

Review

Breaking Barriers: Strategies for Effective Protection of DC Microgrid Systems

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Abstract

The direct current (DC) microgrid's remarkable power delivery performance has led to its development into a promising distribution network. However, creating efficient protective systems remains a major challenge for DC microgrids. Presently, the emphasis on DC microgrids is on architectural structures, control techniques, and energy management, with minimal attention given to fault analysis, detection, and isolation. Thus, the purpose of this paper is to provide researchers with a thorough grasp of DC microgrid protection by examining the current level of research in key fields and evaluating potential protection solutions. Furthermore, this study indicates key areas for future research to solve safety problems and promote the growth of the DC microgrid. Future research focuses on protection and the development of innovative protection devices that use electronic technology to provide flexible protection constraints and enhance appropriate protection schemes. Moreover, this review briefly discusses the protection challenges associated with electric vehicle (EV) integration in DC microgrids.

Keywords: DC microgrid; renewable energy resources; fault characteristic; fault current; protection technique; electric vehicle



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1. Introduction

The global transition toward low-carbon energy systems has accelerated the deployment of renewable energy sources (RESs), energy storage systems (ESSs), electric vehicles

(EVs), and DC-native loads. As countries pursue carbon neutrality and improve energy efficiency, microgrids have emerged as an attractive solution for integrating distributed energy resources while improving power quality, system reliability, and operational flexibility [1,2]. Microgrids can be categorised as either direct current (DC) or alternating current (AC) systems based on their electrical architecture. Due to their similarity compared to conventional AC power systems, AC microgrids have been the subject of numerous studies. DC microgrids (DCMGs) are receiving increasing attention from academics around the world because of their proven benefits. DC microgrids can transmit more power via a single line conductor and require fewer conversion stages than AC microgrids (ACMG).

Furthermore, since DC systems are unaffected by the skin effect, they can lower line losses and increase efficiency [3]. Although high-voltage DC (HVDC) technologies are widely used, the deployment of medium-voltage (MV) and low-voltage (LV) DC microgrids remains in its early stages. Particular applications for DC microgrids have been examined, such as LV (maximum of 1.5 kV DC) data centers [3] and LVDC distribution systems [4]; MV (maximum of 35 kV DC) systems installed on electric ships; and offshore wind power facilities [5]. Global initiatives such as FREEDM [6], UNIFLEX [7], and HEART [8] are being implemented by academic and industrial institutions in recognition of this potential. Each of them aims to elevate this technology to an exceptional level of research [9,10]. Given the excellent advantages of DC microgrids, developing appropriate protection mechanisms for DC microgrids is exceedingly complex. Besides that, there is a dearth of globally accepted protection norms and guidelines for usage in manufacturing and commercial environments. Certain organizations, including ETSI EN 300 132-3-1 [11–13], IEEE Standard 946 [14,15], and IEC SMB Strategic Group 4 [16,17], have formulated practical standards that cater to particular domains. For example, ETSI EN 300 132-3-1 applies to data and telecommunication systems, IEEE Standard 946 addresses DC auxiliary power systems and IEC SG4 covers LVDC distribution systems. Nevertheless, there is no officially recognized protective norm, and significant standardization remains a significant barrier.

In contrast to these advantages, protection continues to be one of the most significant challenges to broad deployment of DC microgrids. Contrary to regular AC distribution networks, DC microgrids have unique electrical characteristics that make conventional protection techniques ineffective. Bidirectional power flow and the limited fault current contribution from converter-interfaced sources lower relay sensitivity and jeopardize protection selectivity, while the lack of a natural current zero-crossing makes fault interruption more complicated. Furthermore, protection coordination becomes more complex when grid-connected and islanded operating modes are switched between often. Consequently, compared to traditional AC networks, fault detection, isolation, and protection coordination become far more difficult. Although energy management, control, and stability in DC microgrids (DCMGs) have been extensively studied [18], protection remains a critical and comparatively underdeveloped research area. Consequently, recent research has increasingly focused on addressing protection-related challenges, including fault detection, fault isolation, grounding strategies, and the integration of electric vehicles (EVs) and dynamic DC loads [19,20]. Failure to address these protection challenges may result in relay maloperation, delayed fault isolation, equipment damage, reduced system reliability, and increased operational costs. Consequently, the development of reliable, adaptive, and fast protection schemes has become one of the most critical research priorities for ensuring the safe and resilient operation of modern DC microgrids.

DC microgrid protection has been the subject of numerous thorough review studies, yet their primary interest and scope are distinct. Bayati et al. [18] reviewed DC microgrid protection methods, Srivastava and Tripathy [21] discussed protection issues and schemes, Baidya and Nandi [22] examined protection schemes and future research direc-

tions. Alam et al. [23] reviewed planning and protection aspects, while Kant and Gupta [24] and Beheshtaein et al. [25] provided comprehensive discussions of protection challenges and protection technologies. Following on these important contributions, considerable new research has been conducted recently due to the rapid advances in converter-interfaced renewable energy resources, intelligent protection methods, power electronic protection devices, electric vehicle integration, and cyber-secure protection frameworks [22,26]. For example, growing adoption of electric vehicles introduces bidirectional power flow, quick charging dynamics, and greater fault current levels, while intelligent and cyber-secure protection technologies are taking shape to cope with the growing level of complexity of modern DC microgrids [27,28]. Consequently, an updated review that synthesizes these developments within a unified framework is timely and necessary. Accordingly, this review provides a comprehensive assessment of DC microgrid protection by integrating fault characteristics, grounding methods, protection devices, relay coordination, converter-based protection, intelligent protection techniques, the protection implications of electric vehicle integration, and cyber-secure protection approaches. In addition, this review presents comparative evaluations of existing protection strategies and discusses current research gaps and future research directions toward adaptive and resilient DC microgrid protection systems.

Thus, this study reviews recent research developments to provide researchers with a clearer understanding of the protection challenges in DC microgrids. Furthermore, this paper briefly discusses the protection issues related to electric vehicle integration in DC microgrids and considers the use of emerging intelligent protection methods. The study also compares existing protection systems and highlights their strengths and limitations. It then discusses newer solutions that could improve the reliability, selectivity, and resilience of future DC microgrids. The key topics addressed in this paper are as follows:

- (a) The progression of DC microgrids and the obstacles encountered during their implementation.
- (b) Suitability of conventional protection schemes for DC microgrids and the obstacles they present.
- (c) Recent advances in protection schemes and their integration into existing DC microgrid architectures.
- (d) A brief discussion of the protection implications associated with electric vehicle integration in DC microgrids.
- (e) Future research directions, particularly those involving intelligent and adaptive protection techniques.

The paper is organized as follows. Section 2 describes the narrative literature review methodology, including the search strategy, selection criteria, and literature-screening process. Section 3 provides an overview of DC microgrid features, including system topologies, control strategies, and fault characteristics. Section 4 discusses the major challenges associated with DC microgrid protection, including fault current characteristics, protection coordination, grounding configurations, and protection-device limitations. Section 5 evaluates conventional and advanced protection schemes and discusses the protection challenges associated with electric vehicle integration. Section 6 presents the main research findings and recommendations for future DC microgrid protection systems. Finally, Section 7 concludes the paper.

2. Methodology of Narrative Literature Review

This study utilises a structured narrative literature review methodology instead of a typical systematic review [29]. While the literature selection followed predefined search strategies, criteria for inclusion and exclusion, and a structured screening process, the main goal was to carry out a comprehensive qualitative synthesis of recent developments

in DC microgrid (DCMG) protection instead of performing a statistical meta-analysis. Accordingly, the review critically examines recent developments in DCMG protection strategies to identify current protection challenges, evaluate existing protection techniques, analyse their advantages and limitations, and highlight future research directions.

Relevant literature was retrieved from four major scientific databases, including IEEE Xplore, Scopus, Web of Science, and ScienceDirect [30]. The literature search covered publications from 2008 to 2025 using combinations of keywords such as “DC microgrid”, “DC microgrid protection”, “fault detection”, “fault current”, “relay coordination”, “protection schemes”, “converter-based protection”, “artificial intelligence”, and “electric vehicles”. Only peer-reviewed journal articles and high-quality conference papers published in English were included. Publications irrelevant to DC microgrid protection, duplicate studies, and papers lacking adequate technical information were removed. Recent research with analytical, simulation, experimental, or hardware validation received greater interest.

The selected studies were evaluated and divided into primary themes, including DC microgrid topologies, fault attributes, protection challenges, conventional protection schemes, modern protection approaches, and electric car integration. Every protective technique was rigorously assessed in terms of its operational principle, benefits, drawbacks, practical relevance, and implementation challenges. This review presents a complete assessment of existing DC microgrid protection approaches, as well as outlining current research gaps and future directions for research. The literature search procedure used in this narrative review is depicted in Figure 1. The workflow includes an overview of the entire review process, starting with the database and keyword search and moving on to the application of eligibility criteria, literature screening, research classification, critical analysis, and compilation. This methodical process helps ensure that the selected papers were pertinent, technically solid, and reflective of the status of DC microgrid protection research at the time.

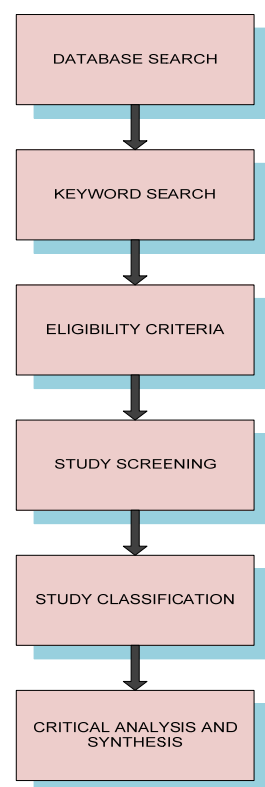


Figure 1. Literature search workflow adopted in this narrative review for the identification, screening, classification, and critical analysis of relevant studies on DC microgrid protection.

3. DC Microgrid (MG) Features

DCMGs can be utilized for a wide range of power applications, including small-scale power generation, backup power systems, energy storage applications, data centers, sensitive loads on ships and other vessels, and industrial applications. Renewable energy sources are intermittent. Therefore, microgrids require energy storage systems to maintain a reliable power supply. A clear understanding of DC microgrid design is important for addressing current and future network challenges.

The DC microgrid can operate in both grid-connected and islanded modes, depending on the specific requirements [31]. The coupling of the DC microgrid with the AC grid is one of the more complex aspects of the protection approach because several connection configurations are possible [9,22]. Thus, a clear understanding of the DCMG structure is required. DC microgrids must properly manage unexpected load variations, changes in operating mode, and the integration of several generating units. Consequently, different topologies can be used, including multiple-bus systems for reliable power sharing and single-bus systems for voltage regulation. Furthermore, different reconfiguration strategies have been proposed to connect DC microgrids to AC microgrids and utility networks [22].

3.1. DC Microgrids Topologies

A microgrid (MG) is an independent power system comprising multiple renewable energy sources (RESs), energy storage devices, energy conversion equipment, loads, and monitoring and protection mechanisms [32]. It can perform control, protection, and management operations independently. MGs can operate independently or connect to a broader network. Microgrids can be classified as AC, DC, or hybrid AC/DC systems according to their bus configuration. Most DC microgrid systems consist of four main components: loads, power sources, conversion devices, and energy storage systems. Figure 2 depicts a ring-bus layout used in a DC microgrid. Renewable energy sources in a DC microgrid can be classified as AC or DC sources [33]. Photovoltaic systems and other renewable DC sources are connected to the DC bus through a DC/DC converter [34]. Similarly, wind turbine generators are commonly connected to the DC bus through an AC/DC converter, which reduces the number of conversion stages [35]. Therefore, DC microgrids involve fewer energy conversion stages than AC microgrids, which may improve efficiency [36]. Different converters are used to connect sources and loads and to meet requirements such as efficiency, galvanic isolation, and voltage regulation.

Energy storage plays an important role in managing the transient power changes caused by the intermittent operation of renewable energy sources. It also helps improve power quality and provides emergency power support [3]. Common energy storage systems include batteries, supercapacitors, and flywheels [21,37]. Batteries and supercapacitors can be connected directly to the DC bus, while flywheel systems require a machine and a converter for integration. DC microgrids are also suitable for supplying sensitive electronic loads [3]. They can support applications such as security systems, communication and information systems, and lighting systems. Some DC and AC loads can be connected directly to the DC bus, while others require converters.

3.2. Control Strategies of DC Microgrids

DC microgrids depend on effective control systems to operate reliably and efficiently. Their control methods can generally be grouped into distributed, centralised, and hierarchical control [38]. Decentralised control uses local measurements and does not require a communication system, which can help maintain reliability and improve resource utilization [39]. This approach is particularly suitable for lower-capacity DC microgrids [40]. Droop control is a common form of decentralised control. It is often used to manage power

sharing among multiple sources and energy storage systems through the droop characteristics of the converters. Since the control method affects the transient behaviour of a DC microgrid, it can also influence the performance of the protection system. Therefore, control techniques need to be improved continuously to achieve a better transient response during fault conditions. For example, the droop control method proposed in [41,42] prioritises charging and discharging, protecting batteries against transient cycles.

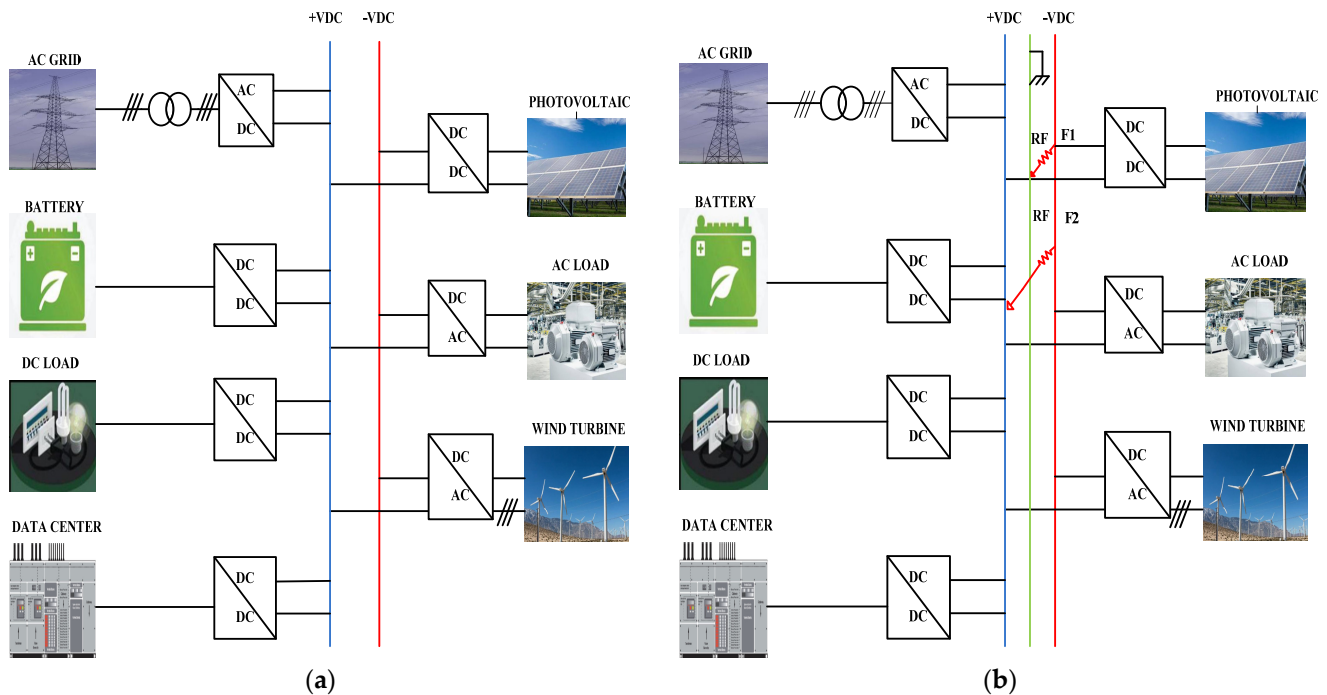


Figure 2. DC Schematic of a DC microgrid during (a) normal conditions and (b) fault illustrating the AC grid, renewable energy sources, battery-energy storage system, and load. The fault condition illustrates the fault location and associated fault current path.

The studies in [22,43] introduced a dynamic droop method for a hybrid energy storage system (HESS) that has been demonstrated to be more efficient than the previous droop management approach. DC microgrids have become more reliable as a consequence of both new and improved control systems.

3.3. Characteristics of a Fault

DC microgrids can experience several types of faults, including pole-to-pole (PP) and pole-to-ground (PG) faults. PG faults occur when one or both conductors come into contact with the ground, and high-impedance faults are commonly associated with this type of fault. In contrast, PP faults usually have low impedance, making them more severe but easier to detect [44]. Figure 3 shows the Thevenin equivalent circuits of DC and AC systems [18]. In DC systems, the fault current response can be divided into transient and steady-state components. The transient component mainly results from the discharge of DC-link capacitors and converter-side cables, while the utility grid contributes to the steady-state fault current [37]. The following equation can be used to find the short circuit (SC) contributed by the DC-link capacitor:

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

where i_c is the fault current (A), L is the line inductance (H), R is the line resistance (Ω), and C is the DC-link capacitor's capacitance (F). The energy stored in the cable inductance

is also discharged during faults and converter switching. The cable discharge current is given by the following formula:

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

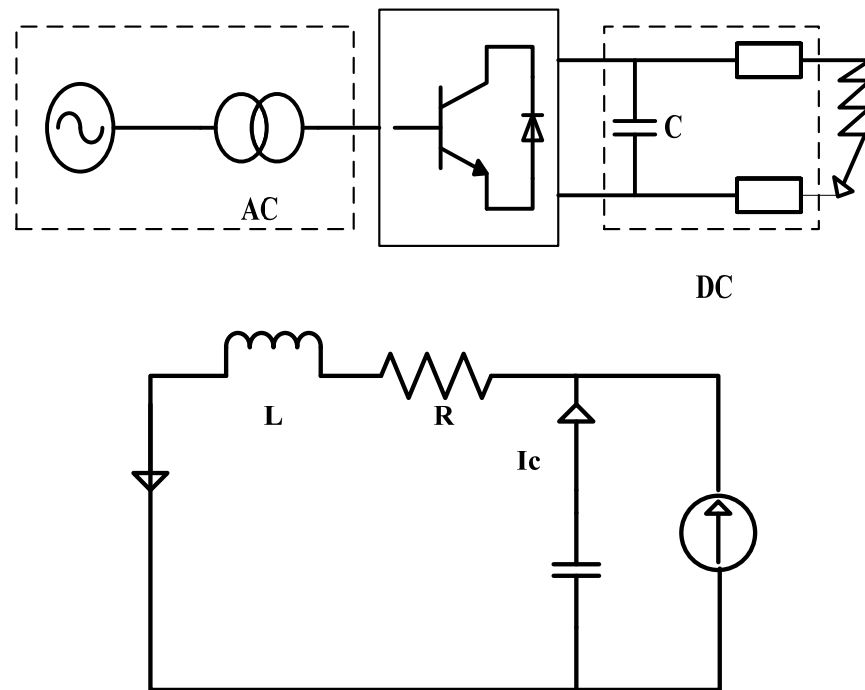


Figure 3. Thevenin equivalent circuit of a DC microgrid.

Hence, the transient current resulting from the fault comprises i_L and i_C , as depicted in Figure 3 [18] where i_L is the cable discharge current (A), L is the line inductance (H), R is the line resistance (Ω), and t is the time (s). Additionally, the transient component of the fault current can be classified into three categories: slow, medium, and fast front transients. The most common causes of slow front transients are batteries, converter control, and voltage-dependent loads. A fast front transient is caused by transient recovery voltage at the PD opening, while a medium front transient is caused by surge current in the filter's capacitors.

Although the equivalent RLC model provides a useful explanation of the transient fault response in DC microgrids, the actual fault behaviour is also influenced by converter control methods, DC bus impedance, converter operating modes, and the current-limiting characteristics of power electronic converters. For this reason, simplified circuit models may not always predict the actual fault current accurately [22,27]. Reliable fault detection and protection coordination should therefore consider both the electrical characteristics of the network and the dynamic behaviour of converter-based resources. As shown in Figure 4, DC fault current does not naturally pass through zero. Therefore, conventional AC circuit breakers are generally unsuitable for interrupting faults in DC microgrids [45]. Table 1 summarises the main fault types together with their characteristics and severity. In addition, reactance in a DC system is usually small. As a result, DC faults may reach high peak values and exhibit a rapid rate of current rise. This makes fault interruption in DC microgrids more challenging than in AC systems [42,46]. Voltage source converters (VSCs), which are widely used in DC microgrids, also have limited fault current withstand capability [25]. Protection systems must therefore operate quickly to prevent damage to the converters. The strength and operating conditions of the upstream grid may also affect the performance and resilience of the protection system [27,28].

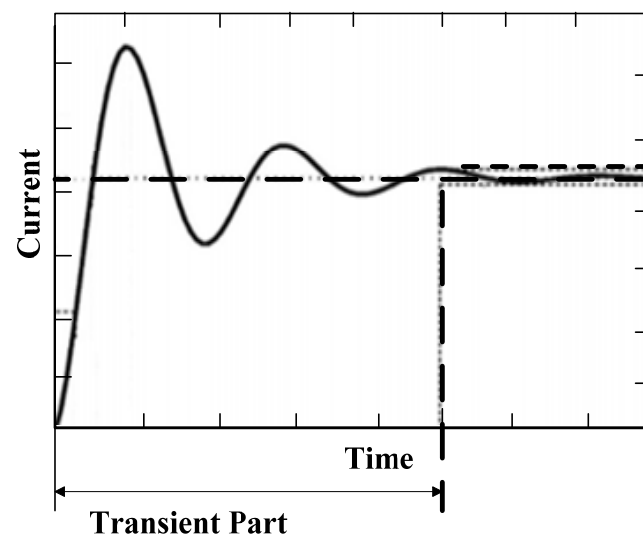


Figure 4. Short-circuit current response in a DC system.

Table 1. Characteristics of a fault in a DC microgrid.

Types of Faults	Feature	Severity
Pole-pole	Low impedance and detectable	Highly dangerous
Pole-ground	Emerge as a result of high impedance and the degradation phase	Medium dangerous
Transient phase	• Capacitor linked with DC • Leakage of line cables • Delayed, conventional, and high transients	Less dangerous
Steady-state phase	Contribution by the grid AC side	Highly dangerous

A grid-connected DC microgrid experiencing a load fault is shown in Figure 5. In a passive DC network, relay R4 must clear the fault current, I_m , supplied by the main grid. However, the battery, photovoltaic system, and wind turbine (WT) may also contribute current during a fault. Therefore, the setting of R4 must take into account the fault current contribution from all connected sources. As the number and capacity of local energy sources increase, their contribution may become more significant than that of the main grid. Relay R1 disconnects the DC microgrid when a fault occurs on the main-grid side. For this reason, the relays must be able to operate bidirectionally [43]. The magnitude of the fault current also depends on the type of generation and the operating mode of the microgrid. Synchronous generators and the utility grid generally provide higher fault currents during grid-connected operation. In contrast, inverter-based distributed energy resources (DERs) usually limit their fault current contribution to approximately 1.2–1.5 p.u. of the rated current to protect power electronic devices [47]. Therefore, the type of connected energy source affects the magnitude of the fault current.

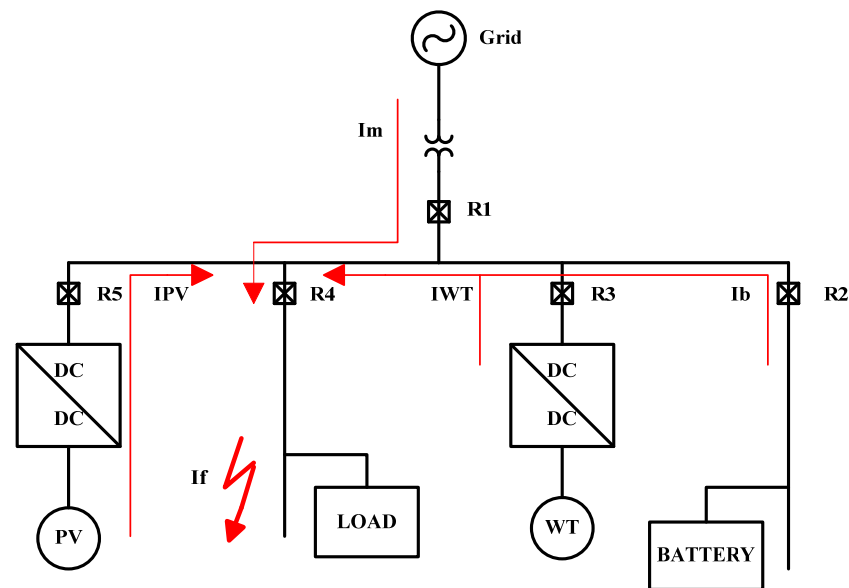


Figure 5. Bidirectional fault current flow in a grid-connected DC microgrid, illustrating the contribution of the utility grid, photovoltaic (PV) system, wind turbine (WT), and battery energy storage system (BESS) during a fault, together with the coordinated operation of protection relays [18].

4. Challenges Associated with DC Microgrid Implementation

The adoption of DC microgrids creates several technical challenges that can affect the performance and reliability of protection systems. Compared with conventional AC distribution networks, DC microgrids behave differently during faults because of bidirectional power flow, converter-interfaced distributed energy resources (DERs), and the absence of natural current zero-crossings [22,26]. As a result, conventional protection methods may not always provide reliable fault detection and coordination under different operating conditions. This section discusses the main protection challenges in DC microgrids, including fault current behaviour, protection coordination, and the limitations of protection devices.

4.1. Fault Current Characteristics

The integration of distributed energy resources (DERs), energy storage systems (ESSs), and bidirectional power converters changes the fault current behaviour of DC microgrids compared with conventional AC distribution networks [48,49]. In radial AC systems, fault current normally flows in one direction from the utility source to the load. In DC microgrids, however, fault current may flow in different directions because several distributed generation (DG) sources can contribute to the fault under different operating modes [43,44]. This means that protection devices must detect both the magnitude and direction of the fault current to isolate the correct faulted section. Conventional non-directional overcurrent relays are mainly designed for one-way current flow. Under bidirectional conditions, they may lose coordination or fail to identify the correct fault location. Therefore, adaptive and directional protection methods are often required [50]. Figure 5 shows the bidirectional flow of fault current in a DC microgrid. During a fault, the utility grid, photovoltaic (PV) system, wind turbine (WT), and battery energy storage system (BESS) may all supply fault current at the same time and from different directions. For this reason, the protection relays must consider both the magnitude and direction of the fault current to achieve selective fault isolation under different operating conditions.

Another important feature of DC microgrids is that the short-circuit current level changes with the network configuration and operating condition [51]. During grid-connected operation, both the utility grid and distributed generators may contribute to the

fault current, resulting in a higher short-circuit level. In islanded operation, however, the available fault current is usually lower because it is mainly supplied by inverter-interfaced distributed energy resources with limited current capability [52]. As a result, protection settings selected for one operating condition may not remain suitable when the operating mode changes [53]. This variation can affect relay coordination and selectivity. Therefore, adaptive protection methods are needed to adjust the relay settings according to changes in the system operating condition [49].

Most inverter-interfaced distributed generators limit their fault current contribution to protect semiconductor devices. During a fault, they usually supply only about 1.2–1.5 p.u. of their rated current [54]. Although this current-limiting feature helps protect the converter, it also reduces the difference between the fault current and the normal operating current. As a result, conventional protection systems may have difficulty detecting some faults [53]. Fault detection becomes even more difficult for remote faults and high-impedance faults. The limited fault current may also reduce relay sensitivity and affect protection coordination [48]. Therefore, future protection schemes for DC microgrids should consider the limited fault current contribution of power electronic converters. Adaptive, communication-assisted, or intelligent protection methods may be needed to maintain reliable fault detection under different operating conditions [49].

4.2. Protection Coordination Challenges

Protection coordination is more challenging in DC microgrids. This is mainly due to bidirectional power flow, changing operating modes, and converter-interfaced DG. Conventional overcurrent protection usually assumes a fixed network structure and predictable fault currents. In DC microgrids, however, fault current magnitude and direction can change with the operating condition. Therefore, relay settings that work in one condition may not work in another. This may cause maloperation, unnecessary tripping, or failure to isolate the fault. Adaptive protection is therefore needed to adjust relay settings based on real-time system conditions [43,50].

Another coordination challenge comes from the different characteristics of pole-to-pole (PP) and pole-to-ground (PG) faults. PP faults usually produce high fault currents because of their low impedance. In contrast, PG faults often produce lower fault currents, especially under high-impedance grounding conditions [48]. As a result, relay settings selected for PP faults may not detect PG faults with enough sensitivity. However, settings adjusted for PG faults may cause unnecessary operation during normal disturbances [49]. These differences make relay coordination and selectivity more difficult. Therefore, adaptive relay coordination and intelligent fault detection methods are needed for both PP and PG fault conditions [53].

Grounding configuration also affects protection coordination in DC microgrids. Common methods include ungrounded, solidly grounded, resistance-grounded, and high-resistance-grounded systems. Each method changes the magnitude and path of the fault current, especially during ground faults [55]. Ungrounded systems may produce very low ground-fault currents. This makes fault detection more difficult. In contrast, solidly grounded systems produce higher fault currents. This can improve protection sensitivity but may increase stress on protection devices. Therefore, the grounding method affects relay sensitivity, fault detection, and coordination. Grounding design should be considered together with the protection system to ensure reliable and selective fault isolation [56].

4.3. Protection Device Challenges

In conventional AC distribution networks, AC circuit breakers (ACCBs) interrupt fault currents at the natural current zero-crossing. This allows the arc to be extinguished effec-

tively [57]. In DC microgrids, however, fault currents do not have a natural zero-crossing point. Therefore, conventional ACCBs are not suitable for direct use in DC systems [52,58]. Therefore, special feature DC protection devices are needed to interrupt rapidly rising fault currents while maintaining system stability and reliable converter operation.

Mechanical DC circuit breakers (DCCBs) use magnetic arc blowout devices and arc-extinguishing chambers to interrupt DC fault currents [45]. Unlike conventional ACCBs, DCCBs are designed to extinguish arcs without relying on a natural current zero-crossing. However, they are often large, complex, and expensive to manufacture. These practical limitations restrict their use, especially in low-voltage DC microgrids. Such systems require compact, affordable, and fast protection devices [59,60]. Converter-based protection offers another possible solution. It uses power electronic devices such as insulated-gate bipolar transistors (IGBTs) and integrated gate-commutated thyristors (IGCTs).

These semiconductor devices can quickly limit and interrupt fault currents. This allows the converters to operate as fast-acting current-limiting circuit breakers [58]. Compared with mechanical DCCBs, converter-based protection offers a faster response and greater flexibility. It can also improve coordination with converter-interfaced distributed energy resources and support adaptive protection methods [61]. However, further research is needed to improve reliability and reduce implementation costs. Challenges related to thermal stress and converter operation during faults must also be addressed [62].

5. Protection Principle and Schemes

DC protection methods can be grouped into several strategies, similar to those used in AC systems. Important factors in protection design include reliability, selectivity, speed, performance, cost-effectiveness, flexibility, and practicality [24,57]. This section compares the main DC microgrid protection methods using these criteria. The comparison highlights the strengths and limitations of each method. It also reflects the technical and operational requirements of modern DC microgrids.

The qualitative ratings (e.g., High, Medium, Low-Medium, and Medium-Low) presented in Table 2 were synthesised from the overall findings reported in the reviewed literature by comparing the relative performance of each protection method against these evaluation criteria, rather than using a standardized quantitative scoring system. In general, a rating of High indicates consistently superior performance across the reviewed studies for a given criterion, Medium indicates satisfactory or condition-dependent performance, whereas Low indicates comparatively limited performance or applicability. Intermediate ratings (e.g., Low-Medium and Medium-Low) represent performance that falls between the adjacent categories. It should be mentioned that various network topologies, converter configurations, fault conditions, operating modes, and validation platforms were used in the conducted studies. Accordingly, direct quantitative comparisons between research are typically impractical. Hence, the comparison in Table 2 should be considered as a qualitative assessment that provides a consistent evaluation framework for emphasising the relative strengths and shortcomings of the assessed protection schemes. This section summarizes the existing suggested protection schemes for DC systems.

5.1. Conventional Protection Schemes

Conventional protection methods include overcurrent, distance, and differential protection. These methods remain widely used in DC microgrids because they have simple operating principles and are well established in conventional power systems [69]. However, DC microgrids have different operating characteristics. These include bidirectional power flow, converter-interfaced distributed energy resources (DERs), and changing operating

conditions. As a result, conventional methods may not always provide reliable protection and often require further improvement [70,71].

Table 2. Comparative evaluation of DC microgrid protection strategies.

Protection Techniques	Response Time	Reliability	Selectivity	Cost-Effectiveness	Adaptability	Practicality
Overcurrent relay [58]	Medium	Low-medium	Low	High	Medium	High
Distance relay [63]	Medium	Medium	Medium	Medium	Low	Medium
Differential relay [64,65]	High	High	High	Medium-Low	High	Low-Medium
Rate of change of (di/dt , dv/dt) [66]	High	Medium	Medium-High	High	Medium	Medium
PV protection method [67,68]	High	Medium	High	Medium	High	Medium

Overcurrent protection is widely used because it is simple to apply and relay coordination is relatively straightforward [70]. However, bidirectional current flow can change both the magnitude and direction of fault current. This can reduce the effectiveness of conventional overcurrent protection in microgrids. Therefore, more advanced low-voltage DC (LVDC) protection methods are needed to disconnect power converters quickly during overcurrent or undervoltage conditions [69]. Baran et al. [58] proposed an overcurrent protection scheme for small ungrounded lines. However, its fault detection capability is limited under certain operating conditions. Overcurrent protection can detect some high-impedance faults (HIFs), but its performance is generally lower than that of other protection methods. Even so, it remains useful in low- and medium-voltage systems because relay thresholds are easy to set and protection devices are easier to coordinate. Adaptive overcurrent relay protection has been introduced to improve fault detection under changing operating conditions [72]. Additionally, load variations and the growing use of distributed generation (DG) present new operational challenges that conventional adaptive OCR is unable to adequately address. Consequently, optimisation techniques, such as Genetic Algorithm (GA), Differential Evolution (DE), Cuckoo Search (CS), Firefly Algorithm (FA), Bat Algorithm (BA), Whale Optimization Algorithm (WOA), and hybrid optimisation approaches, have been investigated to solve the Optimal Reactive Power Dispatch (ORPD) problem while maintaining voltage profiles and network operating constraints [73,74].

Distance protection is widely used in AC transmission systems. It identifies the fault location using impedance measurements and can reduce the effect of fault resistance [75]. However, it cannot be applied directly to DC microgrids. This is because symmetrical-component analysis is not suitable for DC systems, and DC feeders are usually much shorter than AC transmission lines [76]. Yang et al. [77] proposed a voltage-comparison method to detect short-circuit faults during the early transient stage. The method provides good selectivity when suitable threshold values are used. However, its performance may decrease when the fault resistance is high or the transmission line is short. Communication-assisted distance protection for DC microgrids is also still at an early research stage. This limits its practical application.

Differential protection offers high sensitivity because it compares currents measured at different locations. It does not rely only on the magnitude of the fault current. Dhar et al. [67] proposed a method that combines the cumulative sum (CUSUM) technique with the Moore–Penrose pseudo-inverse algorithm. The method improves both fault detection and fault location. Other studies have reported fault-location times of about 0.1 ms. However, fault-isolation times vary from 3.6 ms to 25 ms, depending on the protection arrangement [78]. Differential protection also responds quickly and is less affected by fault current direction and fault resistance. However, it requires reliable communication

channels. More testing using real-time simulation platforms, such as OPAL-RT or Typhoon, is also needed before wider practical use [70,79]. Overall, conventional protection methods remain attractive because they are simple and well established. However, their performance is limited by the changing operating conditions of modern DC microgrids. This shows the need for more adaptive and intelligent protection methods [48].

5.2. Advanced Protection Schemes

Protection methods based on the rate of change in voltage and current detect faults by monitoring dv/dt and di/dt . A fault is detected when either value exceeds a preset threshold. A fault becomes apparent when the measured rate of change exceeds a predetermined threshold. Meghwani et al. [66] applied the current-derivative method to a ring-type DC microgrid. The method used rapid changes in current to identify and locate faults. This approach can provide fast fault detection and restoration for both first- and second-zone faults. However, its performance depends strongly on the selected threshold. It may also become less effective in larger and more complex DC microgrids [80]. Voltage-derivative methods may also mis-operate during close-up faults under certain operating conditions. This can reduce their reliability.

PV-based protection methods are designed to address the operating characteristics of PV-integrated DC microgrids [25]. The protection design must consider the inverter current limit, which protects semiconductor devices during faults. Fault detection is also affected by the voltage-dependent behaviour of PV systems and changes in PV penetration level. Adaptive threshold methods have been proposed to address these issues [80]. For example, a piecewise cubic Hermite polynomial has been used to detect islanding based on the PV penetration level [81]. Differential current protection using the Moore–Penrose pseudo-inverse and cumulative sum (CUSUM) methods has also shown improved fault detection in PV-based DC microgrids [82].

AI-based protection methods have received increasing attention because they can improve fault detection and adapt to changing operating conditions [82]. Artificial neural networks (ANNs) can classify and locate faults using measured current data. However, their performance depends on the quality and quantity of the training data. The trained model may also be limited to the network configuration used during training [83]. Many AI-assisted protection methods rely on communication networks. These networks transfer data between control centres, protection relays, and intelligent electronic devices (IEDs). Communication delays, synchronisation errors, and data loss may slow fault detection and relay operation. Therefore, AI-based protection requires reliable and low-latency communication systems [84]. In this context, Amara et al. [82] proposed a protection method that combines noise measurement with metaheuristic optimisation for gain adjustment. The method improves fault identification. However, it remains less effective for high-impedance faults because it does not consider the initial current derivative. Overall, advanced protection methods can provide faster and more adaptive fault detection than conventional methods. However, they often require additional sensors, communication systems, computational resources, and further validation. Real-time simulation and hardware-in-the-loop (HIL) testing are also needed before practical use in DC microgrids [23].

5.3. Protection Challenges with Electric Vehicle Integration

The growing use of electric vehicles (EVs) creates new protection challenges for DC microgrids. EVs can operate as loads or as distributed energy resources, especially with ultra-fast charging and vehicle-to-grid (V2G) technology [23,48]. During a fault, EV chargers and V2G systems may also contribute fault current. Their bidirectional power flow can therefore affect fault current behaviour and protection coordination. Existing protection

methods may not fully address the changing behaviour introduced by EVs. Further improvements are therefore needed. Protection performance should also be carefully evaluated to ensure reliable operation in future EV-integrated DC microgrids [85,86].

Battery energy storage systems (BESSs) make protection design more difficult. Their fault current contribution depends on the converter control method, state of charge (SoC), and operating condition [26]. During a fault, converter-interfaced BESSs usually produce a transient current due to the discharge of the DC-link capacitor [69]. The converter then limits the steady-state fault current to protect the power electronic devices [87]. As a result, the magnitude and direction of the fault current may change with the operating mode and network configuration. This makes fault detection and relay coordination more difficult, especially in islanded DCMGs. BESS integration may also cause protection blindness, which reduces the sensitivity of overcurrent protection devices [88]. The problem becomes more serious during high-impedance faults because fewer overcurrent devices can detect the fault as the fault impedance increases.

Adaptive protection methods have been proposed to reduce protection blindness and improve relay coordination in EV-integrated DC microgrids [89]. These methods must respond to changes caused by renewable generation, energy storage systems, and EV charging stations [24]. Relay settings may also need to change with V2G operating modes and EV charging demand. These changes can affect both the magnitude and direction of fault current [85,86]. Adaptive relay coordination is therefore important for reliable fault detection and selective fault isolation. One possible approach is to combine intelligent protection methods with adaptive directional overcurrent relay (DOCR) coordination. This can help address intermittent renewable generation, changing charging demand, and bidirectional power flow. However, further research is needed to assess the effect of large-scale EV integration. The proposed methods should also be tested under real operating conditions.

The protection strategies discussed in Section 5 are summarised in Table 3. The table compares each method based on its protection objective, sensing requirements, communication needs, fault coverage, validation platform, response time, cost, implementation maturity, advantages, and limitations. The reviewed studies use different system configurations, fault conditions, operating modes, and validation methods. Therefore, Table 3 provides a common framework for comparing them. It also helps to identify suitable protection methods for different DC microgrid conditions and supports the qualitative evaluation presented in Table 2.

The comparison shows that conventional methods, such as overcurrent and distance protection, remain attractive because they are simple, affordable, and easy to coordinate. However, their performance may be limited by bidirectional power flow and changing fault current levels. Differential protection offers higher sensitivity and faster fault detection. However, it depends on a reliable communication system. Advanced methods, such as PV-based, AI-assisted, and rate-of-change protection, provide greater flexibility in converter-dominated DC microgrids. However, they often require additional sensors, communication systems, or computational resources. Since no single method satisfies all protection requirements, future DC microgrids may require adaptive or hybrid protection schemes. These schemes should balance protection performance, implementation complexity, and cost.

Table 3. Relationship between protection techniques used in a DC microgrid.

Protection Techniques	Protection Objective	Sensing Requirement	Communication Needs	Fault Types Covered	Validation Platform	Response Time	Cost	Implementation of Maturity	Pro	Cons
Overcurrent relay (OCR)	Detect and isolate overcurrent faults while maintaining relay coordination	Current measurement	Low (centralized adaptive coordination may require communication)	PP, PG, HIF (limited capability)	Simulation/experimental	Medium	Low	High	Simple, economical, easy coordination	Poor selectivity under bidirectional power flow; affected by changing fault current levels
Distance relay	Detect faults based on voltage and impedance characteristics	Voltage and current measurement	Low	Short circuit faults	Simulation	Medium	Medium	Medium	Good selectivity; suitable for transmission applications	Less effective for short DC feeders; sensitive to fault resistance
Differential relay	Detect internal line faults by comparing currents at both ends	Line terminals	High	PP and PG faults	Simulation/real-time simulation	Very fast	High	High	High sensitivity	Requires reliable communication
PV protection method	Protect PV integrated DC microgrids and detect islanding/faults	Voltage and current measurements	Medium	PV-side faults, islanding	simulation	fast	Medium	Medium	Adaptive to PV penetration; suitable for converter-based systems	Performance depends on inverter characteristics and PV operating conditions
AI/ANN based protection	Intelligent fault detection classification and localization	Voltage and current measurements	Medium	Multiple fault types	Simulation/experimental	Fast	Medium-high	Emerging	High detection accuracy; adaptive under varying operating conditions	Requires large training datasets computational complexity; limited real-time validation
Rate-of-Change Protection (di/dt, dv/dt)	Detect faults based on rapid transient changes	Voltage and current measurements	Low-Medium	Transient faults PP faults	Simulation	Fast	Medium	Medium	Fast fault detection and restoration	Sensitive to noise; threshold setting is critical

6. Research Findings and Recommendations

This review examined the current development of protection methods for DC microgrids (DCMGs). These include overcurrent, distance, differential, and intelligent protection. The findings indicate that each method performs differently under changing operating conditions and has its own limitations. Conventional methods remain attractive because they are simple and affordable. However, their performance can be affected by bidirectional power flow, converter-limited fault currents, and changes in operating mode. Advanced methods offer better adaptability and fault detection. However, they still require further experimental testing before wider practical use. Based on these findings, several recommendations are proposed to support the development of more reliable, flexible, and secure DC microgrid protection systems.

Overall, the reviewed studies show a clear shift in DC microgrid protection. Protection methods have moved from conventional relay-based approaches towards adaptive, communication-assisted, and intelligent strategies. This change is mainly driven by the growing use of converter-interfaced renewable energy sources, battery energy storage systems, and electric vehicles. These technologies introduce bidirectional power flow, changing operating conditions, and limited fault current contributions. As a result, conventional protection methods may not always provide reliable fault detection and coordination. Advanced protection methods offer better adaptability and protection performance. However, they also introduce challenges related to communication reliability, computational complexity, cost, interoperability, and cybersecurity. Therefore, future DC microgrid protection may benefit from hybrid frameworks. These frameworks can combine conventional protection principles with adaptive and intelligent decision-making methods to improve reliability, selectivity, and resilience.

- **Design and validation of grid structure:** DC microgrid configurations should be constructed and proven to allow enhanced protection strategies, such as decentralized or hybrid structures. Realistic fault scenarios, advanced simulation tools, and hardware-in-the-loop testing should be employed to verify their protection performance.
- **Optimization of fault detection and relay coordination:** Current methods frequently lack adaptability to dynamic microgrid (MG) operational circumstances. Hence, adaptive relay coordination approaches must be deployed to accommodate dynamic changes such as demand fluctuations and the incorporation of renewable energy sources (RES). Additionally, AI-assisted models trained on relevant microgrid datasets should be utilized to increase fault detection accuracy and coordination accuracy.
- **Advanced fault detection techniques:** Despite artificial intelligence (AI) and machine learning (ML) showing tremendous promise for DC microgrid protection, their incorporation alongside conventional protection technologies is still very limited. Therefore, conventional and intelligent fault detection techniques should be integrated to improve the accuracy and reliability of fault detection, particularly in inverter-based DC microgrids operating in islanded mode (grid-off).
- **Impact of integrated EV charging stations on relay coordination:** The dynamic nature of EVs introduces new challenges for relay coordination. Adaptive protection methods should be developed to cater for the fluctuating charging demand and bidirectional power flow associated with EV integration, maintaining system stability and trustworthy protection.
- **Comprehensive analysis of complex integrated networks and high-impedance faults:** Protection solutions should account for the specific characteristics of meshed DC microgrid architectures and use intelligent fault detection approaches, such as high-frequency signal injection or wavelet-based analysis, to improve the identification and mitigation of high-impedance faults [90,91].

- **Secure communication networks for data transmission:** Secure communication infrastructures should incorporate software-defined networking (SDN) and advanced encryption protocols to enhance cybersecurity, communication reliability, and secure data transmission in DC microgrid protection systems.
- **Implementation of Blockchain-based Protection:** Blockchain-based protection frameworks ought to be integrated into DC microgrid protection systems to improve cybersecurity, data integrity, and resilience to cyberattacks. Prototype deployment and pilot-scale validation are advised to assess the viability and durability of blockchain technologies in practical DC microgrid systems [92,93].
- **Experimental and real-time field testing:** Proposed protection mechanisms should be verified through real-time modelling, hardware-in-the-loop testing, and moderated experimental environments to demonstrate their effectiveness under real-world situations. Collaboration with industry partners is recommended to enable pilot-scale implementation and evaluation of protection efficacy throughout grid-connected and islanded activities.

Therefore, these suggestions can greatly aid in the creation of DC microgrid protection techniques that are more dependable, effective, flexible, and secure, which will enable their broader deployment and integration into contemporary power systems.

7. Conclusions

This review presents recent developments in DC microgrid (DCMG) protection and evaluates the main protection methods. It also explains the basic structure of a DC microgrid, including distributed generation, power electronic converters, energy storage systems, and different types of loads. Compared with conventional AC systems, DC microgrids have faster fault current rise, no natural current zero-crossing, limited fault current contribution from converters, and bidirectional power flow. These features make conventional protection more difficult to apply. The review covers overcurrent, distance, differential, communication-based, and intelligent protection methods. It also discusses protection devices, grounding methods, and existing standards. The findings show that each protection method has its own strengths and limitations under different operating conditions. Therefore, wider use of DC microgrids will require protection systems that are reliable, flexible, and properly coordinated.

Based on these findings, future research should focus on advanced DC microgrid designs and protection methods that can respond to changing operating conditions. These methods must also address high renewable energy penetration and bidirectional power flow. AI-assisted fault detection, adaptive relay coordination, and hybrid protection methods deserve further attention. Hybrid methods can combine conventional protection principles with data-driven techniques. More work is also needed on high-impedance fault detection in complex networks. Secure communication using blockchain and software-defined networking should also be explored. Protection for DC microgrids with EV charging stations is another important research area. The proposed methods should be tested using hardware-in-the-loop platforms, real-time simulation, and pilot-scale systems. This will help confirm their reliability and practical performance. Future work should also support compatibility with emerging IEC and IEEE standards. This can improve the integration of protection devices from different manufacturers. Addressing these issues will support the development of reliable, adaptable, and cyber-secure protection systems. It will also help the wider use of resilient DC microgrids in future sustainable power networks.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternate Current
AI	Artificial Intelligent
BA	Bat Algorithm
CB	Circuit Breaker
CUSUM	Cumulative Sum
DC	Direct Current
DCMG	Direct Current Microgrid
DER	Distributed Generation
DG	Distributed Generation
EV	Electric Vehicle
FCL	Fault Current Limiter
GA	Genetic Algorithm
HESS	Hybris Energy Storage System
HIL	Hardware-in-the-Loop
IEC	International Electrotechnical Commission
V2G	Vehicle -to-Grid
RES	Renewable Energy Source
PP	Pole-to-Pole
ACCB	Alternate Current Circuit Breaker
ANN	Artificial Neural Network
BESS	Battery Energy Storage System
CS	Cuckoo Search
DCCB	Direct Current Circuit Breaker
DE	Differential Evolution
DOCR	Directional Overcurrent Relay
ESS	Energy Storage System
FA	Firefly Algorithm
FREEDM	Future Renewable Electric Energy Delivery and Management
HEART	Highly Efficient and Reliable DC Transmission
HIF	High-Impedance Fault
HVDC	High-Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
RLC	Resistor-Inductor-Capacitor

PG	Pole-to-Ground
PV	Photovoltaic

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