This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987

IEEE Open Journal of
Power Electronics

Received XX Month, XXXX; revised XX Month, XXXX; accepted XX Month, XXXX; Date of publication XX Month, XXXX; date of current version XX Month, XXXX.

Digital Object Identifier 10.1109/OJPEL.xxxx.xxxxxxx

Solid-State Circuit Breakers for DC-Powered Buildings: An Overview of Standards, Directives, and Technologies

HENRIQUE BIZZI MORARI*, LUCAS VIZZOTTO BELLINASO*, EDIVAN LAERCIO CARVALHO†(Senior Member, IEEE), SATISH NAIK BANAVATH‡(Senior Member, IEEE), GIOVANNI DE CARNE§(Senior Member, IEEE), DMITRI VINNIKOV¶(Fellow, IEEE).

[1]Power Electronics and Control Group, Federal University of Santa Maria, Santa Maria, Rio Grande do Sul, Brazil
[2]Department of Electrical and Computer Engineering, NOVA School of Science and Technology, NOVA University Lisbon, Lisbon, Portugal
[3]Department of Electrical Electronics and Communication Engineering, Indian Institute of Technology Dharwad, Dharwad, India
[4]Institute for Technical Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany
[5]Department of Electrical Power Engineering and Mechatronics, Tallinn University of Technology, Tallinn, Estonia

CORRESPONDING AUTHOR: Henrique Bizzi Morari (e-mail: henrique.morari@acad.ufsm.br).

ABSTRACT This paper presents a review of low-voltage direct current (LVDC) solid-state circuit breakers (SSCBs) for building power systems, focusing on relevant standards, safety directives, and design requirements for DC protection. A structured classification scheme is proposed for LVDC SSCBs based on key design criteria including the number of poles, bidirectional current capability, isolation method, semiconductor technology, and circuit topology. This paper also proposes a categorization of SSCB protective functions into elementary safety functions (short-circuit interruption, overcurrent and overload protection, and selective coordination) and additional advanced functions (arc-fault detection, insulation monitoring, and earth-fault protection), distinguishing fundamental requirements from enhanced safety features. Furthermore, a risk assessment framework grounded in ISO 12100 principles is introduced and tailored to LVDC installations employing SSCBs. This framework systematically identifies potential hazards and SSCB failure modes, guiding risk mitigation measures and the development of test procedures to ensure compliance with safety standards. Collectively, these contributions provide clear guidelines to support the safe integration, standardization, and future development of SSCBs in emerging DC power distribution networks.

INDEX TERMS Circuit breaker technologies, DC power systems, LVDC distribution, power electronics, risk assessment, safety and standardization in electrical systems, solid-state protection devices.

I. INTRODUCTION

THE transition from centralized AC to highly efficient, greener, and distributed grids has brought increasing interest in DC, especially at low voltage (LVDC) levels for power distribution inside buildings. For this application, LVDC offers many advantages in terms of efficiency, seamless integration of renewable energy sources, and compatibility with modern DC electronic loads [1], [2], [3]. This is driven by technological developments in distributed energy resources (DERs) like photovoltaic (PV), battery energy storage systems (BESS), electric vehicles (EVs), and power electronics-based appliances [4], [5], [6], [7]. For instance, most of the loads found in modern homes and offices rely on USB Power Delivery (USB PD) interfaces, which are DC by default.

Residential and commercial installations typically consist of loads that predominantly operate on DC [3], [4]. Therefore, for such applications, DC can reduce power losses, simplify infrastructure design, and improve copper utilization by eliminating the need for AC-DC power converters and avoiding issues related to power factor correction and reactive power [8], [9], [10].

On the other hand, protection remains one of the most critical challenges for LVDC systems, especially at the building scale. Unlike traditional AC, DC-powered buildings lack natural current zero-crossings, which makes fault inter-

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

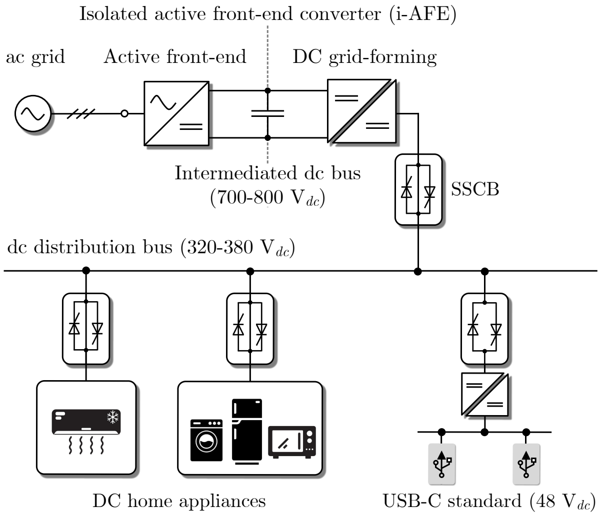


FIGURE 1. **Example of LVDC installation based on an isolated active front-end converter (i-AFE) and multiple SSCB protection devices.**

ruption more challenging. Additionally, fault currents in DC systems tend to rise rapidly and persist longer, increasing thermal and safety risks if not quickly interrupted [11], [12], [13]. In residential and commercial environments, these risks pose significant safety concerns for end-users. Persistent arcs or fault currents can lead to elevated temperatures in cables and terminals, increasing the risk of burns or fire hazards. Additionally, improper insulation or failed fault interruption may expose users to sustained voltages, potentially resulting in electric shock [14].

The key aspects of protection in DC-powered buildings (Figure 1) include accurate fault detection, effective fault isolation, reliable DC current interruption, as well as selectivity and coordination [15], [16], [17], [18], [19], [20], [21], [22]. A wide range of protective devices and methods have been proposed, including fuses, mechanical circuit breakers (MCBs), solid-state circuit breakers (SSCBs) and hybrid breakers [12], [13]. SSCBs are emerging as a key technology for enhancing the protection and digital controllability of modern DC-powered buildings. Unlike conventional mechanical circuit breakers, SSCBs employ power semiconductor devices such as IGBTs, MOSFETs, or thyristors to perform very fast current interruption [23], [24], [25], [26]. Fig. 1 illustrates a LVDC installation including SSCBs as protection devices.

Recent developments have expanded SSCB functionalities, including soft-switching control [27], [28], [29], [30], arc-fault detection, telemetry, IoT functionalities, and integration of advanced materials such as silicon carbide (SiC), gallium nitride (GaN), and bidirectional monolithic devices [29], [30], [31], [32], [33]. In addition, hybrid circuit breakers can combine solid-state and mechanical elements, to balance fast response and efficiency while mitigating losses during steady-state operation [34], [35], [36], [37].

Despite their advantages, LVDC microgrids and SSCBs face several challenges in their adoption. Among them is the absence of unified installation guidelines, safety protocols, and certification methodologies for SSCB [2], [3], [25], [38]. This gap complicates product development, system interoperability and safe operation. However, regarding LVDC installations, efforts such as the NPR9090 [39] and Current/OS [40] initiatives are laying the groundwork for common standards and frameworks.

From an installation point of view, voltage levels between 350 Vdc and 700 Vdc are commonly used for both bipolar and unipolar DC systems, with 350 Vdc being the most prevalent in building applications, according to Current/OS. Some of the existing standards related to SSCBs include IEC 60947-2 [41], IEC 60947-4-3 [42], and IEC 62314 [43]. However, these standards do not fully address the specific failure modes, switching characteristics, performance benchmarks, testing requirements, and operating limits of SSCBs in accordance with NPR9090 and Current/OS. As SSCB technology continues to evolve, these standards must be revised to ensure safe and effective adoption in building-scale applications.

In the current literature, several review papers have addressed the topic of DC protection, covering a range of scopes from general protection strategies for low (LVDC), medium (MVDC), and high-voltage (HVDC) DC systems, to specific topics on DC circuit breakers, SSCBs, and HCBs. These works provide in-depth information on fault detection methods, grounding schemes, device topologies, and challenges in protection coordination. Table 1 provides a summary and comparison of these works.

From the authors' point of view, the current literature lacks a systematic classification of solid-state circuit breakers (SSCBs) and their different topologies. More critically, there is a significant gap in standards and directives specifically tailored for DC-powered building applications. Addressing this gap is essential from multiple perspectives. For the industry, clear guidelines are needed to support the design and development of compliant and safe products. Testing laboratories require standardized procedures for certification and performance evaluation. Most importantly, from the end-user's perspective, SSCBs play a critical role in ensuring safety in buildings by mitigating risks related to electric shocks, fire hazards, and equipment damage. Without a standardized framework, the widespread and safe adoption of DC-powered buildings remains limited. However, the appropriate development and standardization of SSCBs can act as a key enabler to accelerate this transition.

This paper presents a comprehensive review focused on the application of solid-state circuit breakers (SSCBs) in DC-powered buildings. It provides guidelines and a framework for classifying LVDC SSCB technologies and protection requirements based on installation criteria. In addition, it discusses the risk assessment of SSCB failure modes and proposes test procedures aligned with safety standard com-

This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987

TABLE 1. **Review papers on the topic of SSCBs in the literature**

Scope	Reference	Review summary
Protection in LVDC microgrids.	[12]	• LVDC standards, grounding, fault location, and protection methods. • Gaps and future research in LVDC protection.
	[11]	• Fault detection methods in LVDC. • Existing standardization and gaps for LVDC protection.
	[15]	• Indicators for fault identification. • CB types and semiconductor devices for fault interruption.
	[17]	• Types of DC faults, grounding and protection devices. • Fault detection, location and recovery methods.
Protection in general DC microgrids.	[44]	• DC microgrid topologies, faults, and grounding strategies. • Protection schemes including SSCBs and intelligent methods. • Challenges and research gaps in DC microgrid protection.
	[23]	• Fault detection, location and isolation methods. • Analysis of grounding schemes. • Comparison of protection devices based on cost, speed, and losses.
	[45]	• Comparison of DC protection methods and devices. • Analysis of constant power load impact on protection.
	[46]	• DC microgrid configurations, grounding and control strategies. • Protection schemes considering communication needs.
	[47]	• Fault types, detection methods and CB technologies. • Grounding, communication, and coordination challenges. • Need for standardization above ELVDC.
	[20]	• Fault detection, location, isolation and backup protection in DC. • Real-world protection schemes in LVDC shipboard applications.
Protection in HVDC grids.	[48]	• Flexible DC technologies applied to HVDC. • Fault detection, interruption and recovery methods.
DC circuit breakers	[49][50][51] [52][53][54]	• Design, performance and coordination of DCCBs. • Mechanical, hybrid and solid-state topologies.
	[55]	• Short-circuit protection in LVDC and MVDC (fuses and circuit breakers).
Solid-state circuit breakers	[56][57][58] [26]	• Classification of SSCB based on topology, semiconductor device and protections.
	[34]	• Topologies for HCB and SSCB.
	[59]	• Z-source topologies applied to HVDC distribution.
	[60][61]	• Classification of impedance-source SSCB.
	[62]	• SSCB technologies applied to shipboard systems.
Hybrid circuit breakers	[63]	• Classification, component selection and performance of HCB topologies.
	[64]	• Design and standardization of HCB.

This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987

pliance. Relevant existing and related standards are also analyzed, offering directives for future standardization efforts specifically targeting LVDC applications of SSCBs. No previously published study has offered the same level of detailed overview and analysis on this topic. Furthermore, these contributions are crucial for bridging the gap between current technological capabilities and the regulatory and safety requirements of DC-powered buildings.

The remainder of the paper is organized as follows: Section II brings applications where the adoption of LVDC SSCBs is beneficial. Section III describes the general architecture of LVDC SSCBs. Section IV proposes a categorization of SSCB protection functions into elementary, additional, and smart non-critical features, covering short-circuit and overcurrent protection, arc-fault detection, insulation monitoring, and earth-fault protection. Section V presents a classification of DC SSCBs based on the number of poles, isolation, bidirectional power flow capability, semiconductor technologies, and circuit topologies. Section VI presents the critical standardized tests applied to LVDC SSCBs and the risk assessment framework defined by ISO 12100, showing its application in the context of LVDC installations with SSCBs. Finally, Section VII presents our conclusions.

II. APPLICATIONS AND MOTIVATION FOR LVDC SSCB

SSCBs offer fast, arc-less interruption, flexible protection characteristics, and rich diagnostic capabilities that are not achievable with traditional mechanical circuit breakers. At the same time, SSCBs introduce higher device cost and additional conduction losses, which naturally raises the question of why they should be adopted in LVDC installations over conventional breakers.

A. LIMITATIONS OF MECHANICAL CIRCUIT BREAKERS IN LVDC INSTALLATIONS

MCBs in LVDC installations are typically derived from technologies tuned to AC systems that, when applied to DC systems, show limitations. A primary challenge is that DC current has no natural zero-crossing, requiring additional auxiliary circuitry to force current zero-crossing for interruption [65], or the design of complex arc-chambers [66]. As a consequence, interruption times tend to be longer, and contacts are damaged. Furthermore, the steep di/dt of LVDC must be detected and interrupted quickly to protect the installation from thermal damage [49]. These constraints are especially critical in environments such as data centers, hospitals, or shipboard systems, where faults and outages translate to significant safety risks, and can be addressed by the adoption of SSCBs.

B. HIGH-AVAILABILITY INSTALLATIONS

High-availability LVDC systems (such as data centers, telecommunications, and medical facilities) require protection schemes that guarantee supply continuity. Traditional coordination is challenging in these networks due to the absence of natural current zero crossings. SSCBs address this by providing microsecond-scale interruption and controllable characteristics that enable deterministic selectivity [67]. By combining advanced sensing with local intelligence, they effectively manage high transient faults [68]. Furthermore, experimental research [69], [70] confirms that optimized time-current characteristics allow for secure, selective protection without relying on communication infrastructure.

Specific applications in DC data centers [29], [71], [72], [73], [74] highlight the advantages of SSCBs, including autonomous operation, inrush current limiting, and integrated diagnostic functions that enable local fault isolation without triggering widespread outages.

C. BATTERY ENERGY STORAGE

BESS constitute another important application domain for SSCBs, as they typically exhibit very low short-circuit impedances that can drive extremely high transient fault currents. These currents often exceed the interruption capabilities of mechanical devices and pose severe stress to the semiconductor switches of interfacing converters. SSCBs provide the fast bidirectional interruption required in such environments. [75] shows that a coupled inductor-based SSCB can both mitigate DC-bus voltage ripple and significantly reduce short-circuit current peaks in BESS, enabling reliable microsecond-scale fault clearing. Likewise, [76] demonstrates that bidirectional Z-source SSCBs integrated in DC microgrids achieve intrinsic current limiting, natural commutation, and reliable isolation of battery faults.

III. DC SSCB BASIC ARCHITECTURE

Although topologies vary significantly, all SSCBs must implement a set of minimum safety functions dictated by installation-level standards (IEC 60364 series) and device-level performance requirements (IEC 60947 series, IEC 60898 series, IEC 62314). This section provides a general description of SSCB components and their functions, establishing the conceptual foundation for the detailed classification presented in Section V.

A SSCB is commonly composed of a set of parts that enable fast interruption, protection, and reliable operation in LVDC installations. Figure 2 shows an overview of the SSCB architecture. At the core of the device lies the power-switching stage, typically implemented using semiconductor technologies such as silicon MOSFETs, silicon IGBTs, SiC MOSFETs, or monolithic bidirectional switches. Regardless of the technology, the switching devices must withstand the full blocking voltage of the DC bus, maintain stable behavior under surge conditions, and safely interrupt fault currents without violating their Safe Operating Area (SOA) [56], [77]. Along with the semiconductor switch, SSCBs incorporate an auxiliary protection stage to absorb the electrical stress on the switch during turn-off. This stage often includes RCD snubbers, metal-oxide varistors (MOVs), active clamping circuits, or Z-Source topologies [60], [78].

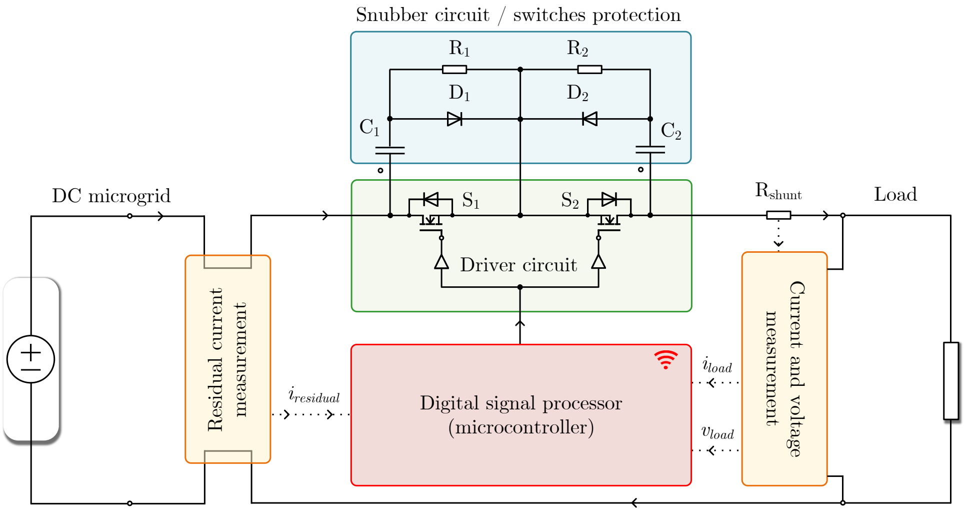


FIGURE 2. SSCB example architecture, composed of semiconductor switch stage, switch protection circuit, sensing circuits, gate driver and controller. Protection functions are implemented in the controller.

Accurate and robust sensing is another essential part of SSCB architecture. Current measurement may rely on shunt resistors, Hall-effect sensors, or high-bandwidth devices such as Rogowski coils, enabling the controller to detect short-circuit currents as fast as possible [56]. Voltage sensing can be used to monitor that over-voltage conditions remain within the operating window of the SSCB circuitry. Temperature monitoring of the semiconductor junctions or PCB hotspots is often integrated to prevent thermal stress and to support the thermal overload protection [77]. The sensing subsystem must maintain reliability even under severe transient conditions.

The gate driver and control unit constitute the supervisory layer of the SSCB. The gate driver provides interface to properly switch the semiconductor devices. The control unit is comprised of a microcontroller or digital-signal-processor (DSP) responsible for aggregating the electrical measurements and executing protection algorithms, selectivity characteristics, and communication tasks.

IV. DC SSCB PROTECTION AND SAFETY FUNCTIONS

Safety requirements for DC SSCBs are guided by international standards, as summarized in Table 2, covering short-circuit protection, earth-fault protection, and coordination within electrical installations. Fig. 3 presents a diagram of the main protection functions of a DC SSCB.

A. ELEMENTARY PROTECTION FUNCTIONS

This subsection focuses on the fundamental protective capabilities, short-circuit and overcurrent protection, that define the primary operation of an SSCB. These functions are governed by specific international standards that dictate breaking capacities, thermal endurance, and operational limits.

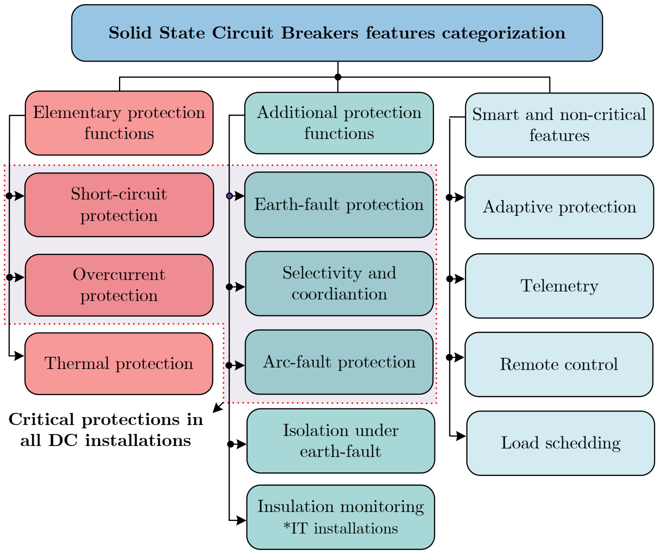


FIGURE 3. Proposed categorization of requirements and functions of DC SSCBs into elementary functions, additional functions (which are not common circuit breaker functions but can be integrated), and smart and non-critical functions.

1) Short-Circuit Protection

Short-circuit protection is a fundamental requirement for SSCBs, ensuring safe interruption of line-to-line, line-to-earth, and line-to-midpoint faults without system damage. IEC 60947-2 [41] defines breaking capacities based on recovery voltages and fault time constants, while IEC 60898-2 [80] and IEC 60934 [82] establish standards for dielectric withstand and operational endurance.

Recent research emphasizes microsecond-scale interruption using RB-IGCT and SiC technologies [97], [98]. Current-limiting techniques, such as those in [99], restrict

This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987

TABLE 2. **SSCB safety reference standards**

Standard	Scope
IEC 60947-1 [79]	Switchgear general requirements in LV
IEC 60947-2 [41]	LVAC and DC circuit breakers
IEC 60947-4-3 [42]	LVAC Solid-state contactors
IEC 62314 [43]	AC and DC solid-state relays
IEC 60898-2 [80]	Circuit breakers for LVAC and DC overcurrent protection
IEC 60898-3 [81]	Circuit breakers for LVDC overcurrent protection
IEC 60934 [82]	LVAC and DC circuit breakers
IEC 60364-4-43 [83]	LV installations overcurrent protection
IEC 60364-4-41 [84]	LV installations protection against electric shock
IEC 60364-4-42 [85]	LV installations protection against thermal effects
IEC 60755-1 [86]	DC residual current protection devices
IEC 61008-1 [87]	LVAC residual current breakers
IEC 61557-8 [88]	Insulation monitoring devices for IT systems
IEC 63112 [89]	Earth-fault protection in LV PV arrays
IEC 60664-1 [90]	LVAC and DC insulation coordination
IEC 62606 [91]	Arc fault detection devices
IEC 63027 [92]	Arc fault detection and interruption within PV arrays
UL 1699B [93]	Arc fault circuit interrupters for PV arrays, requirements and tests
IEC 62109-1 [94]	Safety of PV converters – general requirements
IEC 62109-2 [95]	Safety of PV converters – particular requirements
IEC 60364-1 [96]	LV electrical installations general rules
NPR 9090 [39]	Requirements for LV DC installations and interface with AC

fault magnitude without total power loss, a useful feature for microgrid stability. Hybrid designs also utilize passive components to increase detection accuracy [100], [101].

Modern SSCBs often integrate advanced fault localization and identification. Methods include signal injection [102], inductance-based estimation [74], and decision trees [98] to improve discrimination without extra sensors. Furthermore, designs robust to initial disturbances [103] and communication-assisted coordination [104] enhance reliability in distributed protection schemes.

2) Overcurrent Protection

Overcurrent protection ensures SSCBs respond safely to overload conditions that threaten system integrity despite not being immediate short circuits. IEC 60364-4-43 [83] establishes the general principles for overcurrent protection in LV installations. Per IEC 60947-4-3 [42], semiconductor-based devices must reliably establish and sustain states under defined overloads, operating without failure during repeated high-current cycles.

Testing procedures in IEC 60947-1 [79] verify thermal and electrical integrity under both steady-state and transient conditions. SSCBs must demonstrate durability over a specific number of load operations, ensuring their suitability for industrial and critical infrastructure applications.

B. ADDITIONAL PROTECTION FUNCTIONS

The protection functions presented in this section are related to safety requirements for electrical installations that employ low-voltage DC SSCBs, as guided by the IEC 60364 series [105] and related standards. These requirements ensure protection against hazards such as electric shock, arc faults, insulation failure, and inadequate isolation. Several standards, including IEC 60364-1 [96], IEC 60755-1 [86], IEC 63112 [89], and IEC 63027 [92], provide criteria for implementing fault detection, earth continuity, and proper disconnection functions. Fig. 3 summarizes the main protection functions regarding the installation.

1) Earth-Fault Protection

Earth-fault protection ensures safety against electric shock and fire by facilitating automatic supply disconnection (IEC 60364-4-41). DC-residual current devices (DC-RCDs), governed by IEC 60755-1 [86], fulfill this by detecting residual currents. Per IEC 60364-4-41 [84], devices with rated residual currents $\leq$ 80 mA (up to 220 V or 440 V DC) protect against shock, while IEC 60364-4-42 [85] mandates thresholds $\leq$ 300 mA to mitigate fire hazards. Furthermore, DC-RCDs must resist nuisance tripping from transients and be compatible with TN, TT, and IT systems.

Installation requirements depend on the grounding configuration (Fig. 4). TN systems, featuring earthed neutrals, typically utilize single-pole breakers to interrupt high fault currents rapidly. In contrast, IT systems utilize isolated supplies, requiring multi-pole breakers for complete disconnection and coordinated protection to manage lower initial fault currents without compromising operational continuity. Consequently, DC SSCB designs must provide fast tripping for TN systems while allowing for monitored operation in IT systems, such as photovoltaic (PV) generators [95].

IT systems rely on Insulation Monitoring Devices (IMDs) per IEC 61557-8 [88] to detect symmetrical and asymmetrical faults and issue warnings. For PV installations, IEC 63112 [89] defines criteria for PV Earth-Fault Protection Equipment (PV-EFPE), requiring periodic monitoring and

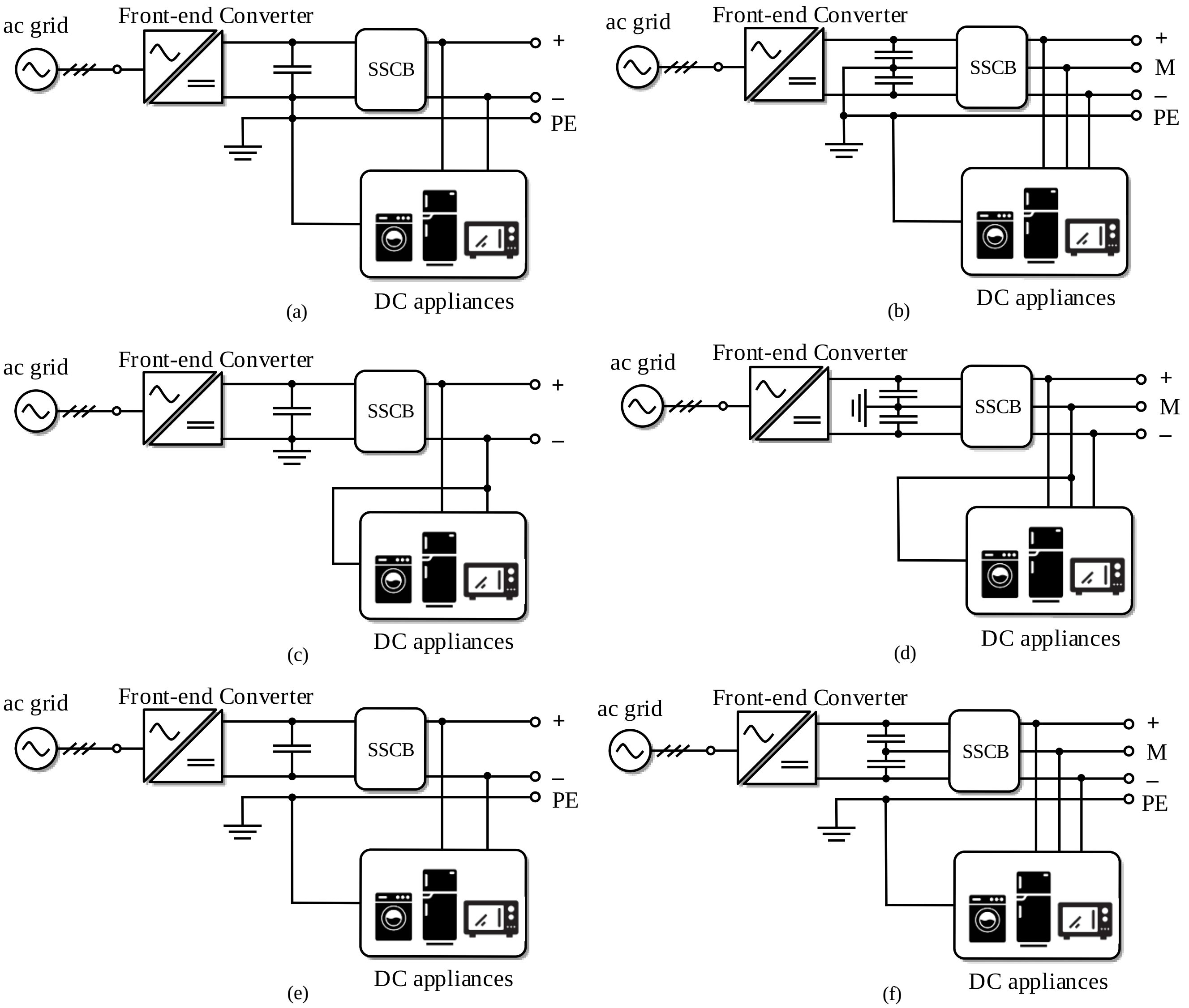


FIGURE 4. **Types of DC installations: a) TN-S system; b) TN-S system with midpoint; c) TN-C system; d) TN-C system with midpoint; e) IT system; f) IT system with midpoint.**

coordinated disconnection. Together, these standards ensure reliable fault detection and enhanced safety across low-voltage DC networks.

2) Selectivity and Coordination

Selectivity and coordination ensure that protective devices isolate only the faulted section, preserving overall system operation (IEC 60947-1 [79]). Proper coordination requires that downstream devices trip before upstream ones, typically verified by plotting time-current characteristic curves (Fig. 5). This sequence reduces system stress and enhances reliability.

Diverse approaches address selectivity in DC systems, particularly for communication-free microgrids. Decentralized schemes include zero-sequence current triggering [67] and the use of fast-acting fuses [106]. Recent studies focus on optimizing the intrinsic time-current characteristics of SSCBs to align response times without external communication [107], [108], [109].

However, high di/dt fault conditions can compromise coordination. Research suggests using compensation circuits and specific design guidelines to mitigate these effects [110], [111]. Additionally, coordinating heterogeneous devices (e.g., SiC MOSFETs and RB-IGCTs) requires precise characterization and tuning to prevent misoperation [112].

3) Arc-Fault Protection

Arc-fault protection mitigates fire risks from insulation breakdown or loose connections (IEC 60364-4-42), filling a gap left by IEC 60947-1, which focuses on internal

This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987

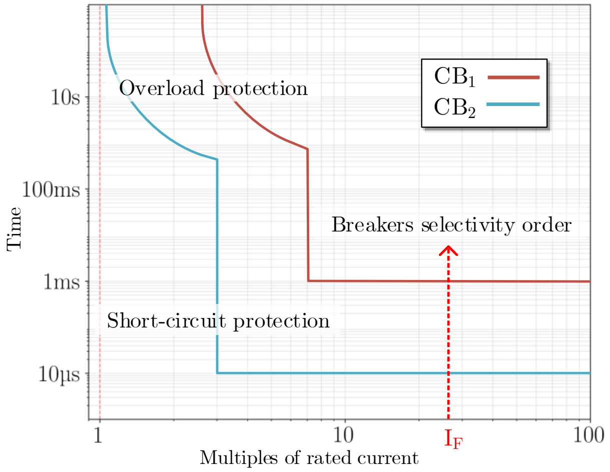


FIGURE 5. Characteristic time-current curves for selectivity and coordination analysis between upstream and downstream SSCBs. In the example, CB_1 is rated at a higher current, and has a longer response time, than CB_2. The arrow indicating the fault current I_F shows that CB_2 will trip first, ensuring selectivity.

switchgear arcing rather than load-side faults. In PV systems, IEC 63027 mandates detection within 2.5 s or before arc energy reaches 750 J [92]. The US standard UL 1699B [93] establishes similar protection thresholds for series arcs but additionally requires fault testing on both the positive and negative poles of PV strings, providing broader fault location coverage [113]. SSCBs can integrate or coordinate with Arc-Fault Protective Equipment (AFPE) to enhance fire safety through rapid interruption.

Literature reviews emphasize the need for robust standardization across batteries [114], PV systems [115], [116], and DC grids [117], [118], often comparing rule-based methods with emerging AI techniques [119], [120].

Detection methodologies:

- **Machine Learning and Statistics:** Used for low-current or noisy conditions, utilizing ensemble models [121], probabilistic grid modeling [122], Hidden Markov Models [123], SVMs [124], Neural Networks [125], [126], kernel learning [127], and time-domain statistics [128].
- **Frequency-Domain:** Isolate high-frequency arc signatures through spectrum analysis [129], [130], [131], [132], [133], spectral similarity [134], autocorrelation [135], and band separation [136].
- **State Observers:** Model faults as disturbances using unknown input observers [137], [138], [139], [140] or residual analysis [141], sometimes integrating cyber-attack detection [142].

In PV installations, detection is well-standardized, employing AI classifiers [143], [144], [145], GAN-generated training data [146], and SVMs [147]. Specialized hardware sensing includes wavelet transforms [148], electromagnetic radiation detection [149], and inverter-integrated monitoring [150].

4) Isolation

Isolation in DC SSCBs provides galvanic separation, ensuring no conductive path exists between the source and load after tripping. This is critical for safety during maintenance on de-energized conductors. Standards IEC 60947-1 [79], IEC 60947-2 [41], and IEC 60664-1 [90] establish requirements for creepage, clearance, leakage current, and impulse voltage resistance between open contacts.

To achieve both rapid interruption and galvanic separation, Hybrid Circuit Breaker (HCB) designs are used. These combine solid-state devices with mechanical switches. Literature reviews [63], [64] classify HCBs by triggering methods and internal components, mechanical switches, semiconductors, and energy absorbers, detailing their performance trade-offs. The choice of power semiconductor is pivotal, as analyzed in [36], IGBTs and IEGTs are optimized for high-current robustness, whereas IGCTs are preferred for low-voltage applications to minimize conduction losses.

5) Single-Fault Protection

Single-fault protection in DC SSCBs ensures that no individual failure of sensing, control, or switching components compromises safety. This tolerance is achieved through hardware redundancy, rapid self-diagnostic routines to detect sensor or driver faults, and fail-safe logic to prevent the device from remaining in a dangerous state. Specifically, IEC 62109-1 [94] mandates that PV inverters integrate redundant protective paths and periodic self-tests, establishing a foundation for risk reduction in DC protective equipment.

At the installation level, IEC 60364-4-41 [84] requires that safety be maintained even during a single fault anywhere in the system. This is implemented through two layers: basic protection (insulation and barriers to prevent contact with live parts) and fault protection (automatic disconnection to prevent shock or fire). In critical IT systems, the standard permits monitoring devices to signal insulation faults rather than immediately disconnecting, facilitating safe maintenance. Ultimately, DC systems should not rely on a single device, SSCBs must be integrated within a layered strategy involving redundant breakers or monitoring systems to ensure continuous protection.

C. SMART AND NONCRITICAL FEATURES

Recent experimental developments, such as those by [151] and [152], demonstrate SSCBs integrated with communication interfaces, enabling real-time telemetry, configurable protection thresholds, and remote switching. These designs transform SSCBs from purely protective components into multifunctional devices that also contribute to load management, system diagnostics, and supervisory coordination within energy management systems (EMS).

Within the IoT-enabled smart grid, [153] shows that IoT technologies integrate sensors, controllers, and communication protocols to enable real-time monitoring and coordinated

This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987

control across multiple voltage levels. Similarly, [154] highlight that distributed edge computing allows fault detection and mitigation to occur locally, improving resilience by reducing communication delays.

However, as networked devices proliferate, the attack surface of the grid expands. The comprehensive survey by [155] identifies that IoT-aided smart grids face a wide spectrum of cyber-physical threats, from denial-of-service and false-data injection to topology manipulation and jamming attacks, necessitating new protection strategies. These vulnerabilities directly affect protection devices such as SSCBs that continuously communicate with higher-level supervisory systems. The cyberattack model described by [156], in which altering breaker states can cause undetectable topology errors, underscores the urgency of cyber-resilient protection architectures. Ensuring the authenticity and integrity of breaker status, control commands, and telemetry data becomes as essential as protecting the semiconductor hardware itself.

Several international standards provide guidance on cybersecurity, communication, and software reliability for smart protective devices. Table 3 summarizes the key standards applicable to IoT-integrated SSCBs, highlighting their scope and relevance.

TABLE 3. **Relevant standards for cybersecurity, communication, and software reliability in IoT-integrated SSCBs**

Standard	Scope
IEC TS 63208 [157]	Cybersecurity aspects for low-voltage switchgear and controlgear, addressing threats to communication and data integrity.
IEC TR 63201 [158]	Guidance on embedded software development and validation in low-voltage switchgear and controlgear.
IEC 62351 [159]	Security mechanisms for power system control and communication protocols (e.g., IEC 61850, DNP3, Modbus).
IEEE 1547.3 [160]	Communication and information models for distributed energy resources (DER) connected to electric power systems.
ISO/IEC 27402 [161]	Baseline cybersecurity and privacy requirements for IoT devices, covering cryptography, event logging, and secure software updates.
ETSI TS 103 701 [162]	Cybersecurity assessment framework for IoT products, defining test procedures for compliance verification.
ETSI EN 303 645 [163]	Baseline cybersecurity requirements for consumer IoT, emphasizing authentication, software updates, and vulnerability management.

Beyond fault protection, SSCBs can play an active role in demand management and load shedding, providing grid-interactive control capabilities that enhance energy efficiency and reliability. As demonstrated by [164], intelligent SSCBs equipped with metering and networked gateways can perform automated demand-response operations by monitoring aggregate power consumption and disconnecting low-priority loads when predefined thresholds are exceeded. Through programmable priority levels, SSCBs enable fine-grained load control and real-time coordination with EMS, mitigating grid stress during peak demand.

V. DC SSCB CLASSIFICATION

DC SSCBs can be classified according to a variety of criteria, each reflecting distinct functional, structural, or operational characteristics. These classifications include bidirectional power flow capability, number of poles, isolation, semiconductor technology, and circuitry used for semiconductor protection. Understanding these categories helps clarify the design choices and application contexts in which SSCBs are implemented. The diagram in Fig. 6 illustrates an overview of these classification branches.

A. BASED ON POWER FLOW

This classification considers the direction in which current flows through the circuit breaker during normal and fault conditions. Depending on whether the SSCB handles current in one or both directions, topologies vary significantly in complexity, application, and required control strategies.

1) UNIDIRECTIONAL TOPOLOGIES

In unidirectional configurations, the SSCB is designed to interrupt fault currents that flow in a single direction. These topologies are typically employed in applications where power flows to the load, or from a generator, without reversal [26], [34].

In their simplest form, unidirectional SSCBs can be realized using a single semiconductor switch (Fig. 7.a). While the simplicity of this approach yields a reduced component count and fast response times, the device's SOA often limits its capacity to absorb transient fault energy [77]. To address this limitation, designers typically incorporate auxiliary protection circuits, like snubber networks or voltage-clamping circuits, that help dissipate or redirect the excess energy, thereby safeguarding the semiconductor from overvoltage or thermal overload [26].

To overcome the SOA constraints inherent to single-device designs, unidirectional SSCBs may employ multi-device configurations (Figures 7.b and 7.c). In these approaches, multiple semiconductor devices are arranged in series or parallel [56]:

- Series configurations distribute the fault voltage across several devices, increasing the overall voltage block-

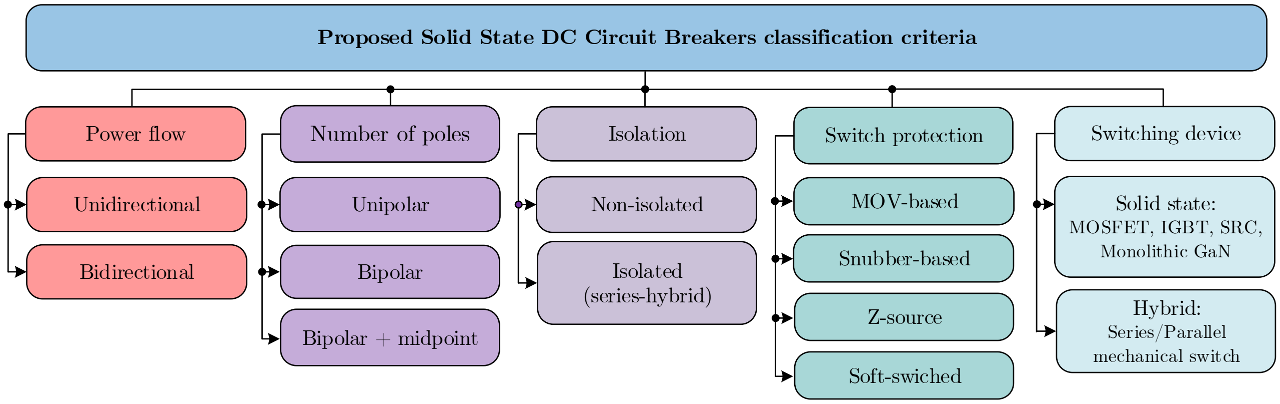
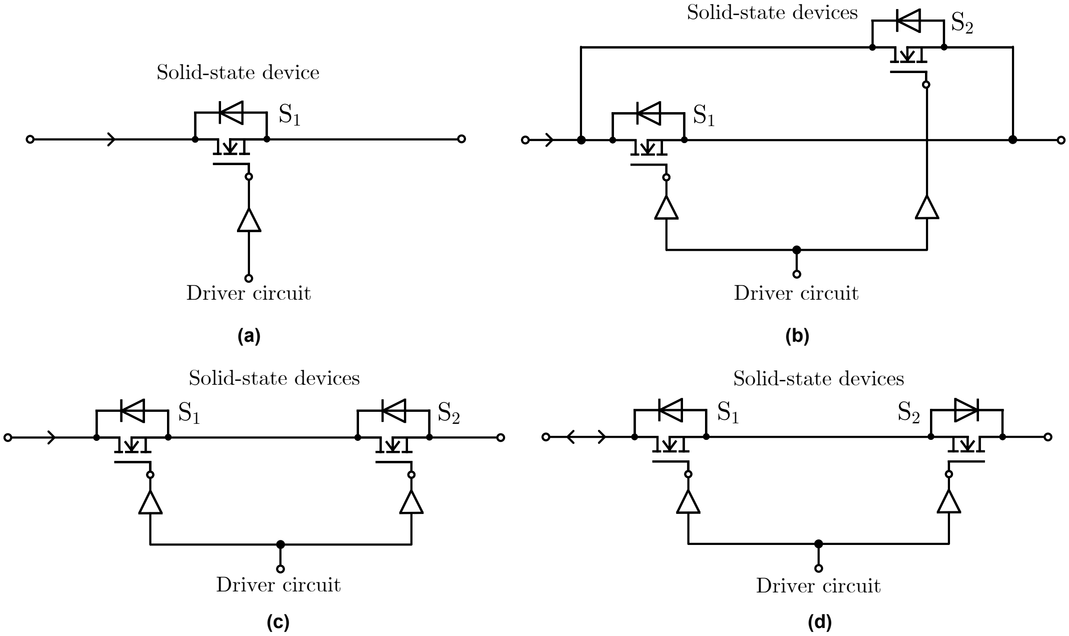


FIGURE 6. **Proposed classification criteria for DC SSCBs.**



(a)

(b)

(c)

(d)

FIGURE 7. **Semiconductor device arrangements. a) single-device; b) parallel multi-device; c) series multi-device; and d) anti-series bidirectional.**

ing capability. Although voltage imbalance must be accounted for.

- Parallel configurations share the conduction current, reducing individual device stress and lowering conduction losses. In this configuration, current sharing imbalance can be a problem.

2) BIDIRECTIONAL TOPOLOGIES

When fault currents may arise in either direction, SSCBs must be designed to interrupt both polarities. This capability is particularly relevant in systems with reversible power flows, such as DC microgrids, renewable generation, and energy storage units [25], [26].

To achieve this, bidirectional protection typically relies on multi-device arrangements that allow current conduction and blocking in both directions, as exemplified in the arrangement of Fig. 7.d. Common examples include back-to-back and anti-parallel configurations, where two semiconductor switches are connected to independently manage current paths. Such arrangements enable the circuit breaker to operate effectively regardless of current polarity [34], [56].

Because of these requirements, bidirectional SSCBs are central to the safe operation of modern energy systems that integrate distributed resources and flexible load management. Their inherent complexity, arising from voltage balancing, current sharing, and reliable bidirectional switching, necessitates advanced control strategies and auxiliary protection measures such as snubbers and voltage clamps to ensure robust performance under transient conditions [25], [77].

B. BASED ON NUMBER OF POLES

SSCBs can be classified by how many active conductors they disconnect during a fault. In the Unipolar topology, only one conductor (typically the unearthed pole) is interrupted. This configuration is often found in TN systems where the return path is grounded, and shutting off the live conductor is sufficient to clear faults. However, in IT systems a unipolar breaker may leave the remaining conductor at a dangerous potential relative to earth, so full isolation is not guaranteed.

The Bipolar topology disconnects both the positive and negative conductors simultaneously, which significantly improves protection against earth-faults. This configuration is particularly advantageous in IT systems, where neither conductor is referenced to earth. In such networks, an earth-fault on one pole can elevate the potential of the opposite pole relative to ground. In split-bus DC systems (bipolar systems with a midpoint), the Bipolar with Midpoint configuration extends this concept by also disconnecting the neutral or midpoint conductor. This additional pole of isolation is also especially important in IT systems, since the midpoint can become energized relative to earth following a single earth-fault. By isolating all active conductors, including the midpoint, the breaker guarantees complete de-energization of the system and prevents secondary faults, or electric shock and fire hazards, that could arise from residual currents between live conductors and earth [84], [94].

C. BASED ON ISOLATION

Isolation concerns whether the SSCB is designed to provide complete galvanic isolation from the power source after fault interruption. In practical implementations which require galvanic isolation, SSCBs must be complemented by mechanical switches.

Hybrid circuit breakers combine the solid-state and electromechanical switches to address the challenges inherent in protecting DC systems [63]. To achieve galvanic isolation a series hybrid configuration must be employed, as in Figure 8.a. A hybrid circuit breaker in a parallel configuration is also possible, as in Figure 8.b, but its advantage would be limited to reducing on-state losses, not providing galvanic isolation. Traditional electromechanical switches offer low conduction losses and robust insulation, but present slow response times and arcing issues, especially problematic in DC systems where there is no inherent zero current crossing. On the other hand, solid-state switches provide fast and arc-free operation, though they tend to have higher on-state losses and can be more sensitive to transient electrical stress.

Beyond the conventional series and parallel hybrid configurations, a mixed series-parallel SSCB topology can also be employed to leverage the advantages of both arrangements, combining galvanic isolation with reduced on-state losses while improving transient fault current handling. The resulting hybrid configuration, as demonstrated in [165] and illustrated in Fig. 8.c, achieves current transfer from the parallel mechanical-switch branch to the solid-state switch branch before the series mechanical switch completes the galvanic separation. This mixed topology offers a trade-off, combining low losses in normal operation with robust galvanic isolation, with the downside of increasing the total interruption time, compared to fully solid-state topologies, due to the reliance on a mechanical device.

D. BASED ON SEMICONDUCTOR PROTECTION

The semiconductor type, whether conventional silicon or wide-bandgap (WBG) devices such as SiC and GaN, dictates specific protection requirements related to overvoltage, overcurrent, overheating, and switching transients. Traditional methods rely on metal-oxide varistors (MOVs), snubber networks, active clamping, and thermal sensing, while more advanced topologies such as Z-source and soft-switched SSCBs achieve protection intrinsically through controlled current shaping and resonant energy exchange [166].

1) MOV-BASED PROTECTION

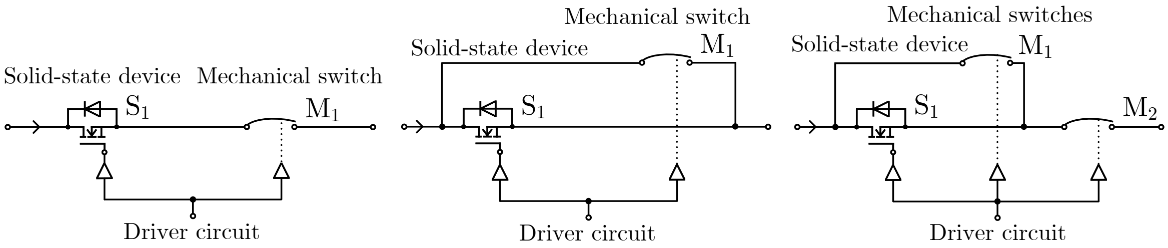
Metal-oxide varistors (MOVs) are widely used as voltage-clamping devices in SSCB designs to protect semiconductor switches from overvoltage transients during fault interruption. When the main switch turns off, the inductance in the circuit drives a rapid voltage rise across the device. A parallel-connected MOV clamps this voltage to a safe level and absorbs the stored inductive energy [97], [167], [168]. Compared to other methods, MOV-based protection offers a simpler implementation with fewer components, and the clamping voltage is inherently defined by the varistor characteristics. However, MOVs exhibit large transient voltage fluctuations and are susceptible to degradation under repeated fault events, while offering short fault clearing times at low cost [169], [170].

2) SNUBBER

Recent studies demonstrate that the topology and coordination of snubber circuits are central to semiconductor protection [78]. Passive designs like RCD snubbers (Fig. 9), as well as hybrid MOV-RCD configurations, are widely employed to mitigate overvoltage and oscillations during turn-off events [171], [172]. Advanced implementations further incorporate bidirectional or hybrid damping structures to ensure symmetrical protection and improved transient response in SiC-based breakers [173].

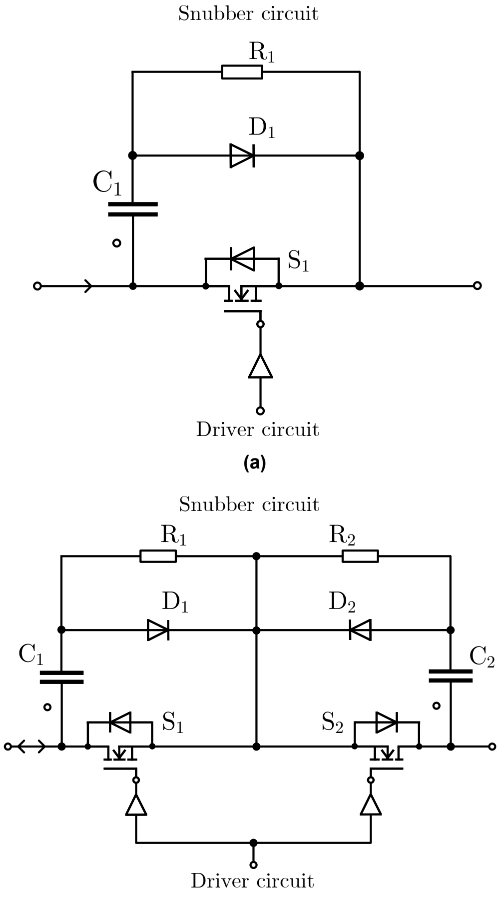
In [174], the authors point out the limitations and risks of passive voltage clamping circuits applied to SSCB design. To mitigate risks, active snubber architectures capable of isolating MOVs during steady-state conditions and dynamically engaging them during transients improve efficiency and prevent component degradation [175].

This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987



(a) (b) (c)

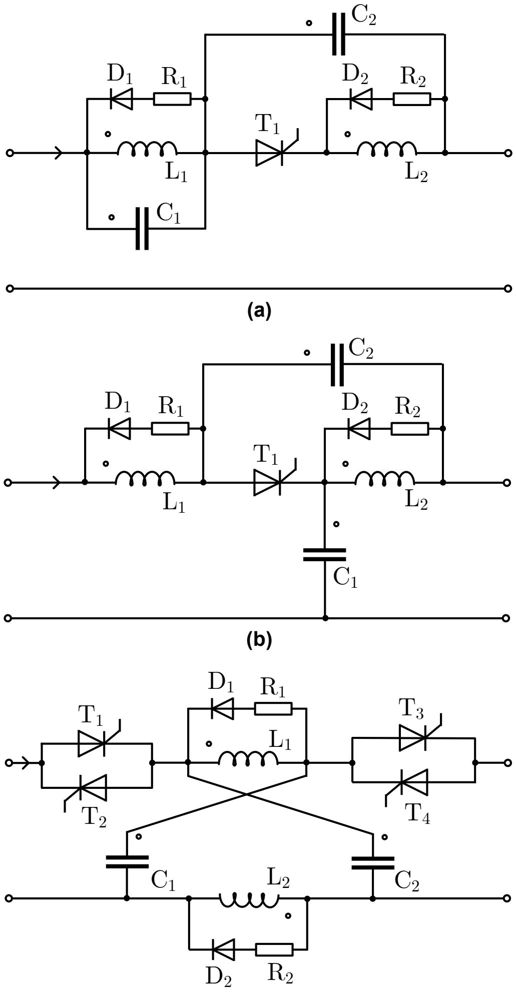
FIGURE 8. **Hybrid circuit breaker arrangements. a) series configuration. b) parallel configuration. c) mixed series-parallel configuration. [63]**



(a)

(b)

FIGURE 9. **Snubber circuits. a) unidirectional switch with snubber circuit. b) Bidirectional switch arrangement with snubber circuit. [78]**



(a)

(b)

(c)

FIGURE 10. **ZSSCB topologies. a) parallel ZSSCB. b) series ZSSCB. c) bidirectional crossed ZSSCB. [59]**

3) Z-SOURCE

Z-source DC SSCB (ZSSCB) topologies employ a passive LC network that provides a natural current compensation mechanism, enabling fault interruption through the discharge of stored capacitor energy. Depending on the configuration, ZSSCBs can operate as unidirectional or bidirectional devices, making them suitable for a wide range of DC distribution applications [59]. However, the Z-source topologies reliance on capacitors introduces a potential weak point, as their degradation may limit overall device lifespan and compromise interruption reliability. Fig. 10 shows examples of ZSSCB topologies.

The primary advantages of Z-source SSCBs are their simplicity and inherent reliability. Unlike conventional solid-state designs that rely on fast detection and complex control, ZSSCBs can achieve fault interruption autonomously once triggering conditions are met. This yields fast response times, reduced device cost, and compact structures. Additionally, the LC impedance network not only supports fault current compensation but also introduces filtering properties, acting as resonant, notch, or low-pass filters depending on the topology, which helps suppress transient disturbances and improves overall power quality [59].

4) SOFT-SWITCHED TOPOLOGIES

Soft-switched DC SSCBs are an approach to mitigate the problems of sudden switching that occur during breaking or making. One implementation combines a soft turn-off technique with a self-charging capability: in this method, a current-limiting inductor and reverse current injection cooperate to force the main switch into a near-zero current turn-off, thereby avoiding large power shocks and reducing device stress [30]. Another strategy employs an active injection circuit that achieves zero-current switching (ZCS) by injecting a countercurrent, ensuring that both main and auxiliary switches turn off under minimal current conditions, significantly improving the breaker's reliability [27]. At turn-on, a PWM-based soft-start mechanism may be applied, where the controller gradually adjusts the pulse width to ramp up load voltage and limit inrush current, preventing abrupt surges that would otherwise stress the semiconductors [28].

By employing these soft-switching techniques, transient stresses on semiconductor devices are significantly lowered by reducing high di/dt and dv/dt events. Experimental results confirm that these methods suppress gate oscillations and overvoltages while shortening interruption response times to the microsecond range [27], [28], [30].

E. BASED ON SWITCHING DEVICES

Recent advancements in semiconductor device technology have significantly shaped the design and performance of solid-state circuit breakers (SSCBs). Conventional silicon-based switches, such as IGBTs and MOSFETs, remain widely used due to their maturity, controllability, and cost-effectiveness [176]. However, the emergence of wide-bandgap (WBG) semiconductors, particularly silicon carbide (SiC) and gallium nitride (GaN), has enabled a new generation of high-performance SSCBs. These materials offer higher breakdown voltage, lower on-state resistance, and superior thermal conductivity, resulting in faster fault interruption, higher current density, and reduced conduction and switching losses [177].

Beyond discrete WBG devices, monolithic bidirectional semiconductor devices (MBDSs) have recently been proposed as promising candidates for future SSCBs [33]. MBDSs integrate bidirectional switching within a single monolithic structure, eliminating the need for back-to-back transistor pairs traditionally used in DC or AC breakers. This compact integration minimizes parasitic inductances, reduces conduction losses, and improves board-level efficiency, achieving lower on-state resistance per chip area compared to discrete solutions. In parallel, hybrid circuit breakers (HCBs) combine semiconductor switches with mechanical contacts to leverage their respective advantages: rapid solid-state fault interruption and reliable galvanic isolation [63]. As illustrated in Fig. 8, HCB topologies offer a practical trade-off between speed, isolation, and efficiency, and remain an essential configuration for applications requiring both fast protection and compliance with safety isolation standards.

F. EMERGING SSCB TECHNOLOGIES

Recent research has introduced several emerging SSCB technologies that push beyond conventional designs. Coupled-inductor assisted SSCBs have been proposed both for DC microgrids [178] and for battery energy storage systems [75], exploiting magnetic coupling to shape interruption dynamics and reduce component stress. Air-core inductive limiters have also been integrated into SSCB to mitigate high transient currents without magnetic saturation [179]. Modular SSCB architectures are another direction, allowing current sharing, fault-tolerant operation, and scalable interruption capability as demonstrated in bidirectional aircraft protection systems [180]. Multiport SSCBs [181] integrate shared commutation circuits across several feeders to reduce weight and component count, an essential requirement in more-electric aircraft. Even though the cited topologies have not yet reached industrial adoption, these developments collectively demonstrate a growing diversity of SSCB designs that improve switching speed, efficiency, and system integration for next-generation LVDC architectures - as explored in the following section.

G. PERFORMANCE COMPARISON OF SSCB TOPOLOGIES AND TECHNOLOGIES

The selection of an SSCB topology involves critical trade-offs between interruption speed, conduction efficiency, and power density [36], [52]. For instance, whereas conventional silicon-based devices are often preferred for high-current applications, WBG materials such as SiC and GaN have redefined performance benchmarks by achieving microsecond or even sub-microsecond response times [31], [32], [36]. Experimental data reveal that interruption speed is highly dependent on the auxiliary protection circuitry and sensing bandwidth [174].

Conduction losses remain a disadvantage to SSCB adoption. However, emerging WBG devices have demonstrated high efficiencies, matching traditional mechanical protection in steady-state operation [31], [72]. Table 4 summarizes key performance metrics of representative SSCB prototypes in the literature and classifies each entry according to the proposed framework. The rows are ordered by classification criteria in the sequence they appear: power flow, number of poles, isolation, semiconductor protection, and switching device.

TABLE 4. Comparison of Topologies and Technologies of SSCB and HCB prototypes in the literature.

Reference	V_{rated} (V) / I_{rated} (A)	Interruption Time	$R_{\text{DS(on)}}$ (mΩ)	Classification
[182]	450 / 50	0.35 μs	10	U·1P·NI·SN·Si
[32]	180 / 3	0.28 μs	35	U·1P·NI·SN·WBG
[183]	1200 / 75	1.5 μs	90	U·1P·NI·MOV·WBG
[167]	400 / 38	2 μs	45	U·1P·NI·MOV·WBG
[97]	340 / 38	2.1 μs	45	U·1P·NI·MOV·WBG
[168]	310 / 38	10 μs	45	U·1P·NI·MOV·WBG
[30]	375 / 100	143 μs	8	U·1P·NI·MOV·WBG
[73]	380 / 4.4	0.57 μs	60	U·1P·NI·—·WBG
[184]	400 / 30	0.68 μs	—	U·1P·NI·—·WBG
[185]	100 / 3	38 μs	—	U·1P·NI·ZS·Si
[186]	35 / 14	75 μs	—	U·1P·NI·ZS·Si
[187]	600 / 30	10 μs	—	U·1P·I·—·HCB
[188]	30 / 6	5 μs	—	B·1P·NI·ZS·Si
[178]	400 / 15	<50 μs	—	B·1P·NI·ZS·Si
[189]	120 / 3	190 μs	—	B·1P·NI·ZS·Si
[190]	250 / 40	2.6 μs	—	B·1P·NI·—·WBG
[191]	300 / 10	0.8 μs	200	B·1P·NI·—·MB

Classification coding (Power flow·Poles·Isolation·Protection·Device):
Power flow: U=Unidirectional, B=Bidirectional; Poles: 1P=Unipolar;
Isolation: NI=Non-isolated, I=Isolated;
Protection: MOV=MOV-based, SN=Snubber, ZS=Z-Source;
Device: Si=Silicon, WBG=Wide-Bandgap,
MB=Monolithic Bidirectional, HCB=Hybrid CB.

H. MAPPING OF COMMERCIAL IMPLEMENTATIONS

Table 5 maps five representative commercial LVDC SSCB products against the classification framework developed earlier. The products span a wide range of ratings, from 16 A residential devices to 2,500 A industrial breakers, and from 320 V to 1,500 V DC. Four of the five products support bidirectional operation, reflecting the prosumer characteristic of modern installations. Also, semiconductor technology stratifies by power level, with RB-IGCT and IGBT dominating high-power applications, while SiC and silicon MOSFETs are preferred at lower ratings.

VI. SSCB RISK ASSESSMENT AND DISCUSSION

The integration of SSCBs into DC electrical installations introduces a paradigm shift in protection strategies. While offering superior performance in terms of speed, controllability, and interruption without arcs, their application needs a risk assessment process [43]. Unlike traditional electromechanical breakers, which follow long-established standards, SSCB technology and its associated risks are still under discussion. Standardized safety functions testing and risk assessment procedures are therefore critical to ensure that these devices achieve their performance potential without compromising the safety objectives of an electrical installation. The rest of this section presents and discusses the topics of testing and risk assessment of SSCBs.

A. STANDARDIZED TESTING PROCEDURES FOR LVDC SSCB

The following is a summary of the standardized testing procedures to use as reference for testing the safety functions of LVDC SSCB devices. The current landscape is fragmented, relying on standards for mechanical breakers, contactors, or specialized installations (e.g., PV), necessitating a framework to address semiconductor-specific failure modes. It is important to note that short-circuit and overcurrent protection is the universally mandatory baseline function for any SSCB device under existing standards. The remaining protection functions discussed below, such as earth-fault detection, insulation monitoring, and arc-fault detection, may be required at the installation level or optionally integrated into SSCBs depending on the specific application and system configuration.

1) Short-Circuit and Overcurrent Protection

These tests verify the device's ability to safely interrupt high-magnitude faults and sustain temporary overloads without failure or excessive degradation.

- **Reference Standards:** IEC 60947-2 [41], IEC 60898-3 [81], IEC 60947-4-3 [42], IEC 62314 [43].
- **Breaking Capacity:** The rated short-circuit current and breaking capacities are evaluated using an $O - t - CO$ operation cycle (Open - time interval - Close-Open).
- **Semiconductor Let-through Energy (I^2t):** Tests must verify that the switching devices can withstand the peak current and let-through energy during a fault at maximum operational voltage and current.
- **Tripping Characteristics:** Verification of time-current behavior includes testing at around the set short-circuit current to ensure reliable tripping while preventing nuisance operations during inrush events.
- **Overload Withstand:** The device must establish and sustain an ON-state under designated levels of load and overload currents without failure or damage.
- **Standardization Gaps and Improvements:** Current breaker standards focus on mechanical arc extinction, while semiconductor contactor standards (IEC 60947-4-3) often lack rigorous breaking capacity verification for high-magnitude faults. An improvement in DC SSCB testing procedures would be to ensure that semiconductor temperature remains within the SOA during high di/dt events.

TABLE 5. Mapping of commercial LVDC SSCB products against the proposed classification framework, with claimed ratings and protection functions. Not all classification dimensions could be determined for every product; unknown values are marked as "—" in the table.

Manufacturer	Product	Voltage	Current	Key Protection Functions	Classification
ABB	SACE Infinitus	1,000 V	2,500 A	Short-circuit (<25 μs), arc mitigation, earth-fault	B·—·I·HCB
Astrol	Marine Breaker	1,500 V	350–3,000 A	Short-circuit (8 μs)	B·—·NI·Si
DC Systems	Current Router	250–800 V	16 A	Short-circuit (<1 μs), current limiting, earth-fault	B·1P·NI·—
Redler Tech	Power Rider	9–350 V	25–150 A	Overcurrent, overvoltage, overtemperature	U·—·NI·Si/WBG
Blixt Tech	Blixt Zero	320 V	16 A	Short-circuit	B·—·NI·Si

Classification coding (Power flow·Poles·Isolation·Device):
Power flow: U=Unidirectional, B=Bidirectional; Poles: 1P=Unipolar; Isolation: NI=Non-isolated, I=Isolated;
Device: Si=Conv. Silicon, WBG=Wide-Bandgap, HCB=Hybrid CB.

2) Earth-Fault and Residual Current Protection

Tests in this category focus on protecting from electric shock (direct contact) and preventing fires caused by leakage currents.

- **Reference Standards:** IEC 60755-1 [86], IEC 61008-1 [87], IEC 63112 [89], IEC 62109-2 [95].
- **Tripping Current Accuracy:** Standard procedures involve a steady increase of DC residual current until fire hazard thresholds.
- **Shock Hazard Monitoring:** Testing of sudden change current monitoring functions to ensure rapid disconnection to mitigate shock hazards.
- **Test Device Verification:** Current standards require a manual push-to-test function to verify device integrity. However, since SSCBs incorporate embedded electronics and control logic, this manual procedure can be replaced by an automatic self-test performed upon each reconnection event, analogous to the self-testing requirements for PV systems under IEC 63112 [89].
- **Insulation Monitoring (IT Systems):** In unearthed (IT) systems, insulation faults constitute a form of earth fault. Embedded insulation monitoring devices (IMDs) must provide continuous supervision of insulation resistance to earth (IEC 61557-8 [88], IEC 63112, IEC 62109-2 [95]). Tests verify the ability of the IMD to detect a reduction in insulation resistance below specified response values and trigger warning signals.

3) Arc-Fault Detection and Interruption

Arc-fault protection is one of the most critical safety concerns for the widespread adoption of LVDC installations, as DC arcs do not have natural zero-crossings. Parallel arc faults are relatively straightforward to detect because they produce overcurrent signatures that can be identified by conventional overcurrent protection. Series arc faults, on the other hand, are significantly more challenging to identify because they manifest only as an increase in the existing load impedance without triggering overcurrent thresholds, making them difficult to distinguish from normal load variations. Furthermore, both types of arcs can be masked by system impedances. The following procedures validate a breaker's capacity to identify these hazardous events using standardized arc generators to simulate series and parallel faults.

- **Reference Standards:** IEC 63027 [92], IEC 62606 [91].
- **Response Time and Energy Limits:** Current standards for AFPE mandate detection and interruption within specific thresholds, such as 2.5 seconds or before reaching a 750 Joule energy limit for PV inverter protection as defined in IEC 63027.
- **Load Discrimination Capability:** SSCBs must demonstrate a robust ability to discriminate between true arc signatures and normal switching transients across a diversity of loads typical of modern building appliances.
- **Standardization Gaps and Improvements:** Existing standards are either PV-specific (IEC 63027) or for AC circuits AFDDs (IEC 62606). Future research and standards must evaluate the proper energy thresholds for different installation conditions of branch circuits (e.g. 750 J for PV installations defined by IEC 63027), where lower energy arcs can still pose significant fire hazards depending on cable and construction materials. Also, standards must define rigorous testing procedures with standardized loads (including non-linear electronic loads), line impedance, arc generator electrodes or wiring interruption procedures, to ensure that arc-detection techniques do not compromise system availability through nuisance tripping.

B. RISK ASSESSMENT FRAMEWORK

The safety standard for solid-state relays, IEC 62314, recommends the risk assessment procedure based on ISO 12100 [192]. While ISO 12100 is originally intended for machinery, its principles are universally applicable to electrical safety engineering. The standard provides a structured framework for identifying hazards, estimating and evaluating risks, and implementing protective measures to eliminate hazards or reduce risks to an acceptable level.

This article has been accepted for publication in IEEE Open Journal of Power Electronics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/OJPEL.2026.3687987

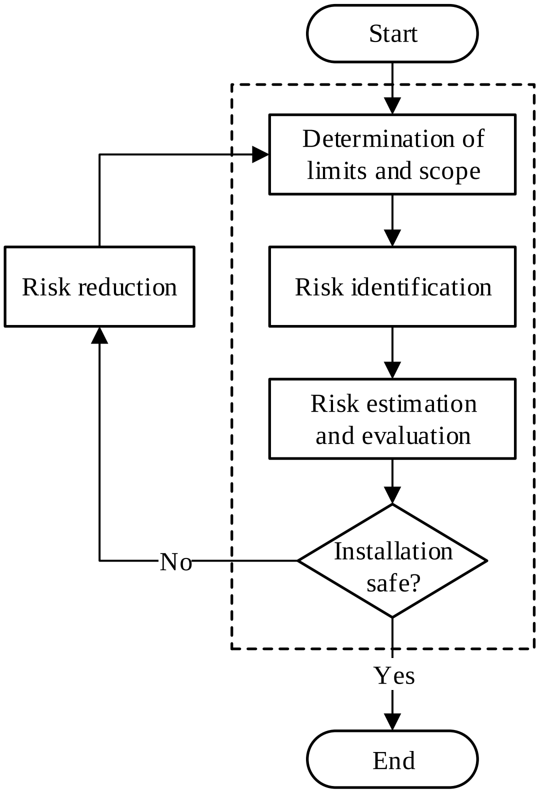


FIGURE 11. ISO 12100 risk assessment process.

The risk assessment process is an iterative cycle. Fig. 11 outlines the ISO 12100 procedure, which begins with a thorough analysis of the system's limits and intended use. The core of the process involves:

1) **Risk Identification:** Identifying potential hazards.
2) **Risk Estimation and Evaluation:** Evaluating the severity of potential harm and the probability of its occurrence, and determining whether the estimated risk requires reduction based on predefined safety objectives.
3) **Risk Reduction:** If risk is deemed too high, protective measures are implemented. These measures can comprise inherently safe design, safeguarding and information for use for example. The process then repeats to verify that the risk has been sufficiently reduced, continuing until an acceptable risk level is achieved.

The rest of this section applies the risk assessment methodology to a high-availability IT data center installation, mapping each risk to the SSCB protection features required to mitigate it and distinguishing between standardized mandatory functions, important but not yet standardized features, and optional enhancements.

C. INSTALLATION EXAMPLE

To illustrate how SSCB protection must adapt to the installation context, the following data center installation employing an isolated (IT) system is considered, where continuity under single faults is prioritized.

Fig. 12 illustrates an isolated DC distribution system for a high-availability data center. The defining feature of an IT system is that it is not referenced to earth, allowing it to continue operation uninterrupted upon a single fault to ground, appropriate for critical loads such as servers, data storage and networking equipment.

The following is the mapping of risks in the example IT installation. Also summarized in Table 6.

- **Main SSCB (i):** Acts as the main protective interface of the data center IT DC system. Its standardized functions include automatic disconnection for overcurrent and overload and surge protection. Important non-standardized functions include DC arc-fault detection to mitigate fire risk, and optional galvanic isolation (mechanical breaker) for maintenance and additional safety.
- **Critical Data Center Appliances SSCB (ii):** Protects critical loads (servers, data storage, networking, and cooling systems) that must remain operational during single-fault conditions. Standardized functions include automatic disconnection for overcurrent and overload, as well as insulation monitoring through an IMD to detect first insulation faults. Important non-standardized functions include redundancy for fault tolerance and DC arc-fault detection to prevent fire hazards.
- **Diesel Generator SSCB (iii):** Protects the auxiliary generator and its interface with the DC distribution system. Standardized functions include automatic disconnection under overcurrent and overload conditions and the inclusion of surge protection devices (SPD) to protect against transient surges. Important but non-standardized functions include two-pole isolation to prevent floating voltages and back-feed during switching, and DC arc-fault detection to improve fire safety.
- **BESS SSCB (iv):** Provides bidirectional protection between the BESS and the DC bus, managing both charge and discharge operations. Standardized protection includes automatic disconnection for overcurrent and overload. Important non-standardized functions include bidirectional current blocking, two-pole isolation to prevent floating voltages, and DC arc-fault detection to prevent fire hazards.
- **PV Generator SSCB (v):** Protects the photovoltaic generator that injects current into the DC bus. Standardized functions include automatic disconnection for overcurrent and overload. Important non-standardized features include two-pole isolation to prevent floating voltage hazards and DC arc-fault detection to prevent fire hazards.

D. DISCUSSION ON RISK REDUCTION

From the analysis of the installation example one can conclude that while standardized features, like overcurrent

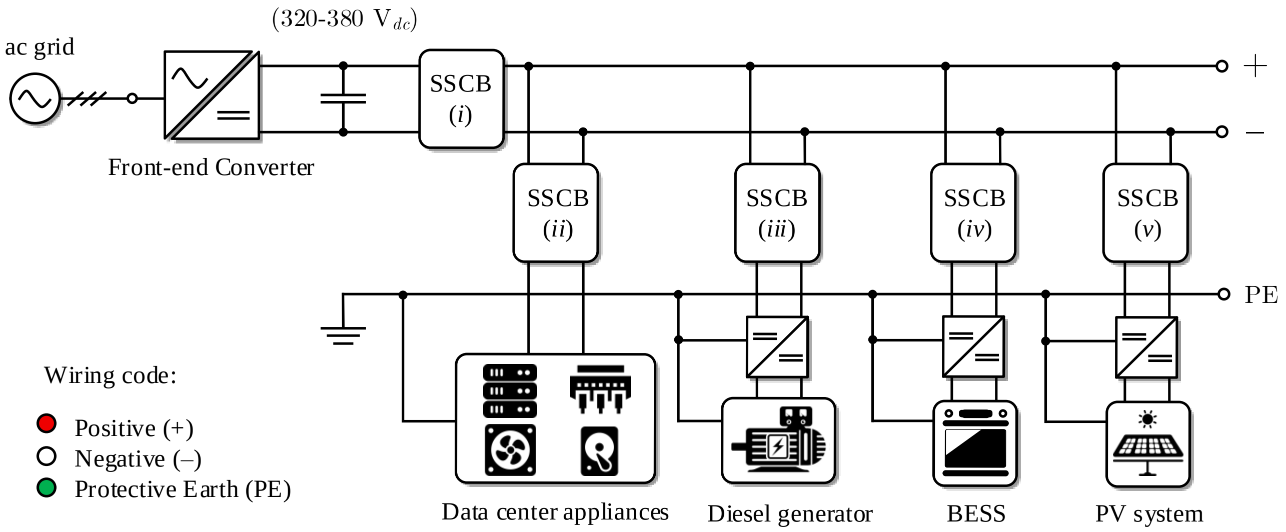


FIGURE 12. **Example IT data center installation with critical loads and wiring colour codes according to Current/OS protocols.**

protection, form the baseline safety inherited from AC systems, significant risks in DC systems are addressed by non-standardized protections, such as arc-fault protection. Furthermore, the type of installation significantly alters the risk evaluation. For instance, in TN-S residential systems, a protection mechanism like an RCD is mandatory, whereas in an isolated IT system it is not effective to achieve the acceptable risk level.

A complete risk assessment for DC SSCBs must extend beyond checking compliance with existing standards. It must actively identify hazards unique to DC systems and power electronics converters and specify performance requirements for the advanced protective functions that SSCBs are capable of providing. The ongoing standardization efforts must prioritize codifying these features to ensure that the adoption of SSCBs translates into a net positive gain in both system performance and safety.

1) Power Converters

As observed in the evolution of photovoltaic converters, many designs have moved from converters incorporating galvanic isolation to non-isolated (transformerless) converters, motivated by gains in efficiency, reduction in weight, and cost savings. In the context of PV inverters, IEC 62109 specifies that when galvanic isolation is removed, safety must be preserved through other means [94], [95]. The standard establishes a set of protective measures that become particularly relevant for LVDC installations safety requirements. Redundant relays are required to ensure reliable disconnection from the grid under fault conditions, preventing a single fault from leading to unsafe operation. Automatic self-testing must be performed before normal operation so that faulty functioning of safety devices does not compromise protection. Isolation tests are also required prior to connection, verifying that insulation resistance is above defined thresholds (a function of the inverter's power specification) and that no leakage paths exist. Beyond initial measurements, continuous monitoring of isolation is required through residual current monitoring units (RCMUs), so that any degradation or sudden change in isolation triggers immediate disconnection.

A comprehensive overview of the mandatory and smart features expected from AC-DC interlinking converters for DC buildings is presented in [194], including grid compatibility, isolation requirements, and the role of solid-state protection as a complementary function. In LVDC installations adopting non-isolated Active Front-End (AFE) converters, similar hazards arise: the lack of galvanic separation increases the risk of residual currents, insulation degradation, and earth-faults. Non-isolated topologies are expected to become increasingly attractive for their higher power density, lower cost, and improved efficiency. Without galvanic isolation at the converter stage, the main branch SSCB must be complemented by a mechanical breaker to provide protection against isolation-related risks. These protective functions — redundant switching devices, automatic self-tests, isolation verification, and continuous residual current monitoring — can also be integrated into the converter itself, as is already the case in PV inverters under IEC 62109, making the AFE converter part of the installation's layered protection alongside external circuit breakers.

2) Arc-fault

Arc-fault protection is another area where DC-specific hazards require standardization. The recent IEC 63027 [92] establishes performance and testing requirements for DC arc detection and interruption in photovoltaic systems. It ensures that protective devices can reliably identify and

TABLE 6. Risk Reduction Features of SSCBs in Data Center IT Installation.

SSCB	Risk Categories	Risk Reduction Features
Main SSCB (i)*	• Overcurrent / Short-Circuit • Overload / Thermal • Arcing • Surge / Transients	• **Mandatory, standardized** – SPD (IEC 60364-4-44 [193]) • **Important, not standardized** – DC arc-fault detection • **Optional - depending on front-end converter** – Galvanic isolation (mechanical breaker)
Critical data center appliances SSCB (ii)*	• Overcurrent / Short-Circuit • Overload / Thermal • Arcing • Surge / Transients • Isolation monitoring (single-fault)	• **Mandatory, standardized** – Single-fault monitoring with IMD (IEC 61557-8) • **Important, not standardized** – Redundancy – DC arc-fault detection • **Optional - improved selectivity** – Branch SPD
Diesel generator SSCB (iii)*	• Overcurrent / Short-Circuit • Overload / Thermal • Arcing • Surge / Transients • Back-feed / Floating voltages	• **Mandatory, standardized** – SPD • **Important, not standardized** – 2-pole isolation for converter input (prevent floating voltages) – DC arc-fault detection
BESS SSCB (iv)*	• Overcurrent / Short-Circuit • Overload / Thermal • Bidirectional power flow • Arcing • Surge / Transients • Back-feed / Floating voltages	• **Important, not standardized** – Bidirectional current blocking – 2-pole isolation for converter input (prevent floating voltages) – DC arc-fault detection • **Optional - improved selectivity** – Branch SPD
PV Generator SSCB (v)*	• Overcurrent / Short-Circuit • Overload / Thermal • Arcing • Surge / Transients • Back-feed / Floating voltages	• **Important, not standardized** – 2-pole isolation for converter input (prevent floating voltages) – DC arc-fault detection • **Optional - improved selectivity** – Branch SPD

*Automatic disconnection on overcurrent or overload is mandatory for all SSCBs.

interrupt series arcs before critical thresholds are reached. The standard prescribes realistic test conditions and trip criteria, such as maximum allowable arc energy and response times. By standardizing requirements for arc detection and interruption, IEC 63027 provides a pathway for incorporating arc protection into SSCBs in DC installations.

PV systems present relatively uniform conditions, often characterized by resistive and capacitive behavior, at the array input. In contrast, LVDC installations must handle a diverse mix of resistive, inductive, and capacitive loads, ranging from electronic appliances and lighting to motor-driven equipment. This diversity affects both the generation of arc signatures and the ability of protective devices to distinguish them from normal switching events. IEC 62606 [91], which defines general requirements for Arc Fault Detection Devices (AFDDs), addresses these challenges by mandating that detection devices be validated under a range of conditions. The standard prescribes tests where AFDDs must prove their capacity to discriminate genuine arc faults from normal load behavior. This requirement is particularly relevant for LVDC grids, where arcs in different localizations relative to the arc detector could be masked by impedance conditions. In this sense, the parameters affecting arc detection (load type, cable length and material, and impedance) must be explicitly considered in both device design and system-level risk assessment.

3) SSCB Semiconductor Devices

The reliability of semiconductor devices is a key determinant of SSCB performance and safety, particularly given their role in both current conduction and fault interruption. An understanding of their failure mechanisms is essential for integrating these components into the risk assessment framework and ensuring safety.

Power semiconductor devices are a common point of failure in power converters and protection systems. According to [195], common device-level failures include bond-wire lift-off and cracking, die-attach delamination, gate oxide breakdown, and short circuits caused by parasitic thyristor activation in IGBTs. These mechanisms are largely driven by thermo-mechanical stresses resulting from thermal expansion, high switching frequencies, and overcurrent or overvoltage transients. Such conditions can lead to increased on-state voltage drop, localized overheating, and eventual short-circuit failure between the device terminals.

Beyond intrinsic device weaknesses, system-level factors play a central role. The authors of [196] emphasize that failures in power electronic systems can be broadly classified into sudden and degraded failures. Sudden failures result from design defects, manufacturing variability, or overstress events, whereas degraded failures stem from long-term electrothermal fatigue processes such as solder fatigue, bond-wire degradation, and gate oxide wear-out. The interaction between thermal and electrical overstress remains the dominant cause of field failures, particularly in high-frequency or high-density converter applications. [197] reinforce that power semiconductor switches and capacitors account for most converter-related failures, with high mean temperature and temperature cycling as the primary stressors. Bond-wire fatigue, solder fatigue, and delamination are cited as the main wear-out mechanisms limiting device lifetime.

In the context of SSCB design, semiconductor failures represent a primary source of risk since the switching devices are the protection element. [198] demonstrates that SiC-based SSCBs, while offering superior switching speed and low conduction loss, exhibit strong dependency on thermal management and overload withstand capability. The study introduced a structured overload design and thermal evaluation process to define the SSCB's safe operating conditions. Using finite-element and transient thermal-network modeling, the authors determined that junction temperature rise is the limiting factor defining the SSCB time-current characteristic. From a risk-assessment perspective, SSCB reliability depends not only on instantaneous fault-clearing speed but also on its ability to sustain prolonged overloads without entering unsafe thermal states. The thermal characteristics of an SSCB should therefore be treated as a critical design specification.

Building upon this, [199] performed a long-term reliability study of a 1.2 kV low-voltage SSCB through over three million operation cycles, identifying five failure modes spanning electrical, mechanical, thermal, and cybersecurity domains. The observed mechanisms included overcurrent-induced IGBT failure, MOV degradation, fast recovery diode short-circuit, snubber resistor failure, and mechanical wear and corrosion. Each was systematically mitigated through design remedies, and the last 2.3 million cycles ran failure-free after all remedies were implemented. The study provides empirical evidence that SSCB reliability can be significantly increased when design refinements are integrated from early development stages.

From a risk assessment perspective, these failure modes directly affect the probability of hazardous events and must be addressed through measures such as thermal derating, device redundancy, and real-time junction temperature monitoring. Incorporating device-level degradation data and lifetime modeling into the risk analysis ensures that SSCBs maintain their protective integrity throughout service life.

VII. CONCLUSION

This paper presented a review of recent LVDC SSCBs developments, proposed a systematic classification scheme for SSCB design, introduced their elementary and additional safety functions, and presented a risk assessment framework for installations utilizing SSCBs. These contributions aim to clarify the design space, functional expectations, and safety considerations for the design of SSCBs in industry and their standardization.

The proposed classification criteria offer a structured approach to SSCB design, enabling consistent evaluation and comparison across different technologies and implementations. The categorization of safety functions into elementary and additional layers helps distinguish between baseline protection and enhanced system safety, facilitating clearer alignment with application-specific safety requirements. The risk assessment framework, grounded in ISO 12100 principles, allows for systematic hazard identification and mitigation planning, particularly in addressing DC-specific challenges such as arc-faults. In addition, the main standards for safety and protection, as well as upcoming directives were analyzed to provide for industry and developers a solid background to increase the technology adoption.

Together, these contributions have significant implications for the development and deployment of SSCBs in DC-powered buildings and infrastructures. They provide a foundational step toward harmonized standards, improved safety, and more informed design decisions in a domain where conventional AC protection principles may not fully apply.

REFERENCES

[1] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC Microgrids—Part I: A Review of Control Strategies and Stabilization Techniques," *IEEE Transactions on Power Electronics*, vol. 31, no. 7, pp. 4876–4891, 2016. DOI: 10.1109/TPEL.2015.2478859.

[2] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC Microgrids—Part II: A Review of Power Architectures, Applications, and Standardization Issues," *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3528–3549, 2016. DOI: 10.1109/TPEL.2015.2464277.

[3] D. Kumar, F. Zare, and A. Ghosh, "DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects," *IEEE Access*, vol. 5, pp. 12 230–12 256, 2017. DOI: 10.1109/ACCESS.2017.2705914.

[4] F. S. Al-Ismail, "DC Microgrid Planning, Operation, and Control: A Comprehensive Review," *IEEE Access*, vol. 9, pp. 36 154–36 172, 2021. DOI: 10.1109/ACCESS.2021.3062840.

[5] M. Fotopoulou, D. Rakopoulos, D. Trigkas, F. Stergiopoulos, O. Blanas, and S. Voutetakis, "State of the Art of Low and Medium Voltage Direct Current (DC) Microgrids," en, *Energies*, vol. 14, no. 18, p. 5595, 2021, Number: 18 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/en14185595.

[6] E. L. Carvalho, A. Chub, A. Blinov, S. N. Banavath, and D. Vinnikov, "Magnetically integrated multiport converter for energy management in dc-powered buildings," *Eletrônica de Potência*, vol. 29, e202445, 2024. DOI: 10.18618/REP.e202445.

[7] R. Weiss, L. Ott, and U. Boeke, "Energy efficient low-voltage DC-grids for commercial buildings," in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 154–158. DOI: 10.1109/ICDCM.2015.7152030.

[8] S. Ferahtia, A. Houari, T. Cioara, M. Bouznit, H. Rezk, and A. Djerioui, "Recent advances on energy management and control of direct current microgrid for smart cities and industry: A Survey," *Applied Energy*, vol. 368, p. 123 501, 2024. DOI: 10.1016/j.apenergy.2024.123501.

[9] E. L. Carvalho, A. Chub, N. Hassanpour, A. Blinov, A. K. Rathore, and D. Vinnikov, "P3r: Partial power postregulated grid-forming converter for prosumer dc buildings," *IEEE Transactions on Industrial Electronics*, vol. 72, no. 2, pp. 1628–1637, 2025. DOI: 10.1109/TIE.2024.3423358.

[10] L. H. Meneghetti et al., "Multifunctional pv converter for uninterrupted power supply," in *2019 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, 2019, pp. 1–6. DOI: 10.1109/ISGT-LA.2019.8895322.

[11] W. Javed and D. Chen, "Low Voltage DC Microgrid Protection System - A Review," in *2018 53rd International Universities Power Engineering Conference (UPEC)*, 2018, pp. 1–6. DOI: 10.1109/UPEC.2018.8541944.

[12] F. Mohan and N. Sasidharan, "Protection of low voltage DC microgrids: A review," *Electric Power Systems Research*, vol. 225, p. 109 822, 2023. DOI: 10.1016/j.epsr.2023.109822.

[13] D. Salomonsson, L. Soder, and A. Sannino, "Protection of Low-Voltage DC Microgrids," *IEEE Transactions on Power Delivery*, vol. 24, no. 3, pp. 1045–1053, 2009. DOI: 10.1109/TPWRD.2009.2016622.

[14] D. Dsa, A. Chinnusamy, S. N. Banavath, and E. L. Carvalho, "Implementation of protection features for a modular bidirectional solid-state battery disconnector," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 13, no. 3, pp. 3000–3012, 2025. DOI: 10.1109/JESTPE.2024.3502157.

[15] L. Hallemans et al., "Fault Identification and Interruption Methods in Low Voltage DC Grids — A Review," in *2019 IEEE Third International Conference on DC Microgrids (ICDCM)*, 2019, pp. 1–8. DOI: 10.1109/ICDCM45535.2019.9232856.

[16] R. Bhargav, B. R. Bhalja, and C. P. Gupta, "Novel Fault Detection and Localization Algorithm for Low-Voltage DC Microgrid," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 7, pp. 4498–4511, 2020. DOI: 10.1109/TII.2019.2942426.

[17] W. Javed, D. Chen, M. E. Farrag, and Y. Xu, "System Configuration, Fault Detection, Location, Isolation and Restoration: A Review on LVDC Microgrid Protections," en, *Energies*, vol. 12, no. 6, p. 1001, 2019, Number: 6 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/en12061001.

[18] S. Z. Jamali et al., "A High-Speed Fault Detection, Identification, and Isolation Method for a Last Mile Radial LVDC Distribution Network," en, *Energies*, vol. 11, no. 11, p. 2901, 2018, Number: 11 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/en11112901.

[19] S. Moussa, M. Jebali Ben Ghorbal, J. Arbi Ziani, and I. Slama-Belkhodja, "Residual-based Short-Circuit fault detection and isolation in LVDC microgrid," *Sustainable Energy Technologies and Assessments*, vol. 54, p. 102 803, 2022. DOI: 10.1016/j.seta.2022.102803.

[20] S. Kim, "Review of Protection Coordination Technologies in DC Distribution Systems," en, 2018.

[21] S. Sarangi, C. Biswal, B. K. Sahu, I. S. Samanta, and P. K. Rout, "Fault detection technique using time-varying filter-EMD and differential-CUSUM for LVDC microgrid system," *Electric Power Systems Research*, vol. 219, p. 109 254, 2023. DOI: 10.1016/j.epsr.2023.109254.

[22] Y. Reddy O, S. Chatterjee, A. K. Chakraborty, and A. R. Bhowmik, "Fault detection and location estimation for LVDC microgrid using self-parametric measurements," en, *International Transactions on Electrical Energy Systems*, vol. 30, no. 9, e12499, 2020, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2050-7038.12499. DOI: 10.1002/2050-7038.12499.

[23] S. Beheshtaein, R. M. Cuzner, M. Forouzesh, M. Savaghebi, and J. M. Guerrero, "DC Microgrid Protection: A Comprehensive Review," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2019, Conference Name: IEEE Journal of Emerging and Selected Topics in Power Electronics. DOI: 10.1109/JESTPE.2019.2904588.

[24] X. Song, P. Cairoli, Y. Du, and A. Antoniazzi, "A Review of Thyristor Based DC Solid-State Circuit Breakers," *IEEE Open Journal of Power Electronics*, vol. 2, pp. 659–672, 2021, Conference Name: IEEE Open Journal of Power Electronics. DOI: 10.1109/OJPEL.2021.3134640.

[25] S. N. Banavath, A. Pogulaguntla, G. De Carne, M. Joševski, and R. Singh, "Transformative Role of Solid-State Circuit Breakers in Advancing DC Systems for a Sustainable World," *IEEE Power Electronics Magazine*, vol. 11, no. 4, pp. 61–72, 2024, Conference Name: IEEE Power Electronics Magazine. DOI: 10.1109/MPEL.2024.3494452.

[26] A. Y. Liu, B. Xingwen Li, C. W. Lei, D. Zhaozi Zhang, and E. C. Gao, "A Review of Research Progress on Low-Voltage DC Solid-State Circuit Breakers," in *2024 IEEE 10th International Power Electronics and Motion Control Conference (IPEMC2024-ECCE Asia)*, 2024, pp. 3551–3556. DOI: 10.1109/IPEMC-ECCEAsia60879.2024.10567620.

[27] R. Kheirollahi, S. Zhao, H. Zhang, and F. Lu, "Fully Soft-Switched DC Solid-State Circuit Breakers," *IEEE Transactions on Power Electronics*, vol. 38, no. 6, pp. 6750–6754, 2023, Conference Name: IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2023.3237785.

[28] S. Zhao et al., "Soft Turn-Off DC Solid-State Circuit Breakers With Flexible Dual Tripping Schemes," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 12, no. 1, pp. 997–1010, 2024, Conference Name: IEEE Journal of Emerging and Selected Topics in Power Electronics. DOI: 10.1109/JESTPE.2023.3330637.

[29] Y. Zhou, Y. Feng, T. Liu, and Z. J. Shen, "A Digital-Controlled SiC-Based Solid State Circuit Breaker with Soft-Start Function for DC Microgrids," in *2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, ISSN: 2329-5767, 2018, pp. 1–7. DOI: 10.1109/PEDG.2018.8447563.

[30] X. Wu et al., "Low Voltage DC Solid-State Circuit Breaker With Soft Turn-Off and Self-Charging Operation," *IEEE Transactions on Power Electronics*, vol. 39, no. 10, pp. 13 071–13 080, 2024, Conference Name: IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2024.3427019.

[31] Y. Zhou, R. Na, Y. Feng, and Z. J. Shen, "GaN-Based Tri-Mode Intelligent Solid-State Circuit Breakers for Low-Voltage DC Power Networks," *IEEE Transactions on Power Electronics*, vol. 36, no. 6, pp. 6596–6607, 2021, Conference Name: IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2020.3037541.

[32] G. E. Mejia-Ruiz, M. R. A. Paternina, A. Zamora-Mendez, J. C. Rosas-Caro, and G. Bolivar-Ortiz, "A Novel GaN-Based Solid-State Circuit Breaker With Voltage Overshoot Suppression," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 9, pp. 8949–8960, 2022, Conference Name: IEEE Transactions on Industrial Electronics. DOI: 10.1109/TIE.2021.3116557.

[33] J. Huber and J. W. Kolar, "Monolithic Bidirectional Power Transistors," *IEEE Power Electronics Magazine*, vol. 10, no. 1, pp. 28–38,

2023, Conference Name: IEEE Power Electronics Magazine. DOI: 10.1109/MPEL.2023.3234747.

[34] S. M. Sanzad Lumen, R. Kannan, and N. Z. Yahaya, "DC Circuit Breaker: A Comprehensive Review of Solid State Topologies," in *2020 IEEE International Conference on Power and Energy (PECon)*, 2020, pp. 1–6. DOI: 10.1109/PECon48942.2020.9314300.

[35] A. Shukla and G. D. Demetriades, "A Survey on Hybrid Circuit-Breaker Topologies," *IEEE Transactions on Power Delivery*, vol. 30, no. 2, pp. 627–641, 2015. DOI: 10.1109/TPWRD.2014.2331696.

[36] Z. Chen et al., "Analysis and Experiments for IGBT, IEGT, and IGCT in Hybrid DC Circuit Breaker," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 4, pp. 2883–2892, 2018. DOI: 10.1109/TIE.2017.2764863.

[37] C. Li, J. Liang, and S. Wang, "Interlink Hybrid DC Circuit Breaker," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 11, pp. 8677–8686, 2018. DOI: 10.1109/TIE.2018.2803778.

[38] E. L. Carvalho, A. Blinov, A. Chub, P. Emiliani, G. de Carne, and D. Vinnikov, "Grid Integration of DC Buildings: Standards, Requirements and Power Converter Topologies," *IEEE Open Journal of Power Electronics*, vol. 3, pp. 798–823, 2022. DOI: 10.1109/OJPEL.2022.3217741.

[39] NEN, *Dc installations for low voltage*, NPR Guideline No. NPR 9090:2024, 80 pages; up to 1 500 V DC; relates to NEN 1010; ICS 91.140.50, Delft, The Netherlands, 2024.

[40] Current/OS Foundation, *Current/os system public document*, version 2.1.0, © Current/OS 2022–2024. Last saved: 06 Nov 2024. Public version of the Current/OS System Reference Document describing low-voltage DC prosumer installations., www.currentos.foundation: Current/OS Foundation, 2024.

[41] International Electrotechnical Commission, *Low-voltage switchgear and controlgear – part 2: Circuit-breakers*, IEC Standard No. IEC 60947:2:2024, 6th ed., ICS 29.130.20, Stability date 2026, ISBN 978-2-8322-9521-2, Geneva, Switzerland, 2024.

[42] International Electrotechnical Commission, *Low-voltage switchgear and controlgear – part 4-3: Contactors and motor-starters – semiconductor controllers and semiconductor contactors for non-motor loads*, IEC Standard No. IEC 60947-4-3:2020, 3.0 ed., ICS 29.130.20; Stability date 2027; ISBN 978-2-8327-0251-2, Geneva, Switzerland, 2020.

[43] International Electrotechnical Commission, *Solid-state relays – safety requirements*, IEC Standard No. IEC 62314:2022, 2.0 ed., Technical Committee 94 (TC 94), stability date 2025, Geneva, Switzerland, 2022.

[44] M. Mishra, B. Patnaik, M. Biswal, S. Hasan, and R. C. Bansal, "A systematic review on DC-microgrid protection and grounding techniques: Issues, challenges and future perspective," *Applied Energy*, vol. 313, p. 118 810, 2022. DOI: 10.1016/j.apenergy.2022.118810.

[45] N. Bayati, A. Hajizadeh, and M. Soltani, "Protection in DC microgrids: A comparative review," en, *IET Smart Grid*, vol. 1, no. 3, pp. 66–75, 2018, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1049/iet-stg.2018.0035. DOI: 10.1049/iet-stg.2018.0035.

[46] L. Zhang, N. Tai, W. Huang, J. Liu, and Y. Wang, "A review on protection of DC microgrids," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 6, pp. 1113–1127, 2018. DOI: 10.1007/s40565-018-0381-9.

[47] S. Augustine, S. Brahma, J. E. Quiroz, and M. J. Reno, "DC Microgrid Protection: Review and Challenges," English, Sandia National Lab. (SNL-NM), Albuquerque, NM (United States), Tech. Rep. SAND-2018-8853, 2018. DOI: 10.2172/1465634.

[48] J. He, K. Chen, M. Li, Y. Luo, C. Liang, and Y. Xu, "Review of Protection and Fault Handling for a Flexible DC Grid," *Protection and Control of Modern Power Systems*, vol. 5, no. 2, pp. 1–15, 2020. DOI: 10.1186/s41601-020-00157-9.

[49] M. Moradian, T. T. Lie, and K. Gunawardane, "DC Circuit Breaker Evolution, Design, and Analysis," en, *Energies*, vol. 16, no. 17, p. 6130, 2023, Number: 17 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/en16176130.

[50] Q. Huo, J. Xiong, N. Zhang, X. Guo, L. Wu, and T. Wei, "Review of DC circuit breaker application," *Electric Power Systems Research*, vol. 209, p. 107 946, 2022. DOI: 10.1016/j.epsr.2022.107946.

[51] J. Kolli and A. S. Rana, "Systematic Review and Meta-analysis of DC Circuit Breaker Technologies for Sustainable DC Grids," en, *Journal of The Institution of Engineers (India): Series B*, vol. 105, no. 3, pp. 701–712, 2024. DOI: 10.1007/s40031-024-01018-x.

[52] S. Zheng, R. Kheirollahi, J. Pan, L. Xue, J. Wang, and F. Lu, "DC Circuit Breakers: A Technology Development Status Survey," *IEEE Transactions on Smart Grid*, vol. 13, no. 5, pp. 3915–3928, 2022. DOI: 10.1109/TSG.2021.3123538.

[53] Z. Yu, R. Bai, Y. Zhang, and Y. Zhu, "Review of DC Circuit Breaker Technology Development," in *2022 7th Asia Conference on Power and Electrical Engineering (ACPEE)*, 2022, pp. 621–626. DOI: 10.1109/ACPEE53904.2022.9783627.

[54] Q. Guo, J. Zhang, and T. Chi, "Review of DC Circuit Breaker Technology," in *2022 IEEE Sustainable Power and Energy Conference (iSPEC)*, 2022, pp. 1–5. DOI: 10.1109/iSPEC54162.2022.10033027.

[55] B. Perea-Mena, J. A. Valencia-Velasquez, J. M. López-Lezama, J. B. Cano-Quintero, and N. Muñoz-Galeano, "Circuit Breakers in Low- and Medium-Voltage DC Microgrids for Protection against Short-Circuit Electrical Faults: Evolution and Future Challenges," en, *Applied Sciences*, vol. 12, no. 1, p. 15, 2022, Number: 1 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/app12010015.

[56] R. Rodrigues, Y. Du, A. Antoniazzi, and P. Cairoli, "A Review of Solid-State Circuit Breakers," *IEEE Transactions on Power Electronics*, vol. 36, no. 1, pp. 364–377, 2021, Conference Name: IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2020.3003358.

[57] Z. J. Shen, Z. Miao, and A. M. Roshandeh, "Solid state circuit breakers for DC micrgrids: Current status and future trends," in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 228–233. DOI: 10.1109/ICDCM.2015.7152044.

[58] I. Almutairy, "Solid state circuit breaker protection devices for DC microgrid in review," in *2016 5th International Conference on Electronic Devices, Systems and Applications (ICEDSA)*, ISSN: 2159-2055, 2016, pp. 1–3. DOI: 10.1109/ICEDSA.2016.7818478.

[59] C. E. Ugalde-Loo, Y. Wang, S. Wang, W. Ming, J. Liang, and W. Li, "Review on Z-Source Solid State Circuit Breakers for DC Distribution Networks," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 1, pp. 15–27, 2023, Conference Name: CSEE Journal of Power and Energy Systems. DOI: 10.17775/CSEEJPES.2022.04320.

[60] S. Rahimpour, O. Husev, and D. Vinnikov, "Impedance-Source DC Solid-State Circuit Breakers: An Overview," in *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2022, pp. 186–191. DOI: 10.1109/SPEEDAM53979.2022.9842138.

[61] M. R. Abed, A. Oday A., B. Ghassan A., and P. Gomez, "A comprehensive review of impedance source network DC circuit breaker topologies," *Cogent Engineering*, vol. 11, no. 1, p. 2 340 275, 2024, Publisher: Cogent OA _eprint: https://doi.org/10.1080/23311916.2024.2340275. DOI: 10.1080/23311916.2024.2340275.

[62] R. Rodrigues, T. Jiang, Y. Du, P. Cairoli, and H. Zheng, "Solid state circuit breakers for shipboard distribution systems," in *2017 IEEE Electric Ship Technologies Symposium (ESTS)*, 2017, pp. 406–413. DOI: 10.1109/ESTS.2017.8069314.

[63] A. R. F. Bento, F. Bento, and A. J. M. Cardoso, "A Review on Hybrid Circuit Breakers for DC Applications," *IEEE Open Journal of the Industrial Electronics Society*, vol. 4, pp. 432–450, 2023. DOI: 10.1109/OJIES.2023.3320900.

[64] Y. He, C. Xu, Y. Li, and F. Z. Peng, "A Survey of Hybrid Circuit Breakers: Component-Level Insights to System-Wide Integration," *IEEE Open Journal of Power Electronics*, vol. 5, pp. 513–533, 2024. DOI: 10.1109/OJPEL.2024.3381000.

[65] D. Jovcic, "Series LC DC circuit breaker," en, *High Voltage*, vol. 4, no. 2, pp. 130–137, 2019, _eprint: https://ietresearch.onlinelibrary.wiley.com/doi/pdf/10.1049/hve.2019.0003. DOI: 10.1049/hve.2019.0003.

[66] J. Yin, Y. Zhao, J. Duan, and S. Liang, "Study on the effect of arc chamber structures on the post-arc characteristics of generator circuit breaker," *Electric Power Systems Research*, vol. 233, p. 110 428, 2024. DOI: 10.1016/j.epsr.2024.110428.

[67] R. Lazzari et al., "Selectivity and security of DC microgrid under line-to-ground fault," *Electric Power Systems Research*, vol. 165, pp. 238–249, 2018. DOI: 10.1016/j.epsr.2018.09.001.

[68] A. A. S. Emhemed and G. M. Burt, "An Advanced Protection Scheme for Enabling an LVDC Last Mile Distribution Network,"

IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2602–2609, 2014. DOI: 10.1109/TSG.2014.2335111.

[69] N. H. Van Der Blij, P. Purgat, T. B. Soeiro, L. M. Ramirez-Elizondo, M. T. J. Spaan, and P. Bauer, “Decentralized Plug-and-Play Protection Scheme for Low Voltage DC Grids,” en, *Energies*, vol. 13, no. 12, p. 3167, 2020. DOI: 10.3390/en13123167.

[70] N. H. V. D. Blij, P. Purgat, T. B. Soeiro, L. M. Ramirez-Elizondo, M. T. J. Spaan, and P. Bauer, “Protection Framework for Low Voltage DC Grids,” in *2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC)*, Gliwice, Poland: IEEE, 2021, pp. 331–337. DOI: 10.1109/PEMC48073.2021.9432618.

[71] K. Tan, X. Song, C. Peng, P. Liu, and A. Q. Huang, “Hierarchical protection architecture for 380V DC data center application,” in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, USA: IEEE, 2016, pp. 1–8. DOI: 10.1109/ECCE.2016.7855145.

[72] S. S.-M. Wong, X. Li, T. C.-Y. Lau, and R. T.-H. Li, “A Design of Cost-Efficient Solid-State Circuit Breaker for LVDC Grid Applications,” *IEEE Transactions on Power Electronics*, vol. 41, no. 1, pp. 1241–1252, 2026. DOI: 10.1109/TPEL.2025.3596810.

[73] D. Marroqui, J. M. Blanes, A. Garrigos, and R. Gutierrez, “Self-Powered 380 V DC SiC Solid-State Circuit Breaker and Fault Current Limiter,” *IEEE Transactions on Power Electronics*, vol. 34, no. 10, pp. 9600–9608, 2019. DOI: 10.1109/TPEL.2019.2893104.

[74] Y. Zhou, Y. Feng, T. Liu, and Z. J. Shen, “Short Circuit Fault Location in DC Power Network Using Intelligent SiC Solid-State Circuit Breaker,” in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, 2018, pp. 485–491. DOI: 10.1109/ECCE.2018.8557923.

[75] K.-Y. Lo, T.-W. Huang, and K.-H. Liu, “A Solid-State Circuit Breaker Based on Coupled-Inductor for Battery Energy Storage System,” *IEEE Access*, vol. 12, pp. 180 903–180 912, 2024. DOI: 10.1109/ACCESS.2024.3510403.

[76] S. Chevale, S. Mahajan, J. Bedarkar, A. Mathew, A. V. D. Prasad, and A. Mitra, “Application of Z-Source Circuit Breaker in a Solar PV based DC Microgrid with Battery Storage,” in *2021 9th IEEE International Conference on Power Systems (ICPS)*, Kharagpur, India: IEEE, 2021, pp. 1–6. DOI: 10.1109/ICPS52420.2021.9670127.

[77] P. Purgat, S. Shah, N. van der Blij, Z. Qin, and P. Bauer, “Design criteria of solid-state circuit breaker for low-voltage microgrids,” en, *IET Power Electronics*, vol. 14, no. 7, pp. 1284–1299, 2021, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1049/pel2.12089. DOI: 10.1049/pel2.12089.

[78] G. Gregis, L. Piegari, L. Raciti, and T. Masper, “A Review of Voltage-Clamping Methods for Solid-State Circuit Breakers,” *IEEE Open Journal of Power Electronics*, vol. 5, pp. 873–890, 2024. DOI: 10.1109/OJPEL.2024.3411110.

[79] International Electrotechnical Commission, *Low-voltage switchgear and controlgear — part 1: General rules*, IEC Standard No. IEC 60947-1:2020, 6th ed., ICS 29.130.20, Stability date 2026, ISBN 978-2-8322-8026-3, Geneva, Switzerland, 2020.

[80] International Electrotechnical Commission, *Electrical accessories – circuit-breakers for overcurrent protection for household and similar installations – part 2: Circuit-breakers for ac and dc operation*, IEC Standard No. IEC 60898-2:2016, 2nd ed., ICS 29.120.50, Stability date 2026, ISBN 978-2-8322-3553-9, Geneva, Switzerland, 2016.

[81] International Electrotechnical Commission, *Electrical accessories – circuit-breakers for overcurrent protection for household and similar installations – part 3: Circuit-breakers for dc operation*, IEC Standard No. IEC 60898-3:2019/AMD1:2022, Edition 1.1, ICS 29.120.50; Stability date 2026; ISBN 978-2-8322-4698-6, Geneva, Switzerland, 2022.

[82] International Electrotechnical Commission, *Circuit-breakers for equipment (cbe)*, IEC Standard No. IEC 60934:2019, 4th ed., Technical Committee 23/SC 23E, ICS 29.120.40 / 29.120.50, Stability date 2030, ISBN 978-2-8322-6391-4, Geneva, Switzerland, 2019.

[83] International Electrotechnical Commission, *Low-voltage electrical installations — part 4-43: Protection for safety — protection against overcurrent*, IEC Standard No. IEC 60364-4-43:2023, 4th ed., ICS 29.120.50; cancels and replaces the 2008 edition; technical revision including new clause “Terms and definitions”, restructuring, and added requirements for neutral or mid-point conductors., Geneva, Switzerland, 2023.

[84] International Electrotechnical Commission, *Low-voltage electrical installations — part 4-41: Protection for safety — protection against electric shock*, IEC Standard No. IEC 60364-4-41:2005+A1:2017 (Edition 5.0 with Amendment 1), Consolidated version of 2005 edition + Amendment 1; ICS 13.260 91.140.50; ISBN 978-2-8322-3813-4; Stability date 2027; 28 pages, Geneva, Switzerland, 2017.

[85] International Electrotechnical Commission, *Low-voltage electrical installations — part 4-42: Protection for safety — protection against thermal effects*, IEC Standard No. IEC 60364-4-42:2024, 4th ed., ICS 29.120.50; ICS 91.140.50; Stability date 2029; ISBN 978-2-8322-9909-8; 64 pages, Geneva, Switzerland, 2024.

[86] International Electrotechnical Commission, *General safety requirements for residual current operated protective devices – part 1: Residual current operated protective devices for dc systems*, IEC Standard No. IEC 60755-1:2022, 1st ed., ICS 29.120.50; ISBN 978-2-8322-5867-5; Technical Committee 23/SC 23E; Group Safety Publication, Geneva, Switzerland, 2022.

[87] International Electrotechnical Commission, *Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (rccbs) — part 1: General rules*, IEC Standard No. IEC 61008-1:2024, 4th ed., ICS 29.120.50; 240 pages; ISBN 978-2-8327-0007-5, Geneva, Switzerland, 2024.

[88] International Electrotechnical Commission, *Electrical safety in low-voltage distribution systems up to 1 000 v a.c. and 1 500 v d.c. — equipment for testing, measuring or monitoring of protective measures — part 8: Insulation monitoring devices for it systems*, IEC Standard No. IEC 61557-8:2014 (3rd ed.), Technical Committee 85; ICS 17.220.20/29.080.30; Includes Annex C: Insulation monitoring devices for photovoltaic systems (PV-IMD)., Geneva, Switzerland, 2014.

[89] International Electrotechnical Commission, *Photovoltaic (pv) arrays — earth fault protection equipment — safety and safety-related functionality*, IEC Standard No. IEC 63112:2021, 1st ed., ICS 27.160; Stability date 2028; ISBN 978-2-8322-9872-5; 154 pages, Geneva, Switzerland, 2021.

[90] International Electrotechnical Commission, *Insulation coordination for equipment within low-voltage supply systems — part 1: Principles, requirements and tests*, IEC Standard No. IEC 60664-1:2020, Edition 3.0, ICS 29.080.30; Basic safety publication; Edition 3.0; Amendment 1 planned; ISBN 978-2-8322-8287-8, Geneva, Switzerland, 2020.

[91] International Electrotechnical Commission, *General requirements for arc fault detection and protection devices (afdds)*, IEC Standard No. IEC 62606:2013/AMD2:2022, Edition 1.0 (Consolidated), Technical Committee 23/SC 23E; ICS 29.120.01, 29.120.50; Stability date 2026; ISBN 978-2-8322-5963-4; 52 pages, Geneva, Switzerland, 2022.

[92] International Electrotechnical Commission, *Photovoltaic power systems — dc arc detection and interruption*, IEC Standard No. IEC 63027:2023, 1st ed., Technical Committee 82 (Solar photovoltaic energy systems); ICS 27.160; Stability date 2029; ISBN 978-2-8322-6743-1; 131 pages, Geneva, Switzerland, 2023.

[93] Underwriters Laboratories Inc., *Photovoltaic (pv) dc arc-fault circuit protection*, UL Standard No. UL 1699B, Edition 1 (Red Line) dated July 9 2024, ANSI approved July 9 2024; covers PV DC arc-fault protection devices rated 1500 V or less in photovoltaic electrical energy systems., Northbrook, IL, USA, 2024.

[94] International Electrotechnical Commission, *Safety of power converters for use in photovoltaic power systems — part 1: General requirements*, IEC Standard No. IEC 62109-1:2010, 1st ed., ICS 27.160; Stability date 2025; ISBN 978-2-88910-621-9; 316 pages, Geneva, Switzerland, 2010.

[95] International Electrotechnical Commission, *Safety of power converters for use in photovoltaic power systems – part 2: Particular requirements for inverters*, IEC Standard No. IEC 62109-2:2011, 1st ed., 64 pages; ISBN 978-2-88912-491-6, Geneva, Switzerland, 2011.

[96] International Electrotechnical Commission, *Low-voltage electrical installations — part 1: Fundamental principles, assessment of general characteristics, and definitions*, IEC Standard No. IEC 60364-1:2025, 6th ed., ICS 91.140.50; Stability date 2031; ISBN 978-2-8327-0677-0; 99 pages, Geneva, Switzerland, 2025.

[97] K. Palaniappan, W. Sedano, M. Vygoder, N. Hoeft, R. Cuzner, and Z. J. Shen, “Short-Circuit Fault Discrimination Using SiC JFET-Based Self-Powered Solid-State Circuit Breakers in a Residential DC

Community Microgrid," *IEEE Transactions on Industry Applications*, vol. 56, no. 4, pp. 3466–3476, 2020. DOI: 10.1109/TIA.2020.2995114.

[98] P. Pan and R. K. Mandal, "Intelligent Short-Circuit Protection with Solid-State Circuit Breakers for Low-Voltage DC Microgrids," *IETE Journal of Research*, vol. 70, no. 3, pp. 3187–3203, 2024, Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/03772063.2023.2181228. DOI: 10.1080/03772063.2023.2181228.

[99] S. Munasib and J. C. Balda, "Short-circuit protection for low-voltage DC microgrids based on solid-state circuit breakers," in *2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, ISSN: 2329-5767, 2016, pp. 1–7. DOI: 10.1109/PEDG.2016.7527062.

[100] K. A. Saleh, A. Hooshyar, and E. F. El-Saadany, "Hybrid Passive-Overcurrent Relay for Detection of Faults in Low-Voltage DC Grids," *IEEE Transactions on Smart Grid*, vol. 8, no. 3, pp. 1129–1138, 2017. DOI: 10.1109/TSG.2015.2477482.

[101] J. Gehring, R. Schwanninger, A. Nowak, B. Wunder, V. Lorentz, and M. März, "Method for Detection and Limitation of Short-Circuit Currents for Semiconductor Circuit Breakers in LVDC Grids Using a Pre-Saturated Inductor," *IEEE Open Journal of Power Electronics*, vol. 6, pp. 524–536, 2025. DOI: 10.1109/OJPEL.2025.3555797.

[102] W. Liu, F. Liu, X. Zha, M. Huang, C. Chen, and Y. Zhuang, "An Improved SSCB Combining Fault Interruption and Fault Location Functions for DC Line Short-Circuit Fault Protection," *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 858–868, 2019. DOI: 10.1109/TPWRD.2018.2882497.

[103] H. Shen, L. Qi, X. Zhang, C. Jiao, and S. Zhang, "High reliability overcurrent protection of DC circuit breaker under DC short-circuit fault," *CSEE Journal of Power and Energy Systems*, pp. 1–10, 2023. DOI: 10.17775/CSEEJPES.2023.02030.

[104] A. Shabani and K. Mazlumi, "Evaluation of a Communication-Assisted Overcurrent Protection Scheme for Photovoltaic-Based DC Microgrid," *IEEE Transactions on Smart Grid*, vol. 11, no. 1, pp. 429–439, 2020. DOI: 10.1109/TSG.2019.2923769.

[105] International Electrotechnical Commission, *Iec 60364: Low-voltage electrical installations – series*, IEC Standard IEC 60364, all parts, Covers fundamental principles, protection for safety, selection and erection of equipment, verification, special locations, energy efficiency, etc., Geneva, Switzerland.

[106] D. M. Bui, S.-L. Chen, C.-H. Wu, K.-Y. Lien, C.-H. Huang, and K.-K. Jen, "Review on protection coordination strategies and development of an effective protection coordination system for DC microgrid," in *2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, ISSN: 2157-4847, 2014, pp. 1–10. DOI: 10.1109/APPEEC.2014.7066159.

[107] R. Kheirollahi, H. Zhang, J. Wang, X. Lu, and F. Lu, "Optimal Coordination of Ultrafast Solid-State Circuit Breakers in DC Microgrids," in *2021 IEEE Fourth International Conference on DC Microgrids (ICDCM)*, 2021, pp. 1–5. DOI: 10.1109/ICDCM50975.2021.9504676.

[108] R. Kheirollahi, S. Zhao, H. Zhang, X. Lu, J. Wang, and F. Lu, "Coordination of Ultrafast Solid-State Circuit Breakers in Radial DC Microgrids," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 4, pp. 4690–4702, 2022. DOI: 10.1109/JESTPE.2021.3109483.

[109] B. K. Choudhury, G. K. Rao, and P. Jena, "A Novel Protection Coordination Strategy for Zonal DC Microgrids," *IEEE Transactions on Industry Applications*, vol. 60, no. 4, pp. 5624–5636, 2024. DOI: 10.1109/TIA.2024.3398618.

[110] G. Chavan, X. Song, D. Chatterjee, A. Patni, and P. Cairoli, "Coordination of Solid-State Circuit Breakers for DC Grids Under High-Fault-di/dt Conditions," in *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, 2022, pp. 1–5. DOI: 10.1109/ECCE50734.2022.9947849.

[111] G. Chavan, C. Xu, A. Patni, S. Englebretson, and P. Cairoli, "Coordination of RB-IGCT-based Solid-State Circuit Breakers for high-di/dt faults in DC EV microgrids," in *2024 IEEE Applied Power Electronics Conference and Exposition (APEC)*, ISSN: 2470-6647, 2024, pp. 3086–3091. DOI: 10.1109/APEC48139.2024.10509291.

[112] A. Patni, G. Chavan, C. Xu, Z. Dong, and P. Cairoli, "Investigation of Coordination Limits between SiC-based and IGCT-based SSCBs," in *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, 2024, pp. 7365–7369. DOI: 10.1109/ECCE55643.2024.10860982.

[113] J. L. Putzke, L. Michels, and L. V. Bellinaso, "Electric Arcs in Photovoltaic Systems: A Comparative Analysis of IEC 63027, UL 1699B, and GB-t 39750 Standards," in *2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP)*, ISSN: 2832-2983, 2023, pp. 1–5. DOI: 10.1109/SPEC56436.2023.10407946.

[114] W. Xu, X. Wu, Y. Li, H. Wang, L. Lu, and M. Ouyang, "A comprehensive review of DC arc faults and their mechanisms, detection, early warning strategies, and protection in battery systems," *Renewable and Sustainable Energy Reviews*, vol. 186, p. 113 674, 2023. DOI: 10.1016/j.rser.2023.113674.

[115] S. Lu, B. T. Phung, and D. Zhang, "A comprehensive review on DC arc faults and their diagnosis methods in photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 89, pp. 88–98, 2018. DOI: 10.1016/j.rser.2018.03.010.

[116] A. H. Omran, D. M. Said, S. H. Abdulhussain, S. M. Hussin, and N. Ahmad, "MODELS, DETECTION METHODS, AND CHALLENGES IN DC ARC FAULT: A REVIEW," en, *Jurnal Teknologi (Sciences & Engineering)*, vol. 83, no. 4, pp. 1–16, 2021, Number: 4. DOI: 10.11113/jurnalteknologi.v83.15101.

[117] X. Yao, J. Wang, and D. L. Schweickart, "Review and recent developments in DC arc fault detection," in *2016 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2016, pp. 467–472. DOI: 10.1109/IPMHVC.2016.8012887.

[118] Z. Li, D. Cai, S. Luo, Z. Yang, H. Lu, and Q. Huang, "A Review on Arc Fault Diagnosis Methods for DC Distribution Networks," in *2024 6th Asia Energy and Electrical Engineering Symposium (AEEES)*, 2024, pp. 639–644. DOI: 10.1109/AEEES61147.2024.10544464.

[119] K. C. Paul, D. Waldmann, C. Chen, Y. Wang, and T. Zhao, "Artificial Intelligence for DC Arc Fault Detection in Photovoltaic Systems: A Comprehensive Review," *IEEE Access*, vol. 13, pp. 90 766–90 794, 2025. DOI: 10.1109/ACCESS.2025.3572521.

[120] Y. Mao, S. Safa, G. Smith, L. Wurth, R. Weiss, and J. Hagemeyer, "Why AI: A Comparative Study for Detection Methods in DC Series Arc Fault," *IEEE Access*, vol. 13, pp. 42 703–42 722, 2025. DOI: 10.1109/ACCESS.2025.3548309.

[121] V. Le, X. Yao, C. Miller, and B.-H. Tsao, "Series DC Arc Fault Detection Based on Ensemble Machine Learning," *IEEE Transactions on Power Electronics*, vol. 35, no. 8, pp. 7826–7839, 2020. DOI: 10.1109/TPEL.2020.2969561.

[122] K. Gajula, V. Le, X. Yao, S. Zou, and L. Herrera, "A Probabilistic Approach to Series Arc Fault Detection and Identification in DC Microgrids," *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 5, no. 1, pp. 27–38, 2024. DOI: 10.1109/JESTIE.2023.3331183.

[123] R. D. Telford, S. Galloway, B. Stephen, and I. Elders, "Diagnosis of Series DC Arc Faults—A Machine Learning Approach," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 4, pp. 1598–1609, 2017. DOI: 10.1109/TII.2016.2633335.

[124] W. Miao, Q. Xu, K. H. Lam, P. W. T. Pong, and H. V. Poor, "DC Arc-Fault Detection Based on Empirical Mode Decomposition of Arc Signatures and Support Vector Machine," *IEEE Sensors Journal*, vol. 21, no. 5, pp. 7024–7033, 2021. DOI: 10.1109/JSEN.2020.3041737.

[125] J. Yan, Q. Li, and S. Duan, "A Simplified Current Feature Extraction and Deployment Method for DC Series Arc Fault Detection," *IEEE Transactions on Industrial Electronics*, vol. 71, no. 1, pp. 625–634, 2024. DOI: 10.1109/TIE.2023.3247721.

[126] V. Le, C. Miller, B.-H. Tsao, and X. Yao, "Series Arc Fault Identification in DC Distribution Based on Random Forest Predicted Probability," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 6, pp. 5636–5648, 2023. DOI: 10.1109/JESTPE.2022.3228421.

[127] Z. Yin, L. Wang, B. Zhang, L. Meng, and Y. Zhang, "An Integrated DC Series Arc Fault Detection Method for Different Operating Conditions," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 12, pp. 12 720–12 729, 2021. DOI: 10.1109/TIE.2020.3044787.

[128] H.-L. Dang, J. Kim, S. Kwak, and S. Choi, "Series DC Arc Fault Detection Using Machine Learning Algorithms," *IEEE Access*, vol. 9, pp. 133 346–133 364, 2021. DOI: 10.1109/ACCESS.2021.3115512.

[129] S. Chae, J. Park, and S. Oh, "Series DC Arc Fault Detection Algorithm for DC Microgrids Using Relative Magnitude Comparison,"

IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 4, pp. 1270–1278, 2016. DOI: 10.1109/JESTPE.2016.2592186.

[130] M. H. Riza Alvy Syafi'i, E. Prasetyono, M. K. Khafidli, D. O. Anggriawan, and A. Tjahjono, "Real Time Series DC Arc Fault Detection Based on Fast Fourier Transform," in *2018 International Electronics Symposium on Engineering Technology and Applications (IES-ETA)*, 2018, pp. 25–30. DOI: 10.1109/ELECSYM.2018.8615525.

[131] S. Zhao, Y. Wang, F. Niu, C. Zhu, Y. Xu, and K. Li, "A Series DC Arc Fault Detection Method Based on Steady Pattern of High-Frequency Electromagnetic Radiation," *IEEE Transactions on Plasma Science*, vol. 47, no. 9, pp. 4370–4377, 2019. DOI: 10.1109/TPS.2019.2932747.

[132] Q. Xiong et al., "Series Arc Fault Detection and Localization in DC Distribution System," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 1, pp. 122–134, 2020. DOI: 10.1109/TIM.2019.2890892.

[133] M. Dołegowski and M. Szmajda, "A Novel Algorithm for Fast DC Electric Arc Detection," en, *Energies*, vol. 14, no. 2, p. 288, 2021, Number: 2 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/en14020288.

[134] H. Qian, B. Lee, Z. Wu, and G. Wang, "Research on DC arc fault detection in PV systems based on adjacent multi-segment spectral similarity and adaptive threshold model," *Solar Energy*, vol. 264, p. 112 011, 2023. DOI: 10.1016/j.solener.2023.112011.

[135] W. Miao, Z. Wang, F. Wang, K. H. Lam, and P. W. T. Pong, "Multi-characteristics Arc Model and Autocorrelation-Algorithm Based Arc Fault Detector for DC Microgrid," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 5, pp. 4875–4886, 2023. DOI: 10.1109/TIE.2022.3186351.

[136] J. Kim and S. Kwak, "Detection and Identification Technique for Series and Parallel DC Arc Faults," *IEEE Access*, vol. 10, pp. 60 474–60 485, 2022. DOI: 10.1109/ACCESS.2022.3180750.

[137] G. Yang, L. K. Marepalli, L. Herrera, and X. Yao, "Series DC Arc Fault Detection in DC Microgrids Based on Distributed Unknown Input Observers," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 3, pp. 4766–4781, 2024. DOI: 10.1109/TTE.2023.3318430.

[138] G. Yang, L. Herrera, and X. Yao, "Data-Driven Observer Based Detection for Series Arc Fault in DC Microgrids," in *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, 2024, pp. 1477–1483. DOI: 10.1109/ECCE55643.2024.10861403.

[139] X. Yao, V. Le, and I. Lee, "Unknown Input Observer-Based Series DC Arc Fault Detection in DC Microgrids," *IEEE Transactions on Power Electronics*, vol. 37, no. 4, pp. 4708–4718, 2022. DOI: 10.1109/TPEL.2021.3128642.

[140] T. Wang, L. Liang, Z. Hao, A. Monti, and F. Ponci, "A Comprehensive Fault Detection and Isolation Method for DC Microgrids Using Reduced-Order Unknown Input Observers," *IEEE Transactions on Power Delivery*, vol. 39, no. 1, pp. 479–495, 2024. DOI: 10.1109/TPWRD.2023.3274123.

[141] W. Miao, F. Zhi, F. Wang, X. Zhou, and Y. Luo, "Arc Fault Detection and Location Technique Based on State Space Modeling for DC Microgrid," in *2022 7th International Conference on Power and Renewable Energy (ICPRE)*, ISSN: 2768-0525, 2022, pp. 452–457. DOI: 10.1109/ICPRE55555.2022.9960322.

[142] G. Yang, L. Herrera, and X. Yao, "Detection of False Data Injection and Series Arc Faults in DC Microgrids Based on Unknown Input Observers," in *2023 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, 2023, pp. 1155–1159. DOI: 10.1109/ECCE53617.2023.10362745.

[143] W. Zhang, P. Xu, Y. Wang, D. Li, and B. Liu, "A DC arc detection method for photovoltaic (PV) systems," *Results in Engineering*, vol. 21, p. 101 807, 2024. DOI: 10.1016/j.rineng.2024.101807.

[144] Y. Wang, C. Bai, X. Qian, W. Liu, C. Zhu, and L. Ge, "A DC Series Arc Fault Detection Method Based on a Lightweight Convolutional Neural Network Used in Photovoltaic System," en, *Energies*, vol. 15, no. 8, p. 2877, 2022, Number: 8 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/en15082877.

[145] P. Zhang, Y. Xue, R. Song, X. Ma, and D. Sheng, "Photovoltaic DC arc fault detection method based on deep residual shrinkage network," en, *Journal of Power Electronics*, vol. 24, no. 11, pp. 1855–1867, 2024. DOI: 10.1007/s43236-024-00840-2.

[146] S. Lu, T. Sirojan, B. T. Phung, D. Zhang, and E. Ambikairajah, "DA-DCGAN: An Effective Methodology for DC Series Arc Fault Diagnosis in Photovoltaic Systems," *IEEE Access*, vol. 7, pp. 45 831–45 840, 2019. DOI: 10.1109/ACCESS.2019.2909267.

[147] X. Cai and R.-J. Wai, "Intelligent DC Arc-Fault Detection of Solar PV Power Generation System via Optimized VMD-Based Signal Processing and PSO–SVM Classifier," *IEEE Journal of Photovoltaics*, vol. 12, no. 4, pp. 1058–1077, 2022. DOI: 10.1109/JPHOTOV.2022.3166919.

[148] J.-B. Ahn, S.-J. Jeong, C.-G. Cho, and H.-J. Ryoo, "DC Series Arc Fault Detector With Differential DWT and Variable Threshold Method for Photovoltaic Systems," *IEEE Transactions on Industrial Informatics*, vol. 20, no. 7, pp. 9343–9351, 2024. DOI: 10.1109/TII.2024.3383541.

[149] Q. Xiong, S. Ji, L. Zhu, L. Zhong, and Y. Liu, "A Novel DC Arc Fault Detection Method Based on Electromagnetic Radiation Signal," *IEEE Transactions on Plasma Science*, vol. 45, no. 3, pp. 472–478, 2017. DOI: 10.1109/TPS.2017.2653817.

[150] H.-P. Park, M. Kim, J.-H. Jung, and S. Chae, "Series DC Arc Fault Detection Method for PV Systems Employing Differential Power Processing Structure," *IEEE Transactions on Power Electronics*, vol. 36, no. 9, pp. 9787–9795, 2021. DOI: 10.1109/TPEL.2021.3061968.

[151] A. Jose, A. M. Varghese, F. E. Jenson, P. Jacob, D. M. Anumod, and D. Thomas, "Solid-State Circuit Breaker based Smart Distribution Board with IoT Integration," in *2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT)*, Tirunelveli, India: IEEE, 2020, pp. 54–61. DOI: 10.1109/ICSSIT48917.2020.9214172.

[152] T. Jalakas and S.-E. Viiding, "Configurable Solid State Protection Devices for Residential DC Microgrids," in *2025 IEEE Seventh International Conference on DC Microgrids (ICDCM)*, 2025, pp. 1–5. DOI: 10.1109/ICDCM63994.2025.11144706.

[153] Y. Kabalci, E. Kabalci, S. Padmanaban, J. B. Holm-Nielsen, and F. Blaabjerg, "Internet of Things Applications as Energy Internet in Smart Grids and Smart Environments," en, *Electronics*, vol. 8, no. 9, p. 972, 2019. DOI: 10.3390/electronics8090972.

[154] S. Chen et al., "Internet of Things Based Smart Grids Supported by Intelligent Edge Computing," *IEEE Access*, vol. 7, pp. 74 089–74 102, 2019. DOI: 10.1109/ACCESS.2019.2920488.

[155] J. Sakhnini, H. Karimipour, A. Dehghantanha, R. M. Parizi, and G. Srivastava, "Security aspects of Internet of Things aided smart grids: A bibliometric survey," en, *Internet of Things*, vol. 14, p. 100 111, 2021. DOI: 10.1016/j.iot.2019.100111.

[156] D. Deka, R. Baldick, and S. Vishwanath, "One breaker is enough: Hidden topology attacks on power grids," in *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, USA: IEEE, 2015, pp. 1–5. DOI: 10.1109/PESGM.2015.7286568.

[157] International Electrotechnical Commission, *Low-voltage switchgear and controlgear — security aspects*, IEC Technical Specification No. IEC TS 63208:2020, 1st ed., ICS 29.130.20; ISBN 978-2-8322-8021-8; 46 pages, Geneva, Switzerland, 2020.

[158] International Electrotechnical Commission, *Low-voltage switchgear and controlgear — guidance for the development of embedded software*, IEC Technical Report No. IEC TR 63201:2019, 1st ed., ICS 29.130.20; Stability date 2028; ISBN 978-2-8322-7006-6; 27 pages, Geneva, Switzerland, 2019.

[159] International Electrotechnical Commission, *Power systems management and associated information exchange — data and communications security (iec 62351 series)*, IEC Standard No. IEC 62351 (All Parts), Edition 1.0, Series covering cyber-security of power system communication protocols (TC 57). ICS 33.200., Geneva, Switzerland, 2025.

[160] Institute of Electrical and Electronics Engineers, *Ieee guide for cybersecurity of distributed energy resources interconnected with electric power systems*, IEEE Standard No. IEEE 1547.3-2023, Supersedes IEEE 1547.3-2007; provides guidelines for cybersecurity of DER interfaces., New York, NY, USA, 2023.

[161] International Organization for Standardization and International Electrotechnical Commission, *Cybersecurity — iot security and privacy — device baseline requirements*, ISO/IEC Standard No. ISO/IEC

27402:2023, 1st ed., ICS 35.030; Edition 1; 16 pages, Geneva, Switzerland, 2023.

[162] European Telecommunications Standards Institute, *Cyber security for consumer internet of things: Conformance assessment of baseline requirements*, ETSI Technical Specification No. ETSI TS 103 701 V2.1.1 (2025-05), Version 2.1.1; Reference RTS/CYBER-00143; provides methodology and test cases to assess conformance of consumer IoT devices against ETSI EN 303 645., Sophia-Antipolis, France, 2025.

[163] European Telecommunications Standards Institute (ETSI), *Cyber security for consumer internet of things – baseline requirements*, ETSI European Standard No. ETSI EN 303 645 V3.1.3 (2024-09), Reference REN/CYBER-00127; 13 high-level categories, 68 provisions; applies to consumer IoT devices., Sophia-Antipolis, France, 2024.

[164] B. A. Kumar and D. Leoni, "Solid-State Circuit Breakers in Distributed Energy Resources," in *2019 IEEE 16th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT and AI (HONET-ICT)*, Charlotte, NC, USA: IEEE, 2019, pp. 105–109. DOI: 10.1109/HONET.2019.8907953.

[165] L. Ravi et al., "Surge Current Interruption Capability of Discrete IGBT Devices in DC Hybrid Circuit Breakers," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 3, pp. 3195–3207, 2023. DOI: 10.1109/JESTPE.2023.3264933.

[166] E. L. Carvalho et al., "Extended zvs-on/zcs-off range for cf-dab converter under dcm operation for residential energy storage systems," *IEEE Access*, vol. 11, pp. 119 231–119 243, 2023. DOI: 10.1109/ACCESS.2023.3327219.

[167] Z. Miao, G. Sabui, A. Moradkhani Roshandeh, and Z. J. Shen, "Design and Analysis of DC Solid-State Circuit Breakers Using SiC JFETs," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 3, pp. 863–873, 2016. DOI: 10.1109/JESTPE.2016.2558448.

[168] D. He, Z. Shuai, Z. Lei, W. Wang, X. Yang, and Z. J. Shen, "A SiC JFET-Based Solid State Circuit Breaker With Digitally Controlled Current-Time Profiles," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 3, pp. 1556–1565, 2019. DOI: 10.1109/JESTPE.2019.2906661.

[169] F. Zhu, F. Liu, W. Liu, K. Feng, and X. Zha, "Performance analysis of RCD and MOV snubber circuits in low-voltage DC microgrid system," in *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*, ISSN: 2470-6647, 2017, pp. 1518–1521. DOI: 10.1109/APEC.2017.7930900.

[170] I. Zulfiqar, L. Liang, Z. Guo, F. Yang, and X. Wan, "SOA measurement of SiC MOSFETs using different voltage clamping techniques in DC SSCB," *Power Electronic Devices and Components*, vol. 13, p. 100 134, 2026. DOI: 10.1016/j.pedc.2025.100134.

[171] F. Liu, W. Liu, X. Zha, H. Yang, and K. Feng, "Solid-State Circuit Breaker Snubber Design for Transient Overvoltage Suppression at Bus Fault Interruption in Low-Voltage DC Microgrid," *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 3007–3021, 2017, Conference Name: IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2016.2574751.

[172] Z. Wang and E. M. Sankara Narayanan, "Design of a snubber circuit for low voltage DC solid-state circuit breakers," en, *IET Power Electronics*, vol. 14, no. 6, pp. 1111–1120, 2021, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1049/pel2.12092. DOI: 10.1049/pel2.12092.

[173] D. Shin, S.-K. Sul, J. Sim, and Y.-G. Kim, "Snubber Circuit of Bidirectional Solid State DC Circuit Breaker Based on SiC MOSFET," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, 2018, pp. 3674–3681. DOI: 10.1109/ECCE.2018.8557542.

[174] S. Zhao, R. Kheirollahi, Y. Wang, H. Zhang, and F. Lu, "Investigation of Limitations in Passive Voltage Clamping-Based Solid-State DC Circuit Breakers," *IEEE Open Journal of Power Electronics*, vol. 3, pp. 209–221, 2022. DOI: 10.1109/OJPEL.2022.3163072.

[175] R. Kheirollahi, S. Zhao, H. Zhang, and F. Lu, "Novel Active Snubbers for SSCBs to Improve Switch Voltage Utilization Rate," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 3, pp. 2565–2576, 2023, Conference Name: IEEE Journal of Emerging and Selected Topics in Power Electronics. DOI: 10.1109/JESTPE.2022.3211459.

[176] C. Gu, P. Wheeler, A. Castellazzi, A. J. Watson, and F. Effah, "Semiconductor Devices in Solid-State/Hybrid Circuit Breakers: Current Status and Future Trends," en, *Energies*, vol. 10, no. 4, p. 495, 2017, Number: 4 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/en10040495.

[177] Z. J. Shen, G. Sabui, Z. Miao, and Z. Shuai, "Wide-Bandgap Solid-State Circuit Breakers for DC Power Systems: Device and Circuit Considerations," *IEEE Transactions on Electron Devices*, vol. 62, no. 2, pp. 294–300, 2015, Conference Name: IEEE Transactions on Electron Devices. DOI: 10.1109/TED.2014.2384204.

[178] P. Pithanisetty, D. Dsa, S. N. Banavath, E. L. Carvalho, G. De Carne, and D. Vinnikov, "A Coupled Inductor-Based SSCB With Reduced Components for DC Microgrid Protection," *IEEE Transactions on Power Electronics*, vol. 40, no. 8, pp. 11 428–11 441, 2025. DOI: 10.1109/TPEL.2025.3551740.

[179] A. Pogulaguntla et al., "Air-Core Coupled Inductor-Based Modular Solid-State Circuit Breaker With Reduced Components for DC Buildings," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 13, no. 3, pp. 2988–2999, 2025. DOI: 10.1109/JESTPE.2024.3485735.

[180] I. V. Raghavendra, S. N. Banavath, C. N. M. Ajmal, and A. Ray, "Modular Bidirectional Solid-State DC Circuit Breaker for Next-Generation Electric Aircrafts," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 5, pp. 5486–5497, 2022. DOI: 10.1109/JESTPE.2022.3176929.

[181] Y. Wang, Z. Xu, H. Zhao, Y. Fei, and W. Li, "Integrated Multiport DC Circuit Breaker for Distribution Power Systems in More Electric Aircraft," in *2023 IEEE Workshop on Power Electronics for Aerospace Applications (PEASA)*, 2023, pp. 6–10. DOI: 10.1109/PEASA58318.2023.10235661.

[182] M. Popa and O. Luca, "Overcurrent protection for auxiliary loads in Electric Vehicles with E-Fuse," in *2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC)*, ISSN: 2473-0165, 2022, pp. 1–6. DOI: 10.1109/PEMC51159.2022.9962873.

[183] Y. Ren, X. Yang, F. Zhang, F. Wang, L. M. Tolbert, and Y. Pei, "A Single Gate Driver Based Solid-State Circuit Breaker Using Series Connected SiC MOSFETs," *IEEE Transactions on Power Electronics*, vol. 34, no. 3, pp. 2002–2006, 2019. DOI: 10.1109/TPEL.2018.2861920.

[184] E. Tarmoom, S. Chenetz, D. Meyer, X. Zhang, K. Speer, and O. Esparza, "SiC-Based Auxiliary E-Fuse Technology Demonstrator for EV Applications," in *PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2023, pp. 1–10. DOI: 10.30420/566091230.

[185] J. Xue, Z. Xin, J. Chen, Y. Yue, and J. Kang, "A Load-Independent Controllable Z-Source Circuit Breaker With an Intrinsic Fault Detection Method," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 6, pp. 6366–6376, 2023. DOI: 10.1109/TIE.2022.3192666.

[186] A. H. Chang, B. R. Sennett, A.-T. Avestruz, S. B. Leeb, and J. L. Kirtley, "Analysis and Design of DC System Protection Using Z-Source Circuit Breaker," *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 1036–1049, 2016. DOI: 10.1109/TPEL.2015.2415775.

[187] M. Alashi et al., "Design and Optimization of Air-Core HTS Pulse Transformer for Series-Type Hybrid Circuit Breaker (S-HCB)," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 6, pp. 1–11, 2024. DOI: 10.1109/TASC.2024.3383813.

[188] Y. Yang and C. Huang, "A Low-Loss Z-Source Circuit Breaker for LVDC Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 3, pp. 2518–2528, 2021. DOI: 10.1109/JESTPE.2020.2986804.

[189] S. G. Savaliya and B. G. Fernandes, "Analysis and Experimental Validation of Bidirectional Z-Source DC Circuit Breakers," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 6, pp. 4613–4622, 2020. DOI: 10.1109/TIE.2019.2928284.

[190] P. Alexandrov, X. Li, L. Fursin, C. Dries, J. Zhao, and T. Burke, "Solid-state disconnects based on SiC power JFETs," in *2011 IEEE Vehicle Power and Propulsion Conference*, ISSN: 1938-8756, 2011, pp. 1–5. DOI: 10.1109/VPPC.2011.6043095.

[191] Z. J. Shen et al., "First experimental demonstration of solid state circuit breaker (SSCB) using 650V GaN-based monolithic bidirectional switch," in *2016 28th International Symposium on Power*

Semiconductor Devices and ICs (ISPSD), ISSN: 1946-0201, 2016, pp. 79–82. DOI: 10.1109/ISPSD.2016.7520782.

[192] International Organization for Standardization, *Safety of machinery — general principles for design — risk assessment and risk reduction*, ISO Standard No. ISO 12100:2010, Geneva, Switzerland, 2010.

[193] International Electrotechnical Commission, *Low-voltage electrical installations — part 4-44: Protection for safety — protection against voltage disturbances and electromagnetic disturbances*, IEC Standard No. IEC 60364-4-44:2024 (3rd ed.), Technical Committee 64; ICS 91.140.50; 33.100.10; 33.100.20. This third edition cancels and replaces the second edition published in 2007, Amendment 1:2015 and Amendment 2:2018., Geneva, Switzerland, 2024.

[194] S. Ali, E. L. Carvalho, and D. Vinnikov, "An Overview of Smart and Essential Features in ACDC Interlinking Converters for DC Buildings," in *2025 IEEE 66th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, ISSN: 2768-3338, 2025, pp. 1–7. DOI: 10.1109/RTUCON67996.2025.11415086.

[195] N. Valentine, D. Das, B. Sood, and M. Pecht, "Failure Analyses of Modern Power Semiconductor Switching Devices," en, *IMAPSource Proceedings*, vol. 2015, no. 1, pp. 690–695, 2015, Publisher: IMAPS. DOI: 10.4071/isom-2015-THA56.

[196] H. Wang and F. Blaabjerg, "Power Electronics Reliability: State of the Art and Outlook," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 6476–6493, 2021, Conference Name: IEEE Journal of Emerging and Selected Topics in Power Electronics. DOI: 10.1109/JESTPE.2020.3037161.

[197] A. Abuelnaga, M. Narimani, and A. S. Bahman, "Power electronic converter reliability and prognosis review focusing on power switch module failures," en, *Journal of Power Electronics*, vol. 21, no. 6, pp. 865–880, 2021. DOI: 10.1007/s43236-021-00228-6.

[198] C. Xu, X. Song, and P. Cairoli, "SiC Based Solid State Circuit Breaker: Thermal Design and Analysis," *IEEE Transactions on Industry Applications*, vol. 60, no. 1, pp. 757–764, 2024, Conference Name: IEEE Transactions on Industry Applications. DOI: 10.1109/TIA.2023.3312055.

[199] Y. Liu, K. Chuong, Z. J. Zhang, L. M. Garten, and L. Graber, "Failure modes and remedies of a solid-state low voltage DC circuit breaker through 3,000,000 operation cycles," *Power Electronic Devices and Components*, vol. 12, p. 100 119, 2025. DOI: 10.1016/j.pedc.2025.100119.