Overview of DC Distribution System in Low-Carbon Building—Part II: Key Equipment, Coordinated Control, and Stability Analysis

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***Abstract*—Building energy consumption contributes to approximately 34% of global carbon emissions. Direct current (dc) distribution technology, characterized by its significant advantages in efficiently integrating distributed energy resources and flexible loads, alongside high transmission efficiency, presents promising opportunities for the low-carbon transition of the building sector. This review systematically summarizes the key power electronic equipment, coordinated control strategies, and stability analysis methods within building dc distribution systems. First, it introduces the power electronic converters that interconnect system components, and the dc circuit breakers responsible for fault isolation and operational mode switching. Second, this article discusses recent advancements in hierarchical control architectures (including primary, secondary, and tertiary levels), considering the electrical characteristics of buildings, and provides a classification thereof. Concurrently, this review systematically covers small-signal and large-signal stability analysis methods. Comparative analyses highlight the existing gaps in stability criteria for multivoltage-level systems, particularly when considering line impedance. Finally, focusing on the requirements for building decarbonization and efficient, stable operation, this review provides several future research directions.**

***Index Terms*—Building decarbonization, building energy systems, dc distribution system, dc microgrid, hierarchical control, power electronic equipment, stability analysis.**

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NOMENCLATURE

3L-NPC	Three-level neutral-point-clamped.
AI	Artificial intelligence.
ANN	Artificial neural network.
BCCC	Bus current controlled converter.
BEIC	Bus equivalent impedance criterion.
BGCC	Bidirectional grid-connected converter.
BIC	Bidirectional interlinking converter.
BNIC	Bus node impedance criterion.
BVCC	Bus voltage controlled converter.
CPL	Constant power load.
DAB	Dual active bridge.
DCCB	DC circuit breaker.
DDA	Dynamic diffusion algorithm.
DHB	Dual half bridge.
EMS	Energy management systems.
ESS	Energy storage system.
FSBB	Four-switch Buck-Boost.
GaN	Gallium nitride.
HVAC	Heating, ventilation, and air conditioning.
IBPFC	Interbuilding power flow controller.
IGBT	Insulated gate bipolar transistor.
IGCT	Integrated gate-commutated thyristor.
LVDC	Low-voltage direct current.
MMC	Modular multilevel converter.
MOSFET	Metal-oxide-semiconductor field-effect transistor.
MPC	Model predictive control.
MPPT	Maximum power point tracking.
PBSC	Passivity-based stability criterion.
PINN	Physics-informed neural network.
PLL	Phase-locked loop.
PSO	Particle swarm optimization.
PV	Photovoltaics.
QAB	Quadruple active bridge.
RHP	Right half plane.
RES	Renewable energy source.
SiC	Silicon carbide.
SoC	State of charge.
SSCB	Solid-state circuit breaker.
TCL	Thermostatically controlled load.
T-S	Takagi-Sugeno.

VSC	Voltage source converter.
WBG	Wide bandgap.

I. INTRODUCTION

THE building sector is a major contributor to global energy consumption and CO_2 emissions, accounting for approximately 32% of global final energy consumption and 34% of global CO_2 emissions [1]. Achieving low-carbon operation in buildings is therefore crucial for addressing climate change and mitigating environmental issues.

To achieve building decarbonization, constructing an integrated and highly efficient power distribution system is essential. While traditional buildings utilize alternating current (ac) distribution systems, in recent years, direct current (dc) distribution systems and dc microgrids have garnered significant attention due to their advantages in energy conversion efficiency, control flexibility, and ease of integrating photovoltaics (PV), energy storage system (ESS), and loads [2], [3], [4], [5], [6], [7], [8]. Low-carbon building dc distribution technology, by integrating PV generation, flexible loads, electrochemical ESS, and the building's inherent thermal storage into the low-voltage dc distribution system [9], [10], [11], enables the partial or complete substitution of conventional grid power with clean energy generation and enhances energy transmission efficiency. Therefore, dc distribution technology holds significant potential for achieving energy savings and emission reductions in buildings [8], [12]. Part I of this review series has provided a detailed introduction to the configuration, network topology, and application case of low-carbon building dc distribution systems.

Key elements in low-carbon building dc distribution systems, such as PV, ESS, and flexible loads, are interfaced with the distribution network and achieve fault isolation via power electronic equipment [converters and dc circuit breakers (DCCBs)]. This results in a system highly dominated by power electronics, which consequently exhibits significant nonlinear and weak damping characteristics. Concurrently, the penetration level of distributed generation and flexible loads in low-carbon buildings is increasing, with their power output/consumption exhibiting significant intermittency and volatility [13]. Furthermore, the presence of numerous constant power loads (CPLs) introduces negative damping effects, further degrading system stability [14]. In summary, achieving coordinated control among the various distributed elements within low-carbon buildings and ensuring system stability under diverse operating conditions are crucial for realizing low-carbon and reliable building operation.

Power electronic equipment, coordinated control, and stability analysis are intricately related:

1) Power electronic equipment serves as the actuator for coordinated control and is a key subject of stability analysis; its performance directly impacts system operational efficiency and reliability [15].
2) Coordinated control strategies are implemented through controllable power electronic equipment, and their control parameters largely determine equipment performance while also affecting system stability [16].
3) Stability analysis is crucial for ensuring proper system operation and serves as an important basis for configuring power electronic equipment and optimizing coordinated control strategies.

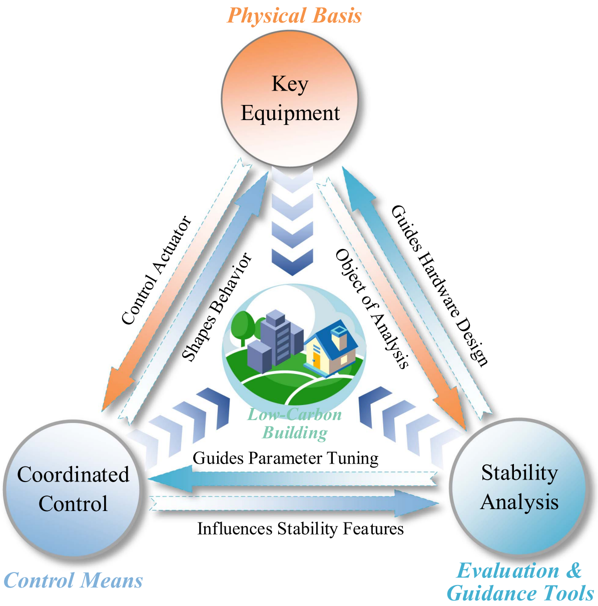

Fig. 1. Overview of low-carbon building critical equipment, coordinated control, and stability analysis.

The relationship among power electronic equipment, coordinated control, and stability analysis in low-carbon dc distribution systems is illustrated in Fig. 1.

Many research studies and review articles are available concerning the power electronic equipment, coordinated control, and stability analysis within distribution systems. Dragičević et al. [3] reviewed the control strategies, stability analysis methods, and stability enhancement control techniques for dc microgrids. Considering the specific pulsed load profiles and power system configurations unique to ships, Xu et al. [17] reviewed the coordinated control strategies, stability analysis, and fault management methods for shipboard dc microgrids. Xu et al. [18] reviewed impedance modeling and stability analysis for more-electric aircraft power systems, with a focus on discussing stability criteria and their applicability within more-electric aircraft systems. Deng et al. [19] investigated the application of microgrids integrating renewable energy sources (RESs) and ESS in the rail transit sector, and reviewed the corresponding system architectures and control strategies. Rivera et al. [8] conducted a comprehensive comparative analysis of ac–dc and dc–dc power electronic converter topologies for bipolar low-voltage dc distribution systems. Rodrigues et al. [20] reviewed various technologies and classifications of SSCBs, highlighting their strong applicability in dc distribution systems. From the perspective of existing standards. Wang et al. [21] outlined the relevant requirements for power electronic equipment in buildings, providing valuable references for engineering practice.

However, for the emerging application scenario of low-carbon building dc distribution, a comprehensive and systematic review encompassing the analysis, classification, and summary of its power electronic equipment, coordinated control, and stability analysis is still lacking in the existing literature. Although previous studies on dc microgrids across various application scenarios

TABLE I
COMPARISON OF THIS ARTICLE WITH REPRESENTATIVE REVIEW ARTICLES IN RELATED FIELDS

Reference	**Publication year**	**Electrical system type**	**Application domain**	**Content**
Dragičević et al. [3]	2016	DC Microgrids	General	• Reviews control strategies for general dc microgrids. • Discusses stability analysis methods. • Summarizes active stabilization techniques.
Rivera et al [8]	2021	Bipolar DC Grids	General, focus on data centers, EV charging	• Reviews power electronics topologies in bipolar dc grids. • Analyzes their operational modes and relevant technical standards.
Xu et al. [17]	2022	DC Shipboard Microgrids	Shipboard/Marine	• Reviews coordinated control architectures for dc shipboard microgrids. • Analyzes stability issues related to constant power and pulsed loads. • Summarizes protection schemes, including grounding and fault management.
Xu et al. [18]	2024	AC/DC Hybrid Power Systems	More-Electric Aircraft	• A deep review of impedance modeling methods for power supply systems in more-electric aircraft. • Summarizes impedance-based stability analysis criteria. • Reviews impedance shaping techniques to enhance system stability.
Deng et al. [19]	2025	AC/DC/Hybrid Microgrids	Railway Infrastructure	• Reviews green microgrids for railway infrastructure. • Covers green energy sources, ESS, and intelligent control strategies.
Wang et al. [21]	2025	DC Microgrids in Buildings	Buildings	• Reviews technology standards for dc microgrids in buildings. • Covers system architecture, voltage levels, power electronics, metering, grounding, and protection.
This article	Current year	Low-Carbon Building DC Distribution Systems	Low-Carbon Buildings	• Provides an integrative technical review framework for low-carbon building dc distribution systems. • Systematically elaborates on the relationships and latest research progress among the three coupled domains of power electronic equipment, coordinated control, and stability analysis.

offer valuable insights for low-carbon building dc systems, the latter's unique characteristics, such as building thermal storage and flexible TCLs, introduce new dynamic behaviors and control challenges. This review aims to systematically review the power electronic equipment, coordinated control strategies, and stability analysis methods within low-carbon building dc distribution systems. It examines recent research progress in related fields and provides a clear classification for each topic, specifically tailored to the context of building applications. A comparison of this article with representative review articles in related fields is shown in Table I.

The remainder of this article is organized as follows. Section II introduces the key power electronic equipment in low-carbon building dc distribution systems, including converters and SSCBs. Section III reviews the hierarchical control architecture (i.e., primary, secondary, and tertiary control) for coordinated control, elaborates on the latest research advancements, and provides the classification of coordinated control strategies. Section IV discusses the small-signal and large-signal stability analysis methods applicable to low-carbon building dc distribution systems and presents their classification. Finally, Section V concludes this article and outlines future research directions.

II. POWER ELECTRONIC EQUIPMENT

Power electronic equipment plays a pivotal role in building dc distribution systems, being responsible for energy conversion, control, and optimization. This equipment is crucial for ensuring stable system operation, efficient energy conversion, and reliable protection control. Power electronic equipment within building dc distribution systems is primarily categorized into two main types: converters and DCCBs. Converters, in turn, can be further subdivided into dc–dc converters and ac–dc converters [7].

A. Power Electronic Converters

1) DC–DC Converters:

a) PV converters: PV converters serve as the critical interface between the PV array and the dc bus, performing voltage conversion and maximum power point tracking (MPPT) to maximize solar energy utilization [22]. Nonisolated unidirectional dc–dc topologies are commonly employed for PV converters. To achieve high voltage gain, cascaded structures or input-parallel output-series configurations can be utilized [23].

b) ESS converters: ESS converters act as the crucial interface connecting energy storage units to the dc bus, enabling bidirectional energy flow to smooth power fluctuations and enhance system stability [24]. Bidirectional dc–dc ESS converters primarily comprise isolated and nonisolated topologies. Nonisolated types are often realized by modifying traditional Buck-Boost or Cuk circuits, typically through the addition of a fully-controlled power semiconductor device [25].

Isolated topologies utilize a high-frequency transformer for galvanic isolation and voltage matching, potentially offering

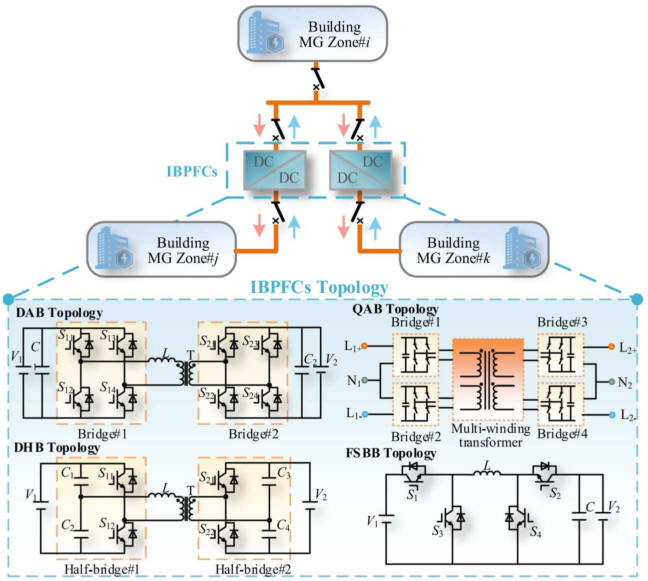

Fig. 2. Schematic diagram of an IBPFC for flexible interconnection of multiple building DC systems.

higher voltage gains and wider regulation ranges via turns ratio adjustment [26]. The DAB is a representative isolated bidirectional converter, widely adopted due to its high efficiency and power density. Furthermore, simplifying the primary and secondary full-bridge structures of the DAB to half-bridges yields derivative topologies like the dual half bridge (DHB). These aim to reduce the switch count, simplify control, and optimize efficiency under specific operating conditions [27].

c) DC load converters: DC load converters supply the required voltage levels for various dc loads within buildings, such as LED lighting and dc appliances. Common topologies include the Buck-Boost converter and the FSBB converter [28]. To enhance efficiency, techniques such as synchronous rectification and soft switching are commonly implemented [29].

d) Bidirectional interlinking converters: The BICs are employed to connect dc buses operating at different voltage levels, facilitating bidirectional power flow and voltage matching. BICs enhance the flexibility and reliability of dc distribution systems by enabling bidirectional energy transfer between buses with different voltages, thereby optimizing overall system operation [30]. For safety considerations in low-carbon dc buildings, isolated bidirectional dc–dc converters are frequently utilized. Representative topologies include the DAB and LLC resonant dc–dc converters.

e) Interbuilding power flow controllers: The IBPFCs connect the dc distribution systems of multiple buildings, forming building clusters to enable energy sharing and optimization among them [31]. The schematic diagram is shown in Fig. 2.

These converters employ coordinated control strategies to flexibly regulate interbuilding power flow, thereby maximizing the utilization of RESs and ESS [32], while concurrently enhancing system reliability and emergency response capabilities [33]. Given the potentially large capacity of building electrical systems, stringent requirements regarding efficiency and safety are imposed on these controllers. Common topologies include isolated bidirectional dc–dc converters. The DAB converter is a mature and widely used topology for IBPFCs [34], leveraging advantages such as high-frequency electrical isolation, high efficiency, and flexible bidirectional power flow control. Additionally, the DHB converter offers significant techno-economic advantages, primarily due to its low component count. The QAB converter, meanwhile, is well-suited for interfacing with bipolar dc systems. Both of these topologies have found relevant applications in IBPFC [27], [35]. Furthermore, nonisolated bidirectional FSBB converters represent another viable option for IBPFC [28].

2) AC–DC Converters:

a) Bidirectional grid-connected converters: The BGCCs serve as the crucial link between the building dc system and the ac grid. It facilitates bidirectional power flow between the ac grid and the dc bus, enabling the building dc system to draw power from the grid and inject surplus power back into it [36]. To comply with grid interconnection standards, the BGCCs are required to exhibit low harmonic distortion and fast dynamic response capabilities. Furthermore, it may possess low-voltage ride-through and high-voltage ride-through capabilities to ensure stable operation during grid faults [37], [38], [39].

Fig. 3 illustrates three different voltage-level topologies of BGCC employed in building dc distribution systems.

The two-level VSC represents a widely utilized topology. For building dc distribution systems requiring a bipolar configuration, a balancer can be incorporated to establish the neutral connection, thereby forming the bipolar system; in contrast, such a balancer is unnecessary for unipolar dc systems [7]. The 3L-NPC converter provides a wide output voltage range. Its capability to generate three voltage levels on the ac side enhances voltage quality and contributes to meeting grid connection requirements [40]. Based on the specific polarity and performance demands of the building dc distribution system, a balancer may optionally be integrated within the 3L-NPC configuration [8]. The neutral point potential balancing issue in 3L-NPC converters significantly impacts the operational reliability of semiconductor devices and the overall system voltage quality [41]. MMCs, owing to their advantages such as high scalability, superior power quality, high efficiency, and low switching frequency operation [42], also represent a viable topology option for BGICs. However, their inherent module redundancy leads to higher initial investment costs [43].

b) AC load converters: To ensure the operational compatibility of existing ac equipment within low-carbon dc buildings, ac load inverters are required to supply power to such equipment. Such inverters can employ either unidirectional isolated or nonisolated topologies.

B. DC Circuit Breakers

Unlike ac systems, which leverage the natural zero-crossing of current for interruption, low-carbon building dc distribution systems, being converter-dominated, face significant challenges due to the absence of natural zero-crossings and their inherent fast dynamics. This leads to rapidly rising fault currents, thereby imposing more stringent requirements on system protection.

Within building dc distribution systems, DCCBs are utilized to manage operational mode transitions and limit the propagation of faults.

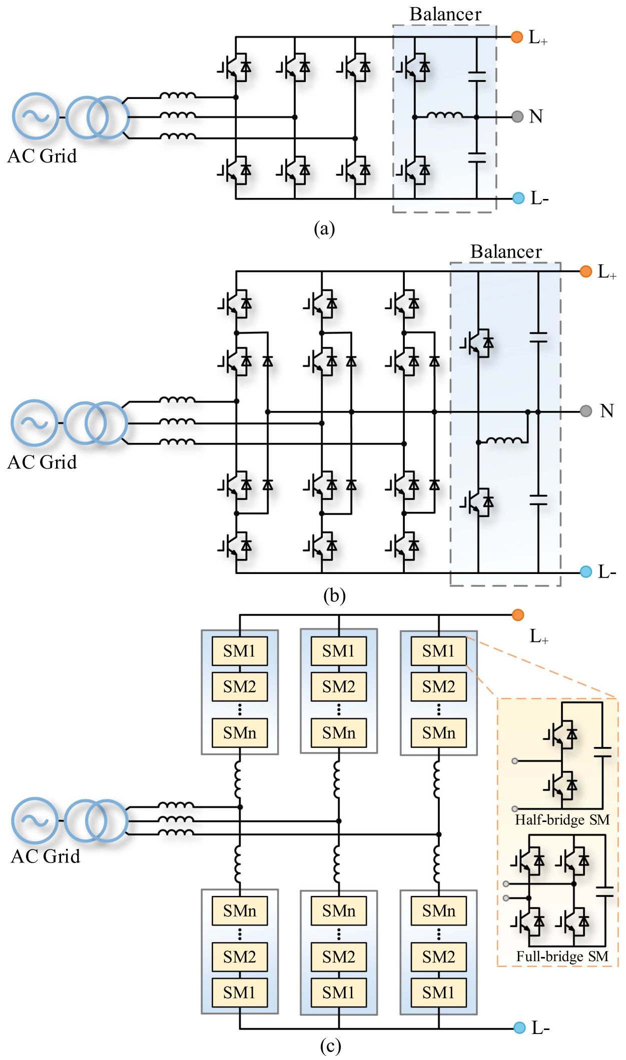

Fig. 3. BGCCs topologies with different voltage levels. (a) 2L-VSC topology. (b) 3L-NPC topology. (c) MMC topology.

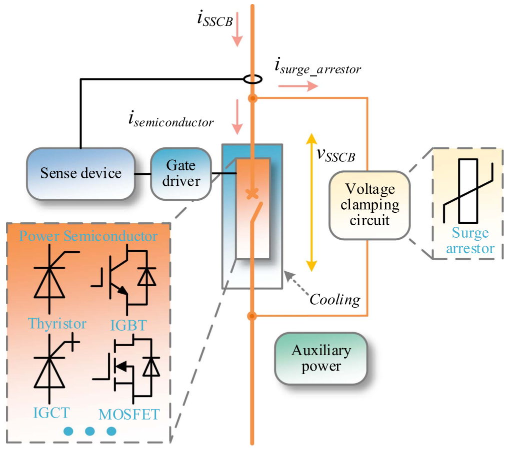

Fig. 4. Schematic diagram of SSCBs.

Currently, fast DCCBs commonly used in building applications mainly include air-type, hybrid, and solid-state types. Among these, SSCBs are the most widely adopted type of fast-acting dc protection equipment for building applications. Fig. 4 shows a schematic diagram of its typical structure.

SSCBs have advantages in LVDC systems. Their fundamental operating principle relies on leveraging the fast-switching characteristics of power electronic equipment to achieve circuit interruption and connection control [20], [44]. Unlike traditional mechanical DCCBs, which rely on the principle of establishing and then extinguishing an arc, SSCBs offer higher reliability and a longer operational lifespan due to the absence of mechanical contacts, thereby eliminating wear issues. More importantly, their fast switching capability effectively mitigates the impact of fault currents on the system, consequently enhancing the operational efficiency and safety of the dc grid.

A SSCB primarily consists of two core components: a main power semiconductor switching unit and an energy absorption unit. The switching unit is the heart of the SSCB, built with power semiconductor devices to perform the current interruption. The energy absorption unit complements this by absorbing and dissipating the energy stored in the external circuit during the interruption process, thereby constraining the voltage stress experienced by the power electronic devices at turn-OFF.

The selection of the power semiconductor device for the switching unit is critical and involves several trade-offs. These devices, which can complete switching actions within microseconds or even hundreds of nanoseconds [45], [46], are typically fully controlled devices such as IGBTs, MOSFETs, and IGCTs. However, as most SSCBs primarily rely on these fully controlled devices, they generally incur high manufacturing costs.

Thyristors, offering both cost-effectiveness and high surge current withstand capability, are considered a viable alternative; however, the challenge of achieving reliable turn-OFF due to their semicontrolled nature must be overcome [47], [48]. Existing literature [49], [50], [51] explores various thyristor-based SSCB topologies that employ carefully designed commutation circuits to achieve forced turn-OFF, thereby enhancing their cost-effectiveness.

Furthermore, a general limitation of conventional silicon-based SSCBs is their relatively high on-state losses, which constrain their thermal performance [52]. To address this, WBG semiconductor devices, primarily SiC and GaN, offer a promising solution. Their inherent advantages, such as high-temperature tolerance and lower losses, can effectively mitigate the thermal performance limitations inherent in conventional SSCBs [53], [54], [55], [56].

Table II shows the key power electronic equipment and its characteristics.

III. COORDINATED CONTROL

DC power distribution systems in low-carbon buildings comprising PV generation, ESS, and flexible loads; consequently, coordinated control strategies developed for dc microgrids are applicable. Key challenges associated with these converter-dominated systems include stability issues, a fast dynamic response, high susceptibility to load disturbances, and inherent uncertainties [57], [58], [59]. Coordinated control strategies are designed to address these challenges, ensuring stable operation and enhancing the system's low-carbon performance.

Operational objectives for building dc distribution systems include:

TABLE II
KEY POWER ELECTRONIC EQUIPMENT FOR BUILDING DC DISTRIBUTION SYSTEMS

Equipment	Topology	Function	Technical feature
PV converters [22], [23]	Unidirectional dc–dc converter (nonisolated), e.g., Boost, Cascaded Boost	Interface PV array to dc bus, performing MPPT and voltage step-up	• MPPT • High voltage gain • Device stress optimization
ESS converters [24], [25]	Bidirectional dc–dc converter (nonisolated/isolated), e.g., Buck-Boost, DAB	Interface energy storage unit with dc bus, managing bidirectional energy flow	• Bidirectional power flow control • Charge/discharge management
DC Load Converters [28], [29]	Unidirectional dc–dc converter (nonisolated), e.g., Buck-Boost/FSBB	Provide regulated voltage/current supply to dc loads	• Precise output regulation • High efficiency
BICs [30]	Bidirectional dc–dc converter (isolated), e.g., DAB, LLC	Interconnect dc buses of different voltage levels, enabling bidirectional power transfer and voltage adaptation	• Bidirectional power flow control • Voltage/current regulation • Coordinated control among multiple units
IBPFCs [31], [32], [33]	Bidirectional dc–dc converter (Nonisolated/isolated), e.g., DAB, DHB	Interconnect multiple building dc systems for interbuilding energy optimization and scheduling	• Bidirectional power flow control • High efficiency
BGCCs [36], [37]	Bidirectional ac–dc converter (isolated/nonisolated), e.g., 2L-VSC, 3L-NPC, MMC	Interface dc bus with ac grid for bidirectional power exchange and grid ancillary services	• Low harmonic distortion • Fault ride-through capability • Overload capability
AC Load Converters	Unidirectional ac–dc converter (nonisolated), e.g., Full-Bridge	Supply power to ac loads	• Low output harmonics
DCCBs [20], [44], [45], [46]	Air/Hybrid/Solid-State	Fast fault current interruption, protection, and system reconfiguration	• High interruption speed • Thermal management • Economic improvement • Bidirectional breaking capability

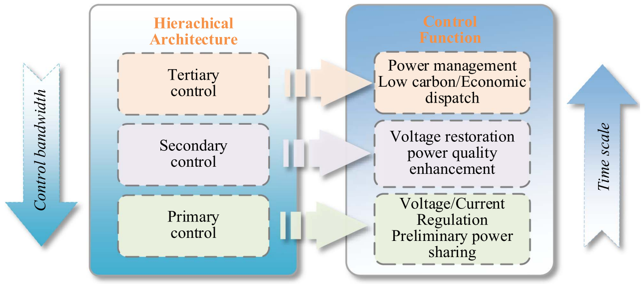

Fig. 5. Hierarchical control architecture.

1) achieving effective voltage support and power allocation under various operating modes;
2) maximizing the local utilization of PV generation through effective energy management strategies, thereby realizing economic benefits and low-carbon operation.

To achieve the aforementioned operational objectives, a hierarchical control architecture is often employed. This architecture enhances system robustness and reliability by introducing functional independence among different control levels, allowing the system to maintain basic operation even if certain communication or control units fail. A typical hierarchical control architecture is illustrated in Fig. 5 [16].

The primary control is responsible for the initial power allocation; the secondary control aims to compensate for voltage deviations resulting from the primary control and to improve power quality; while the tertiary control focuses on optimizing system energy management, achieving low-carbon objectives, and performing economic dispatch [60], [61], [62], [63]. The time scales of these control levels progressively increase from primary to tertiary control.

A. Primary Control

In building dc distribution systems, the primary control directly actuates the power electronic converters responsible for energy conversion between sources and loads. Its core objective is to achieve rapid power response and initial power allocation within very short time scales. Primary control typically comprises fast inner control loops and a droop control loop. A typical structure is depicted in Fig. 6.

Droop control enhances reliability as it facilitates autonomous closed-loop operation using solely local measurements. In low-voltage distribution systems characterized by predominantly resistive line impedance (a category that includes all dc networks and most ac microgrids), active power flow is strongly coupled with voltage magnitude. Leveraging this physical principle, establishing an active power-voltage (P-V) droop characteristic serves as a robust method for achieving autonomous power sharing. That is, power sharing among units is achieved by adjusting the local dc voltage, which indirectly controls the power output.

1) Conventional Linear Droop Control: Fig. 7 shows the linear droop control characteristics of a two-unit parallel system. Under this strategy, each unit utilizes local measurements to achieve dc bus voltage regulation and preliminary power sharing. This approach enables the system to adapt to dynamic source and load variations without relying on communication links.

Conventional linear droop control in dc distribution systems is generally categorized into two main types: current/power-mode

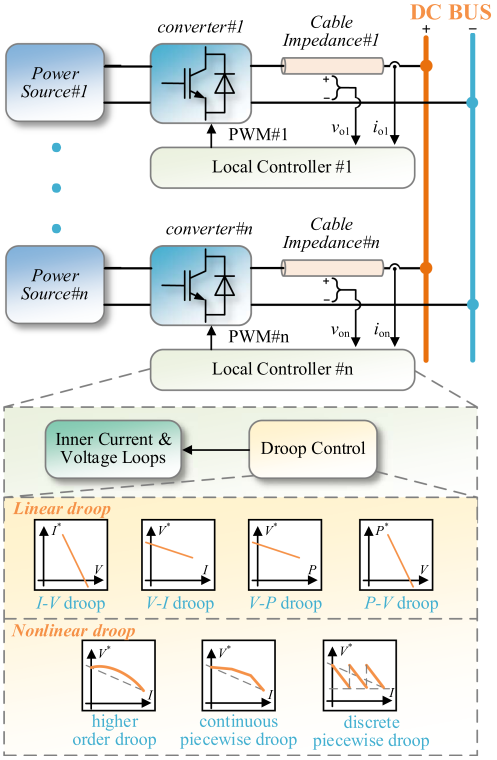

Fig. 6. Block diagram of the primary control structure.

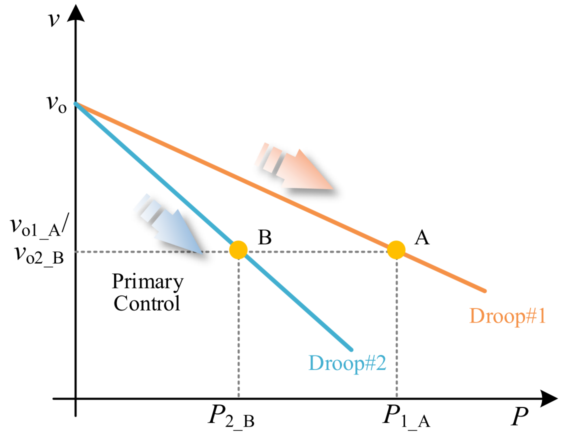

Fig. 7. Droop control characteristics for parallel operation.

droop and voltage-mode droop. The former comprises current-voltage (*I-V*) and power-voltage (*P-V*) droop strategies, while the latter includes voltage-current (*V-I*) and voltage-power (*V-P*) droop strategies [64].

Current-mode droop (e.g., *I-V* or *P-V* strategies) utilizes the locally measured dc voltage to compute the desired injected dc current reference. This current reference is calculated based on a predefined current-voltage (*I-V*) droop characteristic and the real-time measured dc voltage value.

$$I_{dc}^{*} = \frac{V_o - V_{dc}}{k} \tag{1}$$

where V_o is the nominal dc bus voltage, V_{dc} is the measured dc voltage, $I_{dc}{}^{*}$ is the calculated dc current reference, and k is the droop gain.

Voltage-mode droop (e.g., *V-I* or *V-P* strategies), conversely, employs a voltage-current (*V-I*) droop characteristic. It utilizes the measured dc output current of the unit to generate the corresponding terminal voltage reference.

$$V_{dc}^{*} = V_o - kI_{dc} \tag{2}$$

where V_o is the nominal dc bus voltage, k is the droop gain, I_{dc} is the measured dc current, and $V_{dc}{}^{*}$ is the calculated dc voltage reference.

Although conventional linear droop control is widely used in dc microgrids due to its simplicity, communication-less nature, and plug-and-play capability, it has several inherent limitations that have spurred the research into more advanced control strategies.

1) A trade-off between power sharing accuracy and voltage regulation: Linear droop control involves an inherent compromise. Under heavy load conditions, achieving accurate power sharing requires a large droop coefficient, but this leads to a significant steady-state voltage deviation. Conversely, under light load conditions, maintaining precise voltage regulation requires a small droop coefficient, which in turn sacrifices power sharing accuracy.
2) Limited dynamic response performance: Faced with the inherent randomness and volatility of photovoltaic generation and building loads, the transient response of conventional linear droop control is slow. When abrupt changes in load or power sources occur, the system may experience a long regulation time, which is not conducive to achieving a rapid dynamic balance between sources and loads.

2) Improved Droop Control Strategies: To overcome the inherent limitations of the conventional linear droop control methods previously discussed, researchers have developed enhanced droop control strategies. Nonlinear droop control represents a key approach among these advancements, aiming to significantly improve the overall system performance in terms of voltage regulation precision, power sharing accuracy, and voltage deviation mitigation. The advantages of nonlinear droop control include [65]:

1) improved power sharing accuracy under heavy load conditions;
2) more precise voltage regulation under light load conditions;
3) reduced steady-state voltage deviations.

Nonlinear droop control can be broadly classified into two main categories: high-order droop and piecewise linear droop. The latter can be further subdivided into continuous piecewise and discrete piecewise droop strategies. Chen et al. [65] comprehensively investigated the design of nonlinear droop control in dc distribution systems, specifically evaluating its performance concerning power sharing, voltage regulation, system efficiency, and stability. Furthermore, it proposed a generalized polynomial expression to unify various droop equations. Zhao et al. [66] proposed a decentralized adaptive discrete piecewise droop control strategy. This strategy enables effective approximation of continuous command regulation using discrete steps and can robustly handle variations in system parameters and complex load characteristics. Zhang et al. [67] simplified the control structure for *I-V* droop control by eliminating the need for an outer PI controller, thereby achieving faster bus voltage transient response. Yang et al. [68] introduced an improved nonlinear droop control strategy. This strategy utilizes the difference between the square of the nominal voltage and the square of the actual dc voltage as the input to the droop controller. Li et al. [69] proposed a V^2-P control method. This approach integrates bus voltage regulation and power sharing functions within a single control structure, achieving smooth transitions and stable regulation across various operating modes.

While prior research on nonlinear droop control has made progress in improving power sharing accuracy and reducing voltage deviations, addressing the inherent randomness and volatility of PV generation and building loads within low-carbon building dc systems underscores the importance of developing droop control strategies with faster transient response. Such strategies are crucial for facilitating rapid dynamic balance between sources and loads, particularly in systems integrating substantial PV capacity, thereby enhancing overall system stability.

3) Optimization and Improvement of Droop Parameters: Conventional droop control faces an inherent trade-off between power sharing accuracy and bus voltage deviation: increasing the droop gain improves power sharing accuracy but simultaneously leads to larger bus voltage deviations. Given the critical impact of the droop gain on both power sharing accuracy and bus voltage deviation, its optimization has become a significant research focus.

Adaptive droop control methods dynamically adjust the droop gain to maintain both the dc voltage deviation and the unit loading level within predefined safe limits [70], [71]. Specifically for ESS in low-carbon building dc systems, Lu et al. [72] proposed an adaptive droop strategy where the droop gain is proportional to the *n*th power of the ESS unit's SoC, aiming to balance the SoC levels among different ESS units. Khorsandi et al. [73], furthermore, considered the impact of SoC variations during ESS charging/discharging cycles and the effect of line resistances, proposing a stage-wise adaptive design method for the droop gain.

The control objectives of droop control regarding power sharing accuracy and voltage regulation are inherently conflicting, presenting a multiobjective optimization challenge. With the significant advancements in computational power and the continuous development and optimization of algorithms, AI offers promising avenues for optimizing droop gain design, potentially simplifying the design process. Among AI-based optimization methods for droop gain, metaheuristic algorithms and machine learning techniques have garnered considerable attention and application. For instance, the authors in [74] and [75] considered factors such as load conditions and line impedances, employing PSO techniques to determine the optimal droop gain design. Hussaini et al. [76] proposed an optimal droop gain design method based on ANN, which is claimed to feature advantages such as low implementation complexity, good real-time control performance, and reduced computational burden.

AI techniques can enable adaptive tuning of the droop gain under various operating conditions and respond in real-time to changing system conditions, thereby enhancing the control system's dynamic performance [77], [78]. Consequently, these techniques are particularly suitable for low-carbon building dc systems characterized by frequent fluctuations in power generation and load demand.

TABLE III
DC SYSTEMS ALLOWED CABLE VOLTAGE DROP

Nominal Voltage/V	Allowed Cable Voltage Drop ΔU $\Delta U\%=1.4\%/\mathrm{V}$
350	±5
700	±10
1400	±20

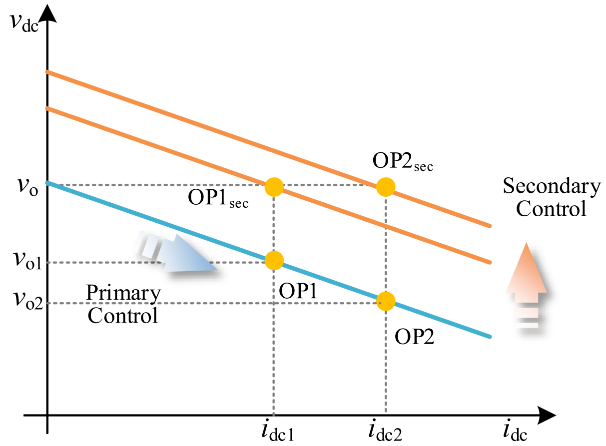

Fig. 8. Principle of voltage restoration via secondary control.

B. Secondary Control

Due to the influence of line impedance, primary control inevitably introduces bus voltage deviations. Considering critical factors such as the efficiency of the dc distribution system, grounding scheme design, and user power quality, the technical report IEC TR 63282:2024 specifies the permissible line voltage drops for specific voltage levels in dc distribution systems [79], as detailed in Table III.

To maintain the bus voltage near its nominal value and compensate for the voltage deviations introduced by primary control, implementing secondary control is necessary. Secondary control operates hierarchically above the primary control layer, regulating its output [57], [80]. Fig. 8 shows the fundamental principle of secondary control.

Under primary control alone, a load current i_{dc1} causes the bus voltage to drop from the nominal value v_{o} to v_{o1} (operating point OP1). If the load increases to i_{dc2}, the voltage further decreases to v_{o2} (operating point OP2). With the introduction of secondary control, the operating point is shifted from OP1 to OP1$_{\mathrm{sec}}$ and from OP2 to OP2$_{\mathrm{sec}}$ by adjusting the reference of the primary controller. This action restores and maintains the dc

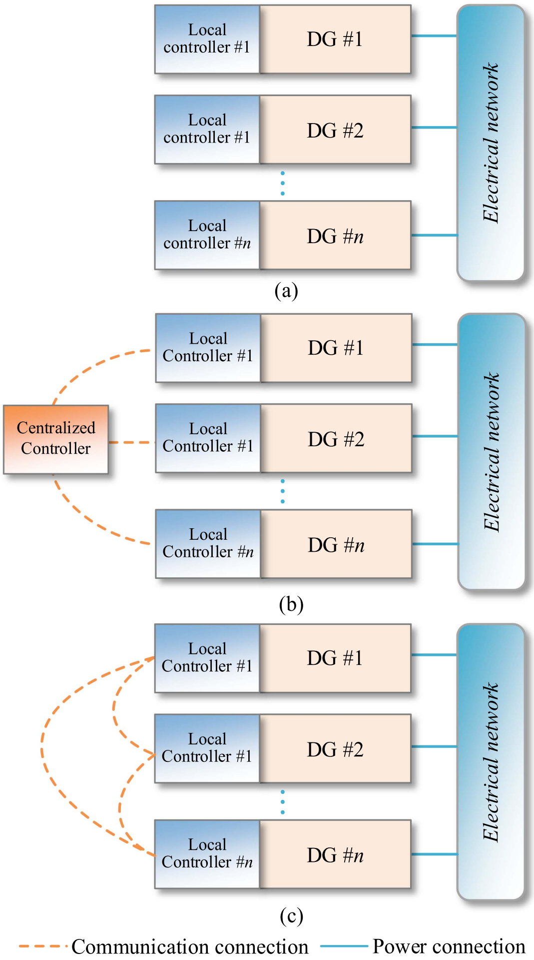

Fig. 9. Classification of secondary control. (a) Decentralized control. (b) Centralized control. (c) Distributed control.

bus voltage at its nominal value v_o [16]. Based on the underlying communication architecture, secondary control strategies can be classified into three main types: centralized, distributed, and decentralized [81], [82], as shown in Fig. 9.

1) Decentralized Control: To overcome the challenges of cost, reliability, and scalability associated with communication networks, advanced communication-less control algorithms have become a significant research direction in the field of dc microgrids. These algorithms primarily rely on local measurements, using innovative control strategies to achieve secondary control objectives such as voltage restoration and accurate power sharing, which traditionally require communication.

One mainstream approach is the signal injection-based control strategy, which utilizes the power line as an inherent channel to broadcast global control information. For instance, Kirakosyan et al. [83] propose a communication-free current sharing strategy where a pilot converter injects an ac signal with a frequency related to its own terminal voltage. Other converters detect this global frequency to estimate and share a common steady-state voltage feedback signal, thereby eliminating the impact of line impedance mismatches on current sharing accuracy. Zhao et al. [84] introduce an adaptive virtual resistance method to address the limitations of the traditional superimposed frequency droop method. The method uses a PI regulator to generate a virtual resistance term to adjust the voltage and resolves key issues such as limited loading capability, severe voltage drop, and large output current ripple.

Another important category is the local parameter self-adaptation strategy, which adjusts local controller parameters in response to system state changes to enhance control accuracy and performance. Montegiglio et al. [85] present a decentralized power and voltage regulation approach based on an auto-adaptive virtual resistance. It formulates the control as a multiobjective optimization problem solved using Lyapunov theory, allowing each converter to dynamically adjust its droop slope to not only track specific power setpoints but also cooperatively constrain the bus voltage within a predefined range. For PV-ESS hybrid microgrids, Li and Ho [86] propose a decentralized coordination control that decouples the ESS controller into high-pass and low-pass paths. Even when the BES is saturated in steady-state, the HPF path can still provide transient dynamic compensation, which significantly improves voltage regulation and dynamic response in PV-dominated operating modes. Gao et al. [87] propose a communication-less decentralized voltage compensation method, which adjusts the reference voltage based on locally measured load current. This method permits the use of larger droop gain, enabling more accurate and faster dynamic load response. Sharma et al. [88] propose a decentralized secondary control method for meshed dc microgrid topologies based on k-partite graphs. This method utilizes a dynamic voltage compensation mechanism to overcome the adverse effects of cable resistance on current sharing accuracy.

2) Centralized Control: In a centralized control architecture, each local controller is connected via communication links to a central controller. This central controller gathers system-wide information, computes unified control commands, and dispatches them to the respective local controllers for execution. Targeting islanded microgrid applications, Mehdi et al. [89] proposed a centralized control method that considers communication network delays, demonstrating good voltage stability. For rural dc microgrids, Samende et al. [90] introduced a centralized control algorithm based on two-stage convex optimization aimed at reducing line losses and battery losses. Liu et al. [91] proposed a voltage regulation strategy that coordinates centralized optimal control with local adaptive droop control. This strategy improves voltage quality by combining global optimization of VSC reference power with local adaptive droop adjustments. Centralized control strategies enable synchronous information exchange, offering high controllability and ease of implementation. However, their strong dependence on reliable communication networks introduces challenges such as single-point-of-failure vulnerability and communication bandwidth constraints.

3) Distributed Control: Distributed control architectures dispense with a central controller, relying instead on peer-to-peer information exchange between neighboring local controllers via communication links. By effectively avoiding single-point-of-failure vulnerabilities, this architecture offers significant advantages in enhancing system reliability and has thus gained widespread application [92]. Based on their core operating principles, distributed control strategies are mainly categorized into iterative algorithm-based and event-triggered approaches.

a) Iterative algorithm-based distributed control: Iterative algorithm-based distributed control enables controllers to iteratively estimate global information or reach a consensus, thereby facilitating coordinated regulation of key system variables. Consensus algorithms are a prominent class of iterative algorithms. Their objective is to drive the state variables of all agents in the network to converge to a common value. Based on convergence characteristics, they can be further classified into types such as finite-time consensus and fixed-time consensus algorithms. Fan et al. [93] employed a consensus protocol to estimate the average voltage information across nodes, thereby achieving optimized power allocation among distributed generators under complex load conditions and enhancing overall system stability. Han et al. [94] proposed a flexible distributed control strategy to achieve a balance between accurate current sharing and voltage restoration. It includes a voltage controller with constraint handling capabilities and a consensus-based current controller. By incorporating the deviation between local voltage and voltage limits into the secondary voltage error term, the voltage can be constrained within a predefined range, rather than merely being restored to the average value. Zeng et al. [95] introduced an improved distributed secondary control strategy for dc shipboard microgrids. Utilizing interneighbor communication and consensus protocols, this strategy simultaneously achieves dynamic balancing of battery SoC, accurate current sharing, and bus voltage restoration.

Compared to consensus algorithms, diffusion algorithms generally offer faster convergence rates and lower Mean Squared Error. They can also effectively track time-varying optimization targets [96], which has led to their widespread attention in recent years. Addressing current sharing and voltage regulation in microgrids, Liao et al. [97] proposed a distributed secondary control scheme based on the DDA. Comparative analysis against consensus and other diffusion algorithms highlighted the superiority of DDA. The study also investigated the impact of communication and control parameters on system stability. Zhang et al. [98] introduced a dynamic diffusion algorithm designed to enhance system dynamic response and stability. A discrete model of the overall system was developed, and the algorithm's effectiveness was validated through laboratory experiments. Liao et al. [99] proposed a secondary control strategy based on the DDA, achieving voltage restoration and accurate current sharing in dc microgrids.

b) Event-triggered distributed control: In contrast to traditional time-triggered mechanisms, event-triggered mechanisms initiate control or communication tasks only when the system state satisfies predefined "event conditions." Event-triggered control can significantly reduce unnecessary communication instances and computational load, thereby lowering communication bandwidth usage and computational resource consumption. Furthermore, it enables faster responses to critical events. Alavi et al. [100] proposed a distributed event-triggered control and state estimation strategy. Combining an improved Kalman Consensus Filter, this strategy aims to achieve voltage stability and energy storage state balancing in dc microgrids. By optimizing the communication mechanism, it effectively reduces network traffic and sensor energy consumption. Addressing the power coupling issue in multibus dc microgrids, Wang et al. [101] proposed a distributed dynamic edge-event-triggered current sharing control strategy. By employing adaptive coupling weights to eliminate reliance on communication and integrating a dynamic edge-triggering mechanism to reduce bandwidth demand and controller update frequency, this strategy is effective in reducing communication burden and enhancing local utilization of renewable energy. For single-bus dc microgrids, Xing et al. [102] introduced an event-triggered distributed secondary control strategy. Utilizing a local autonomous communication decision-making mechanism, it achieves current sharing and bus voltage regulation while significantly reducing interconverter communication overhead. Compatible with both linear and nonlinear mixed loads, its primary advantage lies in low communication costs. Wan et al. [103] proposed a secure consensus control strategy resilient to denial-of-service attacks. This strategy simultaneously achieves bus voltage regulation, multisource current sharing, and energy storage SoC balancing in dc microgrids, while featuring the advantage of low communication resource utilization. Lu et al. [104] introduced an edge-event-triggered distributed control strategy. Employing a novel sampling and triggering mechanism to withstand denial-of-service attacks, this strategy simultaneously achieves bus voltage restoration and accurate current sharing in dc microgrids. Its key advantages include low communication resource consumption and effective resilience against attacks.

In summary, event-triggered distributed control, through optimized communication strategies, effectively reduces communication bandwidth requirements and resource consumption. Concurrently, this mechanism enhances the system's responsiveness and robustness when facing abrupt events such as cyberattacks.

c) Applications in buildings: Due to the unique characteristics of sources, ESS, and loads within building dc distribution systems, such as TCLs and diverse reliability requirements for different loads, distributed control strategies can and should be tailored to leverage these features for effective coordination of controllable resources. Research has begun to address this specific application context. Guo et al. [105] applied distributed secondary control strategies to clusters of dc microgrids. Employing finite-time control methods, it achieved intracluster voltage restoration and power sharing without requiring intercluster communication. The study reports superior transient and steady-state performance compared to decentralized control, and enhanced robustness compared to conventional distributed approaches. Wang et al. [106] proposed a distributed control strategy tailored for building dc systems. This strategy employs a linear quadratic regulator to optimize control gains and coordinates TCLs to mitigate fluctuations from PV generation and energy storage. Its multiple objectives include ensuring user comfort, achieving fair power allocation, and simultaneously providing ancillary services to the grid.

C. Tertiary Control

Tertiary control focuses on promoting the low-carbon operation of buildings through advanced energy management strategies. EMS in low-carbon buildings integrates energy

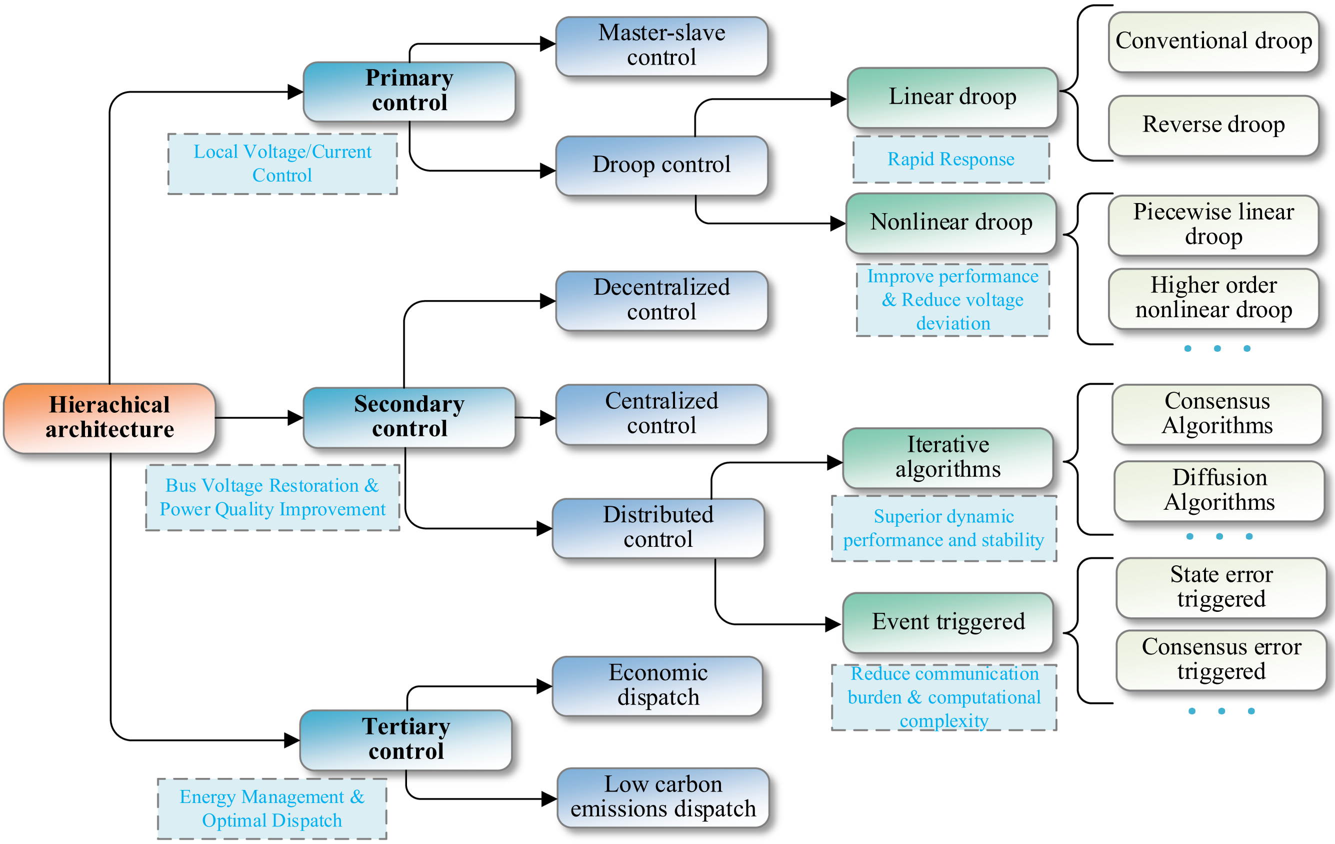

Fig. 10. Classification of hierarchical control in DC distribution systems.

consumption data from building loads and considers factors such as distributed energy resource (DER) characteristics and electricity pricing mechanisms. They aim to optimize operational costs, energy efficiency, and carbon emissions through dynamic load scheduling. These systems typically employ various optimization algorithms to generate optimal load operation schedules.

Yu et al. [107] comprehensively analyzed the core challenges facing EMS in low-carbon buildings, including: the trade-off between model accuracy and computational efficiency, dynamic uncertainties, multiscale spatio-temporal coupling constraints, bottlenecks in large-scale real-time optimization computation, and lack of scenario generalizability. It suggests that data-driven deep reinforcement learning techniques offer a feasible pathway toward achieving adaptive and scalable low-carbon energy regulation. Gao et al. [108] proposed a building energy management system integrating iterative algorithms and Internet of Things technology. This system aims to minimize the mismatch between PV generation and actual building energy consumption through the optimal scheduling of building loads, EV charging, and ESS, while simultaneously considering user comfort. Focusing on the operation of building HVAC systems under energy-constrained scenarios, Li et al. [109] proposed a priority-based distributed MPC strategy. It developed both one-to-one and many-to-one energy allocation mechanisms to meet the specific demands of HVAC systems in particular zones within the building. Rezaei and Dagdougui [110] introduced an energy optimization method based on MPC for multiunit residential buildings. This method effectively controls the heating, ventilation, and HVAC systems of each apartment, aiming to reduce the building's overall electricity costs and improve the alignment between PV generation and load demand. Du and Lu [111] proposed a transfer component analysis algorithm capable of automatically generating user-preference-aware operating schedules based on electricity price and energy consumption forecasts, catering to personalized cost-comfort trade-off requirements. Pallonetto et al. [112] utilized machine learning to construct building predictive models and subsequently developed demand response algorithms based on these models, reportedly achieving a 40% reduction in heating costs and a 39% decrease in carbon emissions. Hu et al. [113] combined load aggregation assessment with distributed control strategies to propose a load following algorithm that effectively enables TCLs to track the variable output of RESs. Hu et al. [114] developed both centralized load shedding and distributed load following control algorithms, implemented on a cloud platform, aimed at coordinating the power supply-demand balance within buildings. Kinhekar et al. [115] proposed a load shifting demand side management strategy based on an evolutionary genetic algorithm. Applied within a building dc microgrid integrating PV and storage, this strategy reportedly reduced the peak load by 19.65% compared to a conventional ac distribution baseline.

Overall, Fig. 10 shows the classification of hierarchical control in dc distribution systems.

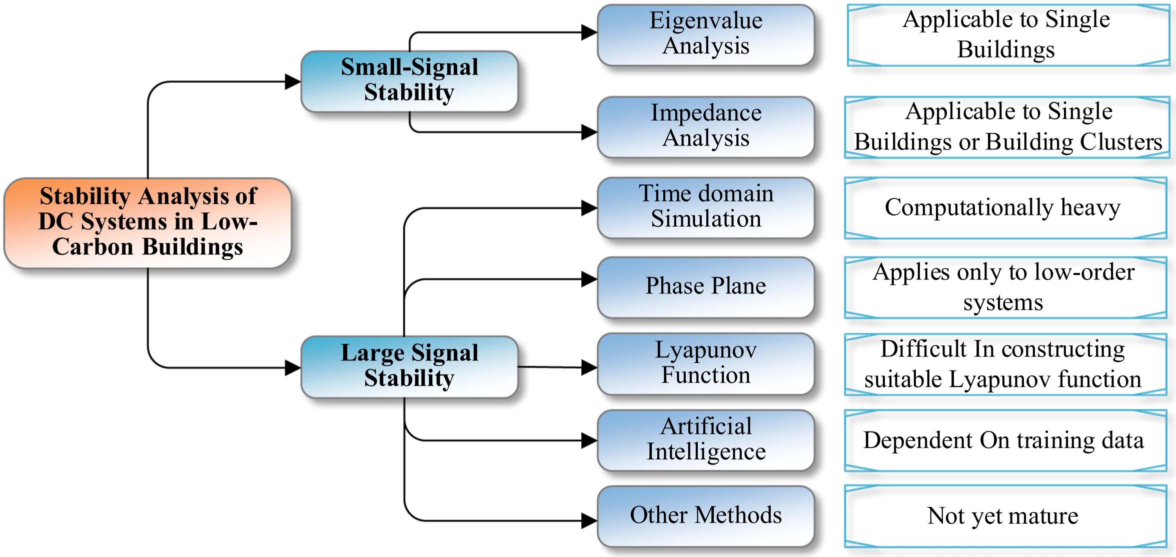

Fig. 11. Classification of stability analysis methods for low-carbon buildings.

IV. STABILITY ANALYSIS

DC power distribution systems in low-carbon buildings, functioning as localized power entities integrating DERs and ESS, exhibit key stability differences compared to large-scale power systems. These differences include a smaller system scale, high penetration of renewables, greater uncertainty, a significantly faster dynamic response, and limited short-circuit capacity [116].

The stability of low-carbon building power systems can be defined, in line with previous definitions for dc microgrids, as the ability of all states to return to a new steady state that satisfies operational constraints after experiencing a disturbance [117].

A. Classification of Stability

Based on the magnitude of the disturbance signal, stability analysis of dc distribution systems can be categorized into small-signal stability analysis and large-signal stability analysis [3], [17]. If the linearized equations adequately represent the system's behavior, the disturbance can be considered small [116]. In this context, small-signal stability analysis is applicable and is commonly used to evaluate potential instabilities and oscillations arising from interactions among power electronic devices. The mechanism of small signal instability mainly involves the interaction between the dynamic characteristics of the system and the control strategy, such as the design flaws of the control loop, the interaction of parallel converters, and the negative impedance effect of CPLs [118], etc.

If the linear equations do not adequately represent the system's behavior, the disturbance is considered large. In such cases, large-signal stability analysis is employed to determine the system's stability boundaries and analyze its transient behavior. Large disturbances include short circuits, transitions between grid-connected and islanded modes, and the loss of power sources [116]. Stability analysis methods of dc systems in low-carbon buildings are categorized in Fig. 11.

B. Small-Signal Stability Analysis

Small-signal stability analysis investigates the dynamic characteristics of a system around its steady-state operating point when subjected to disturbances. It focuses on instabilities and oscillations caused by the interactions of power electronic devices, which is a prerequisite for the safe operation of dc power distribution systems in low-carbon buildings. The underlying principle involves: establishing a mathematical model of the system and determining the steady-state operating point, applying small perturbations and linearizing the model to obtain a linear representation, and finally, analyzing the stability based on linear system theory. Small-signal stability analysis methods include eigenvalue analysis and impedance analysis.

1) Eigenvalue Analysis Method: Eigenvalue analysis of a small-signal model computes the eigenvalues of the system state matrix to assess system stability and identify the dominant oscillation mode. Furthermore, participation factor analysis can be conducted to identify the system parameters and control parameters that have the greatest impact on the stability of the system, and corresponding improvements can be taken to enhance the stability of the system. Yang et al. [119] have studied the influence of multisource multiload coupling interaction on the stable operation of dc microgrids. A detailed small-signal model of the dc microgrid, including three distributed power sources, was established. Then, the relationship between coupling parameters and stability margin was studied by using modal analysis and participation factor. When networking the dc power distribution system of large-scale low-carbon buildings, the stability issues stemming from interactions between different subsystems should also be taken into account. Yao et al. [120] established a small-signal model for a dc microgrid cluster considering multiple time delays, exploring the influence of coupling effects between subsystems on the stability of the entire system. This has significant practical implications for analyzing

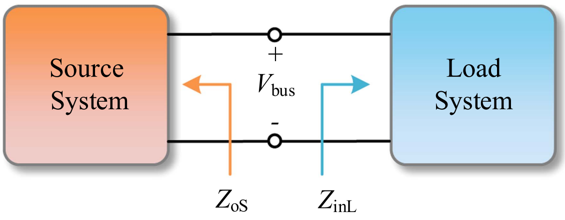

Fig. 12. Schematic diagram of system impedance partitioning for the system.

the stability of low-carbon building dc power distribution systems during integration and interaction.

Although widely used for small-signal stability analysis of dc systems, eigenvalue analysis is limited by the requirement for detailed models of each component and the dramatic increase in state-space dimensionality with increasing node numbers, potentially leading to the “curse of dimensionality” [121]. The complex structure of building clusters makes it difficult to build an overall model of the system. Furthermore, for the protection of trade secrets, equipment manufacturers will not provide detailed models and parameters of the equipment. The difficulty in obtaining these and the complexity of solving high-dimensional models restrict their application in large-scale low-carbon building dc power distribution systems.

2) Impedance Analysis Method: The impedance analysis method divides the system into source and load subsystems, as shown in Fig. 12. System stability is evaluated by calculating the ratio of the source output impedance (Z_{oS}) to the load input impedance (Z_{inL}) (Z_{oS}/Z_{inL}). This method focuses solely on external characteristics and does not require internal models or parameters. Based on the Nyquist stability criterion, several stability criteria have been proposed, such as the Middlebrook criterion [122] and its extensions: the GMPM criterion [123], the OAC criterion [124], the ESAC criterion [125], the RESC criterion [126], and the T-SI criterion [127], among others. These criteria establish forbidden regions for the minor loop gain (Z_{oS}/Z_{inL}) in the polar coordinate system, as illustrated in Fig. 13. If the Nyquist plot does not enter the forbidden region, the system is stable.

Sun [128] highlights that the impedance ratio representation differs between voltage-source and current-source systems: Z_{oS}/Z_{inL} for voltage-source converters and Z_{inL}/Z_{oS} for current-source converters. In low-carbon building dc power distribution systems, various source converters (such as grid interface converter, PV converter, and energy storage converter) can operate as either voltage or current sources under different control strategies. It is a very common operating state that the PV system under MPPT control serves as the current source while the ESS under droop control serves as the voltage source. In this case, the system comprises both types of converters, precluding the direct application of traditional impedance ratio criteria for stability analysis. To address this challenge, Zhang et al. [129] categorize converters into BVCC and BCCC, derive the minor loop gain, which is the ratio of the parallel impedance of the BVCC converter to that of the BCCC converter, and further apply the Nyquist stability criterion to resolve the inapplicability of traditional impedance ratio criteria.

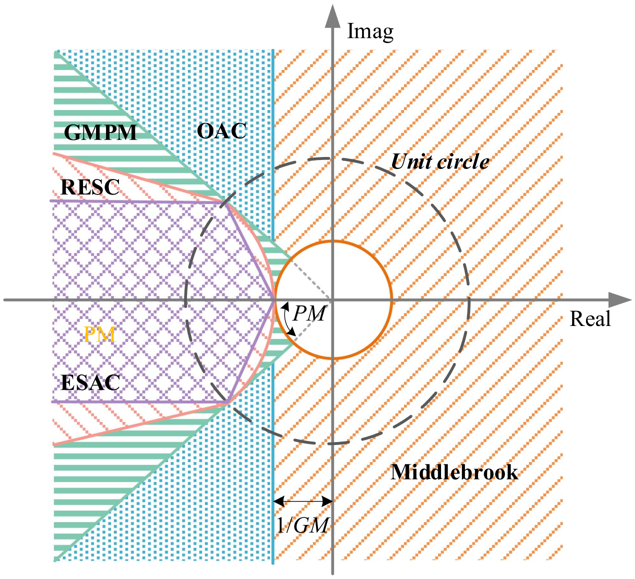

Fig. 13. Schematic diagram of the forbidden region for the impedance ratio criterion.

For these stability criteria, determining the type of converter is typically required to obtain the correct impedance ratio form. However, the impedance sum criteria proposed in [130] and [131] do not necessitate distinguishing converter types. Specifically, for a system comprising two converters or sources, the impedance sum criterion states that if the subsystems are individually stable and the system's impedance sum has no RHP zeros, the entire system is stable. Similarly, He et al. [132] introduced the BNIC, which, in the absence of line impedance, ensures system stability if the bus impedance lacks RHP poles. Another criterion that does not require distinguishing converter types is the PBSC [133]. If the passivity of the system is guaranteed, its stability is assured; however, this is only a sufficient condition for stability, meaning that a stable system is not necessarily passive. For dc distribution systems in low-carbon buildings, line impedance is often a non-negligible factor. Riccobono and Santi [133] derived the BNIC for a dc distribution system considering line impedance, demonstrating that the system is stable when the bus impedance at any node has no RHP poles. Zheng et al. [134] established a full-system impedance model for ac/dc hybrid systems. Based on the impedance participation factor theory, the stability of the system considering line impedance was analyzed, and the instability sources were located.

In the aforementioned stability criteria, it is necessary to determine the number of RHP poles in certain expressions. For instance, the criterion in [129] requires knowledge of the pole locations of the minor loop gain, while [131], [132], [133], and [134] assess whether the impedance possesses RHP poles. In practical dc distribution systems for low-carbon buildings, the available data typically consists of Bode plots of equipment impedances, either provided by manufacturers or measured directly. Liao and Wang [135] proposed a method to estimate the number of poles using Bode plots. However, in complex distribution systems with subsystems comprising multiple parallel converters, the presence of closely located RHP poles and zeros may render this method infeasible, necessitating a detailed analytical model to obtain pole-zero distribution information [136].

Based on the bus node impedance criterion [137], Jiang et al. [138] further investigated the total admittance at the point of common coupling and the individual admittances of each converter component, proposing a stable angle stability criterion. By defining the stable angle as the phase of impedance/admittance at the switching frequency, system stability is ensured if and only if the maximum stable angle of each admittance equals that of the total admittance, without requiring knowledge of the number of RHP poles in subsystems. However, this criterion assumes the existence of at least one stable subsystem with multiple parallel converters, necessitating subsystem stability assessment through the aforementioned impedance-based methods, which still require analytical modeling.

To enable stability assessment solely using Bode plots of equipment impedances, Zhang et al. [139] introduced a combined bus port impedance-based stability criterion. This criterion only requires evaluating whether the Bode phase plot of the combined bus port impedance, which can be derived from existing equipment Bode plots, crosses the phase $(2k \pm 1)\pi$, thereby determining system stability and the oscillation frequency at instability. He et al. [140] proposed a novel stability analysis method based on the determinant of a constructed immittance matrix. Since the RHP poles of the determinant are explicitly proven to be absent, stability analysis only involves determining the net number of times the phase trajectory crosses the ±180° line. Compared to Zhang et al. [139], this method is applicable to stability analysis of systems considering line impedance.

For the stability of multivoltage-level dc distribution systems, different voltage levels are interconnected through power electronic converters rather than transformers, as in ac systems, where these transformers are modeled as impedances during analysis. The dynamic characteristics of these interconnecting converters significantly influence the overall system stability.

Siegers et al. [141] utilized the PBSC proposed in [133] to assess the stability of multivoltage-level dc systems. To ensure stability margins and dynamic performance, the concept of an allowable impedance region was introduced based on the Nyquist contour of bus impedance. Pan et al. [142] derived the equivalent loop gain of a multivoltage-level dc system accurately using a two-port small-signal model of the converters. The loop gain expressions differ when the intermediate bus converter operates in output current or output voltage control modes. System stability criteria were then obtained by applying the Nyquist criterion to the equivalent loop gain. Mu et al. [143] evaluated system stability through the equivalent loop gain on one hand, while on the other, they treated the multivoltage-level dc system as a conventional single-bus dc distribution power system at different interface locations, deriving an impedance ratio-based stability criterion. It was demonstrated that both stability analysis methods-system equivalent loop gain at different interface locations and impedance ratio-based criteria-yield identical stability outcomes. He et al. [144] explored the relationship between the stability of a three-level cascaded dc system and its subsystems, concluding that the entire system may remain stable even if some subsystems are individually unstable. Additionally, a BEIC was proposed, stating that the necessary and sufficient condition for the stability of a three-level cascaded dc system is the absence of RHP zeros in the BEIC. Leng et al. [145] simplified the configuration of multibus dc microgrids using generalized voltage source, current source, and two-port models, deriving the impedance or admittance at each bus port. A stability criterion based on impedance was proposed using a generalized Bode plot for multibus dc microgrids.

It can be seen that the key to stability analysis in multivoltage-level dc systems lies in how to handle the dc transformers (or intermediate bus converter). The basic roadmap for developing stability criteria starts with standardizing dc transformer modeling: Use two-port small-signal models to capture the dynamics of the dc transformers. Then, line impedances are neglected or considered by integrating them as series elements in bus impedance calculations or two-port matrices, ensuring accurate representation of distributed effects and propagation of instabilities across levels. This leads to forming system-level models by aggregating subsystem models into impedance networks or equivalent loop gains (e.g., via matrix formulations or cascade connections), from which stability criteria (e.g., Nyquist-based loop gains or PBSC passivity conditions) can be derived.

However, based on the literature reviewed by the author, no stability criteria for multivoltage-level dc distribution systems have been identified that allow stability assessment solely using equipment Bode plots, as achieved in single-voltage-level systems in [138] and [139]. Furthermore, no stability criteria for multivoltage-level dc distribution systems that account for line impedance [133] have been found.

Table IV shows a comparison of impedance analysis methods.

C. *Large-Signal Stability Analysis*

Low-carbon building dc power distribution systems contain a large number of power electronic devices. Modeling these systems often involves structural nonlinearities due to the products of state variables, and nonlinearities introduced by control loop limitations, duty cycles, hysteresis, and time delays [146]. Considering only small-signal stability is insufficient to determine the boundaries of the stability region and cannot reflect the transient processes under faults, power source switching, and load disturbances [147], [148]. Therefore, in addition to small-signal analysis, large-signal analysis is necessary. Large-signal stability analysis methods mainly include: time-domain simulation, phase-plane methods, Lyapunov function-based methods, AI-based methods, and others.

1) Time-Domain Simulation Method: The time-domain simulation method obtains the time-varying trajectories of system state variables and algebraic variables by solving differential-algebraic equations. It is the most effective method for studying the stability of dc power distribution systems [149], [150], [151]. As a reliable assessment approach, it can analyze arbitrarily

TABLE IV
COMPARISON OF IMPEDANCE ANALYSIS METHODS

Criterion	Application scenario	Prerequisites
Traditional Impedance Ratio Criteria [123] ,[124], [125] ,[126] ,[127], [128]	Single-voltage-level system without considering line impedance	Classify converters; detailed impedance models
Minor Loop Gain Criterion[129]	Single-voltage-level system without considering line impedance	Classify converters; detailed impedance models
Impedance Sum Criterion[131], [132]	Single-voltage-level system without considering line impedance	Detailed impedance models
BNIC[133]	Single-voltage-level system with or without considering line impedance	Detailed impedance models
PBSC[133]	Single-voltage-level system without considering line impedance	System passivity (also require detailed impedance models)
Settling Angle Stability Criterion[137], [138]	Single-voltage-level system with considering line impedance	Stable parallel converter subsystem (also require detailed impedance models);
Combined Bus Port Impedance Criterion [139]	Single-voltage-level system without considering line impedance	Only equipment Bode plots
Immittance Matrix Determinant Criterion [140]	Single-voltage-level system with considering line impedance	Only equipment Bode plots
Multi-voltage-level criteria [141], [142], [143], [144], [145]	Multivoltage-level dc systems without considering line impedance	Detailed impedance models

TABLE V
COMPARISON OF LARGE-SIGNAL STABILITY ANALYSIS METHODS

Methods	Applicable System Order	Computational Complexity	Real-Time Capability	Stability Margin	Physical Interpretability
Time-Domain Simulation[149], [150], [151]	High-Order	High	Low	None	High
Phase-Plan Method[152], [153]	Low-Order	Low	Medium	Limited	Medium
Lyapunov Function Method [154], [157], [156], [158], [159], [160], [161]	High-Order	Medium to High	Medium	Available	High
AI methods[162], [163], [166], [167]	High-Order	Medium	High	Limited	Low to Medium
Bifurcation/Chaos Theory[152], [168]	Low-Order	High	Low	Limited	Medium
Nonlinear Decoupling[169]	High-Order	Medium	Medium	Limited	Medium

Explanation:
- *Applicable system order: High-order systems require more complex methods.*
- *Computational complexity: Affects the method's practicality.*
- *Real-time capability: Critical for online monitoring and control.*
- *Stability margin: Provides quantitative information on proximity to instability boundaries.*
- *Physical interpretability: Ability to reveal mechanisms of instability.*

complex models and control strategies and is often used as a benchmark for validating other large-signal analysis methods. However, its limitations include: slow numerical integration, and a dramatic increase in computational burden with the increasing order of state variables, making it difficult to meet the real-time requirements of online monitoring and control; it cannot provide stability margin information, nor can it reveal the underlying mechanisms of instability.

2) Phase-Plane Method: The phase-plane method is a graphical large-signal analysis technique that selects state variables and plots phase trajectories based on dynamic differential equations. Phase portraits are formed by phase trajectories corresponding to different initial conditions, and stability is judged by the direction of these trajectories. Tahim et al. [152] analyzed the stable boundary of a typical PV storage system by using the phase plane method. Potty et al. [153] constructed a phase trajectory model and found that a separatrix divides the stable and unstable regions. After introducing intelligent resistance compensation, phase trajectory analysis showed that the system was forced to move along a predefined resistance slope. Comparing clusters of phase trajectories under different control gains and droop coefficients confirmed the stability of the compensation measure across the entire phase plane. The phase-plane method is suitable for handling nonlinear elements such as limiters and hysteresis in controllers, but it is only applicable to simple, low-order systems. It is not suitable for complex, high-order systems like low-carbon building dc power distribution systems, which are difficult to reduce in order.

3) Lyapunov Function-Based Methods: The Lyapunov function is an important mathematical tool for analyzing the stability of dynamic systems, indirectly inferring the stability of equilibrium points through the properties of a scalar function. It must satisfy two conditions: positive definiteness (non-negative within a domain and zero only at the equilibrium point) and a decreasing property (its time derivative along system trajectories is nonpositive or negative definite). Applications include nonlinear system analysis, control law design, and system modeling. Constructing an appropriate Lyapunov function can verify asymptotic stability. It is important to note that this is a sufficient but not necessary condition for stability, and the construction lacks universality. Several Lyapunov function-based large-signal analysis methods are used for transient analysis of dc microgrids, mainly including the Lyapunov direct method [154], [155], mixed potential function method [156], [157], T-S fuzzy model method [158], sum of squares theory [159], Hamiltonian theory [160], and Koopman operator theory [161].

The Lyapunov direct method is the theoretical foundation for large-signal analysis of nonlinear systems, directly determining the global stability of the system through the Lyapunov function and its derivative. Xie et al. [154] analyze in detail the dynamic characteristics of the ac–dc hybrid power system under large disturbances, and determine the analytical estimation of the stable boundary of the system's large signals by using the Lyapunov stability theorem. The mixed potential function is essentially a Lyapunov function, suitable for analyzing nonlinear circuits containing negative impedance components, but the resulting stability boundary is conservative. Jiang et al. [157] developed a transient response model for the input side of load converters, modified the response term of load current to bus voltage in the mixed potential function, and derived an analytical criterion containing circuit and control parameters. This eliminated conservative regions, making the stability boundary highly consistent with simulations and experimental measurements, thereby improving accuracy. Wu et al. [156] proposed a region-of-attraction estimation method based on the Brayton-Moser mixed potential function, which requires less computation and reduces the difficulty of estimating the region of attraction for complex dc microgrids. The T-S fuzzy model method approximates a nonlinear model using a combination of linearized models and judges stability based on Lyapunov theory, proposing a method for finding Lyapunov functions to obtain analytical stability boundaries. Ding et al. [158] investigated the influence of inner-loop current controllers on transient stability through T-S fuzzy, revealing that neglecting the current controller can reduce estimation accuracy. Hamiltonian surfaces are a special type of Lyapunov function that can capture large-signal effects and predict system behavior over a wider time scale. Song et al. [159] proposed a method based on Lyapunov stability theory and sum of squares programming technology to analyze the large-signal stability of a two-stage cascade dc–dc converter system. This method can obtain the maximum stable boundary of the system under large disturbances, and can also analyze the influence of system parameters on the stable region and identify the dominant parameters. Tian et al. [160] analogized a PLL to a synchronous generator and constructed a Hamiltonian energy function for inverters with PLLs under weak grid conditions, simplifying the analysis and reducing conservatism. Zheng et al. [161] proposed a method for estimating the transient stability of power systems based on the Koopman operator, using Koopman eigenfunctions to construct the Lyapunov function, simplifying the process. However, due to the diverse characteristics of nonlinear systems, a unified method for constructing Lyapunov functions is still lacking. If the constructed function does not meet the theoretical conditions, it still cannot be concluded that the system is unstable due to the conservativeness of this approach.

4) Artificial Intelligence Method: Based on vast amounts of data, AI methods rooted in data mining offer the potential to balance real-time performance and accuracy in large-signal analysis. The approach involves: constructing a large-signal assessment model, training it offline with preprocessed sample data to obtain an optimal model, and finally, using measurement units to acquire real-time system data, which is preprocessed and input into the trained model for online assessment. The authors in [162] and [163] introduced deep learning into power system transient stability assessment (i.e., large-signal assessment), enhancing the speed and accuracy of the evaluation. However, the model's accuracy is dependent on the training data. If the measured data deviates from the training data (due to noise interference or information loss), the accuracy of the results decreases, and performance deteriorates. Furthermore, this method cannot reveal the underlying mechanisms of instability. If the system changes, retraining is required, which demands substantial computational resources.

Physics-Informed AI represents an emerging approach that integrates data-driven machine learning with the physical laws governing systems, ensuring that models are not only accurate but also physically meaningful [164]. This approach is particularly reliable in stability analysis. For instance, PINNs [165] have been employed to directly learn Lyapunov functions from system data while adhering to physical constraints, thereby efficiently estimating domains of attraction and stability boundaries. Huang et al. [166] proposed a neural network-based method for learning Lyapunov functions to assess transient stability. For microgrids interfaced with voltage source converters, Mishra and Zhang [167] developed a physics-informed Lyapunov function framework for stability evaluation. Compared to purely data-driven stability analysis, physics-informed AI offers significant potential in enhancing model robustness and interpretability. However, further research is needed to explore its integration with traditional methods.

5) Other Methods: Other large-signal stability analysis methods include bifurcation/chaos theory [152], [168] and nonlinear decoupling methods based on coupling factors [169]. Bifurcation/chaos theory requires a precise discrete mathematical model to obtain stability analysis results, and the analysis process is complex with an extremely large computational burden, making it suitable only for low-order systems. The nonlinear decoupling method based on coupling factors draws inspiration from decoupling concepts, approximately transforming the original high-order nonlinear system into a series of decoupled first-order quadratic and second-order quadratic subsystems. Then, the large-signal stability of these low-order quadratic nonlinear subsystems is analyzed, thereby indirectly reflecting the large-signal stability of the original system. While this method addresses the high-dimensionality challenge of the system, it lacks rigorous mathematical proof, and its effectiveness requires further research and validation.

Large-signal stability analysis of dc microgrids is critical for ensuring their safe operation. Time-domain simulation provides detailed transient information but incurs a high computational burden; phase-plane analysis is intuitive but limited to low-order systems; the Lyapunov function method is theoretically rigorous but challenging to construct; AI-based methods are fast and efficient, with physics-informed AI further enhancing reliability; other approaches, such as bifurcation theory and decoupling methods, show potential in specific scenarios but require further validation. By comparing these methods and integrating insights from recent research, a more comprehensive framework for stability analysis of dc microgrids can be developed.

Table V shows a comparison of large signal stability analysis methods.

V. CONCLUSION

A. Conclusion

This review provides a systematic overview and analysis of the key equipment, coordinated control strategies, and stability analysis techniques pertinent to low-carbon building dc distribution systems. It focuses on the interplay among these elements, their respective recent advancements, and classification. The main contributions of this article can be summarized as follows.

1) *Review of key equipment:* A comprehensive review of the classification and research progress concerning power electronic converters and DCCBs within low-carbon building dc distribution systems is presented. The core functions, typical topological types, and performance requirements of converters in building applications are summarized. The fundamental building blocks of SSCBs are outlined. Furthermore, the selection criteria for their core power semiconductor devices are analyzed from three critical perspectives: cost-effectiveness, thermal management, and interruption speed.
2) *Review of coordinated control:* Recent advancements in coordinated control strategies for building dc distribution systems are reviewed, presented within a hierarchical classification. Primary Control: Developments are examined from two angles: improvements in control principles, such as nonlinear droop control, and advancements in parameter optimization, including AI-based adaptive tuning of droop parameters. Secondary Control: Progress in both centralized and distributed control architectures is outlined. Furthermore, the latest achievements in distributed coordination techniques, particularly those employing iterative algorithms and event-triggered mechanisms, are analyzed. Tertiary Control: System-level optimization scheduling algorithms, designed to achieve carbon emission reduction and enhance economic efficiency for the overall building dc system, are summarized.
3) *Review of stability analysis:* The stability analysis section systematically reviews stability analysis methods, categorizing them into small-signal and large-signal approaches. Small-signal stability, evaluated via eigenvalue and impedance-based criteria, addresses oscillations and interactions among power electronic devices, yet faces dimensionality and parameter acquisition challenges. Large-signal methods, such as time-domain simulation, Lyapunov theory, and AI-driven techniques, assess transient behaviors but vary in computational efficiency and interpretability. Comparative analyses highlight gaps in multivoltage-level system criteria considering line impedance. The review underscores the need for unified, scalable stability frameworks to enhance applicability in complex, evolving low-carbon buildings.

B. Future Trends

1) Efficiency, power density, and cost are critical indicators for evaluating power electronic equipment. WBG semiconductors, SiC, and GaN offer distinct advantages, including high switching frequencies, low on-state resistance, and superior high-temperature operational capabilities. Consequently, they hold potential for enabling higher efficiency and power density in power electronic equipment within low-carbon buildings. Simultaneously, cost-effectiveness remains a critical consideration. Thus, a deliberate trade-off between performance and economic viability is essential during component selection and technology roadmap decisions.
2) At the primary control layer, research into high-bandwidth control strategies is imperative to enhance the system's dynamic response under complex operating conditions, particularly those involving the composite and frequent fluctuations of power sources and loads inherent in low-carbon buildings. At the secondary control layer, communication challenges remain a significant focal point. Consequently, investigating methods to effectively enhance system power quality with minimal communication overhead, or potentially through communication-less approaches, represents a critical research direction. Within the tertiary energy management layer, enhancing the real-time performance and effectiveness of energy balancing control strategies is urgently required. Furthermore, coordinated control strategies leveraging AI offer adaptive regulation capabilities, presenting promising application prospects within building energy systems.
3) Despite significant progress, enhancing the practical applicability of stability analysis for low-carbon building dc systems remains crucial. Future research should prioritize three key areas. First, developing simplified yet precise high-dimensional models is essential to mitigate the "curse of dimensionality," improve scalability for large systems, and reduce computational complexity without sacrificing accuracy for practical engineering applications. Second, establishing unified stability criteria, particularly for multivoltage level systems, is needed. These criteria should utilize readily accessible data, such as equipment Bode plots, incorporate line impedance effects, and streamline assessment, thus minimizing reliance on detailed models

and improving analytical efficiency. Third, advancing AI-driven analysis, exploring methods like physics-informed neural networks, holds promise. Integrating AI with traditional physics-based approaches (e.g., impedance analysis, Lyapunov methods) can yield a robust and comprehensive framework that balances accuracy, real-time performance, and physical interpretability, ensuring system stability under diverse operating conditions.

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