designing a protection system for a DCMG [16]. Power flow direction, whether unidirectional or bidirectional, is a crucial issue to consider while designing a protective system [17]. The direction of power transfer largely depends on the topology of the DC microgrid, whether it is a single-bus topology, a multi-bus topology, or a ring-bus topology [18]. Apart from these, the DCMG architecture can also be either unipolar or bipolar topology, as shown in Figure 1 and Figure 2. The bipolar topology of DCMG proves to be superior than unipolar topology in many ways, such as enhanced power handling capacity, enhanced reliability, and more flexibility in terms of DG and load connection [19]. A comparative analysis of the different DCMG architectures has been presented in Figure 3 [20,21].

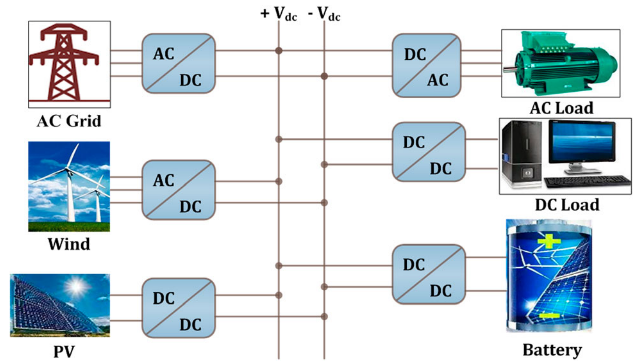


Figure 1: Unipolar topology of the DC microgrid

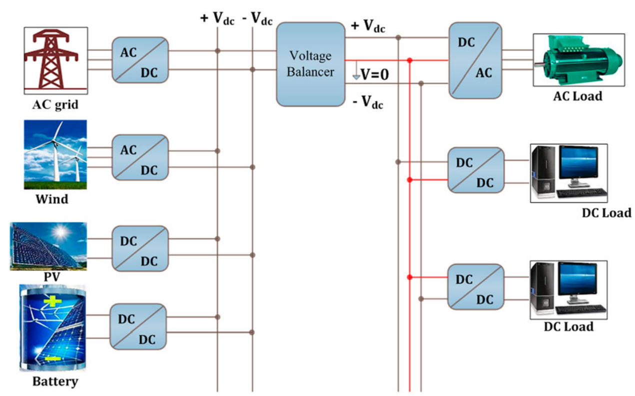


Figure 2: Bipolar topology of the DC microgrid

3. FAULT CLASSIFICATION IN DC MICROGRID

The faults in the DCMG can be broadly grouped as short-circuit faults and arc faults, and again, these two can be further classified as shown in Figure 4. The pole–pole (PP) and pole–ground (PG) faults generally occur on DC buses and DC feeders, while the arc faults, *i.e.* series arc faults or shunt arc faults, generally occur on the source

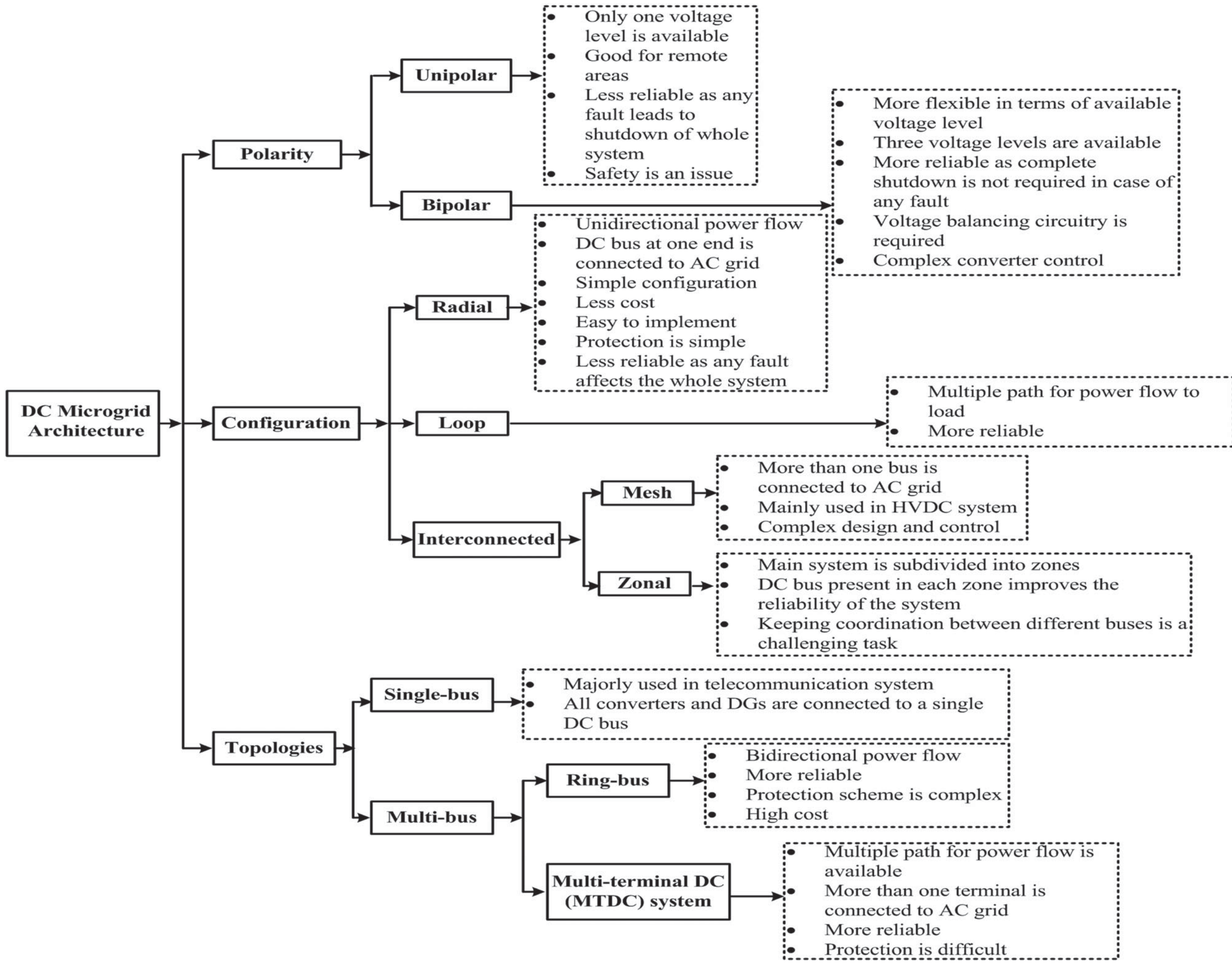


Figure 3: Comparative analysis of different DCMG architecture

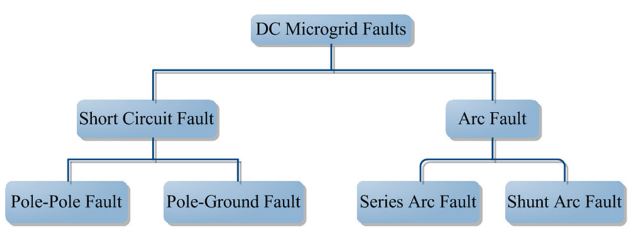


Figure 4: Fault classification in DC microgrid

side or inside the power electronic converter [22]. The magnitude of a fault current in a DC microgrid is determined by the type of fault, fault impedance, type of DERs connected to the microgrid, energy storage devices, grounding methods, and grid connectivity (*i.e.* whether grid connected or islanded). Just like the LG fault in an AC system, the PG fault is the most commonly occurring fault in a DC microgrid. The fault current, in the case of a PG fault, depends on the type of grounding and the ground fault impedance. PP faults very rarely occur in the DC microgrid, but the fault currents in such types of faults are comparatively very high due to the low system resistance.

4. DC MICROGRID PROTECTION CHALLENGES

A secure and reliable protection system is a must for the successful realization of a microgrid. The conventional distribution system is a passive network with unidirectional power transfer from the grid to the load center. However, the distribution system becomes a more dynamic and vibrant distribution network in the case of a microgrid with several DERs connected at various locations [22]. Hence, the designing of protection systems for such a dynamic microgrid network becomes a tedious task. The complexity of the protection scheme increases even more in the case of DCMG, as the fault isolation in DC systems becomes more difficult due to the absence of a natural current-zero point [23]. Some of the key challenges of DC microgrid protection are as follows [24,25].

4.1 Bidirectional Power Transfer

In a conventional distribution system, the power transfer is mostly unidirectional as shown in Figure 5(a). So, the current direction is fixed and the protection scheme will be designed by keeping the fixed direction of the current in mind. But in the case of a DC microgrid, the direction of power flow becomes bidirectional due to the addition of DGs at the distribution level, and the direction of power transfer keeps on changing depending on the availability of the power from DGs [23], as shown in Figure 5(b). This bidirectional power transfer can severely affect the performance of protection devices [26]. Hence, building a protection scheme for such a dynamic system becomes a challenging task.

4.2 Variation in Fault Current Level

The fault current level in a DC microgrid will depend on whether it is operating in a grid-connected mode or an islanded mode. In the case of islanded operation, if a fault occurs then fault current will be the current supplied by the distributed generation sources only, as shown in Figure 6(a). But, in the case of grid-connected operation, the fault current will be supplied by both the grid and the DG source, as shown in Figure 6(b). Hence, there is a notable shift in the fault current level in both operating conditions. This disparity in fault current levels may cause relay operation and coordination problems [27]. Therefore, the protection scheme must be adaptive enough to embrace these operating conditions.

4.3 Rapidly Rising Fault Current

Due to less physical inertia and less resistance shown by the line, fault current in DC microgrids increases to a significantly high magnitude in very short duration of time and may reach the maximum tolerable level very quickly [28]. This rapidly rising fault current may damage the voltage source converters (VSCs) [14]. This necessitates

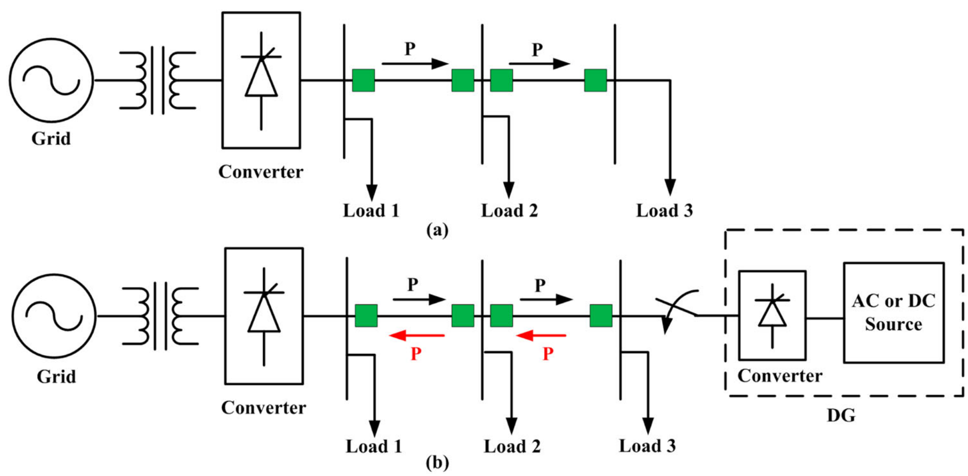


Figure 5: (a) Unidirectional power flow in a conventional distribution system and (b) bidirectional power flow in a microgrid

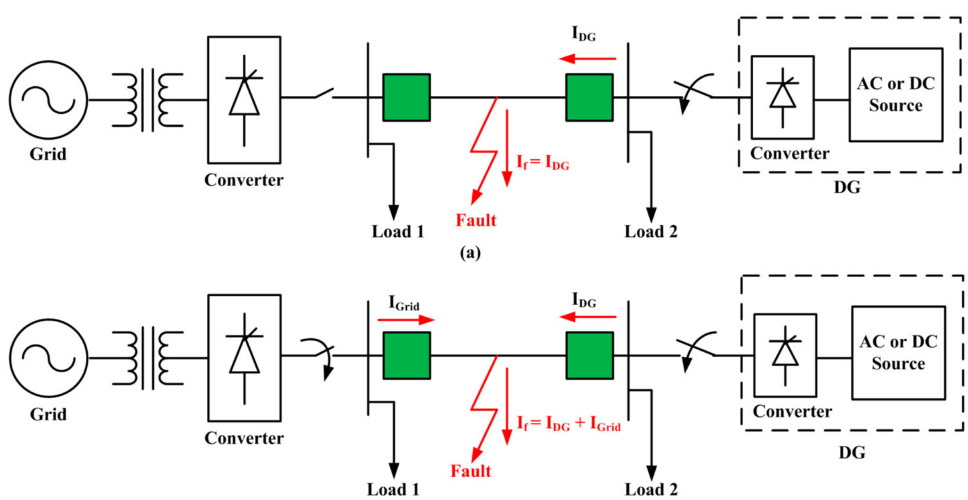


Figure 6: (a) Fault current in case of islanded operation and (b) fault current in case of grid-connected operation

the requirement for ultra-quick fault detection and isolation in DCMG. Hence, the protection scheme for DC microgrid should be fast and capable enough to protect the VSCs against this rapidly rising fault current.

4.4 Selectivity Issue with Overcurrent Relays

As mentioned earlier, DC microgrids possess less inertia, they are highly responsive to even transient or temporary faults. This may cause false tripping of overcurrent relays even in the case of temporary faults, which may cause selectivity issues for over-current relays. For this reason, it is not advisable to use an over-current relay as primary protection in a DC microgrid. However, it can be useful for backup protection.

4.5 Improper Grounding

The effective grounding is one of the requirements of a healthy/normal system. The major advantages of an effective grounding are [29]:

- Ease of fault detection
- Reduction in DC stray current
- Increase in safety of personnel working on the system due to reduction in common-mode voltage (CMV).

Moreover, grounding has a notable effect on the magnitude of fault current, particularly in case if the fault involves ground. Since it has an impact on fault current, the current-based protection methods may not work properly due to improper grounding. The stray current and the CMV both depend on grounding resistance. In the case of high grounding resistance, the stray current will be less but the common-mode voltage (CMV) will be high, and if the grounding resistance is less, the stray current will be high but the CMV will be less [30]. The advantages and disadvantages of differently grounded systems have been shown in Table 1.

According to IEC 30364-1, the three main grounding strategies for DC systems are TT, TN, and IT. TN again has three subcategories like TN-S, TN-C, and TN-C-S. In these notations, the first letter represents the earthing of neutral wire, and the second letter represents the earth connection of exposed metallic parts of the appliances.

The first letters like T and I represent the direct connection to the earth and no connection to the earth, respectively. Similarly, the second and third letters, *i.e.* T and N, represent the direct earthing of exposed metallic parts and the connection of exposed metallic parts to neutral, respectively [31]. The pictorial representation along with some details of these grounding methods has been given in Table 2.

4.6 High Resistance Faults (HRF)

In the event of an HRF, the fault current is very small and may be comparable with the overload current [32]. Hence, it becomes very difficult to distinguish between the HRF situation and an overload condition. Therefore, the protection schemes of DC microgrids should be capable of dealing with such faults.

4.7 Lack of Operational Guidelines and Well-defined Standards

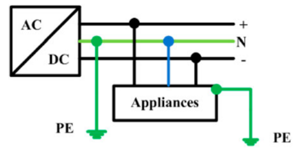
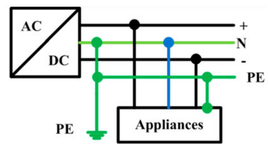
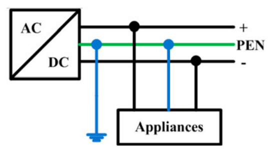
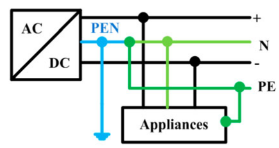
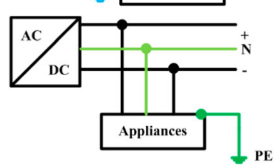
There are several standards and guidelines available for AC microgrid operation and protection requirements [33]. But in the case of the DCMG, there are only a few standards available. Some of the standards available for areas related to DC microgrid are IEEE 1547, IEC standards SG4 for LVDC distribution systems [34], and IEEE standards 946-2020 for DC auxiliary power systems [35]. Due to a lesser no. of rules, regulations, and protection standards, the design of a protection scheme becomes a challenging task.

There must be several improved and globally accepted DC microgrid standards in terms of system voltage,

Table 1: Merits and demerits of different grounding scenarios [26,28]

Grounding systems	Merits	Demerits
Ungrounded system	• Uninterrupted operation during pole-ground fault • Less stray current • Simple and cost effective	• Ground fault detection is difficult • CMV will be high • A second ground fault on another pole will turn into a pole-pole fault • Safety concerns for working personnel
Solidly grounded system	• Fault detection will be easy for such type of system • Low common-mode voltage • Less danger to personnel working on the system	• High stray current • Fault current will be high in case of ground fault
Diode-based grounding	• Low or moderate CMV	• Moderate to high stray current • Moderate/High fault current in case of ground fault
Thyristor-based grounding	• Low to moderate stray current	• Medium to high CMV

Table 2: Details of different grounding methods of dc system [29,37]

Grounding systems	Connection detail	Pictorial representation	Remarks
TT	• Neutral (N) is connected to earth, & Exposed metallic parts of the appliance is also directly connected to earth		• Simple and easy to install • Fault does not propagate to other parts of the grid [38]
TN-S	• Neutral is connected to earth, & the exposed metallic parts of the appliances are connected to neutral • Separate wires for protective earth (PE) and neutral (N) conductors are used		• Due to separate PE & N conductors it has highest electromagnetic compatibility [31] • Higher safety than TN-C • Suitable for tele-communication networks
TN-C	• PE and N conductors are combined to form a PEN conductor		• Cost effective • Poor safety
TN-C-S	• It is a combination of TN-S and TN-C grounding system		• Mainly used in US, UK, Russia, *etc.* • Combines the benefits of both TN-S and TN-C • Identification of fault become difficult in case if neutral is disconnected
IT	• Neutral point is not grounded & the exposed metallic parts of the appliance are separately grounded		• Small line to ground current • Difficult to predict the fault current path through DGs in case a second LG fault occurs simultaneously [39]

communication protocols, protection and safety, grounding, standards for grid-connected and islanded modes of operation, *etc.* [36].

5. AVAILABLE PROTECTION SCHEMES FOR DC MICROGRID

DC microgrid protection has so many challenges, as discussed in the previous section. The designing of protection schemes for DC microgrids is not yet matured and a lot of work needs to be done to design a reliable protection scheme. Because there aren't a lot of important things like frequency, phasor, and sequential components of current, it becomes difficult to find faults in a DCMG. The protection process of a DC microgrid can be divided into four stages: fault detection, fault localization, isolation, and reclosing. Speed of operation, selectivity, and reliability are some of the parameters used to measure the effectiveness of a protection scheme. Based on the literature available so far, a review of different protection schemes has been presented in this section.

5.1 Local Measurement-based Protection Schemes

The voltage and current are the two most important and basic quantities that can be used to determine the occurrence of faults in any system. In the past, many protection schemes have been reported in which local bus voltage and current measurement data are used to detect the fault in the system.

These schemes can further be subdivided as follows:.

1) Current-Based Methods

The current-based protection schemes generally work on overcurrent principle. If the actuating current is greater than the set threshold value, the fault will be detected. In [40], a current-based unit protection scheme for DCMG has been discussed. In this scheme, the current measured by the devices placed at both ends of the line segment is used to decide fault. This scheme employs double-ended measurement, hence the implementation of such schemes in physical networks tends to be costly. Ref. [41] proposes an overcurrent protection scheme for an LVDC microgrid. The proposed scheme is a communication-assisted protection scheme and can also provide back-up protection, which is not possible in the case of a differential protection scheme. The proposed scheme is fast and can detect faults within 2 ms. In [42], a local current measurement-based protection scheme for a standalone DCMG has been discussed. Current and voltage feedback are used in this method for quick and reliable

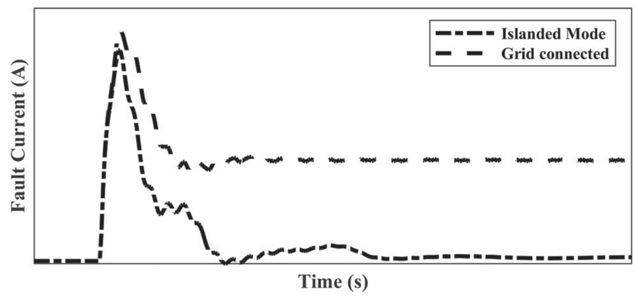


Figure 7: Change in fault current level for a fault during grid-connected and islanded operations

fault detection. In [43], another current-based protection scheme has been proposed. This scheme employs communication links between the intelligent electronic devices (IEDs), which may reduce the reliability of the scheme. In the case of a microgrid, the fault current level changes significantly with a change in the mode of operation, *i.e.* grid-connected and islanded operation. For a typical microgrid, the difference in fault current for a fault in DCMG during grid-connected and islanded operation is shown in Figure 7. This change in fault current level may cause mal-operation of the overcurrent relays. The current-based schemes also fail to protect the HRFs. Due to these reasons, these schemes are rarely used for DCMG protection.

2) Current Derivative-Based Method

The conventional current-based schemes may fail to protect the system against the faults having smaller fault current even if the rate of rise of the current is quite high in a DC system. Further, protection against the rapidly rising current is necessary as this can cause malfunctioning or even damage to the converters present in the system. In current derivative-based schemes, the slope of the current at the relaying points is calculated, and if the rate of change of current is greater than the preset value, the fault will be detected.

In [44], a protection scheme based on the rate of rise of fault current has been presented for the protection of DCMG. The fault current in DCMG increases rapidly. This property of DC fault current is utilized in this scheme to design an accurate, fast, and adaptive protection scheme, which is equally effective in both radial as well as ring-type DCMG architectures. The fault detection time of this scheme is 1 ms. In [45], a similar current derivative (di/dt) based protection scheme has been discussed. This scheme also compares directional currents and uses the adaptive droop technique to find and fix faults and isolate them, as well. This scheme also provides protection against HRF of resistance up to 500 Ω. However, the physical implementation of this scheme may be complex, as it employs both single as well as double-ended measurement. The proposed scheme employs single-ended measurement for protection against normal low-resistance ground faults and double-ended measurement for protection against HRF. This scheme also requires communication infrastructure between relays connected at both ends of the line segments, hence reliability may also be poor due to the vulnerability associated with the communication systems.

3) Voltage-Based Methods

In [46], a protection scheme based on the transient system voltage during fault conditions, has been proposed. The high-frequency components of transient system voltage were extracted using wavelet transform, and this information is then used for decision making during a fault. In [47], a pseudo voltage (PSDV) based fault detection and location algorithm has been presented for a multi-terminal DCMG. The PSDV is defined as the voltage on other buses of the DCMG, calculated based on the voltage and current at the faulty terminals. This method claims to have a better response time, *i.e.* within 0.2 ms, than the other protection schemes. However, this scheme has been tested up to the fault resistance of 2 Ω only, hence the performance of this scheme, for higher fault resistances, needs to be investigated.

5.2 Line Parameter Estimation-based Protection Schemes

Line parameter estimation-based protection schemes present a very good alternative to conventional overcurrent and differential protection schemes. Current-based protection schemes aren't very good at detecting high resistance faults (HRF) and also cannot protect the high rate of rise of fault current. In DCMG, resistance is the only available line parameter, as inductive reactance and capacitive reactance show up only during transients. Hence, most of the line parameter-based schemes are resistance estimation-based methods. In some literature, line inductance-based methods have been presented, but these methods fail during high resistance faults. In [48], a superimposed resistance-based protection scheme for tapped line DCMG has been presented. A DC distribution line can be tapped in two ways: to connect a load or to connect a distributed generator (DG). A protection scheme for such a configuration is essential. In this method, the tapping status of the distribution line is checked with the help of the difference in current available at both terminals of the line segments. In case if the line is untapped, then fault detection is performed using the superimposed current available at both ends of the line segment, and if it is a tapped line, the superimposed resistance method is used for fault detection. Ref. [49] has discussed a resistance estimation-based protection strategy for a ring-bus DCMG. The operation of this scheme does not depend on the fault resistance, and can successfully detect the HRF up to 50 Ω. In [50], a real-time resistance estimation-based method has been presented for a zonal-type LVDC microgrid. The system voltage considered for the LVDC microgrid in this scheme is 50 V, and the operation time is 2–2.5 ms. The resistance-based protection scheme can also be applied to DCMG with constant power loads (CPL). In [51], one such scheme has been presented for a DCMG with high usage of CPLs. The impact of CPL on the protection of DCMG has already been discussed in the previous section. The algorithm of the resistance-based protection scheme for DCMG with CPL is shown in Figure 8.

As shown in the algorithm, first of all the voltage and the current is measured at the relay point. Then the slope of the fault current is calculated from (1). If this slope is greater than the relay-setting value, then fault resistance (R_f) is calculated by (2). Afterwards, the fault location is estimated based on the fault resistance and the slope of fault current, and a trip signal for CB opening is also generated simultaneously. Hence, apart from identifying the fault situation, the proposed scheme can also determine the fault location.

$$Slope = \frac{\Delta I_f}{\Delta V} \tag{1}$$

$$R_f = \frac{P_f}{I_f^2} \tag{2}$$

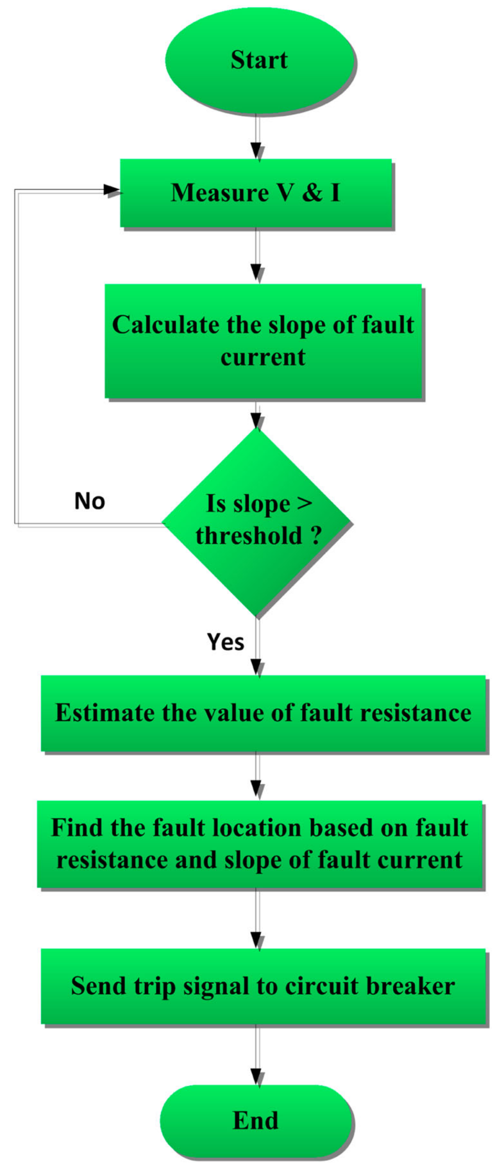


Figure 8: Algorithm for resistance estimation-based protection scheme [51]

In [52], an active impedance estimation (AIE)-based fault detection scheme has been discussed for zonal type DCMG. In [53], the same AIE-based scheme is applied for the protection of DC marine power systems. In [54], a fault detection scheme has been discussed which considers threshold violation in the i–r plane as a fault detection criterion. This method utilizes local measurements only and can be used with both radial and ring bus DCMG.

5.3 Differential Protection Scheme

Differential protection is a conventional but fast, efficient, and simple unit protection scheme. This protection scheme only responds to faults within the protected section and ignores faults outside this section. If the difference between the current entering and the current leaving the protected section is greater than the preset threshold value, the fault will be detected. In [55], a multi-sample differential protection scheme has been presented for a DG-dominated DCMG. In [56], an intelligent differential protection scheme has been discussed in which machine learning techniques are also applied for fast fault detection. In this scheme, a machine learning-based support vector machine (SVM) classifier is used to make the scheme more robust against transient or temporary faults. The fault detection algorithm associated with this scheme is shown in Figure 9. According to this algorithm, the differential current is first calculated with the help of current measurement obtained from the sensors installed at both terminals of the line segment. This differential

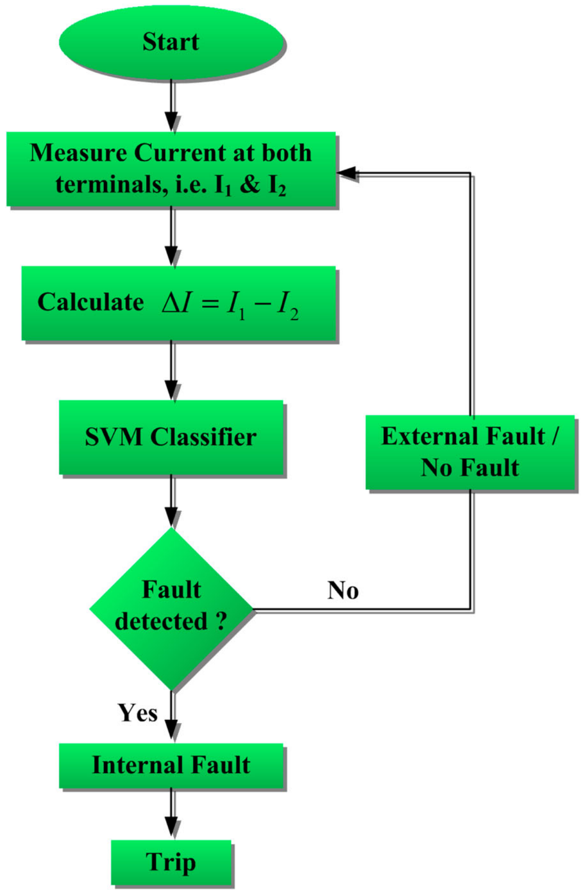


Figure 9: Flow diagram for SVM-based differential protection scheme [56]

current is then fed to the SVM classifier, which makes decision about the fault occurrence. If fault is detected, then it must be an internal fault, and the actuating signal for CB is generated. In [57] and [58], a similar differential protection scheme has been presented for the protection of photovoltaic-based DCMG.

5.4 Distance-Based Non-Unit Protection Scheme

The protection schemes discussed earlier are good for fault detection, but fault location estimation using those methods becomes difficult. Hence, in some literature, a distance-based protection scheme has been discussed for precise fault location. The backup protection can also be implemented using distance protection. In [59], a novel DC distance relay has been presented for the protection of medium voltage DC (MVDC) microgrids. To implement this scheme, a small inductor needs to be installed at the end of each line, and then the distance and directional components are extracted from the local inductor current and voltage.

5.5 Signal Processing-Based Methods

Such methods may have further sub-classification as follows:

1) Travelling Wave-Based Methods

For the various reasons discussed in previous sections, the fault current in DCMG increases very quickly. Hence, to provide proper protection to the equipment connected to the DCMG, the speed of the protection system should be very fast. Hence, to achieve a faster operation, travelling wave (TW) based protection has been discussed in many works of literature. In [60], a protection mechanism based on the TW-based method has been proposed. In this scheme, a discrete wavelet transform (WT) technique is utilized to extract the high-frequency component of the fault current, and then this information is processed through support vector machine (SVM) classifiers and a Gaussian regression engine (GRE) to know the fault type and fault location, respectively. One of the main merits of TW-based schemes is that they do not depend on the magnitude of fault current, and for this reason, these schemes provide satisfactory operation against high resistance faults [61]. In [62], another TW-based protection scheme has been presented for an MVDC microgrid. Another TW-based protection scheme has been proposed in [63]. In this scheme, single-end measurement is needed, hence no communication link is required. Some of the main advantages of TW-based DCMG protection schemes are [64]:

- Ultra-fast operation
- Utilizes local measurement of TW information only. Hence, no communication requirement.
- Back-up protection is possible
- Can handle high resistance fault very efficiently.

2) Oscillation Frequency-Based Method

A fault in a DC microgrid produces an oscillation in DC current during a transient, and this frequency of oscillation depends on the location and the type of fault [65]. In [66], a protection scheme has been proposed which utilizes the oscillation frequency of the fault current for fault identification. This scheme has been implemented for a ring-bus DCMG. In this scheme, the oscillation frequency and the associated transient power in the first cycle of oscillation have been calculated and utilized for designing the protection scheme. The algorithm for this scheme is presented in Figure 10.

According to this algorithm, a disturbance index is calculated by using the current samples obtained from the

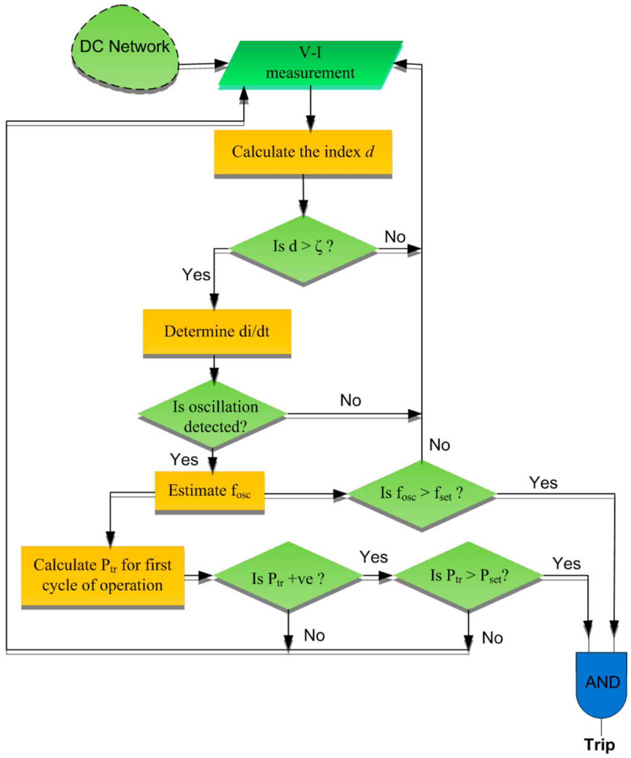


Figure 10: Flow chart of oscillation frequency-based protection scheme [66]

measurement devices placed at the relay points. If this disturbance index is greater than the threshold value, the current derivative is calculated, and if there is any oscillation detected, then the transient power and the frequency of oscillation is determined. The trip signal will be generated only if both the transient power and the oscillation frequency are greater than their respective threshold values.

The mathematical formulation to calculate the disturbance index has been given in (3).

$$d = \frac{1}{N.\Delta t}\left(\sum_{k=1}^{N} |i_{k+1} - i_k|\right) \tag{3}$$

Here, d is the disturbance index and N is the number of time interval of Δt.

In [67], another oscillation frequency-based protection scheme for DC microgrids has been proposed. This scheme presents an improvement to the existing differential current and di/dt-based protection schemes. In the differential current-based schemes, the differential current becomes available after a certain delay, and this delay is mainly due to the delay in measurement and data processing and the communication link delay. The proposed scheme provides a method to minimize this time delay.

3) Mathematical Morphology (MM)-Based Method

MM is a signal processing-based tool that is used to extract the different features of a signal, and these extracted features are used to distinguish between different operating modes of the system. The morphological operators are fast, simple, reliable, and applicable to high-frequency non-periodical signals [68]. In [69], an MM-based fault detection scheme has been proposed for the DCMG. The proposed scheme is fast, reliable, and provides accurate protection against HRFs of up to 50 Ω. The response time of this scheme for HRFs is about 4 ms. In [70], the MM-based technique is employed to design a protection scheme for ring-main DCMG. In the proposed scheme, MM-based filters were used to distinguish between HRFs and low resistance faults (LRFs).

5.6 ANN and AI Based Methods

The artificial neural network (ANN) and artificial intelligence (AI)-based methods are very useful in designing an adaptive protection scheme for DCMG protection. In [71], an ANN-based fault detection technique has been discussed for LVDC microgrids. The ANN-based schemes are very fast and reliable. The neural network is trained for different short-circuit levels to make the system more adaptive to different fault conditions. Based on the literature available till date, a few such schemes have been presented in this section.

1) Support-Vector Machine (SVM)-Based Method

A SVM-based fault location scheme for DCMG has been presented in [72]. Along with determining the fault location, the SVM-based method can also calculate the fault resistance and hence can determine the characteristics of the fault current. This method only looks at the current at one terminal, so there is no need for a communication link.

2) Wavelet Analysis-Based Method

The Wavelet transform (WT) is a very important mathematical tool and is widely used in studies on power system dynamics and protection. Previously, WT was frequently employed to design protection schemes for AC systems and HVDC systems [73], [74], and [75]. Nowadays, it is also been used for the protection of LVDC microgrids. In [76], a protection scheme for LVDC microgrid using wavelet transform has been discussed. In [77], a real-time boundary wavelet transforms-based protection scheme for the protection of multi-terminal DC (MTDC) systems has been discussed. The proposed method is claimed to be a fast, reliable, selective, and sensitive protection mechanism. In [78], another WT and ANN-based protection strategy for DC microgrids has been discussed. In this scheme, the branch current is measured and the WT is applied to the sampled current data to extract the characteristic feature of the current signal during a fault condition. The change in the current characteristic feature over time is used to find out what's wrong with the system.

3) Fuzzy Logic-Based Method

Integration of fuzzy logic in power system protection improves the decision-making process through fast and reliable decision-making. Fuzzy logic enhances the adaptivity of the protection scheme by thoroughly updating the threshold of relays in dynamically changing grid operation [79]. In [80], a fuzzy interface system (FIS) based differential protection scheme has been proposed for the protection of LVDC microgrids. In this scheme, FIS is employed to decide the threshold differential current value, above which the protection scheme should respond. In [81], an ANN and fuzzy logic-based hybrid approach has been discussed to design the protection scheme for a microgrid. Another fuzzy logic-based differential protection scheme for DC microgrids is discussed in [82].

5.7 Several Other Methods

Apart from the methods discussed above, there are several other techniques for DCMG protection that have been discussed in various literatures. In [83], a closed-form mathematical model-based approach for LVDC microgrid protection has been discussed. The proposed method uses single-ended measurement and can be applied to both radial and meshed distribution networks. Due to the application of single-ended measurement, the response time of this scheme is faster than those differential current-based schemes in which both end measurements are required. However, to calculate the current derivative accurately, the current data needs to be sampled at a very high sampling frequency (*i.e.* in MHz range). This can be considered one of the limitations of this protection scheme. In [84], an event classification approach-based method for the protection of a multi-bus DCMG is discussed. In this approach, any fault is first classified into three categories, *i.e.* bus fault, interconnected feeder fault, and adjacent bus fault, and then the decision on fault condition is made depending on the type of fault and the information received from the other interconnected feeders through a communication link. Since this method employs communication links, hence reliability of such a scheme is less due to the chances of communication failure. In [85], a parameter estimation-based protection scheme for fault location in DCMG is discussed. The presented scheme is based on single-end measurement and no communication link is required; hence the cost is less and the chances of failure of the protection scheme are also less as it is independent of the failures of the communication system. However, this scheme may not be very suitable for the protection against high resistance faults. In [86], a way to protect against short-circuit faults in a capacitor-dominated LVDC microgrid has been talked about. In this scheme, the average capacitor current has been considered as a fault detection criterion. For the protection of DCMG, a model-based protection strategy is proposed in [87]. This scheme provides a system-level centralized protection solution and has better selectivity and sensitivity than the model-free methods. This protection scheme claims to have a response time of 1 ms. An active converter injection-based protection scheme has been proposed in [88]. This scheme is designed for the protection of PV-based DC microgrid. Further, a brief overview of the available protection schemes has been presented in Table 3.

6. FUTURE SCOPE AND GAPS

Following are some possible research areas that require attention based on the findings of this study:

- Optimum placement of DERs in the DC microgrid such that the impact of DG integration on the protection and stability should be minimum.
- In DC microgrids, most of the loads are constant power loads and very few available protection schemes have examined this scenario.
- Detection and protection from arc faults are still unexplored areas. A protection scheme must be designed for these faults also.
- Requirement of a fast, reliable, and adaptive protection scheme for protection against HRFs.
- A common protection scheme for both the AC and DC lines of a hybrid AC/DC microgrid can also be a very good research area.

7. CONCLUSION

This paper presents a detailed review of the different protection schemes and their merits and demerits. This

Table 3: **Summary of some widely employed protection schemes for DC microgrid**

Literature	Fault detection/classification technique	Operating Time	Measurement type	Protection against HRF	Communication Link Requirement	Remarks
[48]	Superimposed resistance	3 ms	Double-ended	Yes, up to 30 Ω	Yes	• Applied for tapped DCMG architecture
[41,43]	Overcurrent	1–2 ms	Single-end	Not mentioned	Yes	• Can provide back-up protection
[45]	di/dt + adaptive droop	0.2–1 ms	Single-end for low resistance fault, and double-ended for HRF.	Yes, up to 500 Ω.	Yes	• Proposed for stand-alone DC microgrid • Complex implementation
[46]	Transient voltage + wavelet transform	2.2 ms	Single-end measurement	Yes	No	• Designed for a modular multilevel converter based DCMG
[47]	Pseudo voltage	0.2 ms	Single-end measurement	Not mentioned	No	• Proposed algorithm is fast, but the protection against HRF is not discussed
[49]	Resistance estimation	2 ms	Single-end measurement	Yes, up to 50 Ω	No	• Proposed for ring bus DCMG • Operating time 2 ms
[50]	Real-time resistance estimation	2.5 ms	Single-end measurement	Not mentioned	No	• Proposed for zonal type LVDC microgrid
[52,53]	Active Impedance Estimation	< 100 ms	Single-end measurement	Not mentioned	No	• Proposed for zonal type DCMG • Designed for protection of DC marine system
[56]	Differential current + Machine learning	0.208 ms	Double-ended measurement	Not mentioned	Yes	• Effective against temporary faults
[57]	Differential current	< 100 ms	Double-ended measurement	Not mentioned	Yes	• Proposed for PV based DCMG
[59]	Distance protection	0.1 ms	Single-end measurement	Yes	No	• Can provide backup protection • Designed for MVDC
[60]	Travelling wave + Wavelet transform	0.2 ms	Single-end measurement	Yes	No	• Independent to the magnitude of fault current
[62]	Travelling wave	1–2 μs	Single-end measurement	Yes, up to 200 Ω	No	• Proposed for MVDC microgrid
[89]	VMD based	3.95 ms	Single-end measurement	Yes, up to 20 Ω	No	• Proposed for LVDC microgrid • Uses local measurement only
[72]	SVM based	–	Single-end measurement	Yes, up to 20 Ω	No	• Less costly
[77]	RT-BWT based	0.5 ms	Single-end measurement	Yes, up to 250 Ω	No	• Applied for MTDC system
[78]	WT + ANN	2–5 ms	Single-end measurement	Yes, up to 300 Ω	No	• Fault classification accuracy 98–99%
[82]	Fuzzy logic-based differential protection	–	Double-ended measurement	Not mentioned	Yes	• Fuzzy logic is used to determine the threshold differential current
[84]	Event classification based	0.1 ms	Single-end measurement	Not mentioned	Yes	• Designed for multi-bus DCMG
[85]	Parameter estimation based	–	Single-end measurement	Yes, up to 6 Ω	No	• Less costly

paper also discusses and compares DC as well as AC microgrids. A detailed study of the protection issues in the dc microgrid has been presented and the various protection challenges along with their reasons have been listed in this paper. Some of the key issues of the dc microgrid are the lack of universal operating standards, the unsuitability of the conventional CBs, the effect of grounding systems, and the dynamic nature of the microgrid due to different operating modes *i.e.* grid connected and islanded modes. A brief comparative study of different grounding systems for DCMG has also been presented in this article. A brief overview of the schemes available for DCMG protection has also been presented in this study. Further, it has been found that communication-assisted protection schemes, such as differential protection scheme, over-current protection, *etc*., have better selectivity and some of them can also provide backup protection also, but the problem with such schemes is the slow response and less reliability. Communication-based protection schemes generally have a high response time and less reliability due to the chances of maloperation of communication equipment. Therefore, the possible areas to explore and fill the research gaps can be protection against arcing faults, the effect of constant power loads, and the impact of DERs placement on the protection and stability of the system.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

REFERENCES

1. P. J. Burke, D. I. Stern, and S. B. Bruns, "The impact of electricity on economic development: A macroeconomic perspective," *Int. Rev. Environ. Resour. Econ*, Vol. 12, no. 1, pp. 85–127, 2018. doi:10.1561/101.00000101.

2. I. Arto, I. Capellán-Pérez, R. Lago, G. Bueno, and R. Bermejo, "The energy requirements of a developed world," *Energy Sustain. Dev*, Vol. 33, pp. 1–13, Aug. 2016. doi:10.1016/J.ESD.2016.04.001.

3. A. Hooshyar, and R. Iravani, "Microgrid protection," *Proc. IEEE*, Vol. 105, no. 7, pp. 1332–1353, Jul 2017. doi:10.1109/JPROC.2017.2669342.

4. G. B. Garehpetian, H. R. Baghaee, and M. M. Shabestary. *Microgrids and methods of analysis*, 1st ed. Cambridge: Academic Press, 2021.

5. M. T. Yeshalem, and B. Khan, "Microgrid Integration," in *Special Topics in Renewable Energy Systems*, 1st ed., E. Yüksel, A. Gök, M. Eyvaz Eds. London: IntechOpen, 2018, pp. 51–66.

6. Y. Liu, Y. Gu, D. Yang, and J. Wang, "Fault identification and relay protection of hybrid microgrid using blockchain and machine learning," *IETE Journal of Research*, Vol. in press, pp. 1–11, Mar. 2022. doi:10.1080/03772063.2022.2050307.

7. G. Shahgholian, "A brief review on microgrids: operation, applications, modeling, and control," *Int. Trans. Electr. Energy Syst*, Vol. 31, no. 6, pp. e12885, Jun. 2021. doi:10.1002/2050-7038.12885.

8. L. Ortiz, R. Orizondo, A. Águila, J. W. González, G. J. López, and I. Isaac, "Hybrid AC/DC microgrid test system simulation: grid-connected mode," *Heliyon*, Vol. 5, no. 12, pp. e02862, Dec. 2019. doi:10.1016/J.HELIYON.2019.E02862.

9. F. S. Al-Ismail, "DC microgrid planning, operation, and control: A comprehensive review," *IEEE. Access.*, Vol. 9, pp. 36154–36172, 2021. doi:10.1109/ACCESS.2021.3062840.

10. S. Ali, Z. Zheng, M. Aillerie, J. P. Sawicki, M. C. Péra, and D. Hissel, "A review of DC microgrid energy management systems dedicated to residential applications," *Energies 2021*, Vol. 14, no. 14, pp. 4308, Jul. 2021. doi:10.3390/EN14144308.

11. D. J. Hammerstrom, "AC versus DC distribution systems-did we get it right?" IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24-28 June, 2007, pp. 1–5.

12. S. Faazila Fathima, and L. Premalatha, "Protection strategies for AC and DC microgrid – A review of protection methods adopted in recent decade," *IETE J. Res.*, pp. 1–17, 2021. doi:10.1080/03772063.2021.1990140.

13. M. Mishra, B. Patnaik, M. Biswal, S. Hasan, R. B.-A. Energy, and undefined, "A systematic review on DC-microgrid protection and grounding techniques: issues, challenges and future perspective," *Elsevier*, Vol. 313, no. 10, pp. 1–25, 2022. doi:10.1016/j.apenergy.2022.118810.

14. D. Salomonsson, L. Söder, and A. Sannino, "Protection of low-voltage DC microgrids," *IEEE Trans. Power Deliv*, Vol. 24, no. 3, pp. 1045–1053, 2009. doi:10.1109/TPWRD.2009.2016622.

15. J. J. Justo, F. Mwasilu, J. Lee, and J. W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renew. Sustain. Energy Rev*, Vol. 24, pp. 387–405, 2013. doi:10.1016/J.RSER.2013.03.067.

16. N. Bayati, A. Hajizadeh, and M. Soltani, "Protection in DC microgrids: a comparative review," *IET Smart Grid*, Vol. 1, no. 3, pp. 66–75, Oct. 2018. doi:10.1049/IET-STG.2018.0035.

17. S. Choudhury, "A comprehensive review on issues, investigations, control and protection trends, technical challenges and future directions for microgrid technology," *Int. Trans. Electr. Energy Syst*, Vol. 30, no. 9, pp. e12446, Sep. 2020. doi:10.1002/2050-7038.12446.

18. S. Augustine, J. E. Quiroz, M. J. Reno, and S. Brahma, "DC microgrid protectionâĂŕ: review and challenges," *Researchgate.Net*, no. August, 2018. doi:10.2172/1465634.

19. D. Kumar, F. Zare, and A. Ghosh, "DC microgrid technology: system architectures, AC grid interfaces, grounding schemes, power quality, communication networks, applications, and standardizations aspects," *IEEE. Access.*, Vol. 5, no. August, pp. 12230–12256, 2017. doi:10.1109/ACCESS.2017.2705914.

20. M. H. Ibrahim, E. A. Badran, and M. H. Abdel-Rahman, "On the DC microgrids protection challenges, schemes, and devices - A review," in *DC Microgrids: Advances, Challenges, and Applications* Hoboken, New Jersey: Wiley-Blackwell, 2021, pp. 1–6210.1002/9781119777618.CH1.

21. S. Baidya, and C Nandi, "A comprehensive review on DC microgrid protection schemes," *Electr. Power Syst. Res.*, pp. 1–12, 2022. doi:10.1016/j.epsr.2022.108051.

22. K. Anjaiah, P. Kishore Dash, and M. Sahani, "A new protection scheme for PV-wind based DC-ring microgrid by using modified multifractal detrended fluctuation analysis," *Prot. Control Mod. Power Syst.*, Vol. 7, no. 8, pp. 1–24, 2022. doi:10.1186/s41601-022-00232-3.

23. J. S. Farkhani, M. Zareein, A. Najafi, R. Melicio, and E. M. G. Rodrigues, "The power system and microgrid protection—a review," *Appl. Sci*, Vol. 10, no. 22, pp. 1–30, 2020. doi:10.3390/app10228271.

24. A. A. Sheikh, *et al.*, "A brief review on DC microgrid protection," *Proc. 2020 IEEE 1st Int. Conf. Smart Technol. Power, Energy Control. STPEC*, Vol. 2020, 2020. doi:10.1109/STPEC49749.2020.9297770.

25. C. Srivastava, and M. Tripathy, "DC microgrid protection issues and schemes: A critical review," *Renew. Sustain. Energy Rev*, Vol. 151, pp. 111546, Nov. 2021. doi:10.1016/J.RSER.2021.111546.

26. H. L. R. van der Walt, R. C. Bansal, and R. Naidoo, "PV based distributed generation power system protection: A review," *Renew. Energy Focus*, Vol. 24, pp. 33–40, Mar. 2018. doi:10.1016/J.REF.2017.12.002.

27. S. Beheshtaein, R. M. Cuzner, M. Forouzesh, M. Savaghebi, and J. M. Guerrero, "DC microgrid protection: A comprehensive review," *IEEE J. Emerg. Sel. Top. Power Electron*, 1–1, Mar. 2019. doi:10.1109/JESTPE.2019.2904588.

28. L. Wang, B. Feng, Y. Wang, T. Wu, and H. Lin, "Bidirectional short-circuit current blocker for DC microgrid based on solid-state circuit breaker," *Electron. 2020*, Vol. 9, no. 2, pp. 306, Feb. 2020. doi:10.3390/ELECTRONICS9020306.

29. J. Mohammadi, F. B. Ajaei, and G. Stevens, "Grounding the DC microgrid," *IEEE Trans. Ind. Appl*, Vol. 55, no. 5, pp. 4490–4499, Sep. 2019. doi:10.1109/TIA.2019.2928278.

30. J. Mohammadi. … F. A.-I. T. on, and undefined 2019, "Grounding the DC microgrid," *ieeexplore.ieee.org*.

31. (PDF) Electrical installation guide. According to IEC international standards | bagus istiyawan - Academia.edu."Apr. 29, 2022. Available: https://www.academia.edu/24692935/Electrical_installation_guide_2013_According_to_IEC_international_standards, 2013.

32. R. E. Torres-Olguin, "DC faults in HVDC: Detection, identification, and handling," in *Model. Oper. Anal. DC Grids* USA: Academic Press, 2021, pp. 27–6710.1016/B978-0-12-822101-3.00008-3.

33. D. Rebollal, M. Carpintero-Rentería, D. Santos-Martín, and M. Chinchilla, "Microgrid and distributed energy resources standards and guidelines review: grid connection and operation technical requirements," *Energies*, Vol. 14, no. 3, pp. 1–24, Feb. 2021. doi:10.3390/EN14030523.

34. "IEC Standard SG4." Mar. 02, 2022. Available: https://www.iec.ch/dyn/www/f?p=103:85:0::::FSP_ORG_ID:6019

35. "IEEE SA - IEEE 946-2020." Mar. 02, 2022 Available: https://standards.ieee.org/ieee/946/6139/

36. G. Joos, J. Reilly, W. Bower, and R. Neal, "The need for standardization," *IEEE Power Energy Mag.*, Vol. 15, no. 4, pp. 32–40, 2017. doi:10.1109/MPE.2017.2690518.

37. J. Mohammadi, F. B. Ajaei, and G. Stevens, "DC microgrid grounding strategies," *Conf. Rec. - Ind. Commer. Power Syst. Tech. Conf*, Vol. 2018-May, pp. 1–6, May 2018. doi:10.1109/ICPS.2018.8369995.

38. J. Do Park, and J. Candelaria, "Fault detection and isolation in low-voltage dc-bus microgrid system," *IEEE Trans. Power Deliv*, Vol. 28, no. 2, pp. 779–787, 2013. doi:10.1109/TPWRD.2013.2243478.

39. R. M. Cuzner, T. Sielicki, A. E. Archibald, and D. A. McFarlin, "Management of ground faults in an ungrounded multi-terminal zonal DC distribution system with auctioneered loads," *2011 IEEE Electr. Sh. Technol. Symp. ESTS 2011*, pp. 300–305, 2011. doi:10.1109/ESTS.2011.5770886.

40. R. Mohanty, and A. K. Pradhan, "A superimposed current based unit protection scheme for DC microgrid," *IEEE Trans. Smart Grid*, Vol. 9, no. 4, pp. 3917–3919, 2018. doi:10.1109/TSG.2018.2835645.

41. P. S. Haritha, S. Sambhu, and V. Ravikumar Pandi, "Communication assisted coordinated protection scheme for DC microgrid," *2018 3rd IEEE Int. Conf. Recent Trends Electron. Inf. Commun. Technol. RTEICT 2018 - Proc*, 351–356, 2018. doi:10.1109/RTEICT42901.2018.9012124.

42. R. K. Rachi, S. Member, and M. A. Khan, "Local measurement-based protection coordination system for a standalone DC microgrid," *IEEE Trans. Ind. Appl.*, Vol. 57, no. 5, pp. 5332–5344, 2021.

43. A. Shabani, and K. Mazlumi, "Evaluation of a communication-assisted overcurrent protection scheme for photovoltaic-based DC microgrid," *IEEE Trans. Smart Grid*, Vol. 11, no. 1, pp. 429–439, 2020. doi:10.1109/TSG.2019.2923769.

44. P. Chauhan, C. P. Gupta, and M. Tripathy, "A novel adaptive protection technique based on rate-of-rise of fault current in DC microgrid," *Electr. Power Syst. Res*, Vol. 207, no. July 2021, pp. 107832, 2022. doi:10.1016/j.epsr.2022.107832.

45. S. Augustine, M. J. Reno, S. M. Brahma, and O. Lavrova, "Fault current control and protection in a standalone DC microgrid using adaptive droop and current derivative," *IEEE J. Emerg. Sel. Top. Power Electron*, Vol. 9, no. 3, pp. 2529–2539, 2021. doi:10.1109/JESTPE.2020.2984609.

46. W. Xiang, S. Yang, L. Xu, S. Member, J. Zhang, and W. Lin, "A transient voltage based DC fault line protection scheme for MMC based DC grid embedding DC breakers," *IEEE Trans. Power Deliv*, Vol. 34, no. c, pp. 334–345, 2018. doi:10.1109/TPWRD.2018.2874817.

47. Y. Yang, C. Huang, D. Zhou, and Y. Li, "Fault detection and location in multi-terminal DC microgrid based on local measurement," *Electr. Power Syst. Res*, Vol. 194, no. June 2020, pp. 107047, 2021. doi:10.1016/j.epsr.2021.107047.

48. G. Kesava Rao, and P. Jena, "Unit protection of tapped line DC microgrid," *IEEE J. Emerg. Sel. Top. Power Electron*, Vol. 6777, no. c, pp. 1–10, 2022. doi:10.1109/JESTPE.2022.3143525.

49. G. K. Rao, and P. Jena, "Fault detection in DC microgrid based on the resistance estimation," *IEEE Syst. J.*, Vol. 16, no. 1, pp. 1009–1020, 2020.

50. H. Pradesh, and H. Pradesh, "A real-time resistance based fault detection technique For zonal type Low-voltage DC microgrid applications neelesh yadav narsa reddy tummuru," *IEEE Trans. Ind. Appl.*, Vol. 56, no. 6, 2020. doi:10.1109/TIA.2020.3017564.

51. N. Bayati, and H. Baghaee. … A. H.-I. S., and undefined 2020, "Localized protection of radial DC microgrids with high penetration of constant power loads," *ieeexplore.ieee.org*.

52. E. Christopher, M. Sumner, D. Thomas, and F. De Wildt, "Fault location for a DC zonal electrical distribution systems using active impedance estimation," *2011 IEEE Electr. Sh. Technol. Symp. ESTS 2011*, 310–314, 2011. doi:10.1109/ESTS.2011.5770888.

53. E. Christopher, *et al.*, "Fault location in a zonal DC marine power system using active impedance Estimation," *IEEE Trans. Ind. Appl.*, Vol. 49, no. 2, pp. 860–865, 2013. doi:10.1109/TIA.2013.2243391.

54. V. Nougain, and B. K. Panigrahi, "Detection of DC system faults based on the principle of threshold violation in i-r plane," *IEEE Syst. J*, Vol. 15, no. 1, pp. 856–864, 2021. doi:10.1109/JSYST.2020.3010370.

55. C. Li, P. Rakhra, P. J. Norman, G. M. Burt, and P. Clarkson, "Multi-Sample differential protection scheme in DC microgrids," *IEEE J. Emerg. Sel. Top. Power Electron*, Vol. 9, no. 3, pp. 2560–2573, 2021. doi:10.1109/JESTPE.2020.3005588.

56. N. K. Sharma, A. Saxena, and S. R. Samantaray, "An intelligent differential protection scheme for DC microgrid, in *2021 9th IEEE International Conference on Power Systems (ICPS)*, 2022, pp. 1–6.

57. S. Dhar, R. K. Patnaik, and P. K. Dash, "Fault detection and location of photovoltaic based DC microgrid using differential protection strategy," *IEEE Trans. Smart Grid*, Vol. 9, no. 5, pp. 4303–4312, 2018. doi:10.1109/TSG.2017.2654267.

58. S. Dhar, and P. K. Dash, "Differential current-based fault protection with adaptive threshold for multiple PV-based DC microgrid," *IET Renew. Power Gener*, Vol. 11, no. 6, pp. 778–790, 2017. doi:10.1049/iet-rpg.2016.0577.

59. M. A. Allam, and K. A. Saleh, "A novel DC distance relay for MVDC microgrids," *IEEE Trans. Smart Grid*, Vol. 13, no. 2, pp. 962–974, 2022. doi:10.1109/TSG.2021.3135791.

60. R. Montoya, B. P. Poudel, A. Bidram, and M. J. Reno, "DC microgrid fault detection using multiresolution analysis of traveling waves," *Int. J. Electr. Power Energy Syst*, Vol. 135, pp. 107590, 2022. doi:10.1016/j.ijepes.2021.107590.

61. Y. Zhang, N. Tai, and B. Xu, "Fault analysis and traveling-wave protection scheme for bipolar HVDC lines," *IEEE Trans. Power Deliv*, Vol. 27, no. 3, pp. 1583–1591, 2012. doi:10.1109/TPWRD.2012.2190528.

62. K. A. Saleh, A. Hooshyar, and E. F. El-Saadany, "Ultra-high-speed traveling-wave-based protection scheme for medium-voltage DC microgrids," *IEEE Trans. Smart Grid*, Vol. 10, no. 2, pp. 1440–1451, 2019. doi:10.1109/TSG.2017.2767552.

63. Z. He, X. Li, and S. Chen, "A traveling wave natural frequency-based single-ended fault location method with unknown equivalent system impedance," *Int. Trans. Electr. Energy Syst*, Vol. 26, no. 3, pp. 509–524, Mar. 2016. doi:10.1002/ETEP.2090.

64. M. A. Aftab, S. M. S. Hussain, I. Ali, and T. S. Ustun, "Dynamic protection of power systems with high penetration of renewables: A review of the traveling wave based fault location techniques," *Int. J. Electr. Power Energy Syst*, Vol. 114, pp. 105410, Jan. 2020. doi:10.1016/J.IJEPES.2019.105410.

65. Z. Y. He, K. Liao, X. P. Li, S. Lin, J. W. Yang, and R. K. Mai, "Natural frequency-based line fault location in HVDC lines," *IEEE Trans. Power Deliv*, Vol. 29, no. 2, pp. 851–859, 2014. doi:10.1109/TPWRD.2013.2269769.

66. R. Mohanty, and A. K. Pradhan, "DC ring bus microgrid protection using the oscillation frequency and transient power," *IEEE Syst. J*, Vol. 13, no. 1, pp. 875–884, 2019. doi:10.1109/JSYST.2018.2837748.

67. S. A. Wakode, M. S. Ballal, A. A. Sheikh, and R. R. Deshmukh, "Oscillation frequency component-based protection scheme for DC microgrid," *IEEE Trans. Ind. Appl*, Vol. 57, no. 6, pp. 5747–5757, 2021. doi:10.1109/TIA.2021.3115089.

68. R. Godse, and S. Bhat, "Mathematical morphology-based feature-extraction technique for detection and classification of faults on power transmission line," *IEEE. Access.*, Vol. 8, pp. 38459–38471, 2020. doi:10.1109/ACCESS.2020.2975431.

69. N. Bayati, H. R. Baghaee, A. Hajizadeh, M. Soltani, and Z. Lin, "Mathematical morphology-based local fault detection in DC microgrid clusters," *Electr. Power Syst. Res*, Vol. 192, no. December 2020, pp. 106981, 2021. doi:10.1016/j.epsr.2020.106981.

70. H. M. M. Maruf, F. Kamal, and B. H. Chowdhury, "Mathematical morphological filter based protection scheme for DC ring microgrid system ", in *2018 North American Power Symposium, NAPS* 2018, pp. 1–6.

71. Q. Yang, J. Li, S. Le Blond, and C. Wang, "Artificial neural network based fault detection and fault location in the DC microgrid," *Energy Procedia*, Vol. 103, no. April, pp. 129–134, 2016. doi:10.1016/j.egypro.2016.11.261.

72. N. Bayati, *et al.*, "Locating high-impedance faults in DC microgrid clusters using support vector machines," *Appl. Energy*, Vol. 308, no. July 2021, pp. 118338, 2022. doi:10.1016/j.apenergy.2021.118338.

73. M. Manohar, E. Koley, and S. Ghosh, "A wavelet and ANFIS based reliable protection technique for microgrid", in *2019 8th International Conference on Power Systems: Transition towards Sustainable, Smart and Flexible Grids, ICPS* 2019, pp. 1–6.

74. H. C. Seo, and S. B. Rhee, "Novel adaptive reclosing scheme using wavelet transform in distribution system with battery energy storage system," *Int. J. Electr. Power Energy Syst*, Vol. 97, pp. 186–200, Apr. 2018. doi:10.1016/J.IJEPES.2017.11.009.

75. D. P. Mishra, S. R. Samantaray, and G. Joos, "A combined wavelet and data-mining based intelligent protection scheme for microgrid," *IEEE Trans. Smart Grid*, Vol. 7, no. 5, pp. 2295–2304, Sep. 2016. doi:10.1109/TSG.2015.2487501.

76. H. C. Seo, "Development of New protection scheme in DC microgrid using wavelet transform," *Energies*, Vol. 15, no. 1, pp. 1–24, 2022. doi:10.3390/en15010283.

77. L. Sabug, A. Musa, F. Costa, and A. Monti, "Real-time boundary wavelet transform-based DC fault protection system for MTDC grids," *Int. J. Electr. Power Energy Syst*, Vol. 115, no. March 2019, pp. 105475, 2020. doi:10.1016/j.ijepes.2019.105475.

78. D. K. J. S. Jayamaha, N. W. A. Lidula, and A. D. Rajapakse, "Wavelet-Multi resolution analysis based ANN architecture for fault detection and localization in DC microgrids," *IEEE. Access.*, Vol. 7, pp. 145371–145384, 2019. doi:10.1109/ACCESS.2019.2945397.

79. M. Khederzadeh, "Adaptive setting of protective relays in microgrids in grid-connected and autonomous operation", in 11th IET Int. Conf. Dev. Power Syst. Prot. (DPSP 2012), 2012.

80. A. Abdali, K. Mazlumi, and R. Noroozian, "Fast fault detection and isolation in low-voltage DC microgrids using fuzzy inference system", in *2017 5th Iranian Joint Congress on Fuzzy and Intelligent Systems (CFIS)*2017, pp. 172–177.

81. M. J. Daryani, A. E. Karkevandi, and O. Usta, "A hybrid approach for microgrid protection system based on neural network and fuzzy logic," *Proc. 2019 IEEE PES Innov. Smart Grid Technol. Eur. ISGT-Europe 2019*, 1–5, 2019. doi:10.1109/ISGTEurope.2019.8905476.

82. M. Dashtdar, O. Rubanenko, D. Danylchenko, S. M. S. Hosseinimoghadam, N. K. Sharma, and M. Baiai, "Protection of DC microgrids based on differential protection method by fuzzy systems," *2021 IEEE 2nd KhPI Week Adv. Technol. KhPI Week 2021 - Conf. Proc*, 22–27, Sep. 2021. doi:10.1109/KHPIWEEK53812.2021.9570079.

83. M. Bin Gani, and S. Brahma, "A closed-form mathematical model and method for fast fault location on a Low voltage dc feeder using single-ended measurements," *IEEE Open Access J. Power Energy*, 1, 2022. doi:10.1109/OAJPE.2022.3154705.

84. M. Farhadi, and O. A. Mohammed, "A New protection scheme for multi-Bus DC power systems using an event classification approach," *IEEE Trans. Ind. Appl*, Vol. 52, no. 4, pp. 2834–2842, 2016. doi:10.1109/TIA.2016.2545639.

85. N. Bayati, H. R. Baghaee, A. Hajizadeh, M. Soltani, Z. Lin, and M. Savaghebi, "Local fault location in meshed DC microgrids based On parameter estimation technique," *IEEE Syst. J*, Vol. 16, no. 1, pp. 1606–1615, 2022. doi:10.1109/JSYST.2021.3107905.

86. N. Yadav, and N. R. Tummuru, "Short-Circuit fault detection and isolation using filter capacitor current signature in Low-voltage DC microgrid applications," *IEEE Trans. Ind. Electron*, Vol. 69, no. 8, pp. 8491–8500, 2022. doi:10.1109/TIE.2021.3109523.

87. T. Wang, *et al.*, "Model-based fault detection and isolation in DC microgrids using optimal observers," *IEEE J. Emerg. Sel. Top. Power Electron*, Vol. 9, no. 5, pp. 5613–5630, 2021. doi:10.1109/JESTPE.2020.3045418.

88. K. Jia, Z. Shi, C. Wang, J. Li, and T. Bi, "Active converter injection-based protection for a photovoltaic DC distribution system," *IEEE Trans. Ind. Electron*, Vol. 69, no. 6, pp. 5911–5921, 2022. doi:10.1109/TIE.2021.3086726.

89. N. K. Sharma, S. R. Samantaray, and C. N. Bhende, "VMD-Enabled Current-Based fast fault detection scheme for DC microgrid," *IEEE Syst. J*, 2021. doi:10.1109/JSYST.2021.3057334.

AUTHORS

Kamal Kant received his Bachelor of Technology in electrical engineering from Silicon Institute of Technology, Sambalpur (Odisha), in 2015, and Master of Technology in power system engineering from VSSUT, Burla (Odisha), India, in 2018. Presently, he is pursuing PhD in the Department of Electrical Engineering, NIT Jamshedpur (India). His research area is the protection of electrical power system network including AC as well as DC microgrid.

Corresponding author. Email: 2021rsee004@nitjsr.ac.in

Om Hari Gupta received the PhD degree in electrical engineering from the Indian Institute of Technology Roorkee, Uttarakhand, India. He has visited the University of Ontario Institute of Technology (UOIT), Oshawa, Canada, for research on microgrid operation. Currently, he is an assistant professor in the Department of Electrical Engineering, National Institute of Technology Jamshedpur, India. He is a recipient of Queen Elizabeth II scholarship for pursuing research on microgrid operation at UOIT, Canada. His research interests include power system compensation and protection, microgrid control and protection, and control of drives.

E-mail: omhari.ee@nitjsr.ac.in