Transformative Role of Solid-State Circuit Breakers in Advancing DC Systems for a Sustainable World

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DC power systems support a more sustainable future by lowering carbon footprints. However, these systems provide significant hurdles in terms of fault protection. DC grids demand faster protection devices because fault currents increase so quickly in microseconds. DC circuit breakers (DCCBs) have established themselves as a popular option for replacing fuses and mechanical circuit breakers. Solid-state circuit breakers (SSCBs) are among the DCCBs that offer ultra-fast protection, noise-free, and arc-free operation with a longer lifespan. This article discusses significant research trends in SSCBs for LVDC and MVDC grid applications, their limitations, and prominent global SSCB producers, including commercial products.

DC Technology for Sustainable Future

The famous war of currents in the late 1880s between the two great scientists, Edison and Telsa, ultimately resulted in the adoption of ac systems revolutionizing the power, energy, industrial, residential and transportation sectors globally [1]. In today's modern world, the detrimental consequences of exploiting fossil fuels to cope with increased energy demand on the environment are a cautioning reality that needs a major attention to provide a better future. It's high time to make a steep shift towards exploring renewable energy sources for energy production for a reduced carbon footprint. With the technological advancements in power electronics, dc power grids provide the efficient integration and control of renewable energy sources, battery energy storage, fuel cells, and increasing modern loads such as portable electronics, LEDs. Apart from this, there is no need of frequency and reactive power control in the dc systems. The dc technology also improves the efficiency of overall system due to fewer power conversion stages and low losses. Further aids in achieving better reliability, stability and controllability of the system [2]. The potential markets adopting dc innovation in present and near future are commercial/residential buildings, shipboard power networks, aircraft power systems, electric railways, large electric vehicle (EV) charging stations, data and communication centres, microgrids and industrial centres, green hydrogen production plants integrating multiple renewable energy sources.

The remarkable growth of solar power is set to transform the world and revolutionize traditional methods of power generation, transmission, and distribution. Although it may not be feasible to completely transition to dc systems at present that are powered by renewables and energy storage, the goal is to gradually develop efficient hybrid ac–dc power distribution structures and move later to the complete dc systems. This shift towards fully electric power systems will be supported by advancements in electrical machines, electronics, and semiconductor technologies. DC grids are classified into three types based on their operating voltage levels: low voltage dc (LVDC) grids, medium voltage dc (MVDC) grids, and high voltage dc (HVDC) grids. LVDC grids operate at voltage levels below 1500 V, MVDC grids operate between 2000 V and 100 kV, and HVDC grids operate above 100 kV [3].

LVDC grids are gaining a lot of importance for their applications into datacenters, commercial/residential buildings, EV fast charging stations and green hydrogen production plants. The green hydrogen plants specifically operate at low voltage dc and requires high currents. The typical voltage levels of dc distribution buses for hospitals, homes, offices, and prosumer electrical installations range from 350 V dc to 750 V dc; for data/telecom centers, it is 380 V dc. MVDC powertrain architectures with voltage levels up to 10 kV dc and higher have been identified to be the key enabler for large-body aircrafts with megawatt power requirement. In the state-of-the-art Boeing 787 more electric aircraft (MEA), the research has now focused towards developing the electric power systems (EPS) with a high-voltage dc distribution bus by increasing the voltage levels from 270 V dc to 540 V dc. By boosting the voltage levels in response to the increased on-board power, the current flowing through the conductor is reduced and the weight of the conductors is optimized, thereby achieving high power densities which is a major advantage for the aviation industry [4]. MVDC distribution grids are also being potentially investigated by companies such as ABB for a variety of applications, such as wind farms integration, EV fast charging station, heavy-industry power quality and shipboard power systems [5]. Currently, in Germany, a field demonstrator for MVDC grids is being planned, aiming at improvements in the power quality and power flow control [6]. Large emerging onshore or offshore solar and wind farms can envision the MVDC grid structures. Switching to MVDC has the potential to increase efficiency and reduce the conversion stages required for integrating low-voltage renewables into a high-voltage grid. HVDC systems, on the other hand, are commonly used for transmitting bulk power over long distances, interconnecting high-power ac electricity grids, delivering power from offshore wind farms to the onshore grids, powering up the densely populated metropolitan cities in the future, and bringing power from remote renewable generation points to the load centers. First multi-terminal HVDC networks have been planned and installed in the world, with China, and now Europe [7], leading the effort. Recently, the four German TSOs agreed to develop a four-hub HVDC network, deploying for the first time HVDC breakers [8]. Despite several advantages, dc grid systems pose a major challenge in terms of fault protection, which is hindering the widespread adoption of dc technology. The next section outlines the major drawbacks of dc power systems during faulty events and discusses effective and potential solutions to make the technology more practical.

DC System Protection Challenges, Requirements and Classifications of DCCBs

In contrast to an ac system, which interrupts the fault current at current zero crossings, the primary concern in a dc system is the absence of natural current zero crossing points and the reduced inductance of the line, leading to a fast rise of the current (few milliseconds against tens of milliseconds for ac), as shown in Figure 1. Because of the above-mentioned challenges, the state-of-the-art mechanical circuit breakers (MCBs) operating on pneumatic, hydraulic, magnetic and spring functions cannot be incorporated into the dc power systems. This is due to the dangerous arcs that form between the mechanical contacts while separating, leading to catastrophic damage to the protective devices and system. Current MCB solutions involve ac breakers located in the ac side of the converter, and oversized diodes that allow the full fault current to flow in the dc side of the converter. In the rapidly evolving world of dc applications, DCCBs are essential components due to their capability to interrupt the fault current within few milliseconds. This characteristic is particularly appealing for applications where high-power supply quality is essential, such as datacenters, renewable energy parks, EV charging infrastructure, microgrids, maritime, and railways etc. The key features that should be taken into consideration when designing a DCCB are:

- cost
- reliability
- footprint or power density
- rapid tripping with adequate circuit breaking capacity
- power losses or efficiency
- high fault current limiting and handling capacity
- life cycles
- sensitivity—it must detect all types of faults including high impedance.

DCCB technology can be combined with fault location and current limitation techniques to reduce power outages, improve reliability, and increase compactness. Implementing cooperation among DCCBs can also improve selectivity in isolating faulty portions and clearing short-circuits by nearest circuit breakers in a fast and precise manner [9]. Arc fault detection is also another major concern in the dc based grids, and very limited commercial solutions exist at present.

Also, DCCBs are mainly categorized as modified mechanical circuit breakers (MMCBs), SSCBs, and hybrid circuit breakers (HCBs). Figure 2 provides the block diagrams as well as the merits and demerits of all the classifications of DCCBs. With recent advancements in the power semiconductor industry and development of wide bandgap (WBG) devices such as silicon carbide (SiC) and gallium nitride (GaN), the power switches present significantly lower series resistance and handles good amount of current while equally maintaining thermal stability. The main requirements for a power device used in dc fault protection are high voltage blocking, high current carrying capacity, high surge current, low $R_{DS\text{-}ON}$ and high thermal stability. Because of the arc free, ultra-fast fault isolation, reduced fault current levels, compact and highest power density features, the SSCB takes a transformative role as a promising fault interruption device that aims to solve the issues of dc system protection [3], [10].

The required fault clearing speed for SSCBs depends mostly on the system conditions. An industrial view on the parameters that influence the fault clearing requirements can be found in [11], that highlights the major factors:

- Fault resistance: It determines the amplitude of the short-circuit current. Usually, it is assumed a low resistance fault in order to develop conservative solutions for worst-case scenarios
- Fault limiting inductance: It is installed between the converter and the line and aims at reducing the fault ramp

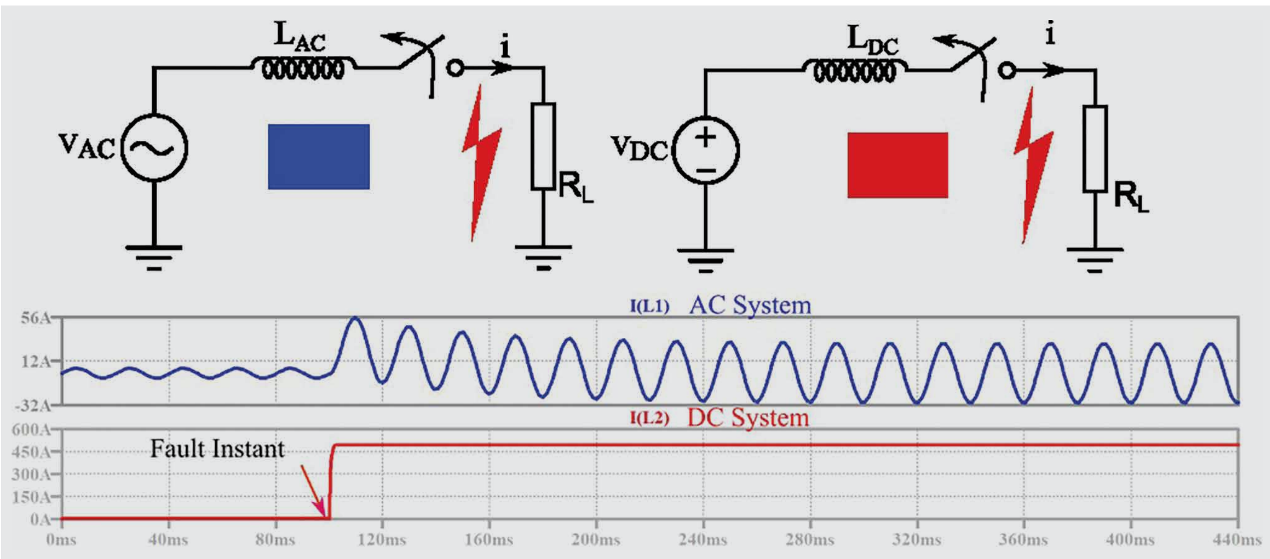

FIG 1 Simulation waveforms showing dc vs ac fault current profiles (considering equal line inductance and resistance of the line); usually the line inductance is significantly low in dc systems ($L_{ac} >> L_{dc}$). The fault current in dc system is shown as saturated, it is mainly due to limitations of simulations platform.

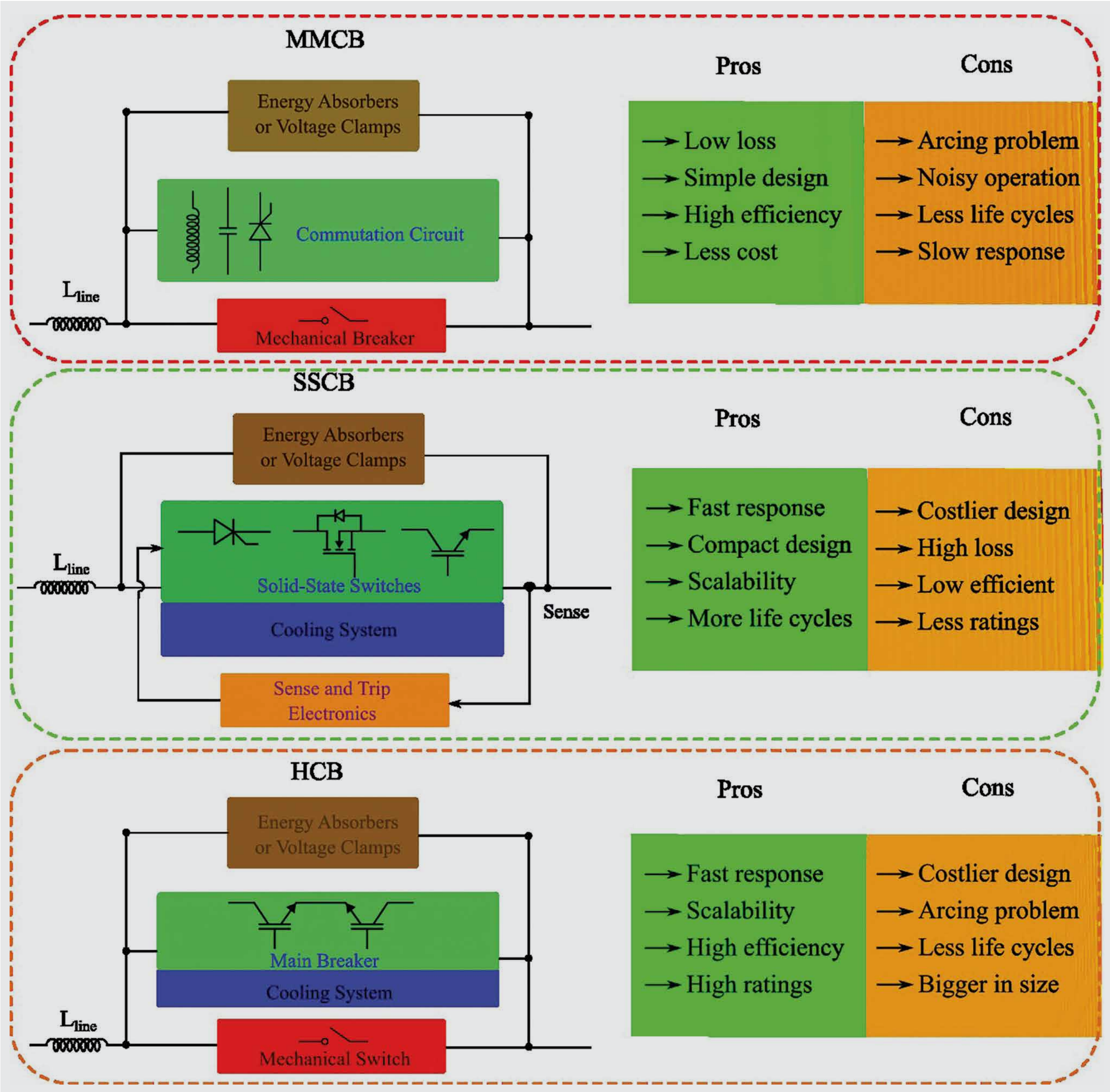

FIG 2 Pros and Cons of the modified mechanical circuit breakers (MMCBs), solid-state circuit breakers (SSCBs), and hybrid circuit breakers (HCBs).

rate. Although a larger inductance helps in slowing down the fault current rise, it increases the operation losses. Thus, it is usually sized together with the breaker technology, allowing a fault rise compatible with the breaker opening time.

- Fault distance: To be conservative, a fault at the converter terminal, after the fault limiting inductance, is considered.

Considering the aforementioned factors, a fault clearing time up to 1 ms can be considered acceptable for SSCBs (but having sub μs interruption brings additional advantages).

Research is being conducted on SSCBs in academia and industry because of their superior benefits. Table. I provides the DCCB technology advisory map for different voltage levels and highlights best suitable circuit breaker technology for a specific application considering restrictions of mechanical devices, and solid-state devices. The power semiconductor's voltage blocking plays a significant role in deciding the application of SSCBs. The highest voltage rated SiC device in the market is of 3.3 kV with current limited to 100 A. Series connection of devices helps in developing high voltage blocking system but brings additional challenges in terms of voltage balancing issues. Taking all these factors into account, Table 1 summarizes guideline for a specific technology's DCCB use with respect to voltage levels.

SSCBs provide ultra-fast protection speeds, noiseless, and arcless operations, reduced fault stress on the system, and a longer life. Additionally, SSCBs do not need arc quenching materials like SF_6 which are non-environmentally friendly. SSCBs are divided based on the power electronic switch utilized in the design. Semiconductor controlled switch based SSCBs, and fully controlled switch based SSCBs are the major topologies that are being studied. The SSCB's primary components include the power semiconductor devices, gate driver, sensor and control circuitry, voltage clamp circuit, auxiliary power supply, and cooling system. In SSCB, the power semiconductor device is the key component that can make or break the power flow through the system [10]. The next section discusses about the research trends, market availability of SSCBs and their limitations.

I. Research Trends, Market Availability, and Limitations of SSCBs

With the increase of dc applications, in particular for low voltage grid and on-board networks, there is the clear need to interrupt the faults in fast and selective way. The SSCB's advantages and disadvantages can be summarized as follows [12]:

Advantages:

- Fast fault clearing capability, within 5 ms, avoiding to reach classical short-circuit currents (bringing it to sub ms level features additional advantages)
- Potential reduction in footprint
- Monitoring functions included in the circuit breaker, i.e. no need for additional logic circuit
- Studying a proper design, the SSCB can be designed to be modular and scalable, without the need for replacement in case of up-scaling.
- Arc free operation results in better reliability and less maintenance.

Disadvantages:

- Higher costs, due to additional semiconductor and logic components
- Higher on-state losses due to the semiconductor path always enabled
- Need for additional circuit separator (e.g., interrupter) for guaranteeing galvanic insulation
- Need for additional energy dissipator (e.g., Metal-Oxide Varistor) to absorb the fault energy in the secondary path.

The thyristor (also known as SCR), GTO/IGCTs are a very good choice especially for dc protection due to their superior characteristics such as high surge current capability, high voltage and current ratings and less conduction loss at increased power levels. Therefore, several SSCB topologies based on these devices have been extensively explored in the academia and many break-through topological designs being reported in the literature. Z-source circuit breaker (ZSCB) which was introduced a decade ago have been proposed for their application into high power HVDC and naval dc power systems with MVDC bus architectures [13]. One of the main advantage of the ZSCBs is automatic fault detection and isolation. Based on the impedance configuration, the ZSCBs have been further classified as classical (shown in Figure 3a), series (shown in Figure 3b), parallel, Q, and O-ZSCBs [14]. Later, several novel modified bidirectional z-source based SSCBs are introduced utilizing coupled inductors as well. Protection against overloads and short circuit faults is the key feature of SSCB. Since the commutation mechanism of the ZSCBs are passive, they fail to provide the protection against overload events and large impedance short circuit faults. Even though active ZSCBs and different overload protection strategies are being proposed [15], they ultimately make the breaker design and control more complex, falling away from making the ZSCBs a market reality.

In the last years, the literature introduced numerous SCR-based DCCB topologies, such as H-bridge, T-type, coupled inductor, and capacitor-capacitor pair-based structures [16]. Modular SCR based SSCBs are also proposed for their implementation into aircraft power systems as well as ship-board power systems. The concept of modularity is more relevant for the systems with low voltage and high currents such as in more electric aircrafts (MEA). The modularity provides fault-tolerant operation, better serviceability, maintenance, and

Table 1. DCCB technology advisory map with voltage levels.

Circuit Breaker Technology	Voltage levels				
	EHVDC	HVDC	MVDC	LVDC	ULVDC
Modified Mechanical DC Circuit Breaker (MMDC)	++	+	+	-	--
Solid State DC Circuit Breaker (SSCB)	--	-	+	++	++
Hybrid DC Circuit Breaker (HCB)	++	+	+	-	--

(++: highly advisable, +: moderately advised, 0: neutral, -: moderately not advisable, --: highly not advisable).

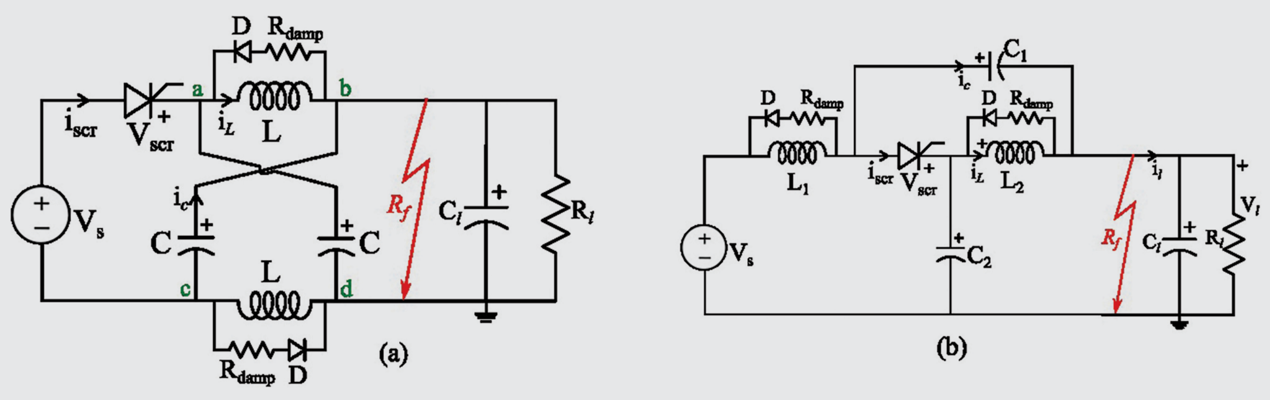

FIG 3 Schematics of ZSCBs. (a) Classical. (b) Series.

Table 2. SSCB topologies from academia.

SSCB Type	Name of Topology	Merits	Limitations
SCR Based SSCBs	Forced commutation thyristor based SSCB [20]: Ratings: 400V/120A	+Efficient +High surge current capability , +Bidirectional voltage blocking capability	- Require Large capacitors - High fault interruption time - High peak fault current level
	Z-source breaker: Rating: < 150 V and < 10 A [16]	+ Low loss + Autonomous short circuit protection + Fast short circuit fault response speed	- Large auxiliary LC circuits - Fault current injected at source - Higer fault interruption time
	T-source SSCB – Rating: 270V/15A [16]	+ Low loss + Autonomous short circuit protection + Detectable fault current level	- Large auxiliary LC circuits -Higer fault interruption time
	SiC ETO based SSCB – Rating: 4500V/200A [21]	+ High blocking voltage capability + Simple ON/OFF gate control + Fast current interruption speed	- High conduction losses - SiC ETO still in academic research stage
	RB-IGCT based SSCB – Rating: 1000V /5000A [22]	+ Low loss + Bidirectional + Fast current interruption speed + High TRLs	- Limited RB-IGCT voltage / current options available
WBG based SSCBs	SiC MOSFET based SSCB – Rating: 400V/30A [23]	+ Simple + Low loss + Fast fault interruption speed	- Anti series connection of SiC MOSFETs for bidirectional
	GaN based SSCB – Rating: 380V/20A [24]	+ Simple + Fast fault interruption speed + Low ON-resistance, +high current density	- Device availability at high voltage and high currents, and cost.

plug-and-play features [17]. Ship MVDC systems also feature IGBT-based SSCBs. Reverse blocking-IGCT (RB-IGCT)-based SSCB topology is preferred over IGBT because of very low conduction losses [18]. Silicon MOSFET based SSCBs are available within low power ratings making their way into LVDC grids. WBG power device-based SSCBs are gradually gaining popularity as semiconductor technology advances. This is mainly because of the material properties of WBG power semiconductors. Because of their high breakdown electric field strength, they are capable of blocking higher voltages. The SSCBs based on WBG devices are more efficient because of lower conduction losses. With reduced die sizes, the parasitic capacitances are minimised, which aids in providing 100 times faster switching than silicon device based SSCBs [19]. Table 2 provides an exhaustive list of SSCB topologies presented in the literature with corresponding voltage and current rating elucidating their merits and limitations. While Table 3 provides a select list of SSCB products available as a protection solution for dc systems from the industry. As noticed from Table 3 there are very limited solutions and products from the industry and requires significant efforts in making the dc system a reality.

The SiC MOSFETs are now available at higher ratings, and because of its better thermal conductivity and low conduction loss, are emerging as the promising candidates for the SSCBs in MVDC to HVDC applications. Its superior thermal conductivity makes it more robust at high power levels. SiC MOSFET with low resistance, superior thermal performance, small size, and reliability are paramount. The basic configuration of the SiC-MOSFET based bidirectional SSCB is shown in Figure 3. This topology is simple with minimum component count which enhances power density and provides bidirectional protection. Proper loss estimations and thermal modelling is an important analytical aspect which is necessary for SiC based topologies to ensure the junction temperature of the devices in limit. Although, SSCB topologies seem simple and easy to design, there are still technological challenges, such as (i) ultrafast fault detection and location, limiting the overheating of semiconductor components; (ii) vertical selectivity with the upstream breakers to avoid mis operations; (iii) bidirectionality of the power flow; (iv) different current thresholds in case of power flow bidirectionality, when the circuit breaker from becomes the most upstream breaker of its zone.

Standard short circuit and overcurrent protection techniques for SiC MOSFETs have been presented in the literature. They are classified into current-based methods and voltage-based methods. The current-based protection techniques include: 1) shunt resistor-based method, 2) Rogowski coil-based method, 3) parasitic-inductance-based method. Desaturation detection protection strategy applies to the SiC devices as a protection mechanism against semiconductor short circuits [25], shown in Figure 4.

The drain-source voltage of the MOSFETs is also sensed using innovative current sense ICs which allows for conventional current sensing resistors or transformers to be eliminated, as well as their associated power losses and cost. Like thyristor-based SSCBs, several topologies have been studied based on SiC MOSFETs. Recent popular topologies are fully soft-switched SSCB, soft-turn off and self-charging operation based SSCB, fault current bypass-based SSCB, T-type, Y-type, and H-type SSCB, and their performance is validated for implementation into LVDC grids [26]. The basic SSCB topology shown in Figure 3 imposes a power shock to the SiC device while turning off. The soft-switching structures for SSCBs as listed above can be an alternate solution to avoid power shocks. For high voltage and current applications, the series and parallel connection of the SiC modules are promising solutions. Full-bridge T-type modular SSCB based on SiC is proposed for medium voltage applications. This topology not only interrupts the fault current rapidly, but also ensures the dc grid stability in case of load power or voltage fluctuations [27]. Another modular MVDC SSCBs based on scalable power electronics building block (PEBB) units using SiC MOSFETs which provides flexible series and parallel expansion is elucidated in [28]. Schaltbau group from Germany has started to design smart circuit breakers offering modular solutions for the growing requirements of today's dc applications for supplying critical systems and infrastructures. Atom Power revolutionized the circuit breaker by creating the world's first commercial UL-listed digital SSCB based on SiC device. On the other side, the material properties of GaN switches exhibit comparative advantages for the reduction of on-state resistance and turning-off time compared with SiC and Si devices. While the GaN device based SSCBs have a bright future, they are still a long way from the voltage and current ranges of silicon and SiC devices. Very few GaN based SSCBs have been reported in the literature with the voltages up to 600 V dc and breaking currents up to 45 A [10].

The main limitations in the advancements of SSCBs include no proper standards for testing and designing, limitations on WBG devices in terms of current and voltage ratings, less awareness on shifting towards dc and very limited solutions of LV to MV and MV to HV converters to enable end to end dc network.

Table 3. SSCB topologies from Industry.

Company Name	DCCB – Type and Technology	Ratings
THYCON	■ SSCB based on IGCT and IGBT devices ■ Can be used for both AC and DC	Voltage - 415 V Power–up to 3000kVA Speed - < 300 μs IEC 60947-2 certified
ABB's SACE Infinitus	■ SSCB based on RB-IGCT	Voltage - 1 kV Current –up to 2.5 kA Speed - < 25 μs
Blixt Tech AB	■ SSCB based on MOSFETs ■ Can be used for both AC and DC	Voltage – 230 V Current – up to 10 kA (fault), 16 A nominal Speed - < 10 μs
Current router from DC Systems	■ SSCB based on MOSFETs	Voltage – 350 V &700 V Current – 16 A (fault) Speed - < 10 μs
Sécheron UR series - DC circuit breakers	■ Mechanical Based – captured based on the speed from the datasheet	Voltage – Up to 3600 V Current – Up to 1000 A Speed - < Few ms

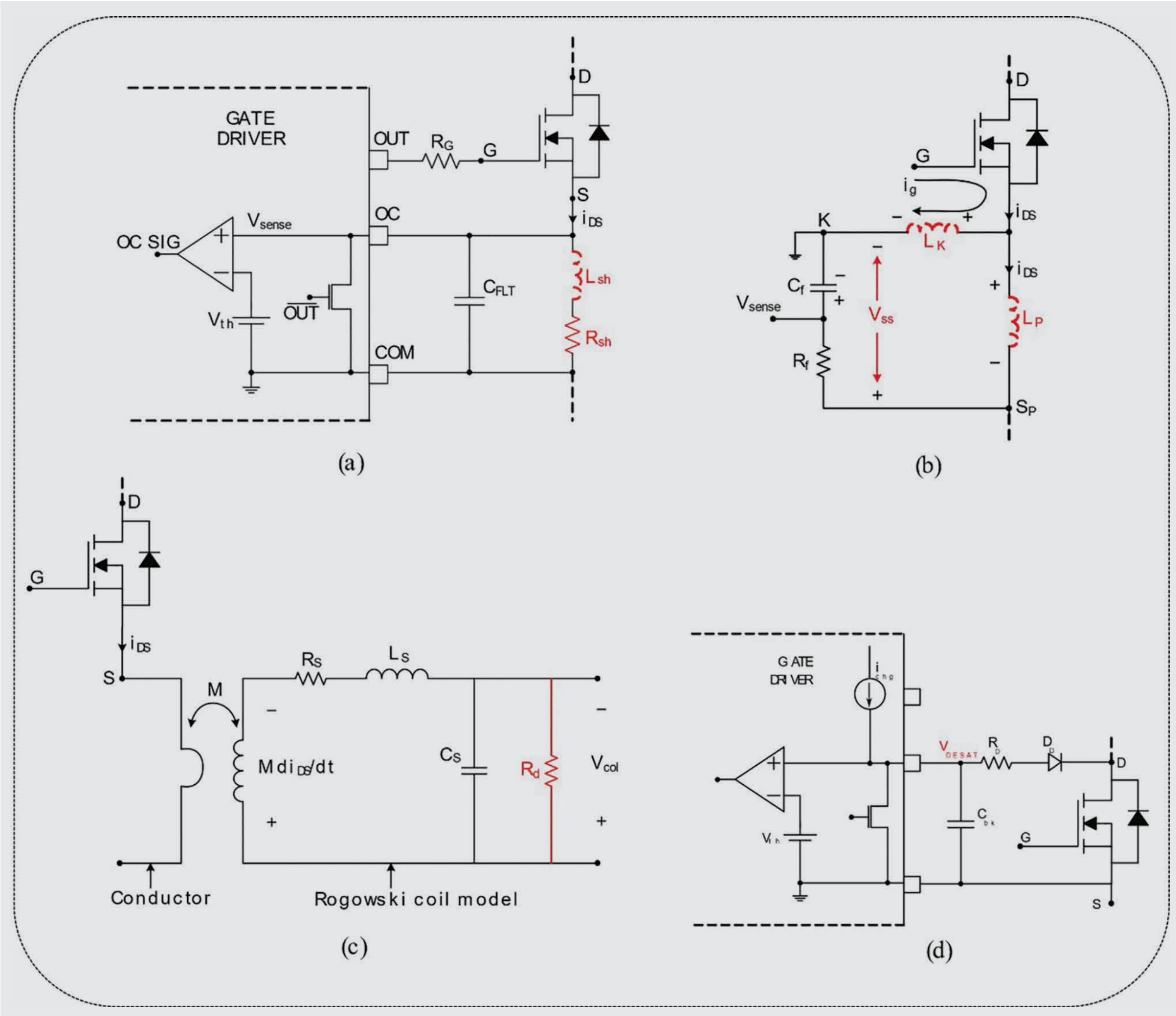

FIG 4 **Short circuit current and overcurrent protection schemes for SiC MOSFET: (a) shunt resistor based, (b) parasitic inductance based, (c) Rogowski coil based and (d) DESAT detection based.**

In recent times, European Union (EU) has focused on dc systems and hosted several funding opportunities for research in this field. Popular funding projects include SHIFT2DC. SHIFT2DC Horizon Europe is a currently running project that plans to introduce a novel approach on the way dc solutions are used in power systems by creating a smarter, more efficient, and ecofriendly energy systems. Focusing on the integration of dc solutions in four main infrastructures—Datacenters, Ports, Buildings, EV charging and various industrial applications. This project has many leading industrial partners and academic institutions across EU, with consortium of 40 plus institutions. Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely (BREAKERS) is another project call for adoption of dc systems introduced by Advanced Research Projects Agency - Energy (ARPA-E), Department of Energy, USA. Table 4 summarises the recent steps and project fundings on DCCBs for advancements in dc systems. These funding calls show the importance of the field, and it is a welcoming step to the researchers to focus on development of dc systems which aims to address several issues including climate action. As discussed above, there are several open challenges and both academia and industry need to work together in harmony to address the problems to make the dc system a feasible solution.

Major requirements of SSCBs or in general dc protection systems are as follows, and existing literature provides solutions with very limited functionalities.

- Fast fault interruption speed (of the order less than few 100 µs)
- Good isolation voltage levels
- Detection and interruption against short circuit faults
- Detection and interruption against over current faults with inverse current characteristics (ICT) profiles

Table 4. Project fundings on DCCBs and dc systems.

S. No	Funding Agency	Project Partners	Main Objectives
1	Shift2DC by Horizon Europe	More than 25 participants from Industry and Academia, a few of them includes EATON, Schneider, Hitachi Energy, RWTH AACHEN University, Tallinn University of Technology, DC Systems, etc.	The SHIFT to Direct Current (SHIFT2DC) project plan is to create smarter, more efficient, and environmentally friendly energy infrastructures through direct current (DC) solutions. The SHIFT2DC project aims to transform the way DC solutions are used in our power systems
2	Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely (BREAKERS) by APRPA-E DOE, USA	Drexel University, Eaton Corporation, General Electric (GE) Global Research, Georgia Tech Research Corporation, Marquette University, Sandia National Laboratories, The Ohio State University, Illinois Institute of Technology	BREAKERS in another major project funding call supported by the USA for advancing the DC system. BREAKERS aimed at developing novel technologies for medium voltage direct current (MVDC) circuit breakers, applicable to markets including electrified transportation, MVDC grid distribution, renewable interconnections, and offshore oil, gas, and wind production
3	Scottish Enterprise High Growth Spin-out Programme (HGSP)	University of Aberdeen (UA)	This project focuses on developing the LC Direct Current Circuit Breaker (LC DC CB), a key technology hoped to advance renewable energy integration in Scotland
4	Progress on Meshed HVDC Offshore Transmission Networks (PROMOTION) - EU Horizon 2020 project	Work Package 4 – 6: Mainly on DC Circuit breakers and protection of DC systems Hitachi Energy is one of the partners.	PROMOTioN aimed at addressing technical, legal, regulatory, economic and financial barriers to the implementation of a meshed offshore HVDC transmission network. By connecting key stakeholders from industry, academia, consultancies and transmission system operators. PROMOTioN provides a platform for interdisciplinary development and increases acceptance of required novel technologies and frameworks
5	Agency of the Czech Republic (TAČR)	Eaton European Innovation Center (EEIC) with University of West Bohemia's Regional Innovation Center for Electrical Engineering (RICE)	This project aimed at developing digital circuit breakers that are essential to solving protection issues of DC Systems, given their ability to merge both intelligent control and fast-switching protection devices, and also optimize digital circuit breakers.
6	Strategic Innovation Fund (SIF), UK Research & Innovation (UKRI)	SSEN Transmission	Provides implementation of DCCBs by further developing industry knowledge and understanding of the opportunities, and challenges to deliver DCCBs from a technical, regulatory and commercial perspective
7	U.S. Southeastern Center for Electrical Engineering Education	AMPERE Laboratory, University of Kentucky, USA	This project fully concentrated around development of Solid-State DC Circuit Breaker for Microgrid Applications
8	NR Canada	ecoENERGY R&D University of Toronto, Canada	Design and Development of DC Arc-Free Circuit Breaker for Utility-Grid Battery Storage System. Mainly to develop two novel DC-CB concepts that show promise of providing a commercially viable option
9	Mitsubishi Electric-Japan R&D	University of Strathclyde, UK	To develop HVDC converter models, control and novel AC and DC fault ride-through strategies
10	Anusandhan National Research Foundation, India (formerly SERB)	Indian Institute of Technology Dharwad, India	Development of DC circuit breakers for residential and transportation systems
11	Mitsubishi Electric Corporation acquires SciBreak AB, a Swedish-based company that develops direct current circuit breakers (DCCBs)		The two firms aim to strengthen the competitiveness of their unified business by working closely on developing DCCB technologies to support the increasing global deployment of renewable energy

- Over voltage and under voltage protections
- Ground fault detection and isolation
- Highly efficient and power dense
- Cost effective and smart features to interface and communicate with servers
- Arc fault detection and isolation

Discussions and Views: Merits, Limitations, and Future Research Directions

Merits of SSCBs:

- More than 100 times faster fault interruption speeds compared to the traditional fastest circuit breakers—enables longer service life and reliability

- Consumes almost 80% less energy compared to the traditional fastest circuit breakers (energy loss in the actuators, relay mechanism, etc., contributes significant power loss, which is absent in SSCBs)—helps maximize the energy efficiency, mainly due to the advanced low turn on resistance of the devices.
- Provides excellent endurance—mainly due to the absence of the movable parts and arc-free operation.
- Very minimal arc energy release during fault current interruption, enabling arcless operation and related safety concerns.
- Reduced fault current magnitudes during the fault with the SSCBs—the dc system during the fault does not experience high fault current—limited to a maximum of 2 times the nominal load current compared to a very high fault current of the order a few kA in traditional fastest circuit breakers.

Limitations:

- Sensing Technology: DC system currents of high magnitudes require a very high bandwidth current sensor to detect the fault events. Delay in sensing the fault current imposes a significant delay in the fault protection. Hall-effect based current sensing provides better bandwidths but limited to low currents, however, for high current measurement hall-effect sensor does not provide good bandwidths. Sense resistors provide excellent response and very good bandwidth, but with a penalty on power loss, and cost if targeted at low series resistance.
- Requirements on fault interruption time (speed): currently there are no standards that provides a guideline for SSCBs and how fast these devices should interrupt the fault. Based on experience and personal opinions, SSCBs must be designed to interrupt the fault at a very fast rate of the order less than a few 100 µs. This will help in restricting the fault current magnitude on the dc system well below 2 time the rated current (unlike a 10 s of kAs in traditional solutions), enables all the downside converters and components to experience low stress. Furthermore, the energy accumulated in network gets limited and requires a smaller energy suppressor (MOV). Additionally, the switching power losses in the SSCB devices will be restricted and provides economical thermal designs.
- Cost: SSCBs at present are costly solutions, however, the cost is greatly compensated by the features and benefits that it offers. The components that take major chunk of cost in SSCB design at present are:
  - Cost of power devices
  - Cost of sensing and control circuits
  - Cost of heat sink
- Size and weight: SSCBs as they dissipate power loss in the form of heat, require a heat sink. This would lead to over size and weight over the conventional solutions. Since, the SSCBs are installed in a closed package (in a power distribution box), keeping devices cool could be a challenge. With low series resistance SiC devices it is possible to optimize the size and weight however with a penalty on the cost.
- Awareness on dc system usage: Though there are several advantages and benefits of implementing dc systems, the lack of awareness on the technology is seen as one of the possible factors.
- Non availability of standards: At present there is a very limited data and standard protocols in place, however, standards agencies like, IEC (IEC60947-3), BIS, ISO, and CIGRE have started to work towards this.
- MOV reliability issue, due to the continuous fault clearing operations. The reliability of the MOV varies strongly on the energy to be dissipated during the fault clearing. Depending on the applications, these data are not always available and further studies are needed in this regard.
- Lack of off-grid demonstrators: Currently the main focus for DCCBs is for distribution and transmission grids, with limited investigation for off-grid demonstrators (e.g., in ships, airplanes, etc.). However, these represents potential large markets for DCCBs, but more practical installation and maintenance aspects need to be addressed for these applications.

Conclusion and Future Advancements in SSCBs

This article discusses the necessity of dc technology for a sustainable future and highlights the short-circuit safety concerns posed by dc grids. Later, a brief discussion on major classifications of DCCBs is provided, with the main focus on SSCBs. The research trends and limitations of the SSCBs are presented in brief, and a few global SSCB manufacturers are highlighted. The SSCBs in the near future should adopt:

- Residual current detection, arc-fault detection, ground fault detection, over-voltage and under-voltage protection, and in-built digital inverse current characteristics based over current protection.
- A soft-start PWM-current limiting function should be incorporated in SSCBs to avoid false tripping in the case of inrush currents of capacitive loads.
- SSCB should be designed as a smarter node, integrating smart features such as intelligent remote control, self-diagnostics and data collection providing integrated intelligence and self-reporting health, local decisions based on the measurements, and communication of the measured data to a higher-level unit.

WBG power devices such as SiC and GaN in SSCBs offer potential benefits for MVDC and HVDC systems in terms of efficiency, size, and reliability.

- However, a major challenge lies in designing effective snubber and energy absorption circuits. Rapid turn-off of WBG devices can lead to residual energy causing voltage overshoots, potentially damaging the device. Therefore, attention to snubber and energy absorption circuit design is crucial for achieving higher turn-off current capability in MVDC and HVDC systems.
- Surge current capabilities of WBG devices are limited by fault clearing time and fault inductance.
- Fast fault detection circuits with low propagation delays are essential at high power levels to keep junction temperatures within limits.
- As SiC device voltage ratings increase, channel on-state resistance (R_{DS-ON}) rises due to the wider drift layer, resulting in higher conduction losses. Commercially available SiC power MOSFETs have maximum voltage ratings up to 3.3 kV from Wolfspeed and Infineon. This limits the full potential of WBG devices and requires series and parallel connection of devices for achieving higher voltage and currents respectively. Therefore, requires active voltage and current balancing technology.
- While 10 kV and 6.5 kV SiC power modules exist as engineering samples, they have not yet been fully commercialized. These devices would reach to economy scale with the growth of dc systems (as cost per unit reduces significantly with quantity of components) and the day all the technical problems are solved.
- SSCBs gain attention from the semiconductor device manufacturers, where SiC MOSFETs specially designed for circuit protection applications, including SSCBs have been released, where low resistance, superior thermal performance, small size, and reliability are paramount. One such device is from Qorvo with part UJ4N075004L8S which offers R_{DS-ON} of 4 mΩ available in TOLL package which is 60% smaller than competing devices in TO-263 package.

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