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Review

A Comprehensive Review of DC Microgrids: Controls, Topologies, Protection and Future Trends

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Abstract

Microgrids are important technologies for increasing the penetration of renewable energy sources (RESs). Compared with AC microgrids, DC microgrids avoid frequency regulation and reactive-power compensation. Moreover, many RES interfaces and energy storage systems (ESSs) are DC or DC-link based; therefore, they can be integrated into DC buses with fewer conversion stages, reducing conversion losses. Consequently, DC microgrids have attracted increasing attention. This paper reviews DC microgrid topologies, hierarchical control methods, and protection schemes. First, the representative topologies are compared from the perspectives of structural features, control implications, protection requirements, and application scenarios. Next, primary, secondary, and tertiary control strategies are analyzed, with emphasis on droop control, virtual impedance, virtual inertia, fractional-order control, communication delay, and energy management. Protection issues, including fault detection, fault interruption, and ground-fault protection, are then discussed with respect to topology–control interactions. Finally, future research trends and challenges for DC microgrids are summarized.

Keywords: DC microgrid; energy management system; fractional order control; hierarchical control system; protection system

1. Introduction

The rising energy demand from human activities increases CO_2 emissions and depletes fossil fuels. Renewable energy sources (RESs), being environmentally friendly, have seen wide adoption in power systems. Statistics suggest that by 2050, RESs will generate over 50% of global electricity, becoming the dominant source [1]. Due to their intermittent and stochastic nature, RESs require supplementary measures to maintain stable supply and meet load demands [2,3]. Energy storage systems (ESSs) offer an effective solution [4]. When load is lower than RES generation, the ESS charges to absorb excess energy; when generation falls short, it discharges to supply the system [5]. Thus, ESS acts as an energy buffer, smoothing power fluctuations and ensuring stable microgrid operation [6,7]. A small-scale system composed of RESs, ESSs, and loads is defined as a microgrid [8].

Microgrids offer benefits to both the main grid and end users: (1) they can serve as controllable loads or generation units, providing power and ancillary services to upstream networks [9]; (2) they transform end-users into prosumers, enabling active participation in grid operation [10]. Microgrids can operate in grid-connected or islanded modes and are

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categorized as AC or DC based on bus voltage. Many RES and ESS units are DC in nature, making DC microgrids more compatible with these sources, reducing conversion stages and losses [11]. Compared to AC microgrids, DC systems achieve higher efficiency [12] and do not need to address frequency or reactive power issues, such as frequency regulation and reactive power compensation [13], which has increased research interest.

Hierarchical control remains the prevailing architecture for DC microgrids. Within this framework, primary control handles rapid local stabilization and basic power sharing; secondary control restores the bus voltage while enhancing the current sharing accuracy; and tertiary control focuses on global energy management and economic dispatch. However, conventional integer-order control schemes often prove inadequate in regulating the complex nonlinear dynamics inherent in DC microgrids. They are highly susceptible to parameter uncertainties, line impedance variations, and large-signal disturbances, which consequently degrade system stability and power-sharing accuracy [14]. To overcome these limitations, fractional-order (FO) control has garnered significant attention. By integrating fractional calculus into the control loops, FO controllers introduce additional degrees of freedom. With appropriate design and tuning, FO controllers can improve dynamic response, robustness, and stability margins compared with conventional integer-order controllers. Furthermore, the reliable operation of DC microgrids cannot be guaranteed by control strategies alone. Fundamentally, the system topology dictates the propagation paths of power and fault currents. The control strategy governs the dynamic evolution during pre- and post-disturbance phases. Then, the protection approach determines whether the system can sustain safe operating boundaries following a fault. Consequently, topology, control, and protection are not merely parallel concepts; rather, they form a deeply coupled entity anchored by the hierarchical control architecture.

Currently, many review papers have discussed control approaches, topologies and protection in DC microgrids [15–24]. For example, ref. [15] reviews the control architectures of DC microgrids, with a specific focus on evaluating the advantages and limitations of decentralized, centralized, and distributed control topologies. Furthermore, it highlights that communication-based distributed cooperative control can effectively mitigate issues such as voltage and current deviations. Ref. [19] systematically reviews six control technologies in smart microgrids and their applications across different control hierarchies, alongside an analysis of state estimation methods for system operation. Furthermore, it proposes a future development framework for microgrid control and estimation, aiming to drive the evolution of microgrids toward autonomous and intelligent operation. Ref. [22] discusses the current research on protection schemes and topologies in DC microgrids, with a primary focus on analyzing the challenges confronting conventional protection methods. Furthermore, it explores intelligent protection solutions based on signal processing and artificial intelligence. Table 1 provides an overview of review articles on microgrid control, topologies and protection.

Although the articles mentioned in Table 1 have reviewed different aspects of DC microgrids, their shortcomings can be summarized as follows:

- Existing studies on hierarchical control lack in-depth discussions regarding virtual impedance, virtual inertia and optimization techniques. The impact of communication delays on system performance remains inadequately evaluated.
- The methods mentioned above primarily focus on integer-order control methods. Fractional-order control techniques are frequently overlooked in related studies.
- Although some existing studies have explored topology and protection technologies, a joint analysis integrating them with control techniques remains lacking.

Table 1. An overview of previous review articles on DC microgrid research.

Ref.	Hierarchical Control	FO-Based Methods	Topologies	Protections
[15]	No virtual impedance, virtual inertia, communication delay and optimization included	×	×	×
[16]	No virtual impedance, virtual inertia, communication delay and optimization comparison included	×	×	Lack of analysis on various protection techniques
[17]	No virtual impedance, virtual inertia, communication delay and optimization comparison included	×	×	×
[18]	No communication delay and optimization included	×	×	Focuses on AC systems
[19]	No virtual impedance, virtual inertia and communication delay included	×	×	×
[20]	×	×	Lack of joint analysis with control and protection	Lack of analysis on various protection techniques
[21]	×	×	Lack of joint analysis with control and protection	×
[22]	×	×	Lack of analysis on various topologies	Lack of joint analysis with topology and control
This paper	√	√	√	√

In order to address these issues, this paper presents a comprehensive review on the control system, protection and topologies of DC microgrids. The contributions of this article are summarized below:

(a) A comparison of representative DC microgrid topologies is provided, and the constraints imposed by each topology on hierarchical control and protection design are analyzed.
(b) Hierarchical control methods are reviewed from the primary, secondary, and tertiary layers, with particular attention to virtual impedance, virtual inertia, fractional-order control, optimization methods, and communication-delay effects.
(c) Protection requirements are synthesized from the perspective of topology, control and protection co-design, emphasizing the coordination among fault detection, selective isolation, and post-fault recovery.

The rest of this paper is organized as follows. The topologies of DC microgrids are described in Section 2. Section 3 presents the control methods in DC microgrids. Section 4 describes the protection system. Section 5 presents the future trends and challenges. Conclusions are drawn in Section 6.

2. Topologies of DC Microgrids

The topology of a DC microgrid is not merely a static structural choice isolated from its control and protection systems. In practice, factors such as the number of buses, rated voltage levels, and network reconfiguration capabilities collectively dictate the power flow paths, equivalent line impedances, and fault propagation characteristics. Consequently, the topology directly impacts the power sharing accuracy in primary control, the voltage restoration range and state of charge (SoC) coordination in secondary control, and the economic power dispatch in tertiary control [25–29]. Motivated by this, this section categorizes and analyzes representative DC microgrid topologies, with a specific focus on their constraints on hierarchical control and protection schemes. The typical structures investigated in this paper are illustrated in Figure 1.

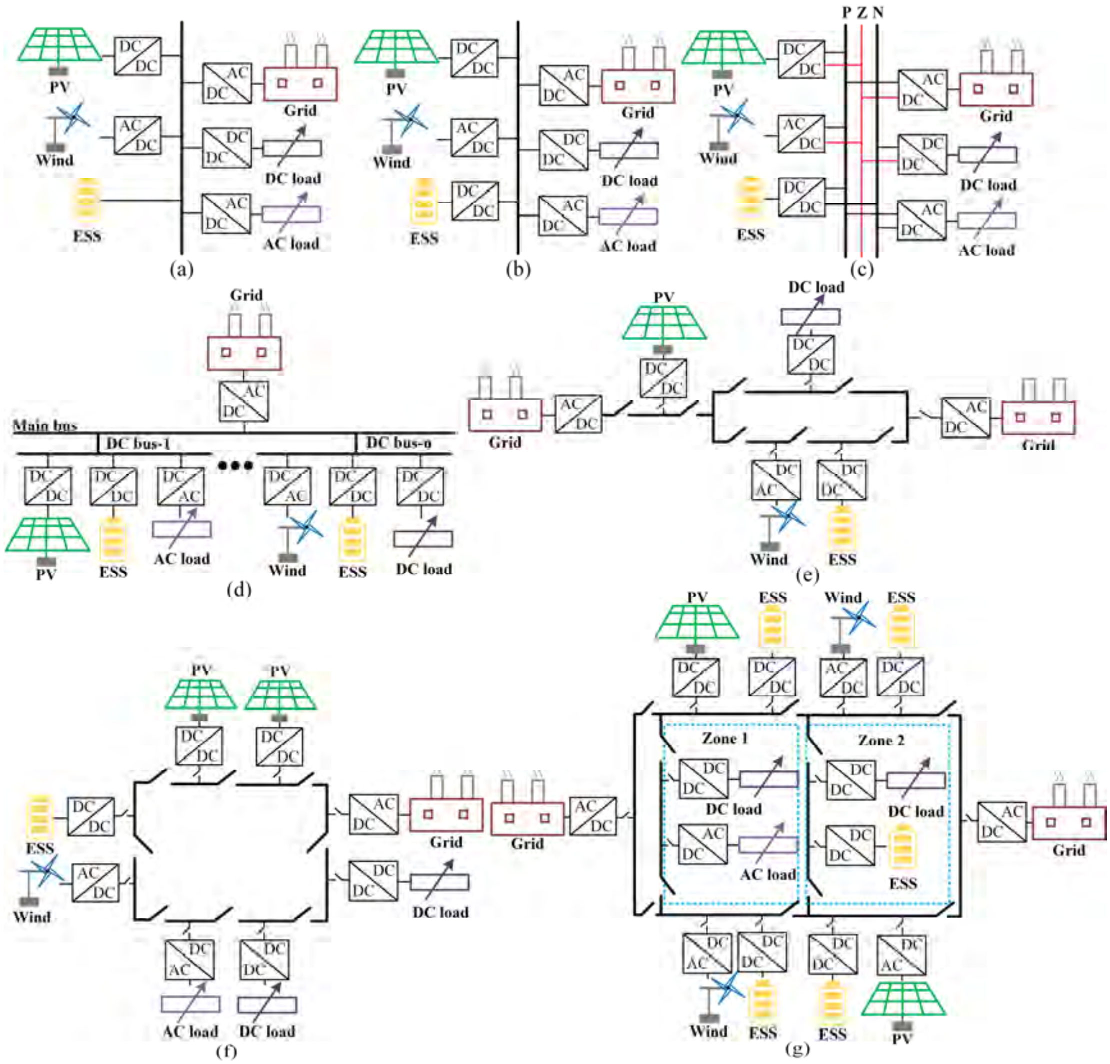

Figure 1. The equivalent topology diagrams of DC microgrids: (**a**) single-bus topology (passive type); (**b**) single-bus topology (active type); (**c**) bipolar single-bus topology; (**d**) multi-bus topology; (**e**) multi-terminal bus topology; (**f**) ring-bus topology; (**g**) zonal topology.

It should be noted that architecture classification in the DC distribution literature is not limited to the number of buses. From the viewpoint of network connectivity, DC microgrids can be categorized as radial, ring, meshed, and reconfigurable structures. From the viewpoint of polarity, they can be unipolar, bipolar, or hybrid-polarity systems. From the viewpoint of voltage level and application, they include LVDC building or data-center systems, MVDC shipboard or aircraft systems, and multi-terminal DC grid-connected systems. From the viewpoint of interface structure, they can also be implemented as centralized DC-bus, sectionalized-bus, multi-port-converter-coupled, or hybrid AC/DC-interface architectures. This paper retains the bus-based classification as the main thread because the bus structure directly determines power-flow paths, equivalent line impedances, fault-current propagation paths, and protection-zone boundaries.

2.1. Topology Comparison and Analysis

As indicated in Table 2, while the evolution of topologies from single-bus to multi-bus, ring, and zonal configurations generally enhances system redundancy and power supply continuity, it simultaneously escalates the design complexity associated with inter-bus coordination, interconnected converter control, and protection selectivity. Consequently, the selection of an appropriate topology should not be dictated solely by structural complexity or component count; rather, it necessitates a comprehensive trade-off that incorporates control objectives, protection requirements, and specific application scenarios.

Table 2. Comparison of DC microgrid topologies.

Topology	Structural Features	Control Implications	Protection Implications	Overall Assessment
Single-bus (passive)	One common bus; ESS directly connected; lowest redundancy	Primary and secondary control are the most straightforward, but bus voltage is strongly coupled to the ESS operating point	Protection coordination is relatively simple, but a common-bus fault affects a large portion of the system	Lowest cost; suitable for small and structurally simple LVDC systems
Single-bus (active)	One common bus; ESS interfaced through a bidirectional DC/DC converter	Facilitates voltage support, SoC management, and current limiting, but scalability remains limited	Converter control can help limit fault current, yet the common bus remains a critical fault location	Better controllability than the passive form at the cost of additional converter hardware
Bipolar single-bus	Positive, negative, and neutral conductors; supports multiple voltage levels; limited redundancy under specific contingencies	Requires pole-voltage balancing and management of asymmetric loading	Protection must coordinate pole-to-pole and pole-to-ground faults together with the grounding scheme	More flexible and more resilient than a unipolar structure, but more difficult to implement
Multi-bus	Several local buses coupled through interlink converters or a common backbone	Requires coordination of local bus voltages, bus selection, and inter-bus power flow	Supports local fault containment, but protection selectivity across buses becomes more complex	Well suited to multi-voltage and geographically distributed systems, with a clear increase in control and optimization complexity
Multi-terminal bus	Several converter-interfaced terminals share a DC network and enable flexible power routing	Strong terminal coupling requires higher-layer coordination of terminal voltages and power exchange	Multiple infeed paths increase the difficulty of fast and selective fault isolation	Appropriate for larger-scale or higher-power applications, but with higher hardware and coordination burdens
Ring-bus	Closed-loop network with sectionalizing switches or intelligent electronic devices; supply path is reconfigurable	Control parameters should remain robust to switching-state changes; distributed or supervisory coordination is attractive	Bidirectional fault propagation and looped paths increase the difficulty of fault location and selectivity	High service continuity, but substantially higher protection complexity
Zonal	Local source–storage–load–protection sets organized by zone; redundant inter-zonal connections	Well suited to hierarchical or zone-autonomous control, but requires inter-zonal coordination and reconfiguration logic	Facilitates fault containment by zone, but demands more refined protection coordination	Highest survivability and maintainability among the representative structures, with the highest implementation cost and complexity

2.2. Single-Bus and Bipolar Single-Bus Topologies

Single-bus topologies typically employ radial or feeder-based connections and are well-suited for small-scale DC microgrids with a relatively uniform load voltage level, as shown in Figure 1a. In a passive single-bus architecture, the ESS is directly connected to the common bus. While this mitigates power conversion stages and hardware costs, it results in a strong coupling between the bus voltage and the ESS terminal voltage, thereby imposing stricter requirements on the nominal voltage of the storage units. Conversely, an active single-bus configuration decouples the ESS from the common bus via a bidirectional DC/DC converter, as shown in Figure 1b. This enables the primary control layer to execute voltage support and power regulation with enhanced flexibility, while simultaneously providing a more defined control interface for voltage restoration and SoC management at the secondary control layer. A shared limitation of both single-bus structures is their restricted redundancy; a fault occurring on the common bus or a critical feeder typically impacts a broader scope of connected loads [25].

The bipolar single-bus topology represents a significant extension of its unipolar counterpart, as shown in Figure 1c. By incorporating positive, negative, and neutral poles, this architecture enables the system to simultaneously supply loads of varying voltage levels [30]. Furthermore, provided that grounding and protection schemes are appropriately configured, it can sustain a degree of power continuity during certain single-pole fault scenarios. Although the bipolar single-bus offers superior performance over the unipolar structure regarding voltage level adaptability and power-supply flexibility, it concomitantly introduces more stringent control and protection demands. These include pole-to-pole voltage balancing, neutral-point management, and the coordinated protection against pole-to-pole and pole-to-ground faults. Currently, this structure has been applied in practice, such as Boeing aircraft power systems and residential buildings in France and Portugal [31,32].

2.3. Multi-Bus and Multi-Terminal Bus Topologies

By establishing multiple local DC buses coupled via interconnecting converters or a backbone bus, the multi-bus topology provides a more flexible integration approach for loads characterized by diverse voltage levels, spatial locations, and operational attributes, as shown in Figure 1d [26,33,34]. Compared to single-bus architectures, the multi-bus topology is more conducive to realizing hierarchical power supply and local fault isolation. Furthermore, it facilitates the unified coordination of local subsystems within buildings, industrial parks, or microgrid clusters. However, this configuration simultaneously introduces challenges related to bus selection, interconnected power management, and local bus voltage consistency. Consequently, the secondary control layer can no longer focus solely on voltage restoration for a single common bus; instead, it must balance multi-bus coordination with precise power regulation. Meanwhile, the tertiary control layer may need to incorporate interconnecting converter capacities, inter-bus power transfer limits, and network reconfiguration states as optimization constraints.

The multi-terminal bus topology further enhances the number of accessible terminals and power routing flexibility, as shown in Figure 1e. It is commonly employed in offshore wind power integration, shipboard DC microgrids, and broader DC distribution scenarios [35–37]. This architecture enables flexible power flow distribution among multiple terminals, thereby improving the scalability and operational adaptability of the system. Nevertheless, as the number of ports increases, the control system must simultaneously address inter-port coupling, converter power limits, and port voltage coordination. Concurrently, the protection system must manage the proliferation of fault current paths and the increased complexity of protection selectivity criteria resulting from multi-source feed-in.

2.4. Ring-Bus and Zonal Topologies

The ring bus topology achieves power supply path redundancy through closed-loop networks, equipped with sectionalizing switches or intelligent electronic devices [38,39]. The circuit diagram is shown in Figure 1f. Its primary advantage lies in significantly enhancing power supply continuity, as it can sustain power to partial loads via network reconfiguration during fault isolation or maintenance procedures. Concurrently, however, the closed-loop structure introduces stronger topological coupling: fault currents may propagate along bidirectional paths, and any switching actions will alter the equivalent line impedance and power flow distribution. Consequently, the primary control parameters and secondary control strategies within a ring bus must remain robust against network reconfiguration. Furthermore, the protection system must guarantee the speed and selectivity of fault detection, location, and isolation under bidirectional feeding conditions.

The zonal topology partitions the system into several relatively independent zones, each internally configured with local power sources, energy storage units, loads, and protection devices. Inter-zone mutual power supply is facilitated via redundant buses or tie lines [13,40]. The circuit diagram is displayed in Figure 1g. Following a fault, this architecture effectively confines the impact to a localized area and sustains power to critical loads through zonal reconfiguration, making it particularly well-suited for scenarios with stringent requirements for survivability and maintainability. Correspondingly, however, the zonal topology necessitates greater hardware redundancy, more intricate inter-zone coordination logic, and more granular protection zoning designs, thereby significantly escalating both the engineering implementation complexity and the overall system cost.

2.5. Impact on the Hierarchical Control and Protection

The aforementioned comparisons demonstrate that while the topology itself does not directly dictate the exact formulation of control laws, it inherently defines the feasible design space for each control layer. In single-bus systems, characterized by short electrical distances and relatively compact structures, employing decentralized primary control complemented by simplified secondary voltage restoration is typically sufficient to meet operational requirements. However, as systems evolve toward multi-bus, ring, and zonal topologies, the impacts of asymmetrical line impedances, interconnecting converter dynamics, and network reconfiguration become increasingly pronounced. This substantially elevates the difficulty of achieving precise power sharing and multi-bus voltage coordination. Under such conditions, the secondary layer is generally better suited for centralized supervision or distributed coordination strategies [27–29]. Meanwhile, the tertiary layer must incorporate inter-bus power exchange capacities, converter ratings, and network reconfiguration states as fundamental constraints within the energy management system (EMS).

A similar paradigm applies to protection design. While protection coordination in single-bus or radial structures is relatively straightforward, its power supply continuity remains limited. Conversely, although ring and zonal topologies significantly enhance system resilience and service continuity, they demand faster and more coordinated fault detection, selective isolation, and post-fault reconfiguration [25,38]. Therefore, in the context of DC microgrids, the topology is most appropriately regarded as the fundamental constraint underlying the coordinated design of hierarchical control and protection systems.

3. Control Strategies in DC Microgrids

A DC microgrid generally consists of distributed energy sources (DESs) and loads, which must be coordinated to operate efficiently and stably. In grid-connected operation, a DC microgrid can act as a dispatchable power source, whereas in islanded operation it must maintain autonomous operation. Accordingly, a control system with sufficient robustness and flexibility is required. Control strategies for DC microgrids are commonly classified into decentralized, centralized, and distributed methods. In decentralized control, each converter-interfaced DES is regulated by a local controller (LC), which relies only on local measurements. This means that the controller does not need information about the overall system state and does not require communication links [27]. In centralized control, a central controller (CC) is introduced to coordinate the LCs through a low-bandwidth communication network. In general, the CC collects system-level information and sends control commands to the LCs [41]. In distributed control, each controller operates as an independent agent that can obtain local variables and exchange relevant information with neighboring agents to achieve coordinated control [28]. Decentralized, centralized, and distributed methods play different roles in DC microgrid operation. For instance, decentralized control is mainly responsible for voltage/current regulation and power sharing among DESs. By contrast, centralized and distributed control strategies are generally used to compensate for DC-bus voltage deviations and to balance the SoC among ESSs.

DC microgrids may include various types of DESs and loads, and their operation must account for efficiency, coordination, and operating cost [11]. Therefore, a single control strategy is usually insufficient to meet all operational requirements. To coordinate multiple control objectives, a hierarchical control framework is commonly adopted, typically including primary, secondary, and tertiary control layers [42,43]. The primary layer is an autonomous control level mainly responsible for power sharing among DESs and for maintaining system stability, with a typical response time of 10–100 ms. Droop control is a representative primary control method that enables power sharing among DESs without communication. However, it inevitably introduces a steady-state deviation in the DC-bus voltage. Secondary control is therefore used to restore the bus voltage and remove the steady-state deviation, with a typical response time of 1–10 s. Tertiary control optimizes power scheduling under the operating constraints of the DC microgrid to reduce system operating cost, and is also referred to as the energy management system (EMS). Its optimization interval is usually longer than 5 min. The equivalent structure of the hierarchical control scheme is shown in Figure 2. It should also be noted that some studies adopt a two-layer hierarchical structure [29,44], in which the original primary and secondary controls are combined into one control layer, while the EMS is treated as the tertiary control.

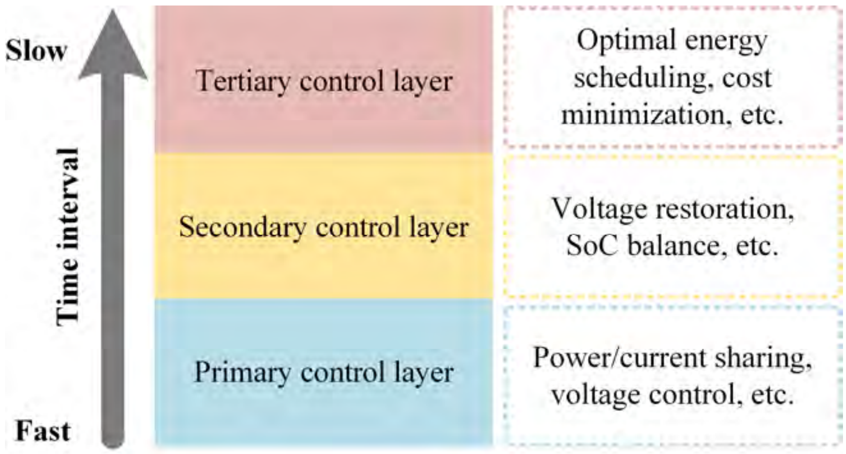

Figure 2. The hierarchical control system.

3.1. Primary Control

As the fastest-responding local control layer in DC microgrids, primary control is tasked with achieving power sharing among parallel systems and limiting converter overcurrent, without relying on high-speed communication. In converter-dominated DC microgrids, primary control typically consists of inner voltage/current regulation loops and an outer power-sharing scheme. While droop control remains the most prevalent approach for the power distribution, conventional static droop laws are often insufficient in practical systems to simultaneously satisfy the demands for wide-operating-range stability, sharing accuracy, and dynamic damping. Consequently, auxiliary components—such as virtual impedance or virtual inertia—are generally integrated with droop control to form a cohesive dynamic shaping mechanism within the primary layer, rather than existing as independent control layers [45,46].

The core challenges confronting primary control include power-sharing inaccuracies caused by line impedance mismatches, the negative incremental impedance effect induced by constant power loads, and parameter mismatches resulting from variations in equivalent impedance and power flow paths. To address these issues, traditional droop control has evolved from linear droop to adaptive, nonlinear, and robust droop strategies [47–49]. Furthermore, by introducing extra degrees of freedom into the droop laws, virtual impedance, and inertia-type support components, FO-based methods empower the primary control with more flexible dynamic shaping capabilities without altering the existing hierarchical structure [50,51].

3.1.1. Droop Control

In DC microgrids, the most prevalent primary control strategy is droop-based local control. The droop control includes current- and power-based controls, which can be written as (1) and (2).

$$v_o = v_r - m_c i_o \tag{1}$$

$$v_o = v_r - m_p P_o \tag{2}$$

where v_r and v_o are the reference and output voltage. i_o and P_o are the output current and power. m_c and m_p are the droop coefficients for current- and power-based droop control. This method utilizes controlled bus voltage deviations to achieve power redistribution among parallel units. Consequently, it inevitably suffers from an inherent trade-off between power-sharing and voltage deviation: a larger droop coefficient facilitates the suppression of circulating currents and enhances sharing robustness, yet it exacerbates steady-state bus voltage deviations. Conversely, a smaller droop coefficient mitigates voltage deviations but significantly increases the system's sensitivity to line impedance mismatches. Table 3 summarizes the integer order-based primary control methods.

In traditional control frameworks, virtual resistance or integer-order virtual impedance is typically coupled with linear droop control to equivalently shape the output impedance of converters, thereby improving current sharing among parallel units and suppressing low-frequency oscillations. Essentially, the objective is not to alter the steady-state targets of the droop control, but rather to enhance the dynamic response by adjusting equivalent output characteristics. For microgrids equipped with hybrid energy storage systems (HESS), coordinated droop control further introduces a dynamic power allocation scheme among distinct storage units, enabling batteries to handle the average power component while supercapacitors (SCs) absorb fast transient power fluctuations [52], as shown in Figure 3. Although such methods effectively improve transient power sharing, they cannot independently resolve the issues of steady-state bus voltage deviation and the SoC recovery of the SCs [53].

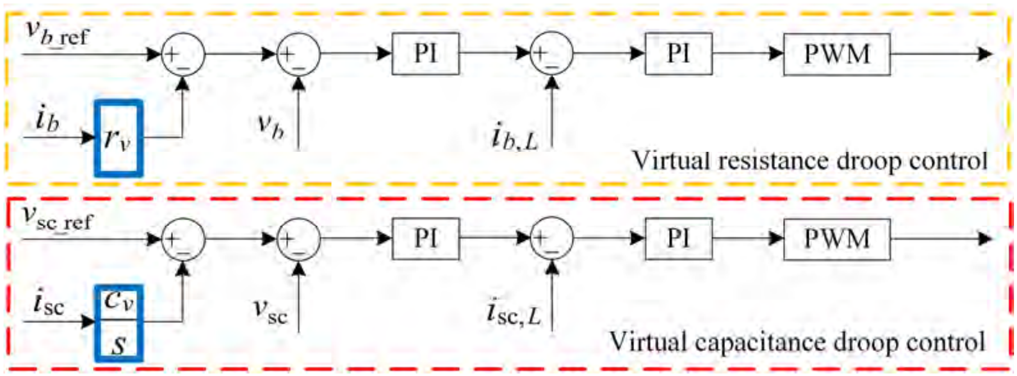

Figure 3. The schematic diagram of the coordinated control for the HESS in DC microgrid.

Table 3. Comparison of droop control methods.

Refs.	Category	Content	Advantages	Limitations
[54–57]	Linear droop	Basic power sharing and local voltage support	Simple structure, local measurements only, plug-and-play capability	Inherent tradeoff between sharing accuracy and voltage deviation; sensitive to feeder mismatch
[52,53,58,59]	Coordinated droop	Average/transient power separation in HESS	Better different dynamic power allocation	Cannot independently restore energy state or long-term balance
[60–64]	Adaptive droop	Mitigation of operating-point change and impedance mismatch	Better adaptability and sharing quality	More complex update mechanism; sensitive to delay and measurement error
[65–70]	Nonlinear/robust droop	Large-disturbance stabilization and uncertainty rejection	Better disturbance rejection and stability margin	Higher tuning complexity and stronger model dependence
[45,46,71,72]	Integer-order virtual impedance	Active damping and interaction shaping	Useful for oscillation mitigation and sharing improvement	Sensitive to bandwidth choice and inner-loop tuning

In scenarios characterized by highly fluctuating operating conditions, adaptive droop control enhances the system's adaptability to line impedance variations, SoC fluctuations, and load disturbances by dynamically adjusting the droop coefficient or virtual resistance online [49,60–64]. While these methods can substantially mitigate power-sharing errors, their efficacy heavily relies on the stability and reliability of the online parameter updating process. Furthermore, when the adaptive mechanism necessitates additional measurements, state estimations, or communication support, the inherent time delays and measurement noises further exacerbate the complexity of the control design.

To alleviate the inconsistent performance of fixed-slope droop strategies across wide operating ranges, nonlinear droop control employs state-dependent or piecewise droop curves, enabling differentiated control designs for light and heavy load conditions [65,73–75]. Although this approach offers superior flexibility under large disturbances and broad load variations, its performance is highly sensitive to the specific formulation of the nonlinear function and parameter boundaries, culminating in a more convoluted tuning procedure. Furthermore, robust droop control suppresses the impacts of parameter uncertainties and external disturbances through the incorporation of observers, sliding mode control, or robust optimization designs [66–68,70]. Compared to conventional linear droop control, these methods exhibit significant advantages in large-signal stability and disturbance rejection capabilities. However, they typically demand explicit model assumptions, higher implementation complexity, and more rigorous parameter tuning.

3.1.2. Double Loop Control

In DC microgrids, the representative implementation of the double loop control is usually the outer voltage loop plus inner current loop based on PID controllers. A typical form can be written as (3).

$$G(s) = k_p + k_i \frac{1}{s} + k_d s \tag{3}$$

where k_p, k_i and k_d are proportional, integral and derivative parameters. The widespread use of these integer-order PID structures in DC microgrids is mainly due to their simple implementation and low computational burden. Despite the maturity of integer-order PI, its limitations are also clear. The number of tuning degrees of freedom is limited, which makes it difficult to achieve a better compromise among overshoot, response speed, damping, and robustness under load disturbances, source fluctuations, and bandwidth constraints [76]. In nonlinear conditions, integer-order PID often requires more aggressive gain selection, which in turn increases noise sensitivity and reduces phase margin.

In this context, fractional-order PID control is introduced as a dynamic enhancement of integer-order PID [77]. The mathematical expression is written as (4) in the frequency domain [78].

$$G(s) = k_p + k_i \frac{1}{s^{\alpha}} + k_d s^{\beta} \tag{4}$$

where α and β are the fractional orders of the integral and derivative terms, respectively. As can be seen from (4), the control method contains five adjustment parameters, so it can meet multiple dynamic performance indicators at the same time. Compared with conventional integer-order control, fractional-order control introduces additional tunable degrees of freedom, thereby enabling more precise adjustment of the phase margin, damping characteristics, and bandwidth allocation within the target frequency band [79,80]. For power-converter-dominated DC microgrids, these added degrees of freedom are particularly advantageous in addressing the complex dynamics induced by sudden load transients, parameter mismatches, and the coupling of multiple energy storage systems.

It is crucial to emphasize that FO-based PID controllers do not eliminate all the inherent limitations of the primary control layer. If conventional droop strategies are retained, steady-state bus voltage deviations still require restoration via secondary control. Furthermore, under significant line impedance mismatches, power sharing errors must still be mitigated through careful droop coefficient design or secondary coordination. Additionally, implementation of fractional-order controllers typically necessitates band-limited approximation or discretization. Consequently, they exhibit higher sensitivity regarding computational complexity, parameter tuning, and the selection of sampling periods compared to conventional PID controllers [81]. Therefore, the rational positioning of FO-based PID should be conceptualized as a dynamic enhancement mechanism for primary-level local dual-loop control in DC microgrids. It is intended to operate synergistically with conventional or coordinated droop strategies, rather than to supplant the hierarchical control framework entirely.

From Table 4, both integer-order and fractional-order PID controllers retain outer droop or coordinated droop as the power-sharing mechanism, while improving local voltage regulation, current tracking, and dynamic bus support. Their main contribution is enhanced local reference tracking; they do not, by themselves, remove the steady-state bus-voltage deviation of primary control or the sharing error caused by feeder-impedance mismatch.

Table 4. Comparison of PID-based control methods.

Refs.	Category	Content	Advantages	Limitations
[82–84]	Integer-order PI/PID local control	Voltage-reference tracking, fast current regulation, local voltage support	Mature structure, simple implementation, low computational burden	Limited freedom in balancing speed, damping, and robustness
[85–87]	Integer-order PI double-loop control	Droop-reference realization, bus stabilization, and local execution	Coordinate with conventional droop and widely used in practice	Still strongly dependent on outer droop design; limited adaptability to wide operating conditions
[79–81,88–90]	FO-based PI/PID control	Enhancement of bus-voltage regulation quality, faster current tracking and improved disturbance rejection	Improved overshoot and transient voltage performance, better dynamic response and robustness	Does not directly determine system-level power sharing; more complex tuning and bandwidth coordination

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3.1.3. Virtual Impedance Method

In the DC microgrids, the fundamental role of virtual impedance is to actively shape the equivalent output impedance of converters, thereby improving current sharing, damping characteristics, and transient stability among parallel systems. The mathematical model can be written as follows [45,91].

$$Z_v(s) = \begin{cases} L_v s \frac{\omega_c}{s+\omega_c} \\ R_v + \frac{1}{sC_v} \end{cases} \tag{5}$$

where R_v, L_v and C_v are virtual resistance, virtual inductance, and virtual capacitance, respectively; ω_c is cut-off frequency of the low-pass filter. As can be observed from Equation (5), integer-order virtual impedance is an impedance shaping technique based on virtual resistance, virtual inductance, and virtual capacitance, which is essentially implemented through dynamic compensation. Although integer-order virtual impedance has a well-defined implementation framework, its limitations remain prominent. The dynamic performance of the system is highly sensitive to the selection of virtual impedance parameters; inappropriate configurations fail to provide effective damping and may instead amplify system oscillations [45,92]. Furthermore, when utilizing virtual impedance to achieve impedance shaping within a specific frequency band, the design of the virtual impedance inherently depends on system conditions such as inner- and outer-loop controller parameters and filter characteristics [93].

Then, fractional-order theory is introduced into the design of virtual impedance. The mathematical models can be expressed as (6) [94,95].

$$Z_v(s) = \begin{cases} (\omega)^{\gamma} L_v \left[\cos(\frac{\gamma\pi}{2}) + j\sin(\frac{\gamma\pi}{2})\right] \\ \frac{1}{(\omega)^{\delta} C_v} \left[\cos(\frac{\delta\pi}{2}) - j\sin(\frac{\delta\pi}{2})\right] \end{cases} \tag{6}$$

where ω is the angular frequency. δ and γ are the fractional orders of the virtual capacitor and virtual inductor, respectively. Compared with its traditional integer-order counterpart, fractional-order methods provide virtual impedance with more flexible degrees of freedom for frequency-domain shaping, thereby improving damping and stability margins over a wider frequency band [96–98]. This superiority is particularly pronounced in scenarios characterized by multi-converter coupling, varying bus impedances, and prominent local oscillation modes.

It is noteworthy that existing research on fractional-order virtual impedance is not restricted to DC microgrids but also encompasses AC microgrids [51,99–101]. Nevertheless, these studies collectively demonstrate that fractional-order impedance shaping can broaden the effective damping frequency range, improve the suppression of interactive oscillations, and enhance system robustness against parameter variations. When integrated into the primary control layer of DC microgrids, this concept can be effectively leveraged to improve bus stability and the interactive dynamics among parallel interfaces.

From Table 5, virtual impedance control in DC microgrids essentially improves current sharing, damping characteristics, and transient stability by actively shaping the equivalent output impedance of converters. At present, the mainstream implementation is still integer-order virtual impedance, including static virtual resistance, dynamic virtual inductance, and capacitance. In addition, fractional-order virtual impedance is mainly grounded in the modeling of fractional-order capacitors and inductors, which provides more flexible frequency-domain shaping and a more realistic representation of the dispersive and memory-dependent behavior of practical energy-storage components. Currently, research on fractional-order virtual impedance remains relatively limited. A unified modeling framework, parameter tuning methods, and experimental validation remain challenges.

Table 5. Comparison of virtual impedance methods in DC microgrids.

Refs.	Category	Content	Advantages	Limitations
[45,91–93,102]	Integer-order dynamic virtual impedance	Adds the virtual resistor, inductor and capacitor to the static droop term	Improves damping and transient stability	Sensitive to parameter selection; poor choices may amplify the response
[94,95,99–101]	FO-based virtual impedance	Extends impedance shaping through fractional-order capacitor/inductor modeling	Better representation of dispersive and memory-dependent component behavior; broader frequency-shaping potential	Model complexity and difficult parameter tuning

3.1.4. Virtual Inertia Method

In DC microgrids, the primary objective of virtual inertia is to enhance the system's resilience against abrupt DC bus voltage fluctuations. Unlike inertia emulation in AC systems, which centers on frequency deviation, DC virtual inertia is specifically designed for bus voltage support and fast-time-scale power buffering. In the existing literature, integer-order virtual inertia remains the most prevalent implementation. Its fundamental principle lies in establishing an inertial control loop via energy storage or grid-interfacing converters to emulate the dynamic response of supplementary energy storage elements. Consequently, during power imbalances, this mechanism provides instantaneous power compensation, effectively mitigating the rate of change in voltage and minimizing transient deviations. The mathematical model can be written as (7) [103].

$$i_{\mathrm{ref}} - i_o - D_v(u_{\mathrm{dc}}^{\mathrm{ref}} - u_n) = C_v u_{\mathrm{dc}}^{\mathrm{ref}} \frac{du_{\mathrm{dc}}^{\mathrm{ref}}}{dt} \approx C_v u_n \frac{du_{\mathrm{dc}}^{\mathrm{ref}}}{dt} \tag{7}$$

where i_{ref} and i_o are the reference and output current; $u_{\mathrm{dc}}^{\mathrm{ref}}$ and u_n are the reference and bus voltage; D_v and C_v are the voltage-damping coefficient and virtual-inertia coefficient. Equation (7) does not represent actual synchronous-machine rotational inertia, but rather a converter-based energy-buffering mechanism. This type of inertial equation is one of the mainstream approaches to virtual inertia in DC microgrids [104].

Based on integer-order virtual inertia, the literature has further developed various implementation forms. Virtual DC motors (VDCMs) and their derivatives enhance the characteristics of inertia simulation. Ref. [105] points out that conventional VDCM suffers from complex modeling, challenging parameter tuning, and a lack of intuitive boundaries for dynamic design. Consequently, reduced-order impedance models and feasible region design methods are required to optimize the parameter configuration process. Another prominent approach is the virtual inertia method based on capacitor current control [46,104,106]. Related studies explicitly highlight that the converter's output impedance distorts the inertia response, thereby necessitating additional feedforward compensation and highly accurate model parameters. To circumvent this dependency, the capacitor current control strategy employs a static gain to directly regulate the capacitor current. This approach achieves equivalent inertia emulation without relying on explicit differential equations, thereby inherently avoiding noise-sensitive derivative operations.

Although integer-order virtual inertia control for DC systems has developed into a well-established implementation framework, it still exhibits certain limitations. First, inertia support based on first-order differential equations is highly sensitive to the rate of change in voltage, rendering practical measurement signals highly susceptible to high-frequency noise amplification. Second, a larger virtual inertia coefficient does not necessarily yield better performance; an excessively large inertia parameter can retard the system's dynamic recovery and even compromise closed-loop stability margins. To address these challenges, FO-based virtual inertia has emerged as a promising alternative. For instance, ref. [50] proposed a FO-based virtual inertia control strategy. Rather than redefining the physical essence of DC inertia, this method substitutes the integer-order derivative in the conventional virtual inertia loop with a fractional-order counterpart. This substitution significantly expands the degrees of freedom for shaping the system's dynamic response. The expression of this approach is given by (8).

$$i_{\text{ref}} - i_o - D_v(u_{\text{dc}}^{\text{ref}} - u_n) = C_v u_{\text{dc}}^{\text{ref}} \frac{d^{\beta} u_{\text{dc}}^{\text{ref}}}{dt} \tag{8}$$

The results demonstrate that the proposed method significantly enhances the system's stability margins and improves the dynamic response characteristics of the DC bus voltage compared to conventional integer-order virtual inertia control. Consequently, the core theoretical value of FO-based virtual inertia lies not in redefining the physical fundamentals of DC inertia, but in leveraging the additional degrees of freedom provided by the fractional order to optimize the dynamic performance and robustness of the inertial response. Moreover, although ref. [107] employed fractional-order sliding mode and current control within a DC microgrid, its virtual inertia formulation essentially retained an integer-order structure. Consequently, such studies are more accurately classified as a combination of integer-order virtual inertia and fractional-order local regulation, rather than a direct implementation of fractional-order virtual inertia [108,109].

From Table 6, the control objective is to provide supplementary inertia support via converter or energy storage interfaces under conditions of power imbalance, source fluctuations, or sudden load changes. This mechanism aims to mitigate the rate of change in voltage and enhance the transient stability of the DC system. From an implementation perspective, integer-order virtual inertia remains the fundamental framework for current DC microgrids, whereas fractional-order virtual inertia represents a further expansion of the capability to shape inertial dynamics. Specifically, virtual inertia methods based on conventional first-order differential equations are typically highly susceptible to the rate of change in voltage measurement noise and the trade-offs of parameter tuning. The VDCM strategy suffers from inherent issues such as model complexity and non-intuitive parameter design. Furthermore, although capacitor current control elegantly avoids explicit derivative operations and feedforward compensation, its practical applicability remains strictly constrained by specific hardware interface topologies. In contrast, fractional-order virtual inertia exhibits significant potential advantages in terms of dynamic flexibility and stability margins. However, direct implementations and systematic experimental verifications tailored to DC microgrids are still limited, establishing this as a promising direction for future research.

Table 6. Comparison of virtual inertia methods in DC microgrids.

Refs.	Category	Content	Advantages	Limitations
[46,103,106,110]	Integer-order virtual inertia	Emulates inertial support through a first-order voltage–current dynamic relationship; Uses capacitor current control directly for inertia emulation without explicit differential equation	Clear structure and straightforward integration with storage-interfaced or grid-interfaced converters	Sensitive to voltage-variation signals and parameter choice; excessive inertia may slow recovery
[105,111,112]	VDCM	Constructs inertia enhancement through DC-machine analogy	Stronger physical interpretation and clearer impedance-based understanding	Model complexity and difficult parameter tuning; multi-converter analysis is still limited

Table 6. *Cont.*

Refs.	Category	Content	Advantages	Limitations
[107–109]	Integer-order virtual inertia plus fractional-order local regulation	Retains integer-order virtual inertia in the outer loop and introduces fractional-order control in the inner loop	Improves local dynamic response and robustness	Does not constitute a direct fractional-order virtual-inertia link
[50,113]	FO-based virtual inertia	Replaces the integer-order inertial link by a fractional-order	Higher stability margin, better bus-voltage dynamic performance, tunable dynamic order	Direct DC literature is still limited and implementation complexity is higher

3.2. Secondary Control

Secondary control is located above the primary layer and typically operates on a timescale of seconds. It is slower than primary control but much faster than tertiary energy management. Primary control achieves fast autonomous operation through droop characteristics, but it inevitably introduces steady-state bus-voltage deviation and may also produce sharing errors under unequal line impedances, different topologies, and varying storage states. The purpose of secondary control is not to replace the primary layer. Instead, it provides slow-timescale compensation for droop-induced steady-state deviations while preserving the fast response and plug-and-play capability of primary control. At the same time, it addresses higher-level coordination objectives such as bus-voltage restoration, correction of current/power sharing among parallel units and SoC balancing [114]. Existing methods can be organized into traditional secondary control and fractional-order secondary control.

3.2.1. Traditional Secondary Methods

Centralized control methods generally rely on a central controller (CC) to acquire the operating state of the system and issue control commands to the primary control layer [115–117]. As illustrated in Figure 4, a typical implementation employs a PI-based feedforward voltage compensator to mitigate the bus-voltage deviation introduced by primary control [42]. The corresponding mathematical model is given in (9) and (10).

$$v_o = v_r - m_c \times i_o + \delta v \tag{9}$$

$$\delta v = k_p \times (v_r^* - v_{\text{bus}}) + k_i \times \int (v_r^* - v_{\text{bus}})dt \tag{10}$$

where δv is the voltage compensating term; v_r^* and v_{bus} are the setting voltage and common DC bus voltage. According to (9) and (10), the voltage difference between the measured DC bus voltage and the reference value is first obtained and then processed by the PI compensator. The resulting voltage-restoration signal is subsequently added to the droop control loop. To ensure proper compensator performance and avoid adverse interaction with the primary layer, the PI parameters should be tuned so that the bandwidth of the voltage compensator remains lower than that of the primary control loop.

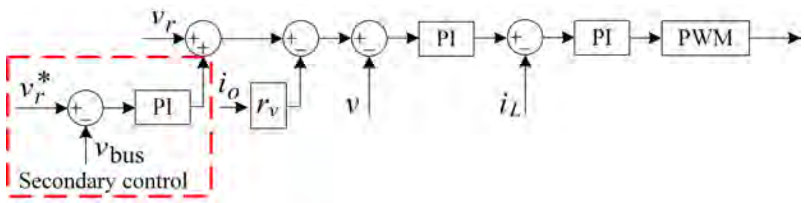

Figure 4. The schematic diagram of the secondary control in DC microgrid.

Recently, a variety of centralized strategies have been developed, including model predictive control (MPC), supervisory control, sliding-mode regulation, and robust control [116,118–120]. The main advantage of centralized control is that it can readily handle global constraints and multiple objectives, which is particularly attractive in coordinated multi-bus networks. Its main drawback is the strong dependence on communication networks and on the availability of the central controller. If the communication link or the central node fails, the performance of the secondary layer degrades markedly and the system may lose coordinated restoration capability.

Distributed secondary control exchanges information only among neighboring controllers through a sparse communication network, thereby removing the need for a single supervisory node [23]. The consensus algorithm is a commonly used distributed algorithm, which can be represented as (11) [59,121,122]. The control diagram is given in Figure 5.

$$h_j(k+1) = h_j(0) + \varepsilon \sum_{i \in N_j} \{\delta_{ji}(k) + a_{ji} [h_i(k) - h_j(k)]\} \tag{11}$$

where k is an iteration counter value. $h_j(k+1)$ is the information status of iteration at k + 1 for jth agent. N_j is the set of the agents that connect with jth agent. $\delta_{ji}(k)$ is a variable that can store cumulative difference between two agents j and i. a_{jl} is connection status between agents j and i. If agent j and agent i are not neighbors, then $a_{ji} = 0$, otherwise $a_{ji} = 1$. ε is used to regulate the convergence speed. The main feature of distributed secondary control is that system-level coordination emerges from local interaction. It is therefore more scalable and more resilient to single-point failures in DC microgrids [55,59,123]. Compared with centralized methods, distributed control provides a better balance between communication burden and structural resilience. However, its convergence speed and stability margin depend on the communication graph, the delay pattern, topology switching, and line-impedance mismatch.

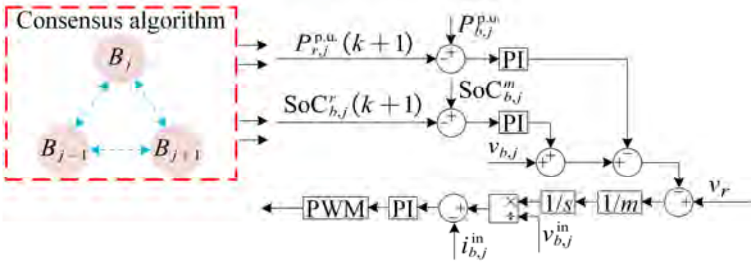

Figure 5. The schematic diagram of the consensus-based voltage compensator in DC microgrid.

Decentralized secondary control depends only on local measurements and does not require explicit communication, which makes it attractive in communication-limited systems or in applications with strong autonomy requirements [124–126]. Controllers autonomously generate compensation signals using local sensors to monitor electrical parameters. These signals are integrated with the primary control output via embedded algorithms (e.g., PI controllers, sliding mode control, etc.) to restore electrical reference (e.g., voltage, SoC, etc.) to nominal values [127]. Their main advantage is structural simplicity and immunity to communication delay in the strict sense. Their main limitation is the absence of global or neighbor information. Therefore, power sharing accuracy may decrease in topology reconfiguration and multi-bus systems.

Table 7 shows that the choice of secondary-control architecture should be aligned with the system topology, the communication conditions, and the control objectives. In systems with a reliable supervisory platform, centralized control is effective for multi-objective coordination. In multi-bus, ring, and zonal systems, distributed methods are structurally more compatible. In systems with unreliable communication or strong autonomy requirements, decentralized methods are more practical, although their system-level coordination capability remains limited.

Table 7. Comparison of traditional secondary control in DC microgrids.

Refs.	Category	Information Structure	Content	Advantages	Limitations	Applications
[116,118–120,128–130]	Centralized secondary control	Global measurements are sent to a central controller, which broadcasts compensation commands	Current/power sharing, voltage regulation, SoC balancing, and multi-objective regulation	Strong global coordination	High dependence on communication and the central node; limited scalability; single-point failure risk	Single-bus systems, and multi-bus networks with reliable communication
[131–136]	Distributed secondary control	Controllers exchange information only with neighbors and coordinate through consensus	Supports current sharing correction, voltage regulation and ESS coordination	Better scalability and resilience; well suited to sectionalized and multi-bus structures	Convergence and stability are strongly affected by the communication graph, delay, and line-impedance mismatch	Multi-bus, ring, zonal, and clustered microgrid applications
[137–141]	Decentralized secondary control	Local measurements and local estimation	Current/power sharing, voltage regulation, SoC balancing, etc.	No dependence on communication; strong autonomy; relatively simple implementation	Difficult to achieve accurate system-wide coordination; less suitable for strongly coupled multi-bus networks	Single-bus systems, local zones, and communication-constrained applications

From the scalability perspective, the key purpose of decentralized control is not only to reduce communication but also to keep the controller-design complexity local as the number of nodes increases. In large-scale DC microgrids, centralized secondary control can handle global objectives, but its communication burden, central-controller reliability, and model-maintenance cost increase with system scale. Scalable decentralized or distributed methods usually follow a plug-and-play design philosophy. Each source-side converter controller relies only on local converter parameters and neighboring line information. When a DG unit is added, removed, or reconfigured, only the affected node and its neighbors need to be re-validated or re-tuned, rather than redesigning the entire system. Such methods are suitable for multi-bus, meshed, and zonal DC microgrids, but constant power loads, line-parameter drift, communication-topology changes, and local controller re-tuning must be explicitly considered to preserve global stability.

3.2.2. Fractional Order Secondary Control

Most conventional secondary controllers are based on integer-order PI, PID, or consensus compensators for voltage restoration and sharing correction. These methods face an evident tradeoff in low-frequency oscillation damping, robustness against uncertainty, and dynamic shaping over a wide operating range. Fractional-order secondary control introduces fractional integration and differentiation, as defined in (4), and therefore provides additional freedom for gain and phase shaping during bus-voltage recovery and coordinated ESS regulation [142–144].

Several studies have incorporated fractional-order concepts into secondary control to achieve objectives such as voltage compensation and SoC balancing [142–145]. For example, Ref. [143] proposes a voltage compensation method for DC microgrids based on a fractional-order differential-integral (FODI) controller. By introducing a FODI-based voltage compensation term into the droop control loop, this method enables autonomous DC-bus voltage restoration and power sharing. The controller also contributes to SoC balancing and coordinated energy management among energy storage units. The reported results indicate that, compared with conventional control methods, this approach provides improved performance in DC-bus voltage regulation, power distribution, and SoC balancing. In Ref. [146], a distributed consensus protocol based on a fractional-order PI (FOPI) controller is developed for voltage restoration and energy-storage balancing in DC microgrids. In this strategy, agents equipped with FOPI controllers coordinate the energy balance of the ESSs while regulating the average bus voltage of the microgrid. The proposed scheme can be applied in both islanded and grid-connected modes, ensuring that the system average voltage converges to its reference value under both operating conditions.

The fractional-order secondary control shows strong potential in dynamic performance. From Table 8, if the control law does not account for line impedance and multi-bus voltage differences, sharing error may still remain. In addition, the discrete-time realization and parameter optimization of the fractional-order controllers are generally more complex than for integer-order methods, so practical adoption depends not only on dynamic performance but also on validation depth.

Table 8. Comparison of fractional order secondary control in DC microgrids.

Refs.	Category	Content	Advantages	Limitations
[142–144,146,147]	FO-based PID, FO-based sliding mode control	Bus voltage restoration, accurate power sharing, SoC balancing	Stronger damping, smaller overshoot, improved robustness and disturbance rejection	Still affected by communication quality, line impedance, and implementation complexity
[50,145]	FO-based MPC	Voltage compensation, current/power sharing, suppression of complex coupled dynamics	Better handling of model mismatch and constraints; more flexible dynamic shaping	Higher computational burden; more sensitive to model quality and parameter tuning

3.2.3. Implementation Challenges of FO-Based Control

Although fractional-order control exhibits significant potential in terms of phase margin, damping shaping, and wideband robustness, its engineering application remains constrained by multiple practical physical and computational limitations. Specifically, due to the deep coupling relationship between the fractional order and the proportional, integral, as well as derivative gains, conventional PI/PID tuning experiences cannot be directly transferred to FOPI/FOPID controllers. Particularly in the context of multi-converter parallel DC microgrids, parameter design must simultaneously satisfy multi-dimensional performance indices, including bus voltage recovery, precise power sharing, and communication delay margins.

Furthermore, the FO calculus operator typically relies on methods such as finite memory approximation, or discrete differencing. System parameters—such as approximation frequency bands, fitting orders, sampling periods, and the word length of digital controllers—interact continuously, thereby restricting phase compensation accuracy and potentially triggering the unexpected amplification of high-frequency noise. When deployed on embedded platforms like DSPs or FPGAs, such complex operator approximations inevitably lead to a sharp increase in computational overhead and storage resource requirements, risking the compression of the effective control bandwidth for both inner current loops and outer voltage loops.

At the performance validation level, evaluating FO controllers urgently needs to break through the limitations of ideal simulation conditions. It must comprehensively cover complex operational scenarios, such as sudden load steps, dynamic network topology switching, sensor noise interference, communication link delays, converter saturation/current limiting, and system fault recovery. In conclusion, within the control architecture of DC microgrids, the reasonable positioning of FO control should be regarded as a key enhancement measure to improve dynamic response and robustness margins, rather than a complete replacement for existing integer-order control schemes or hierarchical control frameworks.

3.2.4. Communication Delay in Secondary Control

Communication delay is an inherent constraint in centralized and distributed secondary control. Since the secondary layer closes the loop through measurement acquisition, data transmission, protocol scheduling, controller computation, and command dispatch, delay is not an external disturbance added afterwards, it is part of the architecture itself. Its direct effect is additional phase lag and a reduction in effective bandwidth, which can slow bus-voltage restoration and reduce consensus convergence speed [148,149].

Existing research mainly focuses on establishing small-signal models with time delays to evaluate the stability and damping variations in centralized and distributed secondary control under different delay conditions [150,151]. Additionally, delay compensation mechanisms, such as lead-lag compensation or other phase correction mechanisms, are designed to mitigate the adverse effects of time delay on closed-loop performance [152,153], as shown in Figure 6. However, most existing studies are still based on fixed or bounded delays. Joint analysis of time-varying delay, packet loss, asynchronous updates, and topology reconfiguration remains limited, as shown in Table 9.

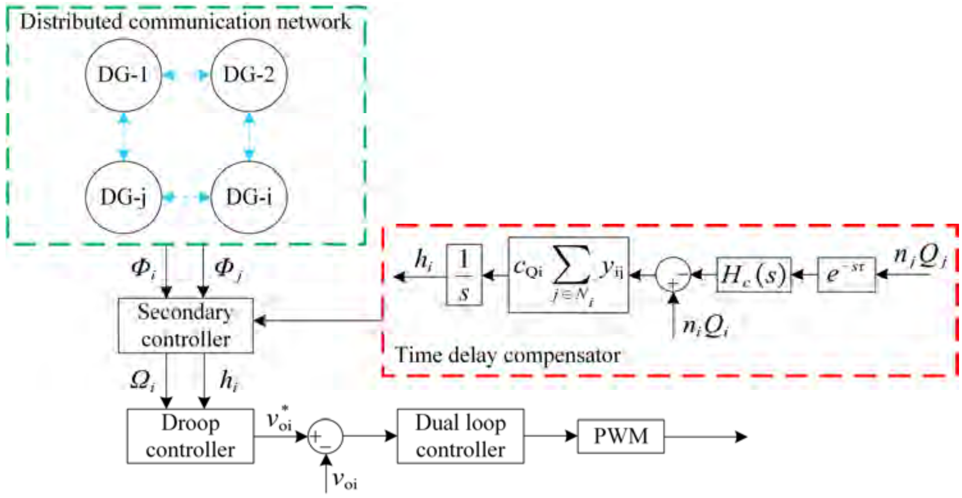

Figure 6. The schematic diagram of the time delay compensator in a microgrid.

Table 9. Comparison of communication-delay effects in secondary control.

Refs.	Category	Source of Delay	Effect	Approach	Limitations
[148,149,152,154]	Centralized secondary control	Global measurement upload, centralized computation, and command dispatch	Slower bus-voltage restoration, reduced phase margin, degradation of global coordination	Delay modeling, compensator design, controller retuning	Coupled effects of packet loss, central-node failure, and delay remain insufficiently studied
[150,151,153,155]	Distributed secondary control	Neighbor-to-neighbor transmission delay, protocol scheduling, and asynchronous updates	Slower consensus convergence, reduced accuracy of average-voltage restoration and sharing correction, possible oscillation	Multi-delay small-signal modeling, stability-margin analysis, phase compensation	Joint design under time-varying delay, topology switching, and event-triggered updating is still limited

3.2.5. Discussions

From an application perspective, linear droop control and PI/PID double-loop control are more suitable for structurally simple and communication-constrained single-bus LVDC microgrids. Adaptive, nonlinear, and robust droop methods are more appropriate for systems with large load variations, significant line-impedance mismatches, or large disturbances. Distributed secondary control is more compatible with multi-bus, ring-bus, and zonal topologies, but its convergence and stability margins must be evaluated under communication-topology changes, time delays, packet losses, and asynchronous updates. FO-based control is attractive when stronger damping shaping and larger dynamic margins are required; however, its engineering application depends on parameter tuning, discrete implementation, and experimental validation. Therefore, the superiority of a control method should be evaluated with respect to topology scale, communication conditions, line impedance, and energy-storage dynamics.

3.3. Tertiary Control (EMS)

The EMS is located at the top control layer of DC microgrids and can be regarded as an intelligent computing platform. It manages the power exchange between the DC microgrid and the main grid while ensuring system constraints are met, enabling both reliable and cost-effective operation [156]. Using information and communication technologies such as ZigBee and digital subscriber lines, the EMS monitors and collects data on power usage, weather conditions, system states, and electricity tariffs. These datasets are accessible to utilities and end users, and are forwarded to the optimization layer to schedule power dispatch.

The optimization layer employs advanced algorithms to coordinate RES, ESS, and load demand dynamically, producing optimal power-dispatch schedules based on forecast data [156]. Optimization objectives typically include operational costs, ESS degradation costs, and carbon emission costs, as illustrated in Figure 7a. Constraints consist of energy balance and the power limits of ESS and RES, as shown in Figure 7b. Numerous studies have proposed various EMS optimization strategies for microgrids to achieve efficient and optimal operation. A systematic review of these strategies and methods is presented in the following subsections.

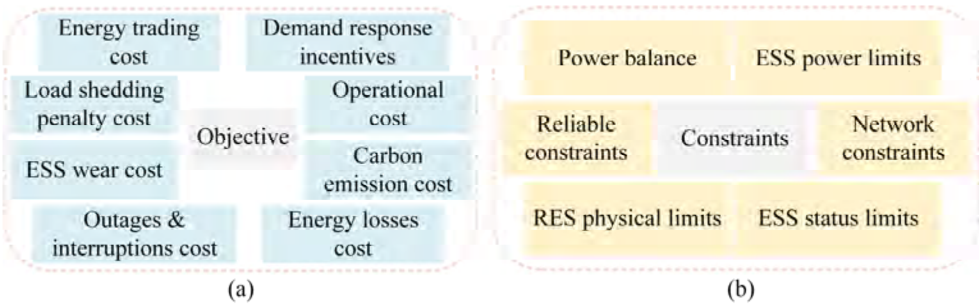

Figure 7. The optimization framework: (**a**) optimization objectives; (**b**) optimization constraints.

Existing optimization strategies for DC microgrid EMS can be mainly divided into MPC, meta-heuristic algorithms, rule-based control, robust/stochastic optimization, and data-driven/reinforcement learning methods. The main differences between them are in model accuracy, constraint-handling capability, online implementation complexity, and uncertainty representation.

MPC is one of the most representative model-based approaches in tertiary control because it explicitly embeds prediction information and physical constraints into a receding-horizon scheduling process [157–159]. Its main advantage lies in the simultaneous handling of power balance, device limits, and grid-exchange constraints. At the same time, it can mitigate the cumulative effect of prediction errors through rolling updates. This makes MPC particularly suitable for DC microgrids with strong multi-interval coupling and ESS participation. However, its performance still depends on model fidelity, forecast quality, and online solution speed. The computational burden rises significantly when the system structure becomes more complex.

Meta-heuristic algorithms, such as genetic algorithms, particle swarm optimization, etc., are effective in solving nonconvex, multimodal, or combinatorial optimization problems [160–162]. These methods are attractive for capacity allocation, discrete switching-state selection, and multi-objective tradeoff problems. Their main limitations are iterative computational burden and uncertain convergence properties in real-time scenarios. Therefore, they are more suitable for day-ahead scheduling, offline optimization, and parameter tuning.

Rule-based control and fuzzy logic control remain important in many practical EMS implementations [163–166]. These methods generate scheduling actions from expert rules, priority logic, or fuzzy inference [167]. Their strengths are low computational cost, direct implementation, and suitability for small-scale systems. Their weaknesses are the lack of guaranteed global optimality and limited transferability of the rule sets. As system topology changes and the operating range expands, the cost of rule design, tuning, and maintenance tends to increase rapidly. Therefore, they are regarded as low-complexity supervisory strategies or backup layers rather than general-purpose optimization engines.

Robust and stochastic optimization are primarily used to address uncertainty in renewable generation, load demand, and electricity price [168]. Robust optimization accounts for worst-case realizations within a prescribed uncertainty set and therefore produces conservative yet feasible schedules, which is attractive in safety-critical systems [169,170]. Stochastic optimization uses probability models or scenario sets to represent uncertainty and is often less conservative, but it depends strongly on scenario quality and distribution modeling [171,172]. In DC microgrids with high renewable penetration, these two classes of methods provide a more realistic treatment of uncertainty than deterministic scheduling. Generally, they introduce additional tradeoffs between modeling effort and computational complexity.

Data-driven and reinforcement learning methods have recently been introduced into tertiary EMS [173–175]. Neural networks can be used as surrogate models, policy approximators, or decision mappings, whereas reinforcement learning can learn dispatch policies through interaction. These methods are promising for strongly nonlinear and highly coupled systems, and once trained, they can produce decisions quickly in real time. However, their performance depends heavily on data coverage, reward design, and the way safety constraints are embedded. In the absence of sufficient experimental validation, data-driven strategies are more appropriate as optimization accelerators, model substitutes, or auxiliary decision modules, rather than independently undertaking scheduling tasks without physical-constraint supervision.

As shown in Table 10, EMS methods exhibit clear differences in their solution mechanisms. Nevertheless, their common objective is to generate executable scheduling schemes while satisfying system constraints, thereby coordinating system economics and power supply reliability. The fundamental differences among these methods mainly lie in their model establishment, representation of uncertainty, capability for constraint handling, and online computational complexity.

A common limitation of existing EMS methods is that no single strategy currently provides comprehensive advantages in terms of global optimality, real-time performance, and engineering deployment. MPC relies heavily on model accuracy and the capability for online optimization. Metaheuristic methods offer considerable flexibility in addressing complex nonconvex problems, but their convergence stability and suitability for real-time applications are often limited. Rule-based control and fuzzy logic control are relatively simple to implement, yet they generally cannot guarantee global optimality. Robust optimization depends on the appropriate construction of uncertainty sets, whereas stochastic optimization relies on the accurate characterization of probability distributions or scenario samples. The performance of data-driven methods and reinforcement learning methods

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is further constrained by the coverage of training data, the way safety constraints are embedded, and the generalization capability of the learned policy.

Table 10. Comparison of optimization methods in DC microgrids.

Refs.	Category	Content	Advantages	Limitations
[176–181]	MPC	Solves a constrained optimization problem over a receding horizon	Strong constraint-handling capability; suitable for multi-interval coupling and storage scheduling; allows online plan correction	Depends on model and forecast quality; computation may become heavy in complex systems
[182–186]	Meta-heuristic algorithms	Uses population-based search or evolutionary mechanisms for nonconvex and combinatorial optimization	Better adaptability to complex objectives and discrete variables; convenient for multi-objective problems	Convergence speed and optimality are not guaranteed; limited real-time suitability
[187–195]	Rule-based/fuzzy logic control	Generates dispatch commands from expert rules, priority logic, or fuzzy inference	Low computational burden; direct implementation; suitable for small-scale systems	No guaranteed global optimality; difficult to maintain when system complexity increases
[169–172,196–198]	Robust/stochastic optimization	Represents renewable, load, and price uncertainty by uncertainty sets or probability scenarios	Explicit uncertainty handling; suitable for high-renewable systems	Robust methods may be conservative; stochastic methods depend on scenario and distribution quality
[199–205]	Data-driven/reinforcement learning	Learns surrogate models, decision mappings, or scheduling policies from data	Potentially suitable for strongly nonlinear systems; fast online inference after training	Dependent on data quality and safety-constraint embedding; limited interpretability and generalization

Hybrid EMS frameworks that account for physical constraints, operational uncertainty, and engineering feasibility represent an important research direction. Such frameworks should ensure that optimization-layer scheduling commands remain compatible with the tracking capability of the primary and secondary control layers, while incorporating ESS degradation, load priority, system resilience, and fast online solvability into a unified design. EMS development should therefore be viewed not as the replacement of one algorithm with another, but as the improvement of coordinated optimization and rapid decision-making under complex operating conditions.

4. Protection in DC Microgrids

Protection in DC microgrids is not determined solely by protective devices. It is jointly shaped by power electronic converters, network topology, and hierarchical control. In contrast to AC systems, DC systems do not have natural current zero-crossing points. Fault currents may rise rapidly because of DC-link capacitor discharge, line inductance energy, and transient injections from multiple parallel converters. At the same time, converter current limiting, droop control, virtual impedance, secondary voltage restoration, and tertiary energy scheduling modify both the pre-fault operating point and the post-fault transient response. Therefore, DC microgrid protection cannot rely exclusively on fixed overcurrent thresholds and should not be designed independently of topology and control strategies.

4.1. Influence of Topology and Control on Protection

Different topologies impose different protection requirements. In single-bus or radial systems, protection boundaries are relatively clear, and local voltage, current, and derivative-based criteria are easier to implement. However, since redundancy is limited, a fault at the common bus or a critical converter interface may interrupt the entire system. Multi-bus structures connect different voltage levels or functional areas through interface converters, thereby improving local isolation capability. However, the faults may propagate through tie converters. Therefore, interface protection, inter-bus selectivity, and communication-assisted criteria should be coordinated. Ring structures provide alternative supply paths after fault isolation, but fault current may be injected from multiple directions, making directional criteria, fault location, and setting coordination more difficult [206]. Zonal structures naturally support sectionalized protection. However, control zones, protection zones, and reconfiguration strategies must remain consistent. Otherwise, conflicts may arise between post-fault power redistribution and voltage restoration [207,208].

The influence of hierarchical control on protection requirements is mainly reflected in fault-feature shaping and protection-action coordination. Primary control directly participates in the initial stage of the fault process. For instance, droop control, virtual impedance, and current limiting will change the peak value and rate of rise in the fault current. If the converter quickly enters the current limiting state, the fault current characteristics may also weaken, making traditional overcurrent protection unreliable [209]. Secondary control is normally used for voltage restoration and sharing correction; however, if restoration actions continue before fault isolation, fault signatures may be masked or the affected area may expand. Secondary control should therefore be coordinated with fault confirmation, isolation, and reconfiguration logic. EMS does not perform millisecond-scale protection actions, but its scheduling decisions change system operating points and post-fault load-restoration priorities, and should therefore support post-fault recovery and service continuity [210–212].

4.2. Fault Detection and Identification Methods

Fault detection methods in DC microgrids can be classified into differential methods, estimation methods, high- and time-frequency feature methods, and data-driven methods according to information source and decision criterion. Local electrical-quantity methods use voltage, current, and their derivatives. They are fast, simple, and weakly dependent on communication, and are suitable for low-voltage systems with simple structures and clear fault signatures. However, a current-threshold-only criterion may suffer from insufficient sensitivity under current-limited converters, high-impedance faults, and strong measurement noise [209,213].

Differential methods compare currents, voltages, or directional information at both line ends to improve internal/external fault discrimination. They are suitable for critical feeders, multi-bus systems, and zonal DC networks. Some methods use reactor-voltage difference or related quantities to improve robustness against high-resistance faults and synchronization errors [214]. Estimation methods identify fault location and fault type through equivalent impedance, fault-path inductance and state estimation. These methods are applicable to systems with relatively clear parameters and stable structures. However, their performance depends on model accuracy and computation resources [213,215]. High- and time-frequency methods capture early transient features and are suitable for fast protection and critical-bus protection. Related studies have used time-frequency analysis, high-frequency impedance estimation, and communication protocols for fault identification and location in multi-source or zonal systems [216,217]. Data-driven methods can handle complex fault patterns and nonlinear features, but their reliability depends on data coverage, generalization capability, interpretability, and maloperation-risk control [218].

From Table 11, the objective of the above methods is to achieve fault identification, location, and type determination under conditions such as the absence of natural zero crossing and rapid rise in fault current. A single method cannot simultaneously meet the requirements of speed, selectivity, robustness, and communication. For example, electrical measurements, differential information, insulation conditions, and model-based estimates can be integrated. The effects of converter current limiting, primary and secondary control on fault characteristics should also be considered.

Table 11. Comparison of fault detection and identification methods.

Refs.	Category	Advantages	Limitations	Applications
[214,219,220]	Differential methods	High selectivity and good internal/external fault discrimination	Require synchronized measurements, communication links, and sensor configuration	Critical feeders, multi-bus, and zonal systems
[215,221,222]	Estimation methods	Support detection, location, and classification	Require accurate models and higher computation	Systems with clear parameters and stable structures
[216,217,223,224]	High- and time-frequency methods	Fast action and high sensitivity to abrupt faults	Require high sampling rate, sensor bandwidth, and noise immunity	Fast protection, shipboard, or zonal systems
[218,225,226]	Data-driven methods	Suitable for complex-condition recognition and auxiliary diagnosis	Depend on data coverage, generalization, and interpretability	Auxiliary protection, condition monitoring, fault classification

Recently, AI-based protection schemes have evolved from offline fault classification to online fault detection, fault location, and auxiliary protection decision-making. Representative approaches include wavelet-, VMD-, EMD-, or time-frequency-feature extraction combined with ANN, SVM, or XGBoost classifiers, open-set recognition for high-impedance or unseen fault conditions, and machine-learning-based multi-agent protection platforms composed of local protection agents. These methods are attractive for ring, meshed, zonal, and multi-terminal DC networks, where fault currents may be shaped by converter current limiting and injected from multiple directions. Nevertheless, AI-based protection should not be used as an isolated black-box criterion. The training set should cover topology reconfiguration, grounding modes, line-parameter variations, converter current-limiting states, sensor noise, communication delays, and abnormal operating conditions. Practical deployment also requires explainable decision logic, bounded inference time, false-trip control, and backup coordination with deterministic differential, directional, and derivative-based criteria. In this sense, AI-based protection is more suitable as an adaptive diagnosis and auxiliary decision layer within a multi-criteria protection framework, rather than as a full replacement for fast hardware protection.

4.3. Fault Interruption and Breaking Technologies

DC fault interruption remains one of the main technical challenges in protection-system design. Since DC currents have no natural zero-crossing points, conventional AC circuit breakers cannot be directly used for DC fault clearing [227]. Mechanical DC circuit breakers offer low conduction losses and relatively low cost, but their operating speed is limited, and auxiliary arc-extinction or commutation measures are usually required [228]. Solid-state circuit breakers can interrupt faults rapidly and are well suited to fast fault isolation; however, they suffer from high conduction losses, high cost, and considerable thermal-management requirements [229]. Hybrid DC circuit breakers integrate mechanical switches with power electronic devices, providing a trade-off between steady-state losses and interruption speed. Therefore, they have promising application potential in DC systems [230,231].

To address the absence of natural zero-crossing points in DC microgrid, existing studies have proposed artificial zero-crossing and forced commutation strategies. Coupled inductors, pre-charged capacitors, and resonant branches can be utilized to establish temporary commutation paths, thereby reducing interruption stress [232,233]. Forced-commutation vacuum DC circuit breakers improve arc extinction reliability through the control of auxiliary switches and stray inductance [234]. Superconducting LC resonant circuit breakers utilize superconducting elements and resonant branches to enhance fault current limiting and interruption capabilities [235,236]. The magnetically controlled air-arc oscillation method drives arc oscillation via an external magnetic field, generating artificial zero-crossing points to achieve mechanical DC interruption [237]. Furthermore, Z-source and O-Z-source circuit breakers utilize impedance networks and natural commutation principles to achieve bidirectional fault interruption, which are applicable to low-voltage DC scenarios requiring fast automatic clearing [238–240].

The selection of fault interruption devices requires a comprehensive evaluation of interruption speed, voltage level, fault energy, conduction loss, cost, protection selectivity, and topology reconfiguration requirements [241]. In low-voltage DC microgrids, fault isolation is typically achieved through the coordination of fuses, contactors, solid-state switches, hybrid circuit breakers, and converter blocking strategies. For multi-bus, ring, and zonal systems, fault clearing must be coordinated with power supply maintenance in non-faulted areas and topology reconfiguration, preventing the protection action from being simplified into a single tripping process [206,207,231].

4.4. Grounding and Pole-Fault Protection

Grounding fault protection is crucial for the safe operation of DC microgrids. Compared to pole-to-pole faults, the current magnitude, transient characteristics and observability of pole-to-ground faults are more easily influenced by grounding methods, insulation status, converter topologies, sensor locations and operation modes [242,243]. Therefore, selecting a grounding method is an integral part of the protection design. Existing studies have systematically explored DC microgrid grounding protection and demonstrated that low-resistance, ungrounded and high-resistance structures exhibit significant differences in fault current magnitudes, insulation stress and protection sensitivity [14,244–246].

Pole-to-pole faults typically generate large currents and are straightforward to detect, yet they demand high interruption speeds, current-limiting capabilities and equipment tolerance [247]. Pole-to-ground faults rely more heavily on grounding methods and insulation conditions [248]. In low-resistance grounding systems, pole-to-ground fault currents are obvious and protection actions can be completed simply [249]. In ungrounded or high-resistance grounding systems, fault currents may be weak, but pole-to-pole voltage unbalance, common-mode potential drift and increased insulation stress still pose safety risks [250,251]. Thus, grounding fault protection should not rely solely on overcurrent thresholds but must integrate information such as voltage unbalance, insulation monitoring, leakage current, common-mode voltage and grounding status. Ref. [251] analyzed the selectivity and safety of DC microgrids under line-to-ground faults. Ref. [252] proposed a fast protection strategy for single-pole grounding faults. Ref. [253] investigated fault detection, location and classification methods from the perspectives of current signal decomposition and voltage sensing, respectively.

From Table 12, ground-fault protection in DC microgrids is mainly challenged by the fact that pole-to-ground fault characteristics are jointly affected by grounding arrangement, fault impedance, insulation condition, sensor location, and topology-dependent operating states. Therefore, a single protection method is insufficient for ground faults. Existing methods are moving from conventional current-threshold protection toward multi-criteria protection by integrating voltage imbalance, leakage current, and insulation monitoring to improve detection sensitivity and selectivity. Future research should further incorporate grounding structure, topology state, converter current limiting, voltage restoration, and post-fault reconfiguration into a unified protection framework, so that ground-fault protection evolves from local fault detection into a coordinated strategy for system safety.

Table 12. Comparison of grounding and pole-fault protection methods in DC microgrids.

Refs.	Category	Advantages	Limitations	Applications
[242,244,245]	Grounding and isolation design	Reduces ground-fault risk from the system design stage	Requires tradeoff among safety, fault-current level, and insulation cost	Low- and medium-voltage DC microgrids
[254–257]	Pole-to-pole fault protection	Systematic pole-to-pole fault-current characterization for protection and equipment design.	Relies on equivalent models and topology/stage assumptions; some schemes add device and control complexity	HVDC, DC grids and distribution networks
[248,252,258]	Pole-to-ground fault protection	Fast and selective pole-to-ground fault protection with some high-resistance/weak-current adaptability	Depends on grounding mode, line capacitance/parameters, and threshold settings; some methods require dual-end quantities or dedicated hardware, mainly simulation-validated	Low- and medium-voltage DC microgrids

5. Future Trends and Challenges

Although DC microgrids have shown clear advantages in renewable-energy integration, storage coordination, and efficient power delivery, their wider practical deployment is still constrained by topology complexity, control scalability, operational uncertainty, and protection selectivity. The preceding review of representative topologies, hierarchical control methods, and protection schemes indicates that future research should move beyond the improvement of individual algorithms or devices and place greater emphasis on the coupling among network architecture, control layers, energy management, and protection actions. This issue becomes particularly important in multi-bus, ring-bus, zonal, and hybrid-storage DC microgrids, where line-impedance variations, converter current limiting, and post-fault service restoration jointly affect system stability and protection reliability. Therefore, Table 13 summarizes the main challenges and research directions for DC microgrids from the perspectives of primary control, secondary control, tertiary control/EMS, and protection, providing a structured basis for future topology, control and protection design.

From an engineering implementation perspective, the design of topology, control, and protection does not imply solving a global comprehensive optimization problem in real time at the millisecond level. Instead, it should adopt an implementation workflow combining offline coordination during the planning phase and layered online adjustment during the operation phase. During the planning phase, the system topology, protection zones, and critical switch locations must be determined based on load levels, power continuity objectives, grounding schemes, and acceptable economic costs. The subsequent control design stage needs to incorporate branch impedances, converter capacities, current-limiting strategies, communication network topologies, and potential system reconfiguration states into the parameter tuning of primary and secondary control. The protection configuration phase must then allocate differential, directional, time-frequency, and artificial intelligence-assisted criteria based on fault current characteristics under current-limiting control and clearly define the operating logic of DC circuit breakers. These designs must be rigorously verified using hardware-in-the-loop, real-time digital simulators, or digital twin platforms to ensure the correct action sequences under grid-connected modes, islanding, topology reconfiguration, communication anomalies, and various fault conditions.

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Table 13. Future research recommendations.

Layer/Aspect	Key Challenges	Research Focus/Recommendations
Primary Control	• Nonlinear disturbances from pulsed/constant power loads • Line impedance mismatch • Topology reconfiguration • Wide operating range of droop control	• Improve dynamic response under large disturbances and topology switches • Integrate fractional-order, virtual impedance/inertia, adaptive and robust control • Address line parameter drift and energy storage dynamic differences
Secondary Control	• Multi-bus, ring, and zonal topologies • Communication constraints: heterogeneous links, delays, asynchronous updates • Limited local information	• Develop unified modeling framework capturing electrical coupling, communication constraints, and operation-mode switches • Design resilient distributed and decentralized secondary control strategies • Validate fractional-order secondary control for improved damping and voltage restoration
Tertiary Control/EMS	• High variability in loads, RES outputs, electricity prices • Uncertainty in physical limits and topology changes • Integration with lower-level control	• Scenario-based, rolling or constrained optimization • Incorporate robust/stochastic optimization and MPC • Integrate power reliability, critical load priorities, storage degradation, carbon emissions • Explore data-driven/reinforcement learning for modeling, fast solving, and decision support
Protection	• Fault current shaped by converters, droop, voltage recovery, and network reconfiguration • Multi-source infeed, topology reconfiguration affecting sensitivity and selectivity • Coordination between protection zones and control zones	• Move from isolated fault criteria to coordinated topology–control–protection co-design • Use data-driven methods, online monitoring, multi-sensor fusion for enhanced fault detection • Guarantee algorithm interpretability, real-time performance, controllable false-trip risk

6. Conclusions

This paper reviewed DC microgrid topologies, hierarchical control methods, and protection schemes. Representative topologies were first compared in terms of structural characteristics, control implications, protection requirements, and application scenarios. Primary, secondary, and tertiary control methods were then analyzed, with particular attention to droop control, virtual impedance, virtual inertia, fractional-order control, EMS optimization, and communication-delay effects. Protection issues were discussed from the perspectives of topology–control interactions, fault detection, fault interruption, and ground-fault protection. The review indicates that future DC microgrid research should move from isolated improvements in topology, control, or protection toward coordinated design that accounts for operating uncertainty, topology reconfiguration, converter current limiting, communication constraints, and post-fault recovery.

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Abbreviations

The following abbreviations are used in this manuscript:

CC	Central controller
DES	Distributed energy source
EMS	Energy management system
ESS	Energy storage system
FO	Fractional order
FODI	Fractional-order differential–integral controller
FOPI	Fractional-order proportional–integral controller
HESS	Hybrid energy storage system
HVDC	High-voltage direct current
LC	Local controller
LVDC	Low-voltage direct current
MPC	Model predictive control
PID	Proportional-integral- derivative
RES	Renewable energy source
SC	Supercapacitor
SoC	State of charge
VDCM	Virtual DC motor

References

1. Qays, M.O.; Ahmad, I.; Habibi, D.; Aziz, A.; Mahmoud, T. System Strength Shortfall Challenges for Renewable Energy-Based Power Systems: A Review. *Renew. Sustain. Energy Rev.* **2023**, *183*, 113447. [CrossRef]
2. San, G.; Zhang, W.; Guo, X.; Hua, C.; Xin, H.; Blaabjerg, F. Large-Disturbance Stability for Power-Converter-Dominated Microgrid: A Review. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109859. [CrossRef]
3. Ergin Şahin, M. A Photovoltaic Powered Electrolysis Converter System with Maximum Power Point Tracking Control. *Int. J. Hydrogen Energy* **2020**, *45*, 9293–9304. [CrossRef]
4. Şahin, M.E.; Blaabjerg, F. A Hybrid PV-Battery/Supercapacitor System and a Basic Active Power Control Proposal in MATLAB/Simulink. *Electronics* **2020**, *9*, 129. [CrossRef]
5. Şahin, M.E.; Blaabjerg, F.; Sangwongwanich, A. A Comprehensive Review on Supercapacitor Applications and Developments. *Energies* **2022**, *15*, 674. [CrossRef]
6. Şahin, M.E.; Blaabjerg, F. PV Powered Hybrid Energy Storage System Control Using Bidirectional and Boost Converters. *Electr. Power Compon. Syst.* **2022**, *49*, 1260–1277. [CrossRef]
7. Omid, M.A.; Şahin, M.E.; Cora, Ö.N. Challenges and Future Perspectives on Production, Storage Technologies, and Transportation of Hydrogen: A Review. *Energy Technol.* **2024**, *12*, 2300997. [CrossRef]
8. Zamora, R.; Srivastava, A.K. Controls for Microgrids with Storage: Review, Challenges, and Research Needs. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2009–2018. [CrossRef]
9. Justo, J.J.; Mwasilu, F.; Lee, J.; Jung, J.W. AC-Microgrids versus DC-Microgrids with Distributed Energy Resources: A Review. *Renew. Sustain. Energy Rev.* **2013**, *24*, 387–405. [CrossRef]
10. Han, Y.; Zhang, K.; Li, H.; Guerrero, J.M. MAS-Based Distributed Coordinated Control and Optimization in Microgrid and Microgrid Clusters: A Comprehensive Overview. *IEEE Trans. Power Electron.* **2018**, *33*, 6488–6508. [CrossRef]
11. Dragicevic, T.; Lu, X.; Vasquez, J.C.; Guerrero, J.M. DC Microgrids—Part I: A Review of Control Strategies and Stabilization Techniques. *IEEE Trans. Power Electron.* **2016**, *31*, 4876–4891. [CrossRef]
12. Van den Broeck, G.; Stuyts, J.; Driesen, J. A Critical Review of Power Quality Standards and Definitions Applied to DC Microgrids. *Appl. Energy* **2018**, *229*, 281–288. [CrossRef]

13. Xu, L.; Guerrero, J.; Lashab, A.; Wei, B.; Bazmohammadi, N.; Vasquez, J.; Abusorrah, A. A Review of DC Shipboard Microgrids—Part I: Power Architectures, Energy Storage, and Power Converters. *IEEE Trans. Power Electron.* **2022**, *37*, 5155–5172. [CrossRef]
14. Xu, L.; Guerrero, J.; Lashab, A.; Wei, B.; Bazmohammadi, N.; Vasquez, J.; Abusorrah, A. A Review of DC Shipboard Microgrids—Part II: Control Architectures, Stability Analysis, and Protection Schemes. *IEEE Trans. Power Electron.* **2022**, *37*, 4105–4120. [CrossRef]
15. Hanzaei, S.H.; Ektesabi, M.; Gorji, S.A.; Korki, M.; Leon, R. Control of DC Microgrids: A Review. In Proceedings of the 2021 31st Australasian Universities Power Engineering Conference (AUPEC), Perth, Australia, 26–30 September 2021; pp. 1–6. [CrossRef]
16. Ahmed, M.; Meegahapola, L.; Vahidnia, A.; Datta, M. Stability and Control Aspects of Microgrid Architectures-A Comprehensive Review. *IEEE Access* **2020**, *8*, 144730–144766. [CrossRef]
17. Yamashita, D.Y.; Vechiu, I.; Gaubert, J.P. A Review of Hierarchical Control for Building Microgrids. *Renew. Sustain. Energy Rev.* **2020**, *118*, 109523. [CrossRef]
18. Hasan, M.M.; Razmi, D.; Babayomi, O.; Davidson, I.; Terzija, V.; Zhang, Z. Advanced Control and Protection Strategies for Grid-Forming Inverters in Microgrids—A Review. *Int. J. Electr. Power Energy Syst.* **2025**, *172*, 111297. [CrossRef]
19. Mbungu, N.T.; Ismail, A.A.; AlShabi, M.; Bansal, R.C.; Elnady, A.; Hamid, A.K. Control and Estimation Techniques Applied to Smart Microgrids: A Review. *Renew. Sustain. Energy Rev.* **2023**, *179*, 113251. [CrossRef]
20. Jithin, K.; Haridev, P.P.; Mayadevi, N.; Harikumar, R.P.; Mini, V.P. A Review on Challenges in DC Microgrid Planning and Implementation. *J. Mod. Power Syst. Clean Energy* **2023**, *11*, 1375–1395. [CrossRef]
21. Dhivar, T.K.; Biswal, M.; Ray, P. A Brief Review on Protection Challenges, DCCB, Solutions and Advancement on DC Microgrids. In Proceedings of the 2025 Fourth International Conference on Power, Control and Computing Technologies (ICPC2T), Raipur, India, 20–22 January 2025; pp. 586–591. [CrossRef]
22. Mishra, M.; Patnaik, B.; Biswal, M.; Hasan, S.; Bansal, R.C. A Systematic Review on DC-Microgrid Protection and Grounding Techniques: Issues, Challenges and Future Perspective. *Appl. Energy* **2022**, *313*, 118810. [CrossRef]
23. Dahale, S.; Das, A.; Pindoriya, N.M.; Rajendran, S. An Overview of DC-DC Converter Topologies and Controls in DC Microgrid. In Proceedings of the 2017 7th International Conference on Power Systems (ICPS), Pune, India, 21–23 December 2017; pp. 410–415. [CrossRef]
24. Haris, M.; Asim, M.; Tariq, M. A Review of Non-Isolated High Gain DC-to-DC Converter Topologies. In Proceedings of the 2022 2nd International Conference on Emerging Frontiers in Electrical and Electronic Technologies (ICEFEET), Patna, India, 24–25 June 2022; pp. 1–6. [CrossRef]
25. Karppanen, J.; Kaipia, T.; Nuutinen, P.; Lana, A.; Peltoniemi, P.; Pinomaa, A.; Mattsson, A.; Partanen, J.; Cho, J.; Kim, J. Effect of Voltage Level Selection on Earthing and Protection of LVDC Distribution Systems. In Proceedings of the 11th IET International Conference on AC and DC Power Transmission, Birmingham, UK, 10–12 February 2015; pp. 1–8. [CrossRef]
26. Dragičević, T.; Vasquez, J.C.; Guerrero, J.M.; Škrlec, D. Advanced LVDC Electrical Power Architectures and Microgrids: A Step toward a New Generation of Power Distribution Networks. *IEEE Electrif. Mag.* **2014**, *2*, 54–65. [CrossRef]
27. Meng, L.; Shafiee, Q.; Trecate, G.F.; Karimi, H.; Fulwani, D.; Lu, X.; Guerrero, J.M. Review on Control of DC Microgrids and Multiple Microgrid Clusters. *IEEE J. Emerg. Sel. Top. Power Electron.* **2017**, *5*, 928–948. [CrossRef]
28. Kumar, J.; Agarwal, A.; Agarwal, V. A Review on Overall Control of DC Microgrids. *J. Energy Storage* **2019**, *21*, 113–138. [CrossRef]
29. Shuai, Z.; Fang, J.; Ning, F.; Shen, Z.J. Hierarchical Structure and Bus Voltage Control of DC Microgrid. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3670–3682. [CrossRef]
30. Kakigano, H.; Miura, Y.; Ise, T. Low-Voltage Bipolar-Type Dc Microgrid for Super High Quality Distribution. *IEEE Trans. Power Electron.* **2010**, *25*, 3066–3075. [CrossRef]
31. Madonna, V.; Giangrande, P.; Galea, M. Electrical Power Generation in Aircraft: Review, Challenges, and Opportunities. *IEEE Trans. Transp. Electrif.* **2018**, *4*, 646–659. [CrossRef]
32. Eskander, M.M.; Silva, C.A. Techno-Economic and Environmental Comparative Analysis for DC Microgrids in Households: Portuguese and French Household Case Study. *Appl. Energy* **2023**, *349*, 121495. [CrossRef]
33. Ekneligoda, N.C.; Weaver, W.W. A Game Theoretic Bus Selection Method for Loads in Multibus DC Power Systems. *IEEE Trans. Ind. Electron.* **2014**, *61*, 1669–1678. [CrossRef]
34. Rodriguez-Estrada, H.; Rodriguez-Segura, E.; Orosco-Guerrero, R.; Gordillo-Tapia, C.; Martínez-Nolasco, J. Novel Multibus Multivoltage Concept for DC-Microgrids in Buildings: Modeling, Design and Local Control. *Appl. Sci.* **2023**, *13*, 2405. [CrossRef]
35. Teixeira Pinto, R.; Bauer, P.; Rodrigues, S.F.; Wiggelinkhuizen, E.J.; Pierik, J.; Ferreira, B. A Novel Distributed Direct-Voltage Control Strategy for Grid Integration of Offshore Wind Energy Systems through MTDC Network. *IEEE Trans. Ind. Electron.* **2013**, *60*, 2429–2441. [CrossRef]
36. Chaudhuri, N.R.; Majumder, R.; Chaudhuri, B. System Frequency Support through Multi-Terminal DC (MTDC) Grids. *IEEE Trans. Power Syst.* **2013**, *28*, 347–356. [CrossRef]

37. Hai, T.P.; Cho, H.; Chung, I.Y.; Cho, J.; Kim, J. Development of Voltage Control System for Multi-Terminal Low-Voltage DC Distribution System. In Proceedings of the 2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 23–26 April 2017; pp. 1–5. [CrossRef]
38. Park, J.D.; Candelaria, J.; Ma, L.; Dunn, K. DC Ring-Bus Microgrid Fault Protection and Identification of Fault Location. *IEEE Trans. Power Deliv.* **2013**, *28*, 2574–2584. [CrossRef]
39. Li, M.; Zhang, D.; Lu, S.; Tang, X.; Phung, T. Differential Evolution-Based Overcurrent Protection for DC Microgrids. *Energies* **2021**, *14*, 5026. [CrossRef]
40. Balog, R.S.; Krein, P.T. Bus Selection in Multibus DC Microgrids. *IEEE Trans. Power Electron.* **2011**, *26*, 860–867. [CrossRef]
41. Levron, Y.; Guerrero, J.M.; Beck, Y. Optimal Power Flow in Microgrids with Energy Storage. *IEEE Trans. Power Syst.* **2013**, *28*, 3226–3234. [CrossRef]
42. Guerrero, J.M.; Vasquez, J.C.; Matas, J.; De Vicuña, L.G.; Castilla, M. Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach toward Standardization. *IEEE Trans. Ind. Electron.* **2011**, *58*, 158–172. [CrossRef]
43. Morstyn, T.; Hredzak, B.; Agelidis, V.G. Control Strategies for Microgrids with Distributed Energy Storage Systems: An Overview. *IEEE Trans. Smart Grid* **2018**, *9*, 3652–3666. [CrossRef]
44. Olivares, D.E.; Mehrizi-Sani, A.; Etemadi, A.H.; Cañizares, C.A.; Iravani, R.; Kazerani, M.; Hajimiragha, A.H.; Gomis-Bellmunt, O.; Saeedifard, M.; Palma-Behnke, R.; et al. Trends in Microgrid Control. *IEEE Trans. Smart Grid* **2014**, *5*, 1905–1919. [CrossRef]
45. Moura, B.C.; Rodrigues, D.B.; Guimaraes, E.C.; de Lima, G.B.; Silveira, J.P.C.; Freitas, L.C.G.; Neto, P.J.D.S. Comparative Analysis of Virtual Impedance Control Techniques for Improved Stability in DC Microgrids. *IEEE Access* **2025**, *13*, 99077–99091. [CrossRef]
46. Swaminathan, G.V.; Periasamy, S.; Lu, D.D.C. Capacitor Current Control Based Virtual Inertia Control of Autonomous DC Microgrid. *IEEE Trans. Ind. Electron.* **2023**, *70*, 6908–6918. [CrossRef]
47. Liang, H.; Huang, Y.; Liu, Z. Research on Nonlinear Drooping Control Strategy of DC Microgrid. In *TENCON 2018—2018 IEEE Region 10 Conference*; IEEE: New York, NY, USA, 2018; pp. 865–870. [CrossRef]
48. Shuai, Z.; He, D.; Fang, J.; Shen, Z.J.; Tu, C.; Wang, J. Robust Droop Control of DC Distribution Networks. *IET Renew. Power Gener.* **2016**, *10*, 807–814. [CrossRef]
49. Belal, E.K.; Yehia, D.M.; Azmy, A.M. Adaptive Droop Control for Balancing SOC of Distributed Batteries in DC Microgrids. *IET Gener. Transm. Distrib.* **2019**, *13*, 4667–4676. [CrossRef]
50. Long, B.; Zeng, W.; Rodriguez, J.; Guerrero, J.M.; Hu, J.; Chong, K.T. Enhancement of Voltage Regulation Capability for DC-Microgrid Composed by Battery Test System: A Fractional-Order Virtual Inertia Method. *IEEE Trans. Power Electron.* **2022**, *37*, 12538–12551. [CrossRef]
51. Zhou, H.; He, L. Fractional-Order Virtual Impedance-Based Low-Frequency Current Ripple Mitigation for a Differential Boost Inverter. *IEEE Trans. Ind. Electron.* **2025**, *72*, 5810–5820. [CrossRef]
52. Xu, Q.; Hu, X.; Wang, P.; Xiao, J.; Tu, P.; Wen, C.; Lee, M.Y. A Decentralized Dynamic Power Sharing Strategy for Hybrid Energy Storage System in Autonomous DC Microgrid. *IEEE Trans. Ind. Electron.* **2017**, *64*, 5930–5941. [CrossRef]
53. Lin, P.; Wang, P.; Xiao, J.; Wang, J.; Jin, C.; Tang, Y. An Integral Droop for Transient Power Allocation and Output Impedance Shaping of Hybrid Energy Storage System in DC Microgrid. *IEEE Trans. Power Electron.* **2018**, *33*, 6262–6277. [CrossRef]
54. Sevostyanov, N.A.; Gorbunov, R.L. Control Strategy to Mitigate Voltage Ripples in Droop-Controlled DC Microgrids. *IEEE Trans. Power Electron.* **2023**, *38*, 15377–15389. [CrossRef]
55. Silva, W.W.A.G.; Oliveira, T.R.; Donoso-Garcia, P.F. An Improved Voltage-Shifting Strategy to Attain Concomitant Accurate Power Sharing and Voltage Restoration in Droop-Controlled DC Microgrids. *IEEE Trans. Power Electron.* **2021**, *36*, 2396–2406. [CrossRef]
56. Ni, J.; Zhao, B.; Goudarzi, A.; Li, Y.; Xiang, J. A Dispatchable Droop Control Method for PV Systems in DC Microgrids. *IEEE Access* **2023**, *11*, 7588–7598. [CrossRef]
57. Tang, Y.; Houari, A.; Guan, L.; Saim, A. Hierarchical Hybrid Control and Communication Topology Optimization in DC Microgrids for Enhanced Performance. *Electronics* **2025**, *14*, 3797. [CrossRef]
58. Xu, Q.; Xiao, J.; Wang, P.; Pan, X.; Wen, C. A Decentralized Control Strategy for Autonomous Transient Power Sharing and State-of-Charge Recovery in Hybrid Energy Storage Systems. *IEEE Trans. Sustain. Energy* **2017**, *8*, 1443–1452. [CrossRef]
59. Lin, X.; Zamora, R.; Baguley, C.A. A Comprehensive Multi-Functional Controller for Hybrid Energy Storage Systems in DC Microgrids. *IEEE Trans. Ind. Appl.* **2023**, *59*, 2985–2994. [CrossRef]
60. Xiao, J.; Setyawan, L.; Wang, P.; Jin, C. Power-Capacity-Based Bus-Voltage Region Partition and Online Droop Coefficient Tuning for Real-Time Operation of DC Microgrids. *IEEE Trans. Energy Convers.* **2015**, *30*, 1338–1347. [CrossRef]
61. Nasirian, V.; Davoudi, A.; Lewis, F.L.; Guerrero, J.M. Distributed Adaptive Droop Control for DC Distribution Systems. *IEEE Trans. Energy Convers.* **2014**, *29*, 944–956. [CrossRef]
62. Ni, F.; Yan, L.; Liu, J.; Shi, M.; Zhou, J.; Chen, X. Fuzzy Logic-Based Virtual Capacitor Adaptive Control for Multiple HESSs in a DC Microgrid System. *Int. J. Electr. Power Energy Syst.* **2019**, *107*, 78–88. [CrossRef]

63. Jiang, Y.; Yang, Y.; Tan, S.C.; Hui, S.Y.R. Adaptive Current Sharing of Distributed Battery Systems in DC Microgrids Using Adaptive Virtual Resistance-Based Droop Control. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 4262–4267. [CrossRef]
64. Zhao, P.; Liu, Z.; Zhao, Y.; Wang, Q.; Liu, J. An Adaptive Piecewise Droop Control Strategy for DC Microgrids. In Proceedings of the 2021 IEEE Fourth International Conference on DC Microgrids (ICDCM), Arlington, VA, USA, 18–21 July 2021; pp. 1–6. [CrossRef]
65. Sharma, S.; Member, G.S.; Iyer, V.M.; Member, S. An Optimized Nonlinear Droop Control Method Using Load Profile for DC Microgrids. *IEEE J. Emerg. Sel. Top. Ind. Electron.* **2023**, *4*, 3–13. [CrossRef]
66. Abdullahi, S.; Jin, T.; Lingom, P.M. Robust Control Strategy for Inductive Parametric Uncertainties of DC/DC Converters in Islanded DC Microgrid. *J. Mod. Power Syst. Clean Energy* **2023**, *11*, 335–344. [CrossRef]
67. Xu, Q.; Xu, Y.; Zhang, C.; Wang, P. A Robust Droop-Based Autonomous Controller for Decentralized Power Sharing in DC Microgrid Considering Large-Signal Stability. *IEEE Trans. Ind. Inform.* **2020**, *16*, 1483–1494. [CrossRef]
68. Veysi, M.; Aghaei, J.; Member, S.; Soltanpour, M.R.; Shasadeghi, M.; Bahrani, B.; Member, S.; Ryan, D.J.; Member, S. Robust, Accurate, and Fast Decentralized Power Sharing Mechanism for Isolated DC Microgrid Using Droop-Based Sliding-Mode Conrol. *IEEE Trans. Smart Grid* **2022**, *13*, 4160–4173. [CrossRef]
69. Shadabi, H.; Kamwa, I. A Decentralized Non-Linear Dynamic Droop Control of a Hybrid Energy Storage System Bluefor Primary Frequency Control in Integrated AC-MTDC Systems. *Int. J. Electr. Power Energy Syst.* **2022**, *136*, 107630. [CrossRef]
70. Tayab, U.B.; Roslan, M.A.B.; Hwai, L.J.; Kashif, M. A Review of Droop Control Techniques for Microgrid. *Renew. Sustain. Energy Rev.* **2017**, *76*, 717–727. [CrossRef]
71. Zheng, L.; Liu, X. A Grid-Forming Battery Energy System with Mode-Adaptive Virtual Inductance Control. *Batteries* **2026**, *12*, 102. [CrossRef]
72. Zhu, Y.; Zeng, Y.; Chen, Y.; Li, X. Research on DC-Side Oscillation Suppression Strategy of MMC-HVDC Based on Composite Virtual Impedance. *Electr. Power Syst. Res.* **2025**, *245*, 111620. [CrossRef]
73. Meng, L.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M. Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC-DC Converters. *IEEE Trans. Smart Grid* **2015**, *6*, 2615–2626. [CrossRef]
74. Sun, Y.; Huang, W.; Wang, G.; Wang, W.; Wang, D.; Zhang, L. Study of Control Strategy of DG Based on Nonlinear Droop Characteristic. In Proceedings of the 2012 China International Conference on Electricity Distribution, Shanghai, China, 10–14 September 2012; pp. 5–6. [CrossRef]
75. Su, C.L.; Lin, K.L.; Chen, C.J. Power Flow and Generator-Converter Schemes Studies in Ship MVDC Distribution Systems. *IEEE Trans. Ind. Appl.* **2016**, *52*, 50–59. [CrossRef]
76. Saleem, O.; Awan, F.G.; Mahmood-ul-Hasan, K.; Ahmad, M. Self-Adaptive Fractional-Order LQ-PID Voltage Controller for Robust Disturbance Compensation in DC-DC Buck Converters. *Int. J. Numer. Model. Electron. Netw. Devices Fields* **2020**, *33*, e2718. [CrossRef]
77. Warrier, P.; Shah, P. Fractional Order Control of Power Electronic Converters in Industrial Drives and Renewable Energy Systems: A Review. *IEEE Access* **2021**, *9*, 58982–59009. [CrossRef]
78. Shah, P.; Agashe, S. Review of Fractional PID Controller. *Mechatronics* **2016**, *38*, 29–41. [CrossRef]
79. Al Alahmadi, A.A.; Belkhier, Y.; Ullah, N.; Abeida, H.; Soliman, M.S.; Khraisat, Y.S.H.; Alharbi, Y.M. Hybrid Wind/PV/Battery Energy Management-Based Intelligent Non-Integer Control for Smart DC-Microgrid of Smart University. *IEEE Access* **2021**, *9*, 98948–98961. [CrossRef]
80. Lakshmi, D.; Vijay Anand, J.; Baskaran, S.; Dinesh Babu, M.; Satish Kumar, S. Enhanced Voltage Regulation for Microgrids with Battery Charger/Discharger Using Fractional Order Predictive-Proportional Integral Controller. *J. Energy Storage* **2025**, *123*, 116703. [CrossRef]
81. Albalawi, H.; Zaid, S.A.; Alatwi, A.M.; Moustafa, M.A. Application of an Optimal Fractional-Order Controller for a Standalone (Wind/Photovoltaic) Microgrid Utilizing Hybrid Storage (Battery/Ultracapacitor) System. *Fractal Fract.* **2024**, *8*, 629. [CrossRef]
82. Hamzeh, M.; Ghazanfari, A.; Member, S. Modeling and Design of an Oscillatory Current-Sharing Control Strategy in DC Microgrids. *IEEE Trans. Ind. Electron.* **2015**, *62*, 6647–6657. [CrossRef]
83. Liu, S.; Zheng, J.; Li, Z.; Li, R.; Fang, W.; Liu, X. Distributed Piecewise Droop Control of DC Microgrid with Improved Load Sharing and Voltage Compensation. In Proceedings of the 2019 IEEE Third International Conference on DC Microgrids (ICDCM), Matsue, Japan, 20–23 May 2019; pp. 1–6.
84. Yang, M.; Zhang, R.; Zhou, N.; Wang, Q. Unbalanced Voltage Control of Bipolar DC Microgrid Based on Distributed Cooperative Control. In Proceedings of the 2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA), Kristiansand, Norway, 9–13 November 2020; pp. 339–344.
85. Effendy, M.; System, A.C. Performance Comparison of Proportional-Integral and Fuzzy-PI for a Droop Control of DC Microgrid. In Proceedings of the 2020 International Conference on Sustainable Energy Engineering and Application (ICSEEA), Tangerang, Indonesia, 18–20 November 2020; pp. 180–184.

86. Li, X.; Member, S.; Jiang, W.; Wang, J.; Member, S.; Wang, P.; Wu, X. An Autonomous Control Scheme of Global Smooth Transitions for Bidirectional DC-DC Converter in DC Microgrid. *IEEE Trans. Energy Convers.* **2021**, *36*, 950–960. [CrossRef]
87. Li, P.; Wang, Y.; Liu, L.; Li, X.; Zuo, Z. Low Frequency Current-Mode Control for DC-DC Boost Converters with Overshoot Suppression. *IEEE Trans. Circuits Syst. I Regul. Pap.* **2022**, *69*, 4702–4713. [CrossRef]
88. Suresh, V.; Pachauri, N.; Vigneysh, T. Decentralized Control Strategy for Fuel Cell/PV/BESS Based Microgrid Using Modified Fractional Order PI Controller. *Int. J. Hydrogen Energy* **2021**, *46*, 4417–4436. [CrossRef]
89. Alatwi, A.M.; Bakeer, A.; Zaid, S.A.; Atawi, I.E.; Albalawi, H.; Kassem, A.M. Intelligent Fractional-Order Controller for SMES Systems in Renewable Energy-Based Microgrid. *Comput. Model. Eng. Sci.* **2024**, *140*, 1807–1830. [CrossRef]
90. Zaid, S.A.; Bakeer, A.; Albalawi, H.; Alatwi, A.M.; AbdelMeguid, H.; Kassem, A.M. Optimal Fractional-Order Controller for the Voltage Stability of a DC Microgrid Feeding an Electric Vehicle Charging Station. *Fractal Fract.* **2023**, *7*, 677. [CrossRef]
91. Zhao, X.; Li, Y.W.; Tian, H.; Wu, X. Energy Management Strategy of Multiple Supercapacitors in a DC Microgrid Using Adaptive Virtual Impedance. *IEEE J. Emerg. Sel. Top. Power Electron.* **2016**, *4*, 1174–1185. [CrossRef]
92. Mi, Y.; Member, S.; Guo, J.; Member, S.; Fu, Y. Accurate Power Allocation of Multienergy Storage Island DC Microgrid Based on Virtual Power Rating. *IEEE Trans. Power Electron.* **2023**, *38*, 261–270. [CrossRef]
93. Chaturvedi, S.; Member, S.; Fulwani, D.; Patel, D. Dynamic Virtual Impedance-Based Second-Order Ripple Regulation in DC Microgrids. *IEEE J. Emerg. Sel. Top. Power Electron.* **2022**, *10*, 1075–1083. [CrossRef]
94. Chen, X.; Chen, Y.; Zhang, B.; Qiu, D. A Modeling and Analysis Method for Fractional-Order DC-DC Converters. *IEEE Trans. Power Electron.* **2017**, *32*, 7034–7044. [CrossRef]
95. Wang, S.; Shen, Y.; Liu, S.; Dai, H.; Li, Q. Fractional-Order Sequence Impedance Modelling and Stability Assessment of Grid-Connected Virtual Synchronous Generators. *IET Gener. Transm. Distrib.* **2026**, *20*, e70227. [CrossRef]
96. Fu, W.; Li, J.; Zhang, Y.; Du, W.; Chen, X. Design and Performance Analysis of a Non-Isolated DC-DC Converter with a Fractional-Order Output Filtering Capacitor. *IEEE Trans. Circuits Syst. II Express Briefs* **2024**, *71*, 4336–4340. [CrossRef]
97. Zhou, H.; He, L.; Yang, Z.; Lin, Z. Virtual Fractional-Order-Inductor Based Second Harmonic Current Suppression Method. *IEEE Trans. Ind. Electron.* **2024**, *71*, 8949–8959. [CrossRef]
98. Cheng, Z.; He, L. Adaptive Fractional-Order Impedance for Current Balancing Control. In Proceedings of the 2024 IEEE 10th International Power Electronics and Motion Control Conference (IPEMC2024-ECCE Asia), Chengdu, China, 17–20 May 2024; pp. 3945–3950. [CrossRef]
99. Ali Azghandi, M.; Masoud Barakati, S.; Yazdani, A. Passivity-Based Design of a Fractional-Order Virtual Capacitor for Active Damping of Multiparalleled Grid-Connected Current-Source Inverters. *IEEE Trans. Power Electron.* **2022**, *37*, 7809–7818. [CrossRef]
100. Cheng, Z.; He, L.; Yang, H. Fewer-Sensors Current Balancing in LLC-DCX Converters Parallel System With Powerless Fractional-Oorder Capacitor. *IEEE Trans. Transp. Electrif.* **2025**, *12*, 464–473. [CrossRef]
101. Ali Azghandi, M.; Masoud Barakati, S.; Yazdani, A. Impedance-Based Stability Analysis and Design of a Fractional-Order Active Damper for Grid-Connected Current-Source Inverters. *IEEE Trans. Sustain. Energy* **2021**, *12*, 599–611. [CrossRef]
102. Dc, D.; Using, M. Energy Management Strategy for Supercapacitor Virtual Impedance. *IEEE Trans. Power Electron.* **2017**, *32*, 2704–2716. [CrossRef]
103. Zheng, F.; Su, M.; Liu, B.; Liu, W. Adaptive Virtual Inertia Control Strategy for a Grid-Connected Converter of DC Microgrid Based on an Improved Model Prediction. *Symmetry* **2023**, *15*, 2072. [CrossRef]
104. Wang, F.; Sun, L.; Wen, Z.; Zhuo, F. Overview of Inertia Enhancement Methods in DC System. *Energies* **2022**, *15*, 6704. [CrossRef]
105. Sun, L.; Member, G.S.; Wang, F.; Tao, X.; Xu, Z.; Tian, J. An Improved Virtual DC Machine Control for Inertia Enhancement in DC Microgrid. *IEEE Trans. Ind. Appl.* **2026**, *62*, 1539–1550. [CrossRef]
106. Wang, C.; Meng, J.; Wang, Y.; Wang, H. Adaptive Virtual Inertia Control for DC Microgrid with Variable Droop Coefficient. In *Proceedings of the 2017 20th International Conference on Electrical Machines and Systems (ICEMS), Sydney, Australia, 11–14 August 2017*; IEEE: New York, NY, USA, 2017; pp. 1–5.
107. Liu, P.; Dong, L.; He, L.; Han, X.; Mao, Y. Virtual Inertia Control Strategy of Oilfield Bidirectional Grid-Connected Converter Based on Improved Dual Sliding Mode Variable Structure Control. *IEEJ Trans. Electr. Electron. Eng.* **2025**, *20*, 1951–1963. [CrossRef]
108. Qi, Z.; Tang, J.; Pei, J.; Shan, L. Fractional Controller Design of a DC-DC Converter for PEMFC. *IEEE Access* **2020**, *8*, 120134–120144. [CrossRef]
109. Ansari, M.M.; Gaidhane, P.J. Virtual Inertia Control Strategies for Renewable Energy Integration. In Proceedings of the 2025 Third International Conference on Microwave, Antenna and Communication (MAC), Bhopal, India, 27–29 June 2025; pp. 1–6. [CrossRef]
110. Su, X.; Wang, M.; Liu, Y.; Chen, J.; Xu, Z.; Xu, Z. A Virtual-Capacitor-Based Inertia Enhancement Method for Switching Converters in DC Microgrids. *IEEE Trans. Ind. Electron.* **2026**, *73*, 1481–1486. [CrossRef]
111. Zhi, N.; Ming, X.; DIng, Y.; Du, L.; Zhang, H. Power-Loop-Free Virtual DC Machine Control with Differential Compensation. *IEEE Trans. Ind. Appl.* **2022**, *58*, 413–422. [CrossRef]

112. Samanta, S.; Datta, S.; Roy, B.K. FPGA Implementation of an Inertia Emulation Control Strategy for a DC Microgrid. *IEEE Trans. Energy Convers.* **2024**, *39*, 999–1010. [CrossRef]
113. Zeng, Y.; Yang, Q.; Lin, Y.; Chen, Y.; Chen, X.; Member, S. Fractional-Order Virtual Inertia Control and Parameter Tuning for Energy-Storage System in Low-Inertia Power Grid. *Prot. Control Mod. Power Syst.* **2024**, *9*, 70–83. [CrossRef]
114. Abhishek, A.; Ranjan, A.; Devassy, S.; Kumar Verma, B.; Ram, S.K.; Dhakar, A.K. Review of Hierarchical Control Strategies for DC Microgrid. *IET Renew. Power Gener.* **2020**, *14*, 1631–1640. [CrossRef]
115. Ghanbari, N.; Bhattacharya, S. Adaptive Droop Control Method for Suppressing Circulating Currents in DC Microgrids. *IEEE Open Access J. Power Energy* **2020**, *7*, 100–110. [CrossRef]
116. Ni, F.; Zheng, Z.; Xie, Q.; Xiao, X.; Zong, Y.; Huang, C. Enhancing Resilience of DC Microgrids with Model Predictive Control Based Hybrid Energy Storage System. *Int. J. Electr. Power Energy Syst.* **2021**, *128*, 106738. [CrossRef]
117. Hou, J.; Song, Z.; Hofmann, H.; Sun, J. Adaptive Model Predictive Control for Hybrid Energy Storage Energy Management in All-Electric Ship Microgrids. *Energy Convers. Manag.* **2019**, *198*, 111929. [CrossRef]
118. Mudaliyar, S.; Mishra, S. Real-Time Coordinated Control of Low-Voltage DC Distribution Network with Soft Opening Point. *IEEE Trans. Power Electron.* **2021**, *36*, 7123–7137. [CrossRef]
119. Mokhtar, M.; Marei, M.I.; El-Sattar, A.A. An Adaptive Droop Control Scheme for DC Microgrids Integrating Sliding Mode Voltage and Current Controlled Boost Converters. *IEEE Trans. Smart Grid* **2019**, *10*, 1685–1693. [CrossRef]
120. Sadabadi, M.S.; Shafiee, Q. Scalable Robust Voltage Control of DC Microgrids with Uncertain Constant Power Loads. *IEEE Trans. Power Syst.* **2020**, *35*, 508–515. [CrossRef]
121. Olfati-Saber, R.; Fax, J.A.; Murray, R.M. Consensus and Cooperation in Networked Multi-Agent Systems. *Proc. IEEE* **2007**, *95*, 215–233. [CrossRef]
122. Olfati-Saber, R.; Murray, R.M. Consensus Problems in Networks of Agents with Switching Topology and Time-Delays. *IEEE Trans. Automat. Contr.* **2004**, *49*, 1520–1533. [CrossRef]
123. Yu, Y.; Liu, G.P.; Huang, Y.; Guerrero, J.M. Coordinated Predictive Secondary Control for DC Microgrids Based on High-Order Fully Actuated System Approaches. *IEEE Trans. Smart Grid* **2024**, *15*, 19–33. [CrossRef]
124. Chang, J.W.; Park, J.Y.; Hwang, P.I. Decentralized Secondary Control of DGs for an Islanded Hybrid AC/DC Microgrid. *IEEE Access* **2024**, *12*, 3597–3610. [CrossRef]
125. Habibullah, A.F.; Kim, K.H. Decentralized Power Management of DC Microgrid Based on Adaptive Droop Control with Constant Voltage Regulation. *IEEE Access* **2022**, *10*, 129490–129504. [CrossRef]
126. Fu, C.; Liu, C.; Fang, J. Estimation-Based Decentralized Secondary Control of DC Microgrids. In Proceedings of the 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 20–24 October 2024; pp. 1064–1068. [CrossRef]
127. Nawaz, F.; Member, S.; Pashajavid, E. A Comprehensive Review of the State-of-the-Art of Secondary Control Strategies for Microgrids. *IEEE Access* **2023**, *11*, 102444–102459. [CrossRef]
128. Kim, S.H.; Byun, H.J.; Jeong, W.S.; Yi, J.; Won, C.Y. Hierarchical Control with Voltage Balancing and Energy Management for Bipolar DC Microgrid. *IEEE Trans. Ind. Electron.* **2023**, *70*, 9147–9157. [CrossRef]
129. Yehia, D.M.; Numair, M.; Mansour, D.E.A. Novel IoT-Based Droop Control for Battery SoC Balancing among Multiple Microgrids. *IEEE Trans. Smart Grid* **2024**, *15*, 1304–1316. [CrossRef]
130. Liu, Q.; Wang, Y.; Wang, S.; Liang, D.; Zhao, Q.; Zhao, X. Voltage Regulation Strategy for DC Distribution Networks Based on Coordination of Centralized Control and Adaptive Droop Control. *IEEE Trans. Power Deliv.* **2022**, *37*, 3730–3739. [CrossRef]
131. Liu, Q.; Zhang, L.; Zhang, H.; Wang, S.; Ji, X. Distributed Secondary Optimal Control with Fast Voltage Recovery and Minimum Generation Cost for Islanded DC Microgrids. *IEEE Trans. Smart Grid* **2024**, *16*, 4–15. [CrossRef]
132. Lu, J.; Jiang, H.; Hou, X.; Wang, P. Distributed Edge-Based Event-Triggered Control for Voltage Restoration and Current Sharing in DC Microgrids under DoS Attacks. *IEEE Trans. Ind. Electron.* **2023**, *70*, 8053–8063. [CrossRef]
133. Fan, B.; Peng, J.; Yang, Q.; Liu, W. Distributed Periodic Event-Triggered Algorithm for Current Sharing and Voltage Regulation in DC Microgrids. *IEEE Trans. Smart Grid* **2020**, *11*, 577–589. [CrossRef]
134. Shi, M.; Chen, X.; Zhou, J.; Chen, Y.; Wen, J.; He, H. Advanced Secondary Voltage Recovery Control for Multiple HESSs in a Droop-Controlled DC Microgrid. *IEEE Trans. Smart Grid* **2019**, *10*, 3828–3839. [CrossRef]
135. Zhang, R.; Hredzak, B.; Morstyn, T. Distributed Control with Virtual Capacitance for the Voltage Restorations, State of Charge Balancing and Load Allocations of Heterogeneous Energy Storages in a DC Datacenter Microgrid. *IEEE Trans. Energy Convers.* **2018**, *34*, 1296–1308. [CrossRef]
136. Lu, J.; Zhang, X.; Zhang, B.; Hou, X.; Wang, P. Distributed Dynamic Event-Triggered Control for Voltage Restoration and Current Sharing in DC Microgrids. *IEEE Trans. Sustain. Energy* **2022**, *13*, 619–628. [CrossRef]
137. Nabatirad, M.; Bahrani, B.; Razzaghi, R. Decentralized Secondary Controller in Islanded Dc Microgrids to Enhance Voltage Regulation and Load Sharing Accuracy. In Proceedings of the 2019 IEEE International Conference on Industrial Technology (ICIT), Melbourne, VIC, Australia, 13–15 February 2019; pp. 1692–1697. [CrossRef]

138. Lin, X.; Zamora, R.; Baguley, C.A. A Fully Filter-Based Decentralized Control with State of Charge Balancing Strategy for Battery Energy Storage Systems in Autonomous Dc Microgrid Applications. *IEEE Access* **2021**, *9*, 15028–15040. [CrossRef]
139. Guo, F.; Lian, Z.; Wen, C.; Xu, Q. Decentralized Communication-Free Secondary Voltage Restoration and Current Sharing Control for Islanded DC Microgrids. In Proceedings of the IECON 2019—45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 14–17 October 2019; pp. 6515–6520. [CrossRef]
140. Guo, F.; Deng, C.; Wen, C.; Zheng, X.; Lian, Z.; Jiang, W. Partially Decentralized Secondary Current Sharing and Voltage Restoration Controller Design for DC Microgrids with Event-Triggered Sampling. *IEEE Trans. Smart Grid* **2023**, *14*, 1777–1789. [CrossRef]
141. Sharma, S.; Iyer, V.M.; Bhattacharya, S.; Zou, K. New Mesh Configurations with Decentralized Droop Control Method for DC Microgrids. *IEEE Trans. Ind. Electron.* **2024**, *71*, 560–571. [CrossRef]
142. Prasad, E.N.V.D.V.; Sahani, M.; Dash, P.K. A New Adaptive Integral Back Stepping Fractional Order Sliding Mode Control Approach for PV and Wind with Battery System Based DC Microgrid. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102261. [CrossRef]
143. Alam, M.S.; Al-Ismail, F.S.; Almehizia, A.A.; Abido, M.A. A Fully Decentralized Control Approach for Hybrid Energy Storage System in DC Microgrids Based on Fractional Order Voltage Compensation. In Proceedings of the 2021 North American Power Symposium (NAPS), College Station, TX, USA, 14–16 November 2021; pp. 1–5. [CrossRef]
144. Mohanty, S.B.; Mohanty, S.; Panda, M.; Dash, S.K. A Novel Reduced-Switch Multilevel Inverter Topology for DC Microgrid Interfacing with V2G/G2V Functionality and Advanced FO-PID Energy Management. *Results Eng.* **2025**, *26*, 105471. [CrossRef]
145. Xu, X.; Peng, Z.; Li, L.; Zhou, W.; Zhao, Z.; Dai, Y. A Fractional Order Model Predictive Control Method for Electric-Hydrogen Hybrid Energy Storage System. In Proceedings of the 2021 China Automation Congress (CAC), Beijing, China, 22–24 October 2021; pp. 7081–7085. [CrossRef]
146. Doostinia, M.; Beheshti, M.T.H.; Alavi, S.A. A Distributed Control Strategy with Fractional Order PI Controller for DC Microgrid. In Proceedings of the 2019 Smart Grid Conference (SGC), Tehran, Iran, 18–19 December 2019; pp. 1–6. [CrossRef]
147. Singh, D.; Singh, S.; Choksi, K.; Bhansali, G.; Luo, F. Advanced Fo-SoC Droop Control for Hybrid Tidal–Battery Systems in Shipboard Microgrids. In Proceedings of the 2025 IEEE Electric Ship Technologies Symposium (ESTS), Alexandria, VA, USA, 5–8 August 2025; pp. 428–435. [CrossRef]
148. Lai, J.; Zhou, H.; Lu, X.; Yu, X.; Hu, W. Droop-Based Distributed Cooperative Control for Microgrids with Time-Varying Delays. *IEEE Trans. Smart Grid* **2016**, *7*, 1775–1789. [CrossRef]
149. Dou, C.; Yue, D.; Guerrero, J.M.; Xie, X.; Hu, S. Multiagent System-Based Distributed Coordinated Control for Radial DC Microgrid Considering Transmission Time Delays. *IEEE Trans. Smart Grid* **2017**, *8*, 2370–2381. [CrossRef]
150. Wu, X.; Xu, Y.I.N.; He, J.; Shen, C.; Guerrero, J.M. Delay-Dependent Small-Signal Stability Analysis and Compensation Method for Distributed Secondary Control of Microgrids. *IEEE Access* **2019**, *7*, 170919–170935. [CrossRef]
151. Dong, C.; Jia, H.; Xu, Q.; Xiao, J.; Xu, Y.; Tu, P.; Lin, P.; Li, X.; Wang, P. Time-Delay Stability Analysis for Hybrid Energy Storage System with Hierarchical Control in DC Microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 6633–6645. [CrossRef]
152. Joshi, M.C.; Samanta, S.; Srungavarapu, G. Frequency Sharing Based Control of Battery/Ultracapacitor Hybrid Energy System in the Presence of Delay. *IEEE Trans. Veh. Technol.* **2019**, *13*, 10571–10584. [CrossRef]
153. Yao, W.; Wang, Y.; Xu, Y.; Dong, C. Small-Signal Stability Analysis and Lead-Lag Compensation Control for DC Networked-Microgrid under Multiple Time Delays. *IEEE Trans. Power Syst.* **2023**, *38*, 921–933. [CrossRef]
154. Mehdi, M.; Kim, C.H.; Saad, M. Robust Centralized Control for DC Islanded Microgrid Considering Communication Network Delay. *IEEE Access* **2020**, *8*, 77765–77778. [CrossRef]
155. Amerian, M.; Narm, H.G.; Hajizadeh, A.; Eren, S. Robust Distributed Control of DC Microgrids Considering Heterogeneous Communication Delays. *IEEE Syst. J.* **2024**, *18*, 462–473. [CrossRef]
156. Zia, M.F.; Elbouchikhi, E.; Benbouzid, M. Microgrids Energy Management Systems: A Critical Review on Methods, Solutions, and Prospects. *Appl. Energy* **2018**, *222*, 1033–1055. [CrossRef]
157. Luo, F.; Ranzi, G.; Wan, C.; Xu, Z.; Dong, Z.Y. A Multistage Home Energy Management System with Residential Photovoltaic Penetration. *IEEE Trans. Ind. Inform.* **2019**, *15*, 116–126. [CrossRef]
158. Aliamooei-Lakeh, S.; Corzine, K.; Parsa, L. Enhancing Voltage Stability and Optimizing Oower Management in DC Microgrids Using Model Predictive Control Considering Various Load Types. In Proceedings of the IECON 2024—50th Annual Conference of the IEEE Industrial Electronics Society, Chicago, IL, USA, 3–6 November 2024; pp. 1–6. [CrossRef]
159. Van Thanh, V.; Su, W.; Wang, B. Optimal DC Microgrid Operation with Model Predictive Control-Based Voltage-Dependent Demand Response and Optimal Battery Dispatch. *Energies* **2022**, *15*, 2140. [CrossRef]
160. Torkan, R.; Ilinca, A.; Ghorbanzadeh, M. A Genetic Algorithm Optimization Approach for Smart Energy Management of Microgrid. *Renew. Energy* **2022**, *197*, 852–863. [CrossRef]
161. El Makroum, R.; Khallaayoun, A.; Lghoul, R.; Mehta, K.; Zörner, W. Home Energy Management System Based on Genetic Algorithm for Load Scheduling: A Case Study Based on Real Life Consumption Data. *Energies* **2023**, *16*, 2698. [CrossRef]

162. Yang, R.; Yuan, Y.; Ying, R.; Shen, B.; Long, T. A Novel Energy Management Strategy for a Ship's Hybrid Solar Energy Generation System Using a Particle Swarm Optimization Algorithm. *Energies* **2020**, *13*, 1380. [CrossRef]
163. Teleke, S.; Baran, M.E.; Bhattacharya, S.; Huang, A.Q. Rule-Based Control of Battery Energy Storage for Dispatching Intermittent Renewable Sources. *IEEE Trans. Sustain. Energy* **2010**, *1*, 117–124. [CrossRef]
164. Jafari, M.; Malekjamshidi, Z.; Zhu, J.; Khooban, M.H. A Novel Predictive Fuzzy Logic-Based Energy Management System for Grid-Connected and off-Grid Operation of Residential Smart Microgrids. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 1391–1404. [CrossRef]
165. Chen, S.; Chang, C. Optimal Power Flows Control for Home Energy Management with Renewable Energy and Energy Storage Systems. *IEEE Trans. Energy Convers.* **2023**, *38*, 218–229. [CrossRef]
166. Şahin, M.E.; Okumuş, H.İ. Parallel-Connected Buck–Boost Converter with FLC for Hybrid Energy System. *Electr. Power Compon. Syst.* **2021**, *48*, 2117–2129. [CrossRef]
167. Şahin, M.E.; Okumuş, H.İ. Comparison of Different Controllers and Stability Analysis for Photovoltaic Powered Buck-Boost DC-DC Converter. *Electr. Power Compon. Syst.* **2018**, *46*, 149–161. [CrossRef]
168. Gil-gonzález, W.; Montoya, O.D. An Energy Management System for the Optimal Operation of BESS in DC Microgrids: A Robust Convex Programming Approach. *IEEE Access* **2023**, *11*, 38168–38181. [CrossRef]
169. Ma, B.; Li, X.; Tan, Q.; Li, F. Multi-Objective Multi-Stage Distributionally Robust Chance-Constrained Low-Carbon Planning Model for a Novel Integrated Multi-Energy Microgrids Incorporating Data Center Considering Real-Time Workload Response and Multiple Uncertainties. *Energy* **2025**, *332*, 137110. [CrossRef]
170. Shen, Y.; Zhai, J.; Kang, Z.; Zhao, B.; Gao, X.; Li, Z. Distributionally Robust Chance-Constrained Energy Management for Island DC Microgrid with Offshore Wind Power Hydrogen Production. *Energy* **2025**, *316*, 134570. [CrossRef]
171. Ebrahimi, M.; Rastegar, M.; Mohammadi, M.; Palomino, A.; Parvania, M. Stochastic Charging Optimization of V2G-Capable PEVs: A Comprehensive Model for Battery Aging and Customer Service Quality. *IEEE Trans. Transp. Electrif.* **2020**, *6*, 1026–1034. [CrossRef]
172. Hussain, A.; Bui, V. Robust Optimal Operation of AC/DC Hybrid Microgrids under Market Price Uncertainties. *IEEE Access* **2018**, *6*, 2654–2667. [CrossRef]
173. Tang, C.; Zhao, J. Distributed Economic Pinning Control Based on Deep Reinforcement Learning for Isolated Microgrids. *Electr. Power Syst. Res.* **2025**, *241*, 111377. [CrossRef]
174. Ramu, S.K.; Vairavasundaram, I.; Palaniyappan, B.; Bragadeshwaran, A.; Aljafari, B. Enhanced Energy Management of DC Microgrid: Artificial Neural Networks-Driven Hybrid Energy Storage System with Integration of Bidirectional DC-DC Converter. *J. Energy Storage* **2024**, *88*, 111562. [CrossRef]
175. Anum, H.; Hashmi, M.A.; Shahid, M.U.; Munir, H.M.; Irfan, M.; Veerendra, A.S.; Kanan, M.; Flah, A. Backward Neural Network (BNN) Based Multilevel Control for Enhancing the Quality of an Islanded RES DC Microgrid under Variable Communication Network. *Heliyon* **2024**, *10*, e32646. [CrossRef] [PubMed]
176. Zhu, Z.; Liu, X.; Kong, X.; Ma, L.; Lee, K.Y.; Xu, Y. PV/Hydrogen DC Microgrid Control Using Distributed Economic Model Predictive Control ☆. *Renew. Energy* **2024**, *222*, 119871. [CrossRef]
177. Abdollahi Arjanaki, A.; Dehestani Kolagar, A.; Alizadeh Pahlavani, M.R. A Two-Level Power Management Strategy in a DC-Coupled Hybrid Microgrid Powered by Fuel Cell and Energy Storage Systems with Model Predictive Controlled Interface Converter. *J. Energy Storage* **2022**, *52*, 104861. [CrossRef]
178. Kouvaritakis, B.; Cannon, M. *Model Predictive Control: Classical, Robust and Stochastic*; Advanced Textbooks in Control and Signal Processing; Springer: Cham, Switzerland, 2016.
179. Elkazaz, M.; Sumner, M.; Naghiyev, E.; Pholboon, S.; Davies, R.; Thomas, D. A Hierarchical Two-Stage Energy Management for a Home Microgrid Using Model Predictive and Real-Time Controllers. *Appl. Energy* **2020**, *269*, 115118. [CrossRef]
180. Yassuda Yamashita, D.; Vechiu, I.; Gaubert, J.P. Two-Level Hierarchical Model Predictive Control with an Optimised Cost Function for Energy Management in Building Microgrids. *Appl. Energy* **2021**, *285*, 116420. [CrossRef]
181. Chen, C.; Chen, J.; Wang, Y.; Duan, S.; Cai, T.; Jia, S. A Price Optimization Method for Microgrid Economic Operation Considering Across-Time-and-Space Energy Transmission of Electric Vehicles. *IEEE Trans. Ind. Inform.* **2020**, *16*, 1873–1884. [CrossRef]
182. Naji Alhasnawi, B.; Jasim, B.H.; Naji Alhasnawi, A.; Hussain, F.F.K.; Homod, R.Z.; Hasan, H.A.; Ibrahim Khalaf, O.; Abbassi, R.; Bazooyar, B.; Zanker, M.; et al. A Novel Efficient Energy Optimization in Smart Urban Buildings Based on Optimal Demand Side Management. *Energy Strateg. Rev.* **2024**, *54*, 101461. [CrossRef]
183. Ran, X.; Leng, S. Enhanced Robust Index Model for Load Scheduling of a Home Energy Local Network with a Load Shifting Strategy. *IEEE Access* **2019**, *7*, 19943–19953. [CrossRef]
184. Liu, Y.; Zhang, Y.; Chen, K.; Chen, S.Z.; Tang, B. Equivalence of Multi-Time Scale Optimization for Home Energy Management Considering User Discomfort Preference. *IEEE Trans. Smart Grid* **2017**, *8*, 1876–1887. [CrossRef]
185. Arun, S.L.; Selvan, M.P. Intelligent Residential Energy Management System for Dynamic Demand Response in Smart Buildings. *IEEE Syst. J.* **2018**, *12*, 1329–1340. [CrossRef]

186. Jasim, A.M.; Jasim, B.H.; Flah, A.; Bolshev, V.; Mihet-Popa, L. A New Optimized Demand Management System for Smart Grid-Based Residential Buildings Adopting Renewable and Storage Energies. *Energy Rep.* **2023**, *9*, 4018–4035. [CrossRef]
187. Hussain, A.; Kim, H. A Rule-Based Modular Energy Management System for AC/DC Hybrid Microgrids. *Sustainability* **2025**, *17*, 867. [CrossRef]
188. Yang, L.; Huang, Z.; Member, S.; Chen, J.; Luo, J.; Wang, Y.; Molinas, M.; Fosso, O.B.; Member, S. Stability Analysis and Interaction-Rule-Based Optimization of Multisource and Multiload DC Microgrid. *IEEE Trans. Power Electron.* **2024**, *39*, 469–482. [CrossRef]
189. Sheikh, A.A.; Lee, D.C. Optimized Energy Management of Seaports with Integrated AMP Technology and DC Microgrid. *IEEE Access* **2023**, *11*, 141217–141231. [CrossRef]
190. Merabet, A.; Tawfique Ahmed, K.; Ibrahim, H.; Beguenane, R.; Ghias, A.M.Y.M. Energy Management and Control System for Laboratory Scale Microgrid Based Wind-PV-Battery. *IEEE Trans. Sustain. Energy* **2017**, *8*, 145–154. [CrossRef]
191. Naidu, B.R.; Panda, G.; Siano, P. A Self-Reliant Dc Microgrid: Sizing, Control, Adaptive Dynamic Power Management, and Experimental Analysis. *IEEE Trans. Ind. Inform.* **2018**, *14*, 3300–3313. [CrossRef]
192. Vivas, F.J.; Segura, F.; Andújar, J.M. Fuzzy Logic-Based Energy Management System for Grid-Connected Residential DC Microgrids with Multi-Stack Fuel Cell Systems: A Multi-Objective Approach. *Sustain. Energy Grids Netw.* **2022**, *32*, 100909. [CrossRef]
193. Rodriguez, M.; Arcos–Aviles, D.; Martinez, W. Fuzzy Logic-Based Energy Management for Isolated Microgrid Using Meta-Heuristic Optimization Algorithms. *Appl. Energy* **2023**, *335*, 120771. [CrossRef]
194. Seng, U.K.; Malik, H.; García Márquez, F.P.; Alotaibi, M.A.; Afthanorhan, A. Fuzzy Logic-Based Intelligent Energy Management Framework for Hybrid PV-Wind-Battery System: A Case Study of Commercial Building in Malaysia. *J. Energy Storage* **2024**, *102*, 114109. [CrossRef]
195. Cakmak, R.; Bayrak, G.; Koc, M. A Fuzzy Logic-Based Energy Management Approach for Fuel Cell and Photovoltaic Powered Electric Vehicle Charging Station in DC Microgrid Operations. *IEEE Access* **2025**, *13*, 49905–49921. [CrossRef]
196. Nikzad, M. Risk-Averse Stochastic Multi-Objective Optimization for Time-of-Use Demand Response Pricing in Smart Microgrids. *Energy* **2025**, *322*, 135733. [CrossRef]
197. Li, Z.; Wu, L.; Xu, Y.; Zheng, X. Stochastic-Weighted Robust Optimization Based Bilayer Operation of a Multi-Energy Building Microgrid Considering Practical Thermal Loads and Battery Degradation. *IEEE Trans. Sustain. Energy* **2022**, *13*, 668–682. [CrossRef]
198. Gong, K.; Member, S.; Wang, X.; Jiang, C. Security-Constrained Optimal Sizing and Siting of BESS in Hybrid AC/DC Microgrid Considering Post-Contingency Corrective Rescheduling. *IEEE Trans. Sustain. Energy* **2021**, *12*, 2110–2122. [CrossRef]
199. Zhang, Y.; Ren, Y.; Liu, Z.; Li, H.; Jiang, H.; Xue, Y.; Ou, J.; Hu, R.; Zhang, J.; Gao, D.W. Federated Deep Reinforcement Learning for Varying-Scale Multi-Energy Microgrids Energy Management Considering Comprehensive Security. *Appl. Energy* **2025**, *380*, 125072. [CrossRef]
200. Xiong, B.; Zhang, L.; Hu, Y.; Fang, F.; Liu, Q.; Cheng, L. Deep Reinforcement Learning for Optimal Microgrid Energy Management with Renewable Energy and Electric Vehicle Integration. *Appl. Soft Comput.* **2025**, *176*, 113180. [CrossRef]
201. Aguila-Leon, J.; Vargas-Salgado, C.; Chiñas-Palacios, C.; Díaz-Bello, D. Energy Management Model for a Standalone Hybrid Microgrid through a Particle Swarm Optimization and Artificial Neural Networks Approach. *Energy Convers. Manag.* **2022**, *267*, 115920. [CrossRef]
202. Srikanth, D.; Sukumar, G.D.; Sobhan, P.V.S. A Convolutional Neural Network Based Energy Management System for Photovoltaic/Battery Systems in Microgrid Using Enhanced Coati Optimization Approach. *J. Energy Storage* **2025**, *119*, 116252. [CrossRef]
203. Khatiri, A.; Mousazadeh Mousavi, S.Y.; Golestan, S. Quantum Neural Networks for Optimal Energy Management in Renewable Based Microgrids with Plug-in Electric Vehicles and Battery Energy Storages. *J. Energy Storage* **2025**, *129*, 117304. [CrossRef]
204. Kumar, K.; Kwon, S.; Bae, S. Deep Reinforcement Learning-Based Control Strategy for Integration of a Hybrid Energy Storage System in Microgrids. *J. Energy Storage* **2025**, *108*, 114936. [CrossRef]
205. Hosseini, E.; Horrillo-Quintero, P.; Carrasco-Gonzalez, D.; García-Triviño, P.; Sarrias-Mena, R.; García-Vázquez, C.A.; Fernández-Ramírez, L.M. Reinforcement Learning-Based Energy Management System for Lithium-Ion Battery Storage in Multilevel Microgrid. *J. Energy Storage* **2025**, *109*, 115114. [CrossRef]
206. de la Cruz, J.; Wu, Y.; Candelo-Becerra, J.E.; Vásquez, J.C.; Guerrero, J.M. Review of Networked Microgrid Protection: Architectures, Challenges, Solutions, and Future Trends. *CSEE J. Power Energy Syst.* **2024**, *10*, 448–467. [CrossRef]
207. Ali, Z.; Terriche, Y.; Hoang, L.Q.N.; Abbas, S.Z.; Hassan, M.A.; Sadiq, M.; Su, C.L.; Guerrero, J.M. Fault Management in DC Microgrids: A Review of Challenges, Countermeasures, and Future Research Trends. *IEEE Access* **2021**, *9*, 128032–128054. [CrossRef]
208. Mirsaeidi, S.; Dong, X.; Shi, S.; Tzelepis, D. Challenges, Advances and Future Directions in Protection of Hybrid AC/DC Microgrids. *IET Renew. Power Gener.* **2017**, *11*, 1495–1502. [CrossRef]

209. Augustine, S.; Reno, M.J.; Brahma, S.M.; Lavrova, O. Fault Current Control and Protection in a Standalone DC Microgrid Using Adaptive Droop and Current Derivative. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, *9*, 2529–2539. [CrossRef]
210. Talha, M.A.; Chowdhury, S.A.; Shakif Bhuiyan, M.S. Renewable Integration and Energy Management in DC Microgrid. In Proceedings of the 2024 6th International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT), Dhaka, Bangladesh, 2–4 May 2024; pp. 634–639. [CrossRef]
211. Shaban, M.; Mosa, M.A.; Ali, A.A.; Abdel-Latif, K.M. Effect of Power Sharing Control Techniques of Hybrid Energy Storage System during Fault Conditions in DC Microgrid. *J. Energy Storage* **2023**, *72*, 108249. [CrossRef]
212. Zhang, X.; Li, Y.; Qi, C.; Qu, Y.; Ling, A.; Sun, X.; Zhang, J. Analysis of Transient and Fault Characteristics of Integrated Photovoltaic Storage and Charging DC Microgrid. In Proceedings of the 2024 3rd International Conference on Power Systems and Electrical Technology (PSET), Tokyo, Japan, 5–8 August 2024; pp. 159–163. [CrossRef]
213. Shareef, R.; Mahmood, T.; Tariq, F. Enhanced Local Measurement Based Online Fault Location Technique for Low Voltage DC Distribution Network. In Proceedings of the 2022 5th International Conference on Energy Conservation and Efficiency (ICECE), Lahore, Pakistan, 16–17 March 2022; pp. 1–6. [CrossRef]
214. Sharma, S.; Tripathy, M. Differential Reactor Voltage Based Fault Detection and Classification for Smart DC Microgrid. *IEEE Trans. Ind. Inform.* **2023**, *19*, 11730–11741. [CrossRef]
215. Mohanty, R.; Pradhan, A.K. Protection of Smart DC Microgrid with Ring Configuration Using Parameter Estimation Approach. *IEEE Trans. Smart Grid* **2018**, *9*, 6328–6337. [CrossRef]
216. Poursaeed, A.H.; Namdari, F. High-Speed Algorithm for Fault Detection and Location in DC Microgrids Based on a Novel Time–Frequency Analysis. *IET Gener. Transm. Distrib.* **2024**, *18*, 4259–4278. [CrossRef]
217. Aboelezz, A.M.; El-Saadawi, M.M.; Eladl, A.A.; Bures, V.; Sedhom, B.E. A Novel Fault Detection and Location Approach for DC Zonal Shipboard Microgrid Based on High-Frequency Impedance Estimation with IEC 61850 Communication Protocol. *IEEE Access* **2024**, *12*, 36212–36228. [CrossRef]
218. Jayamaha, D.K.J.S.; Lidula, N.W.A.; Rajapakse, A.D. Wavelet-Multi Resolution Analysis Based ANN Architecture for Fault Detection and Localization in DC Microgrids. *IEEE Access* **2019**, *7*, 145371–145384. [CrossRef]
219. Saxena, A.; Sharma, N.K.; Samantaray, S.R. An Enhanced Differential Protection Scheme for LVDC Microgrid. *IEEE J. Emerg. Sel. Top. Power Electron.* **2022**, *10*, 2114–2125. [CrossRef]
220. Dhar, S.; Patnaik, R.K.; Dash, P.K. Fault Detection and Location of Photovoltaic Based DC Microgrid Using Differential Protection Strategy. *IEEE Trans. Smart Grid* **2018**, *9*, 4303–4312. [CrossRef]
221. Bayati, N.; Baghaee, H.R.; Hajizadeh, A.; Member, S.; Soltani, M.; Member, S.; Lin, Z.; Member, S. Local Fault Location in Meshed DC Microgrids Based On Parameter Estimation Technique. *IEEE Syst. J.* **2022**, *16*, 1606–1615. [CrossRef]
222. Liu, H.; Han, H.; Shi, G.; Chen, X.; Sun, Y.; Su, M.; Chen, C. Adaptive Threshold-Based Local Fault Diagnosis Method for DC Microgrids. *IEEE Trans. Ind. Electron.* **2026**, *73*, 4917–4929. [CrossRef]
223. Yadav, N.; Tummuru, N.R. Filter Capacitor Current Dynamics-Based Frequency-Domain Fault Detection Approach for Grid-Connected Low-Voltage DC Microgrid. *IEEE Trans. Ind. Electron.* **2023**, *70*, 12784–12794. [CrossRef]
224. Dashtdar, M.; Belkhier, Y.; Bajaj, M.; Sadegh, S.M.; Belik, M.; Rubanenko, O. Protection of DC Microgrids Based on Frequency Domain Analysis Using Fourier Transform. In Proceedings of the 2022 IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek), Kharkiv, Ukraine, 3–7 October 2022; pp. 3–8. [CrossRef]
225. Liu, H.; Han, H.; Zheng, X.; Li, W.; Ling, T.; Su, M.; Liu, Y.; Sun, Y. Local Data-Driven Fault Localization Method for Ring-Type DC Microgrid with Fewer Sensors. *IEEE Trans. Power Electron.* **2025**, *41*, 6683–6697. [CrossRef]
226. Udhaya Sankar, T.P.; Vinodha, R.; Srinivasan, C.; Ganesan, R.; Subashree, M.; Sowmiya, S. Optimizing Fault Detection in Electrical Grids Through Neural Network Models. In *Proceedings of the 4th International Conference on Innovative Mechanisms for Industry Applications, ICIMIA 2025*; IEEE: New York, NY, USA, 2025; pp. 134–139.
227. Zheng, S.; Kheirollahi, R.; Pan, J.; Xue, L.; Wang, J.; Lu, F. DC Circuit Breakers: A Technology Development Status Survey. *IEEE Trans. Smart Grid* **2022**, *13*, 3915–3928. [CrossRef]
228. Bayati, N.; Hajizadeh, A.; Soltani, M. Protection in DC Microgrids: A Comparative Review. *IET Smart Grid* **2018**, *1*, 66–75. [CrossRef]
229. Pei, X.; Smith, A.C.; Cwikowski, O.; Barnes, M. Hybrid DC Circuit Breaker with Coupled Inductor for Automatic Current Commutation. *Int. J. Electr. Power Energy Syst.* **2020**, *120*, 106004. [CrossRef]
230. Shaswat, S.; Sarangi, S.; Gupta, R. A Hybrid Solid State Circuit Breaker for DC System Using Coupled Inductor. In Proceedings of the 2023 9th IEEE India International Conference on Power Electronics (IICPE), SONIPAT, India, 28–30 November 2023; pp. 1–6. [CrossRef]
231. Gao, C.; Zhang, Z.; Xu, J.; Gao, T.; Chen, S.; Li, X. Analysis of LVDC Microgrid Protection Requirements and Application of Hybrid Circuit Breaker. In Proceedings of the 2023 IEEE 68th Holm Conference on Electrical Contacts (HOLM), Seattle, WA, USA, 4–11 October 2023; pp. 1–7. [CrossRef]

232. Keshavarzi, D.; Farjah, E.; Ghanbarih, T. A Hybrid DC Circuit Breaker for DC Microgrid Based on Zero Current Switching. In Proceedings of the 2016 Iranian Conference on Renewable Energy & Distributed Generation (ICREDG), Mashhad, Iran, 2–3 April 2016; pp. 45–49. [CrossRef]
233. Kim, G.; Lee, J.S.; Park, J.H.; Choi, H.D.; Lee, M.J. A Zero Crossing Hybrid Bidirectional Dc Circuit Breaker for Hvdc Transmission Systems. *Energies* **2021**, *14*, 1349. [CrossRef]
234. Cao, P.; Peng, H.; Wang, T.; Fu, L. A New Type of Forced Commutation Vacuum DC Circuit Breaker. In Proceedings of the 2024 The 9th International Conference on Power and Renewable Energy (ICPRE), Guangzhou, China, 20–23 September 2024; pp. 314–318. [CrossRef]
235. Kim, J.; Choi, H. Improvement of LC Resonance Characteristics through Superconducting Elements of DC Circuit Breaker. *IEEE Trans. Appl. Supercond.* **2023**, *33*, 1–5. [CrossRef]
236. Park, S.Y.; Kim, G.W.; Jeong, J.S.; Choi, H.S. The Modeling of the LC Divergence Oscillation Circuit of a Superconducting DC Circuit Breaker Using PSCAD/EMTDC. *Energies* **2022**, *15*, 780. [CrossRef]
237. Zhang, Y.; Wu, Y.; Sun, H.; Wu, Y.; Liu, T. Experimental Investigation on Magnetically Controlled Air Arc Oscillation Characteristics for DC Interruption. *J. Phys. D Appl. Phys.* **2024**, *57*, 375205. [CrossRef]
238. Zhou, Z.; Jiang, J.; Ye, S.; Yang, D.; Jiang, J. Novel Bidirectional O-Z-Source Circuit Breaker for DC Microgrid Protection. *IEEE Trans. Power Electron.* **2021**, *36*, 1602–1613. [CrossRef]
239. Savaliya, S.G.; Fernandes, B.G. Performance Evaluation of a Modified Bidirectional Z-Source Breaker. *IEEE Trans. Ind. Electron.* **2021**, *68*, 7137–7145. [CrossRef]
240. Ugalde-Loo, C.E.; Wang, Y.; Wang, S.; Ming, W.; Liang, J.; Li, W. Review on Z-Source Solid State Circuit Breakers for DC Distribution Networks. *CSEE J. Power Energy Syst.* **2023**, *9*, 15–27. [CrossRef]
241. Augustine, S.; Quiroz, J.E.; Reno, M.J.; Brahma, S. *DC Microgrid Protection: Review and Challenges*; Sandia National Laboratories (SNL-NM): Albuquerque, NM, USA, 2018; pp. 1–57. [CrossRef]
242. Jayamaha, D.K.J.S.; Lidula, N.W.A.; Rajapakse, A.D. Protection and Grounding Methods in DC Microgrids: Comprehensive Review and Analysis. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109631. [CrossRef]
243. Mohammadi, J.; Badrkhani Ajaei, F.; Stevens, G. Grounding the DC Microgrid. *IEEE Trans. Ind. Appl.* **2019**, *55*, 4490–4499. [CrossRef]
244. Lim, S.T.; Oh, C.H.; Lee, K.Y. Ground Fault Protection Strategies for Low-Voltage DC Systems Considering DC/DC Converter Isolation and Grounding Configurations. In Proceedings of the 2025 IEEE International Conference on Energy Technologies for Future Grids (ETFG), Wollongong, Australia, 7–11 December 2025; pp. 1–6. [CrossRef]
245. Guo, G.; Zha, K.; Yang, Y.; Zhang, F.; Wang, J.; Xie, W. Grounding Faults in Series-Connected-Based Offshore Wind Farms: DC Link Current Control. *CSEE J. Power Energy Syst.* **2025**, *11*, 2128–2136. [CrossRef]
246. Peng, N.; Zhou, G.; Liang, R.; Wang, Z.; Hu, Y.; Zhang, P.; Zhao, Z. Single-Pole-to-Earth Fault Section Detection of the MVDC Cables Based on Variation Mechanism of Grounding Line Currents. *IEEE Trans. Smart Grid* **2025**, *16*, 2127–2143. [CrossRef]
247. Nguyen, T.H.; Al Hosani, K.; El Moursi, M.S.; Blaabjerg, F. An Overview of Modular Multilevel Converters in HVDC Transmission Systems with STATCOM Operation during Pole-to-Pole DC Short Circuits. *IEEE Trans. Power Electron.* **2019**, *34*, 4137–4160. [CrossRef]
248. Cho, G.C.; Kim, S.; Kim, G. A Sequential Tripping Protection Scheme for Single Pole-to-Ground Faults in Ring-Structure Medium Voltage DC Grid. *IEEE Trans. Smart Grid* **2026**, *17*, 966–978. [CrossRef]
249. Azizi, M.; Husev, O.; Veligorskyi, O.; Rahimpour, S.; Roncero-Clemente, C. Grounding and Isolation Requirements in DC Microgrids: Overview and Critical Analysis. *Energies* **2023**, *16*, 7747. [CrossRef]
250. Beheshtaein, S.; Cuzner, R.M.; Forouzesh, M.; Savaghebi, M.; Guerrero, J.M. DC Microgrid Protection: A Comprehensive Review. *IEEE J. Emerg. Sel. Top. Power Electron.* **2024**, 1. [CrossRef]
251. Lazzari, R.; Piegari, L.; Grillo, S.; Carminati, M.; Ragaini, E.; Bossi, C.; Tironi, E. Selectivity and Security of DC Microgrid under Line-to-Ground Fault. *Electr. Power Syst. Res.* **2018**, *165*, 238–249. [CrossRef]
252. Peng, Y.; Song, Z.; Zeng, X.; Pan, Z.; Zhang, S.; Shen, X.; Wang, L. Fast Protection Strategy for Monopole Grounding Fault of Low-Voltage DC Microgrid. *Electr. Power Syst. Res.* **2023**, *214*, 108919. [CrossRef]
253. Sharma, N.K.; Samantaray, S.R.; Bhende, C.N. VMD-Enabled Current-Based Fast Fault Detection Scheme for DC Microgrid. *IEEE Syst. J.* **2022**, *16*, 933–944. [CrossRef]
254. Li, Z.; Duan, J.; Lu, W.; Du, X.; Yang, W.; Tu, S. Non-Permanent Pole-to-Pole Fault Restoration Strategy for Flexible DC Distribution Network. *J. Mod. Power Syst. Clean Energy* **2021**, *9*, 1339–1351. [CrossRef]
255. Li, C.; Zhao, C.; Xu, J.; Ji, Y.; Zhang, F.; An, T. A Pole-to-Pole Short-Circuit Fault Current Calculation Method for DC Grids. *IEEE Trans. Power Syst.* **2017**, *32*, 4943–4953. [CrossRef]
256. Li, B.; Jiao, X.; Wen, W.; Wang, W.; Li, B. Study on Calculation Method for Steady-State Short-Circuit Current of MMC During a DC Pole-to-Pole Fault. *IEEE Trans. Power Deliv.* **2022**, *37*, 2492–2502. [CrossRef]

257. Wang, P.; Kuschke, M.; Strunz, K. Analytical Modeling of Modular Multilevel Converter Under Pole-to-Pole DC Fault and Application to System Design and Protection. *IEEE Trans. Energy Convers.* **2022**, *37*, 2722–2736. [CrossRef]
258. Wang, X.; Tian, Y.; Gao, J.; Wei, X.; Zhang, F.; Zhang, Y. Pole-to-Ground Fault Protection Scheme for Flexible DC Distribution Network Based on Time Domain Skewness and Integral Energy. *IEEE Trans. Power Deliv.* **2025**, *40*, 2611–2623. [CrossRef]

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