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Original article

State-of-the-art on advanced technologies of solid-state circuit breaker for reliable and sustainable power supply: A bibliometric analysis and future guidelines

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ABSTRACT

This paper provides a comprehensive bibliometricanalysis of solid-state circuit breakers, including technological developments and control methods in electric power distribution systems. By compiling and analyzing data from the Scopus database, the most cited papers in the field of protection system mechanisms can be identified. These papers, published in influential journals from various countries, covered different subject areas and case studies. Notably, 77.64 % of the articles focused on technological development and experimental control methods, while 22.35 % were review-based studies. This underscores the increasing interest among researchers in advancing the sustainability and reliability of protection devices in electric power distribution systems. The paper aims to identify and analyze the highly cited published articles on the respective field to provide future research direction on the technological development and control methods towards solid-state circuit breaker protection devices. The review also underlines numerous factors, issues, challenges, and difficulties that next-generation power semiconductor should overcome with in regards to system sustainability. Thus, this analysis will strengthen the scopes and provide context for the development of technology and control in the main protection devices in order to achieve an efficient, reliable, cost-effective, and sustainable power supply.

1. Introduction

In recent years, various local facilities especially in the large-scale industrial sector consist of sensitive loads which require a high-quality power supply for stable operation and to reduce rapid voltage interruption problems in the power distribution system. Thus, an advanced technological switching mechanism protection becomes the promising solution to address these problems on a global scale. Moreover, the used of power semiconductor devices with advanced control algorithms can able to control the power and extreme current interruption safely, reliably, and quickly manners [1]. This is because, the lack of advanced technological protection schemes in electrical power distribution systems may bring a significant impact to the power quality issues such as voltage sag, voltage swell, flickering, faults and interference associated with the system [2]. This phenomenon leads to high economic losses and less stability to the system bringing huge effects to the facilities and industrial sector according to the Electric Power Research Institute (EPRI) [3]. In addition, high inrush current and magnetic saturation on the high voltage device such as a transformer or generator on the load side may occur due to these disruptions and be harmful to the devices that impose the high cost of maintenance [4]. Therefore, in order to address power quality problems, it is essential to make significant progress in the development of power semiconductor devices that do not have any moving parts and can offer excellent switching performance and protection mechanisms for the distribution network. This requires rapid technological and control advancements. Moreover, the CBs switching mechanisms must force the current to fall to zero during the fault-breaking process.

Although electromechanical CBs offer low contact resistivity and

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Nomenclature

Designations

i_{Sd}	Current of semiconductor device
i_{SSCB}	Current of solid-state circuit breaker
V_{SSCB}	Voltage of solid-state circuit breaker
kA	Kiloampere
kV	Kilovolts
ms	millisecond

Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage System
BTO	Barium Titanate Oxide
CBs	Circuit Breakers
DAB	Dual Active Bridge
DC	Direct Current
DCCB	Direct Current Circuit Breaker
DCMG	Direct Current Microgrid
ETO	Emitter Turn-Off
FET	Field Effect Transistor
FID	Fault Isolation Device
GaN	Gallium Nitrate
GTO	Gate Turn-Off
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gated-Commutated Thyristor
JFETs	Junction Field Effect Transistors
LVDC	Low-Voltage Direct Current
MB	Mechanical Breaker
MCB	Mechanical Circuit Breaker
MG	Microgrid
MOSFETs	Metal Oxide Semiconductor Field Effect Transistors
MOV	Metal Oxide Varistor
MVDC	Medium Voltage Direct Current
PV	Photovoltaic
RB-IGCT	Reverse Blocking IGCT
RCD	Resistor Capacitor Diodes
SCCB	Single Control Current Balance
SCR	Silicon controller rectifier
SCSVC	Switched Capacitor Series Voltage Controller
SFCL	Superconducting Fault Current Limiter
Si	Silicon
SiC	Silicon Carbide
SITs	Static Induction Transistors
SSCB	Solid-State Circuit Breaker
SSPC	Solid-state Power Controller
SST	Solid-State Transformer
TVS	Transient Voltage Suppression
VSC	Voltage Source Converter
WBG	Wide Bandgap

provide lower conduction power losses during operation in distribution systems [5]. However, the larger breaking time to clear the internal electric arc is the limitation of the electromechanical CBs. Furthermore, the electromechanical CBs also cause arc during an interruption which leads to eroding the breaker contact and increases the maintenance costs [6]. Similarly, this type of CB required an additional arc extinguishing mechanism to drive the fault current to zero due to the absence of natural zero current crossing [7]. These phenomena can potentially cause serious damage to the entire network circuit due to the large peak current occurring on the system if the fault current is not interrupted and processed rapidly. Thus, to overcome these challenges, extensive research towards advanced technologies of power semiconductor devices such as SSCB is a promising solution to this challenge as to enhance the reliability operation [8,9].

The SSCB is a type of custom power device that replaced the traditional solution techniques which can be used to solve the aforementioned disturbances and challenges that are associated with power quality issues. Furthermore, with rapid development technologies on wide bandgap devices such as SiC, SITs, SiC MOSFETs, and SiC junction gate field effect transistors can provide superior switching performance, lower weight, and smaller volume which led to much better than the electromechanical CBs to solve the power quality issues [9,10]. Thus, this type of power semiconductor device with advanced technological developments and control is needed in the standard distribution network to ensure a reliable protection scheme, safety, faster-switching response, and power quality enhancement.

The interruption time of an SSCB is several orders of magnitude shorter than that of an electromechanical CB counterpart. Fig. 1 summarises the comparison behaviour between the SSCB and electromechanical CB for a tripping performance in the power distribution network. The latest electromechanical CB with current limiting capability is only able to limit the fault current within a few milliseconds. In contrast, SSCBs exhibit a significantly faster response time that happens in microseconds or even in nanoseconds due to the rapid reaction speed of power semiconductor devices as shown in Fig. 1(b). The duration of interruption time primarily depends on how quickly and precisely the fault detection circuit operates and the speed at which the power semiconductor device can be turned off. This duration can typically

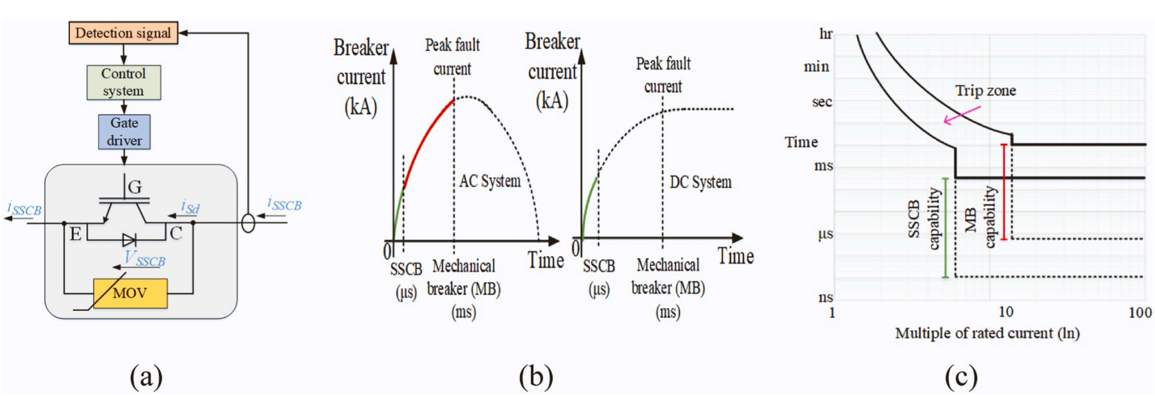

Fig. 1. Comparative of SSCBs performance in the distribution network system. (a) SSCB topology and key components, (b) response time of SSCB over state-of-the-art electromechanical breaker during short-circuit event, and (c) trip profiling curves of electromechanical breaker and SSCB.

range from tens of nanoseconds to tens of microseconds depending on the particular semiconductor technology and controls being utilized. Thus, the ability of SSCBs to instantly trip can be seen in Fig. 1(c) which shows a typical tripping curve for a current-time circuit breaker. This shows that the rapid advancement of technologies and control approaches in the switching mechanism leads to advanced protection and fast fault current clearance in the distribution system to avoid any serious damage to the circuit.

Accessing the technological development and control methods that are associated with the SSCB in specific applications has been difficult due to the extensive alternative, approaches, and complicated matrix performances. Therefore, this paper looks at the most recent scientific literature to examine the future trends in research subjects towards the power quality issues in different applications. Moreover, a quantitative analysis such as bibliometric is employed to provide a precise direction, area, and possible future study opportunities with respect to the SSCB applications. Assessing the research impact of published articles has grown increasingly vital. Citation count is a widely accepted measure for gauging the influence of a research paper, author, or organization within a field of study. A high number of citations signifies a substantial impact. Therefore, identifying the most frequently cited articles through bibliometric analysis aids in recognizing outstanding contributions and shedding light on potential future research avenues. Several considerations are factored in when selecting highly cited articles to prevent bias, including the avoidance of favouring older articles with extensive citation histories.

This review has uncovered groundbreaking contributions featuring comprehensive explanations and analyses of advanced technological developments and control methods in SSCB power system applications. The key contributions are summarized as follows:

- This review conducted a comprehensive analysis of diverse control methods and strategies aimed at advancing SSCB system technology, with the overarching goal of enhancing system sustainability and addressing power quality concerns. These findings offer valuable insights to researchers regarding control architectures and strategies for power semiconductor devices
- Exploring the existing body of knowledge concerning the most frequently cited publications in SSCB devices used for power system protection strategies can provide valuable insights for advancing current expertise and applications in this field.
- This review thoroughly examines the array of existing challenges and issues in the domains of power quality, stability, protection and safety, algorithm complexity, as well as communication and uncertainties.
- Detailed summarization and comparison of the recent control methods approach and technological developments for the SSCB device with different applications to achieve a sustainable supply and overcome power quality issues.
- Lastly, this review offers valuable insights for future advancements and provides practical recommendations to explore the potential directions and advancements of SSCB devices in power system applications.

The rest of the paper contains a detailed description of the surveying or evaluation process of selecting the core objective of this work in Section 2. This section outlines the criteria for choosing the top 85 most cited papers that establish the foundation of bibliometric analysis. Section 3 provides an in-depth analytical evaluation that discusses the technological advancements and control methods in SSCBs. It highlighted the key trend and contribution from the top 85 most cited papers on distribution networks. Moreover, a detailed review and discussion of recent SSCB technologies, such as rapid-breaking mechanical devices, CB, power semiconductor devices for SSCB, classification of power semiconductor technologies, and hybrid switch technologies were discussed in Section 4 to identify the impact of SSCB technologies on the field. The current issues and challenges faced in developing SSCB technologies were also addressed in Section 5 to provide a clear pathway for research study in technological advancements. Finally, Sections 6 and 7 summarized the key findings from the bibliometric analysis and offer recommendations for future research. It emphasizes the importance of continued technological advancements and control method developments in SSCBs. This section provides practical guidelines and potential research directions to enhance SSCB technology in achieving efficient, reliable, cost-effective, and sustainable power supply.

2. Surveying methods or evaluation process

To assess the current level of research progress in stable power supply and sustainable systems through SSCB device operations, a systematic review was conducted on the Scopus database which indexes the majority of academic papers, studies, research areas, and articles on the topic being investigated. Generally, the SSCB power semiconductor device was found in low voltage levels (48–1500 V) and lower range of medium voltage (5–10 kV) DC power distribution [11]. The SSCB is also regarded as a promising solution and alternative approach for fast fault current clearing with advanced control to guarantee the stability and reliability of the power system. Furthermore, it offers many benefits such as a fast mechanical switch, low conduction power losses, good functional characteristics, minimum design complexity, and advanced technology development in switching mechanisms [11–13]. These criteria provide a superior protection performance to isolate the fault current and high-level short circuit rapidly to ensure the stability and power quality of the distribution system [14,15]. Various materials and technologies that are associated with the wide bandgap semiconductor of the switching characteristic are developed to enhance the operation of SSCB. Thus, a comprehensive analysis of recent technological development and control method strategies is necessary to acquire a better understanding that leads to a potential direction and technological growth toward various applications to ensure efficiency, reliability, stability, and quality of delivered power. Therefore, the main objective of this research is to classify, comprehend, and analyze the features of widely cited publications on the SSCB power semiconductor device to fully understand the current technology and control development of the SSCB device.

In order to categorize the selected highly cited publications and as a selection process, certain keywords have been decided in finding out the publication which are SSCB, technologies and control methods with the language of English only. The collected publications will then be organized by the criteria "number of times cited from highest to the lowest". Throughout this process, numerous publications have been found but only the publication that meets the criteria were collected and analyzed. Fig. 2 illustrates a schematic diagram of the surveying methodology and selection process that was implemented in this analysis. Further details of the selection process have been discussed in the next section of the report.

2.1. Data consideration

As earlier mentioned in this report, several criteria are employed during the selection process to collect and analyze the publications based on the Scopus database. The details of data considered in selecting the most 85 cited published papers with regards to SSCB power electronic semiconductor devices associated with advanced technological development and control methods are as follows:

- All papers involving SSCB devices, technological development, and control methods are included in the collection process.
- The publications must be within the year 2014–2023 to be included in the analysis.
- Only English language publications are considered throughout the whole collection and selection process to achieve standardization.

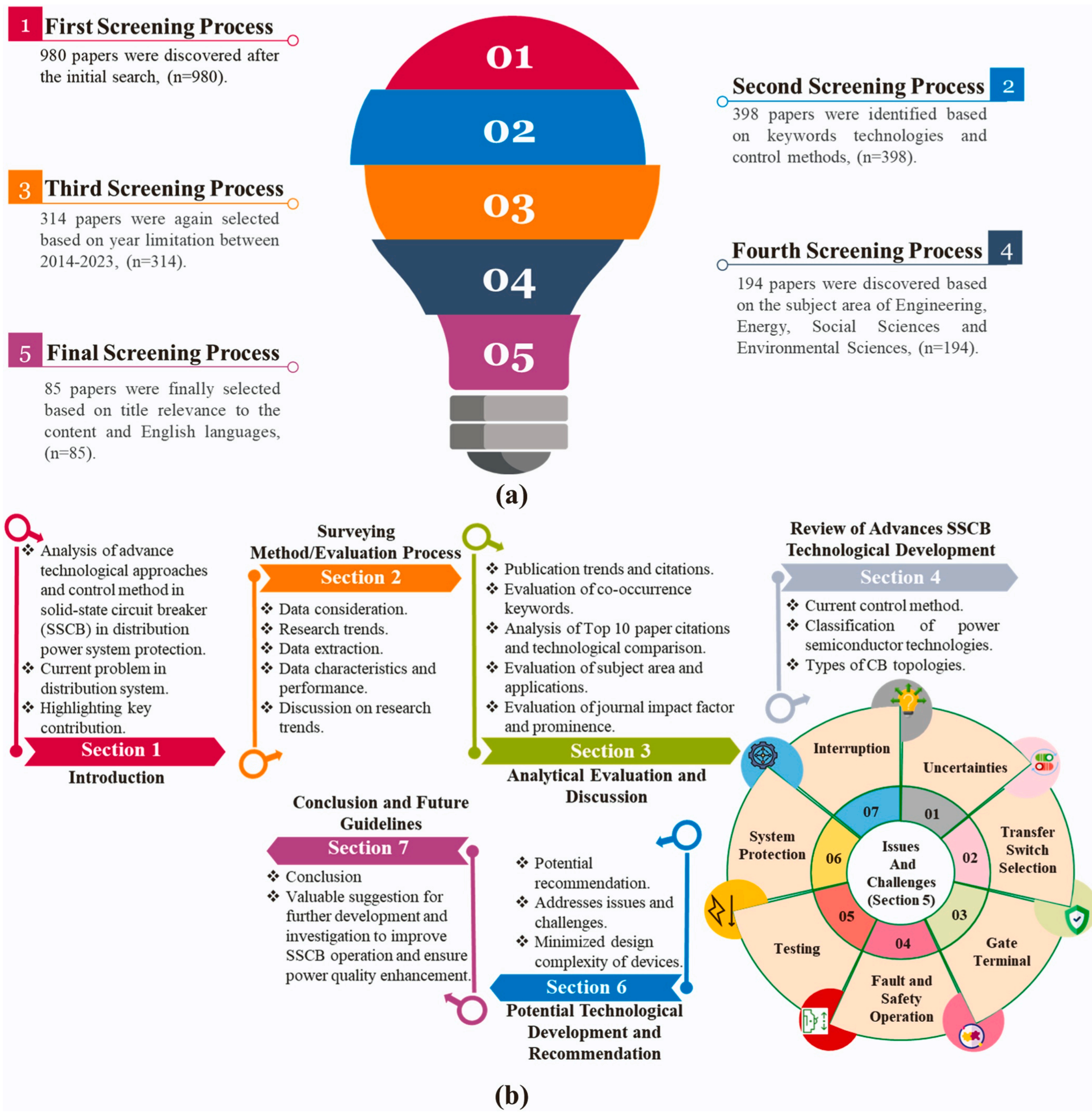

Fig. 2. The flowchart and visual representation for the screening method of the Scopus database for the top 85 most cited paper. (a) Screening method taken with five process to perform a selection process for the analysis, (b) bibliometric analysis flow undertaken for this study that divided by different section.

2.2. Selection process

- After the primary search, a total available number of 980 papers (n=980) were chosen.
- The second screening limited the search scope based on the keyword technologies and control methods in the SSCB device which led to a search number of 398 papers (n=398).
- The next exclusion process was done by limiting the number of published paper documents to between the year 2014–2023 which then lowered the total available number of papers to 314 papers (n=314).
- The fourth exclusion process is limiting the subject of the selected publications to only "Engineering", "Energy", "Social Sciences", and "Environmental Sciences", respectively. This criterion is employed in the selection process which lowers the available number of publications to 194 papers (n=194).
- In the final screening, only 85 (n=85) of the highest cited documents were selected from previously available documents for the final analysis and discussion of this research.

2.3. Research trends

According to a number of papers observed during the selection process, there is consistency and a rapidly growing number of researchers regarding the SSCB power semiconductor devices towards power quality issues to achieving stability and sustainability. Starting from the primary collection process, the analysis has been done according to the number of articles per year starting from 1922 to 2023 illustrated in Fig. 3. It can be observed that the number of publications is in a linear trend starting from 1922 to 1999. The number of published papers is increasing and begin to study in this field starting from the year 2000 onwards with increasing the number of citations. The year 2021 has the highest maximum number of publications 107 followed by the year 2019 which has 84 no. of publication. The total number of publications from the year 1922–2004 is 49 whereas the number of publications from 2009 to 2023 is 386, respectively. Based on the trends, there will less a number of publication releases in 2023 whereby this research study will be done by early the year. For the citation reported, it is remarkable that more than a thousand citations were highlighted from the year 2000–2021, respectively. Generally, papers published in the previous year gained more citations than recent papers. It is expected that this year of publication will likely have a greater citation count than the previous year based on this historical trend. This is because the advanced technological development of SSCB devices in the distribution network system for various applications is a crucial protective device to ensure the power quality and stability enhancement of the system to provide safe operation. This approach tends to provide a superior switching mechanism performance of SSCB device with custom power semiconductor that gives an advanced protection strategy and fast fault current clearance in the distribution system to avoid any serious damage to the circuit. Moreover, this approach leads to providing a reliable protection scheme, safety, faster-switching response, and power quality enhancement on the system.

Among the papers, 50.6 % of papers were published within the year 1922–2018 (96 years) whereas almost half (49.4 %) of papers were published in the last five years.

2.4. Data extraction

The primary data source for this research is the Scopus database, from which publications were selected based on the criteria outlined in the previous section. The extracted data from the chosen publications is presented as follows:

- Documents name and digital object identifier (DOI)
- Authors name.
- Keyword definition by authors.
- Year of publications.
- Type of documents.
- Author's country.
- Citation number
- Last 5 years number of citations.
- Field-weighted citation and prominence percentile of the documents.

Based on the information that has been extracted and analyzed, further analysis has been employed and presented to view the current state of research progress regarding the development technology and control method of SSCB devices to achieve stability and address the power quality issues.

2.5. Data characteristics and performance

Based on the primary search using the Scopus database system, 980 paper publications were found and performed a five-step screening process in order to obtain the top 85, (n=85) papers. The total number of citations from the 85 most cited papers from the year 2014–2023 is 921 ranging from the lowest of 0 citations up to 91 citations. Moreover, the number of citations is 255 for the most recent 5 years of publications. The journal with the most citations during these years is published in "IEEE Electric Ship Technologies Symposium (ESTS)" under IEEE with an impact factor of 1.067 and has been cited by 58 citations several times. After evaluating all the screening processes, the selected 85 most cited papers are analyzed and recorded in Table 1 composed of the DOI and title of the papers, author's name, keywords, publishing year, methods, and research gap followed by citations and fields-weighted impact.

3. Analytical evaluation and discussion

To comprehensively comprehend and interpret the subject, it is crucial to categorize and construe the present trends of research in the relevant domain. The aim of this paper is to clarify the direction of this study and explore the primary impact of research papers in the domain of technological development and control methods of SSCB devices. A thorough examination is conducted and presented to enhance the understanding of future researchers towards the respective field to achieve stability, reliability and sustainable developments as well as enhance power quality improvement. Table 1 presents the top 85 most cited papers from the Scopus Database in the domain of SSCB devices that are subjected to the technological development and control method of the SSCB devices. After implementing the search criteria as discussed in Section 2, the top 85 most cited papers were collected and analyzed.

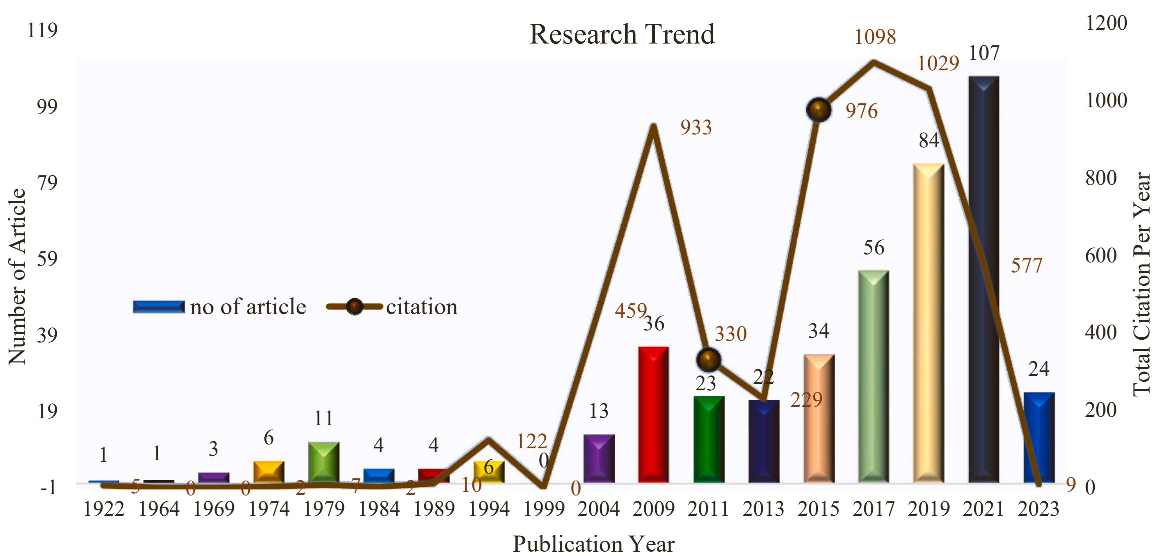

Fig. 3. Research trends of publication subjected to SSCB device from 2014 to 2023.

Table 1
The selected top 85 most cited papers regarding the SSCB device operation in power quality application.

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
1	[16]	10.1049/cp.2014.0859	HVDC, VSC, CBs.	IEEE	Review	Portugal	94	• Summarize a review of the HVDC technologies and modern development. • Analytical toward different technologies and methods of multi-terminal HVDC systems.	• Lack of potential issues regarding the VSC-based HVDC system. • Analytical results and comparison methodology are needed to verify the technological and control approaches.
2	[17]	10.1109/ICDCM.2015.7152044	DC power, SiC JFET, SSCB, WBG semiconductor	IEEE	Review	USA	93	• Low-voltage DC (under 1000 V) distribution application. • Interruption of 180 A current DC bus voltage 400 V. • Sense terminal voltage rises and holds off the wide bandgap semiconductor static switch.	• Potential cost increment for data acquisition inter-module devices. • Required systematic modelling and experimental investigation for further DC distribution analysis.
3	[18]	10.1109/JESTPE.2016.2633223	DC, Distribution, fault protection shipboard, SSCB	IEEE	Article	USA	76	• DC shipboard distribution protection system. • Microcontroller unit with two different algorithms of overload and short circuit protection.	• Required high-speed tripping unit for fast switching mechanism. • Multiple communication requirements to merge the data of each converter.
4	[12]	10.1109/ESTS.2015.7157906	SSCB, Power semiconductor, Thermal management, IGCT.	IEEE	Article	Sweden	74	• Reverse blocking-IGCT of the semi-conductor switch. • Two surge arrestors are used in parallel connection to reduce maximum peak voltage.	• Further detailed analysis of different applications and conditions is necessary to validate the developed system and prototype.
5	[19]	10.1109/JESTPE.2016.2638921	DC distribution, DC fault protection, and shipboard power system.	IEEE	Article	USA	69	• Integrated power system-based ship-board system to improve for medium voltage to ensure survivability and reli-ability of power delivery. • The wide band gap of semiconductor-based SiC.	• Future study is needed considering the different applications of protection schemes. • Critical comparison of protective devices topologies between ‘unit-based’ SSCB operation and ‘breaker-based’ operation.
6	[20]	10.1109/ESTS.2019.8847815	SSCB, DC shipboard power system, RB-IGCT, protection coordination, fault protection.	IEEE	Article	USA	46	• High current SSCB for DC shipboard power system. • SSCB react and limit fault current in a shorter time of less than 20μs. • Parallel connection of silicon RB-IGCT and optimized MOV.	• Required details data of system components to model the MOV characteristic. • Various approximation is needed to obtain the accuracy of MOV detection to achieve better performance and validation.
7	[21]	10.1109/IECON.2014.7049287	SiC device, SSCB, hybrid CB, fault isolation device, distribution system protection	IEEE	Article	USA	45	• Three-phase series SiC IGBT semiconductor connected. • Comparative performance of FID based on Gen II and Gen III SiC FID.	• Further study is needed for different applications to validate the effectiveness of the FID operation in the SSCB operation to provide stablility.
8	[22]	10.1109/ESTS.2017.8069314	SSCB, Fault protection, Trip-curve, power semiconductor.	IEEE	Review	USA	43	• SSCB topologies. • High-performance protection. • Shipboard power distribution system. • The interruption time of short-circuit faults is within a few microseconds.	• Extensive review regarding the issues and challenges. • Address the challenges such as on-state losses, off-state leakage current etc.
9	[15]		Protection devices, DC power supply, fault.	IEEE	Review	Norway	42	• MVDC. • Comparative study of DC circuit breakers namely mechanical CB, SSCB and hybrid CB.	• An extensive study of technological development analysis is needed to examine the topology and operation of CB devices.
10	[23]	10.1109/SPEC.2016.7846117	SSPC, fault isolation, short-circuit current.	IEEE	Review	Singapore	35	• High current development of 270 V DC SSPC.	• Improvement in thermal management would potentially

(*continued on next page*)

Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
								• Analysis towards the market availability, and design challenges of the SSPC system.	lower the junction temperature of the device. • Faster communication such as optical required extensive research.
11	[24]	10.1109/APEC.2016.7467990	SSCB, SiC device, DC system.	IEEE	Article	USA	30	• Development of SSCB-based 380 V DC using SiC material with parallel connection. • Comparative analysis of different characteristic materials of SSCB.	• Detailed formulation and description of topologies of SiC are needed to examine the operation and characteristics of the materials.
12	[25]	10.2514/6.2018–5008	HVAC, SSCB, power electronic.	IEEE	Article	USA	27	• Critical review regarding the power electronics application for high reliability, efficiency and high power density of the SSCB protection devices. • Power converter topologies and system architecture were highlighted and compared.	• Required further experimental validation regarding the DC circuit breaker for more electric vehicles (MEA). • Technical challenges of the power semiconductor device and power converter must be considered.
13	[26]	10.1109/APEC.2014.6803800	SSCB, protection, VSC converter.	IEEE	Article	USA	26	• Protection strategy to limit the fault currents in VSC-based DC systems. • Series connected SSCB with DC capacitor to limit the discharge current.	• Experimental validation is required to validate the novel protection method to guarantee the SSCB operation for current limiter strategy.
14	[27]	10.1109/ECCE.2014.6953414	Fault current, SSCB, IGBT junction	IEEE	Article	United Kingdom	24	• DC fault current limiting and interrupting device. • SSCB-based IGBT switch for fault current limiting.	• Further experimental conceptual is needed to prove the operation of IGBT.
15	[28]	10.1109/IECON.2019.8926684	MVDC, SST, SSCB, short-circuit fault, overcurrent protection	IEEE	Article	China	20	• SSCB series-connected IGBT configuration at BESS terminal. • Achieve voltage balancing and fault isolation through the multi-pulse fault detection method. • Integration of BESS into SST for the energy exchange.	• Further analysis and detailed formulation of the proposed multi-pulse fault detection are needed. • Different fault conditions can potentially be applied to verify the effectiveness of the proposed approach.
16	[29]	10.1109/ICCEP.2015.7177621	MG, CB, converters, PV	IEEE	Article	Italy	18	• Integrated PV system with converter-based MG system. • SSCB-based protection scheme for limiting the fault current on the MG line voltage.	• An extensive analysis of experimental validation is needed to verify the comparative methods between electromechanical and SSCB devices.
17	[30]	10.1109/APEC.2018.8341000	Hybrid DCCB, SCCB, IGBT.	IEEE	Article	China	15	• Bidirectional SSCB switch with series connected IGBT and diode. • Provide voltage and fault current level of 160 kV/9 kA hybrid DCCB with an ultra-fast mechanical switch and current commutation drive circuit.	• Detailed formulation and description of the proposed novel method. • Extensive validation is needed to provide the stable operation of the series-connected IGBT switch in SSCB devices.
18	[31]	10.1109/INTLEC.2016.7749138	DCMG, DCCB, current limiting, overcurrent protection, MOSFET, IGBT, SiC.	IEEE	Article	Japan	15	• SSCB development for DC power network that trips off the fault current within 20μs. • Current limiting function by extending the elapsed time.	• Detailed topology of the MOSFET device should be presented to enhance the state-of-the-art of the components and expand their operation.
19	[32]	10.1109/PEAC.2014.7038038	SSCB, UPS, DC protection	IEEE	Article	China	15	• Two series opposite connection IGBT is designed to cut off short circuit current in both directions. • Optimized the usage of MOV in the SSCB to enlarge the current.	• Detailed modelling of the device is necessary to enhance the concept and methodology of implementation for DCCB.

(*continued on next page*)

Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
20	[33]	10.1109/ICRERA.2015.7418584	DCMG, DC protection, SSCB.	IEEE	Article	Italy	14	• SSCB-based MG application including PV and BESS. • Wide band gap SSCB for efficient protection of home appliances. • Analytical discussion toward community MG system for DC voltage level.	• Provide various technical and societal improvements in the community. • Living laboratory between communities where energy is managed and exchanged efficiently to improve quality and preserve the environment.
21	[34]	10.1109/PEDG.2014.6878653	HVDC, VSC, MOV, CB.short-circuit	IEEE	Article	Canada	14	• New topology development of SSCB HVDC for fault energy absorption. • Fault current isolation for HVDC transmission line without MOV in the SSCB device system.	• Detecting and isolating the fault current within a few milliseconds. • An experimental validation is required to verify the proposed CB. • Fast response and compatible with VSC for DC faults.
22	[35]	10.1109/APEC.2018.8341287	SSCB, SiC JFET, Inrush current.	IEEE	Article	USA	13	• SiC-based SSCB with adjustable current-time (*I-t*) tripping profile for short circuit protection. • Proposed blind zone mode limitation on the SSCB to operate under low fault current conditions.	• The SSCB offers a current time profile with a response time of 0.5–300 μs for short circuit fault current. • Short circuit fault current ranges from 2 to 10 times of nominal current.
23	[36]	10.1049/iet-pel.2017.0283	SSCB, SiC, flyback DC-DC converter, JFET, Fault isolation.	IET	Article	China	13	• SiC JFET-based SSCB is developed to achieve fast protection during fault isolation. • Forward flyback DC-DC converter is utilized for mitigating gate-source voltage.	• Extensive research towards optimum operation of SiC-based SSCB application is necessary to enhance the performance and improve the reliability of the device.
24	[37]	10.1109/TIA.2019.2948923	MG, power converter, K-nearest neighbour, protection, programmable relay unit.	IEEE	Article	USA	11	• Proposed new switching mechanism based intelligent three-tie contactor (ICU) for fast identification selective isolation of short circuits and restoration.	• Accurate fault detection performance with K-nearest neighbour (KNN) technique-based fault classification. • Complex communication on the system.
25	[38]	10.1109/PEAC.2018.8590629	SiC, SSCB, DCMG.	IEEE	Review	USA	11	• An analytical review based on DCMG application of protection system. • 380 V/20 A rated intelligent tri-mode SSCB (*ibreaker*) for DCMG protection.	• Detailed model development and case study are needed to simulate the proposed scheme under different conditions.
26	[39]	10.1109/PESGM.2015.7285787	SSCB, Hybrid CB, Fault current, HVDC.	IEEE	Article	Spain	11	• Hybrid HVDC breakers for fast fault clearing operation and lower losses. • IGBT cell-based switch device that connected bidirectional to allow current flow, increase current rating and protect the entire breaker.	• An extensive analysis towards semiconductor current losses and other control strategies is needed. • Complex formulation of the developed model for HVDC network protection.
27	[40]	10.1109/ICPS.2019.8733334	MG, Power converter, protection, high impedance fault, K-nearest neighbour.	IEEE	Article	USA	10	• VSC-based protection scheme for cost-effective and fast high impedance fault current detection in MG system. • Localized information-based protection using discrete wavelet transform technique with multi-resolution analysis and K-nearest neighbour classification algorithm.	• Accurate fault detection performance with K-nearest neighbour (KNN) technique-based fault classification. • Reduce computational time by optimum wavelet function and feature extraction. • Different applications and voltage levels of the system need to be verified.

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Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
28	[41]	10.1109/SPEC.2016.7846030	HVDC, VSC, IGBT, SSCB, power electronic.	IEEE	Article	China	10	• HVDC breaker-based IGBT main power switch device to improve breaking capacity and decrease current density. • Fault current limitation with the parallel branch of the IGBT device in the HVDC system	• Smallest current stress on the IGBT power device. • Detailed formulation and analysis are presented. Experimental validation is necessary to verify the proposed method.
29	[42]	10.4271/2014–01–2141	SSCB, IGBT, fault current interruption, DC network.	SAE International	Article	England	10	• Protection system estimation based on resistive type SFCL development to examine the weight and losses of the component. • SSCB combined with SFCL to examine the current source control to limit and interrupt the fault current.	• A systematic approach to optimize the architecture and protection system design. • Different scenarios and case studies to examine the proposed approach is necessary to evaluate the model under different conditions.
30	[43]	10.1109/ESTS.2019.8847879	SSCB, DC shipboard power system, RB-IGCT, fault protection.	IEEE	Article	USA	9	• Thermal system high current SSCB for DC distribution system. • SSCB limit the fault current at one order of magnitude faster than traditional mechanical or hybrid solutions.	• Detailed analysis of the thermal resistivity of SSCB. • Further analysis of different voltage levels can potentially be implemented.
31	[44]	10.1109/EPE.2016.7695558	Short-circuit protection, DC solid state power controller (SSPC).	IEEE	Article	China	9	• Control strategy development of DC SSPC to eliminate the short-circuit fault from capacitive load quickly for aircraft power distribution. • Current closed-loop control of MOSFET for large capacitive to limit the output short-circuit current to a preset level by dropping gate voltage of MOSFET to a low value that is equivalent to a constant current source.	• Ability to eliminate the capacitive load from short-circuit fault in a shorter time. • Fast fault detection and distinguishing the larger capacitive loads. • The voltage level of the distribution system and short-circuit current rating are not mentioned.
32	[45]	10.1109/APEC.2019.8721869	SSCB, GaN transistor, heat dissipation.	IEEE	Article	USA	7	• A GaN transistor-based automated SSCB for short-circuit interruption and inrush current elimination during start-up power electronic device. • 380 V/20 A bidirectional GaN-based transistor of SSCB with a tri-mode control strategy.	• Detailed experimental validation and prototype. • High-efficiency operation in the sense of the true short circuit fault scenario.
33	[46]	10.1109/APEC.2017.7930791	SSCB, gate driver, SiC MOSFET, voltage distribution	IEEE	Article	China	7	• The cascaded driving strategy of SiC MOSFET for DC breaker application with 20.4 kV and 20 A rating. • Capacitive coupling for SiC MOSFET series connected for decreasing switching losses and accelerating switching transition during short-circuit fault conditions.	• Detailed conceptual analysis and experimental validation. • Further detailed formulation model and different system scenario is needed to verify the proposed driver strategy.
34	[47]	10.23919/IPEC.2018.8507570	BESS, DCCB, DC-DC converter	IEEE	Article	Tokyo	6	• A bidirectional chopper for charging the auxiliary converter as SSCB to protect the short-circuit fault of the main switches. • A bidirectional chopper series connected with an auxiliary converter is developed to reduce the size and weight of the current smoothing inductor of BESS in an electric railway station motor drive.	• Detailed experimental validation and conceptual formulation are presented. • Auxiliary converters solve the arching issues associated with mechanical breakers. • The thermal management of the converter switch can potentially be considered in future work.

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Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
35	[48]	10.1109/INTLEC.2017.8211688	Power semiconductor, DCCB, MOSFET, IGBT, SiC MOSFET.	IEEE	Article	Japan	6	• Power protection strategy based SiC MOSFET type SSCB for fast-acting switching and current limiting function.	• Detailed control formulation and constraint of the system need to be highlighted.
36	[49]	10.1109/ITEC.2017.7993304	DC power system, H-Bridge CB, DCCB.	IEEE	Article	Thailand	6	• H-bridge structure-based solid state thyristor for DCCB operation. • Enhanced breaker operation by current-reversal H-bridge circuit breaker to minimise component and weight of the device for fault current interruption.	• Experimental validation and model formulation are presented. • Different voltage levels can potentially be verified and experimented with to demonstrate the fault current interruption strategy.
37	[50]	10.1109/APEC42165.2021.9487198	SSCB, DCCB, DCMG, wide bandgap, SiC.	IEEE	Article	USA	5	• T-type modular DCCB for DC network system integrated BESS for fault current signal mismatch control. • Voltage scalability-based T-type modular DCCB during fault transient.	• The detailed design and formulation need to be highlighted in future work. • Extensive results and performance towards fault current analysis in different scenarios are required.
38	[51]	10.1109/IECON43393.2020.9254505	Fuel cell, short-circuit protection, SSCB, bidirectional power flow.	IEEE	Article	China	5	• Novel Z-source bidirectional DC SSCB for proton membrane fuel cell application for fault current isolation and protection fuel cell system. • A 72 V voltage power supply to Saber for validation of novel strategy.	• Test and verification towards the fuel cell hardware system are needed. • Detailed formulation and parameter consideration need to be fully explained.
39	[52]	10.1109/EPE.2016.7695679	Current limiter, protection device, hybrid CB, SSCB.	IEEE	Review	United kingdom	5	• Comparative analysis and method for current-limiting CB with capability fault current interruption in microsecond time.	• Extensive review and analysis towards formulation and control strategy of current-limiting CB is required.
40	[53]	10.1109/EPE.2016.7695675	SSCB, phase shift control, protection device, current limiter.	IEEE		United kingdom	5	• Current limiting phase shifting strategy based SSCB without impedance integration. • Current limiting with 400 V/500 A rated capability. • Si and SiC wide bandgap material used in the SSCB device.	• High current harmonic and complex control formulation. • Further experimental validation towards the current limiting strategy and detailed model formulation is needed.
41	[54]	10.1109/iEECON.2014.6925920	IGBT, SSCB, short-circuit, under voltage, leakage current, overload.	IEEE	Article	Thailand	5	• IGBT-based SSCB switching mechanism for fast switching speed with five different scenarios case of over voltage, leakage current, under voltage, overload, and short circuit condition.	• Detailed experimental and performance evaluation is presented. • Different switching technology is necessary to be presented as a comparative evaluation.
42	[55]	10.1109/ESTS.2019.8847821	SSCB, power electronic device, DC distribution system,	IEEE	Article	USA	4	• SSCB operation for shipboard application-based 1 kV DC testbed digital real-time simulator for protection system. • The flow of common mode current examination in the shipboard system-based DC testbed for fault current isolation.	• Ground fault detection protection logic needs to be considered in future work. • Medium voltage shipboard consideration is necessary to verify the performance of the testbed and achieve reliability.
43	[56]	10.1049/cp.2016.0030	DC, Shipboard, SSCB, distribution.	IET	Review	USA	4	• Analysis towards SSCB device operation in DC shipboard distribution system protection. • Comparative analysis of the SSCB device switching technology and protection methods.	• An extensive review regarding the technological SSCB development and control formulation is needed to prove the operation and verify the performance.
44	[57]	10.1109/IECON48115.2021.9589224	DCCB, voltage limiting, series-connected, single gate driver.	IEEE	Article	USA	3	• TVS diodes-based power semiconductor for limiting the turn-off voltage of the	• Detailed control formulation and characteristics of the TVS operation is needed.

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Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
								power devices and current return path for gate capacitor discharging.	• Fault current condition performance must be present.
45	[58]	10.1109/APEC39645.2020.9124240	Integrated design, circuit breaker, DC-DC converter.	IEEE	Article	China	3	• T-source type CB integrated with a DC-DC converter which can able to cut-off the short-circuit fault and filter the output ripple of the load to improve the stability of the system.	• Extensive research towards different constraint and various component parameters on the performance of the device needs to be considered to verify the effectiveness.
46	[59]	10.1109/APEC39645.2020.9124547	SSCB, dynamic voltage unbalancing.	IEEE	Article	USA	3	• Diode clamped-based SSCB for MV application for fault current isolation and eliminate the voltage unbalancing in the network. • Diode clamped-based SSCB on the MV system can limit the increase of fault current and reduce the MOV volume.	• Detailed experimental validation and prototype performance are presented. • Different fault current situations and control architecture of the model can potentially be considered to proof the operation.
47	[60]	10.1109/ICAGE.2014.7050176	Solid-state protection, thermal trip, short-circuit fault current, overload current, heat sink.	IEEE	Article	India	3	• Solid-state protection device breaker for home DC appliance. • Comparative analysis with electromechanical CB and detailed control formulation is described based on the thermal trip zone and magnetic trip zone condition.	• An intelligence controller approaches for different parameter optimization such as monitoring, measurement of power and power consumption can be considered in future work.
48	[61]	10.1109/ICDCM50975.2021.9504627	Bidirectional DCCB, hybrid CB, protection device, fast CB	IEEE	Article	Italy	2	• New voltage bidirectional hybrid CB for short-circuit interruption. • The power electronic switch and DC relay are integrated as an SSCB mechanism to isolate the fault current to provide a fast and reliable protection scheme.	• Proper parameter and component sizing are necessary in designing the hybrid CB to ensure reliable operation. • An experimental-based validation is needed to verify the proposed approaches.
49	[62]	10.1109/ICDCM50975.2021.9504627	DCCB, MOV, current interruption.	IEEE	Article	USA	2	• Design methodology of MOV-RCD snubbers for MV SSCB for the current interruption. • A prototype implementation of MOV-RCD snubber SCCB to realize fast response speed for a broad range of current fault magnitude.	• Specific snubber capacitance values give a long response time and exceed the safe range of voltage. • The capacitance value should be fixed and examined to achieve a good design of the MOV-RCD device.
50	[63]	10.1109/COASE.2019.8843247	SSCB, DC breaker, mechanical circuit relay.	IEEE	Article	China	2	• SSCB-based current limiting circuit for HVDC current interruption.	• Detailed analysis of the topology of the device is needed.
51	[64]	10.1109/ISIE.2019.8781361	Fault current interruption, DCMG, protection, real-time simulation, dual active bridge (DAB), series voltage regulator (SVR)	IEEE	Article	India	2	• SCSVC to limit short-circuit current rapidly during fault conditions. Reducing voltage sag on the main bus-bar during fault conditions.	• An extensive conceptual analysis is needed to demonstrate the proposed strategy on the DCMG system with different voltage levels and constraints. Detailed switching time is necessary.
52	[65]	10.1109/INTLEC.2018.8612397	Power semiconductor, current limiter, overcurrent protection, power MOSFET, IGBT, SiC MOSFET.	IEEE	Article	Japan	2	• SSCB power switching device for current interruption and overcurrent protection based power semiconductor device of Si, SiC and IGBT for low voltage DC power network.	• Experimental validation is necessary to prove the performance of the proposed strategy at any condition to validate the time response and operation for reliable protection system.
53	[66]	10.1109/SIELA.2014.6871855	Semiconductors, solid-state switch, inductive type fault current.	IEEE	Article	United kingdom	2	• Fault current limiter control method comparison based SSCB devices switch to examine and analyze the power dissipation, switching time, and cost evaluation.	• An extensive review of different topologies and types of switches is necessary to examine the details conceptual operation of power transistors.

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Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
54	[67]	10.1109/SeFeT55524.2022.9909364	DCMG, DC bus protection, CB.	IEEE	Article	Hyderabad	1	• Bi-directional short-circuit current blocker-based SSCB for fault current protection and fast switching speed in DCMG.	• Extensive research on DCMG fault current protection considering different conditions is needed.
55	[68]	10.1109/ITEC53557.2022.9813955	MVDC, CB, SiC MOSFET, fault current limiter, solid-state.	IEEE	Article	USA	1	• SiC MOSFET with superconducting fault current limiter to improve the efficiency of the SSCB device operation in the DC power network.	• Improved efficiency switching operation over conventional SSCB device in DC power network.
56	[69]	10.1109/APEC43599.2022.9773378	SSCB, Power semiconductor, overcurrent, thermal model, failure.	IEEE	Article	China	1	• Electrical thermal model for overcurrent protection capability in SSCB. • Comparative technology of SiC MOSFET and Si IGBT device.	• Detailed analysis towards the topology and operation of both Si IGBT and SiC MOSFET devices for overcurrent protection capability.
57	[70]	10.1109/APEC43599.2022.9773555	SSCB, DCCB, DCMG, wide bandgap devices, SiC.	IEEE	Article	USA	1	• T-type modular DCCB is proposed to minimise ride-through of grid transient. • Incorporating shunt compensation function for voltage compensation.	• Stability improvement based T-Type modular DCCB in MG system. • Different compensation functions can be included in future.
58	[71]	10.1109/APEC43599.2022.9773380	SSCB, unclamped inductive switching, parallel connection.	IEEE	Article	Japan	1	• SiC MOSFET and SiC diode in SSCB device with avalanche voltage clamping for conduction loss and increased breaking capability for efficient protection.	• Sufficient avalanche tolerance during current interruption. • The SiC diode can tolerate up to 50 A current interruption.
59	[72]	10.23919/ EPE21ECCEEurope50061.2021.9570659	CB, Conduction loss, Fault detection, SSCB	IEEE	Article	United Kingdom	1	• Extensive review towards DC SCCB is discussed under different viable bi-directional SSCB topology configurations considering thermal activity.	• Si IGBT power semiconductor considered the most effective technology in DC SCCB application for electric protection system.
60	[73]	10.1109/ECCE47101.2021.9595117	SSCB, SCCB, fault protection, short circuit test.	IEEE	Article	USA	1	• Testing circuit for pulse provider to interrupt the short-circuit current at SSCB for achieving thermal equilibrium.	• Significant fault current capability successfully achieved fopr the test circuit under 12 kV and 2 kA rating system.
61	[74]	10.1109/IECON.2019.8927420	MVDC, protection, DCCB, Current regulation.	IEEE	Article	United Kingdom	1	• Proposed interlinked SCCB configuration for DC fault current blocking and current regulator capability.	• Current regulator were effectively simulated and tested that active fully controlled at 8.5 s duration to −0.5 kA.
62	[75]	10.1109/ESTS.2019.8847791	Active mode, linear mode, current limiter, current control, voltage balance.	IEEE	Article	USA	1	• Current limiter circuit for voltage and current balancing through series connected FETs for DC and AC medium voltage application. • Parallel FET connection	• Minimum conduction losses and limited fault ride-through current to prevent arc-flash events. • Fast turn-off capability in SSCB device.
63	[76]	10.1109/ICCEP.2019.8890213	Active clamp gate driver, overvoltage protection, circuit protection, power losses.	IEEE	Article	Italy	1	• To model the active clamp circuit for power loss calculation IGBT power semiconductor-based SSCB operations.	• Details concept and formulation is highlighted for power losses calculation of the active clamp model in the IGBT devices.
64	[77]	10.1109/PEAC.2018.8590581	A heat sink, SSCB, IGCT.	IEEE	Article	China	1	• Thermal analysis on the parallel connection IGCT and diode bridge for the SSCB device operation considering 15 kA and 2.4 kV rating system.	• Achive better heat dissipation performance based experimental validation at 7.9 K/kW at junction temperature.
65	[78]	10.1109/TIA.2022.3229655	SSCB, DC power distribution system, fault current.	IEEE	Review	USA	0	• Cascaded JFET switch operation strategy on the SSCB device for voltage balancing during switching transition and prevent over-voltage.	• Achieve balance network with 6 kV/ 15 A rated voltage of capability handling leakage current during ON and OFF transitions.
66	[79]	-	CB, current limiting, SiC.	IEEE	Article	German	0	• Thyristor dual functionality based SiC SSCB device for short-circuit clearance with self-sensing and self-triggered devices on DC network.	• Short-circuit clearance at 122 ns at 800 V voltage is achieved on the DC system to isolate the fault with efficient operation.

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Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
67	[80]	10.1109/ITEC53557.2022.9813998	SSCB, DC distribution network, wide bandgap, fast-acting protection.	IEEE	Article	USA	0	• Test methods-based evaluation of WBG semiconductor devices for SSCB operation for fast action speed, high power density and efficient operation in electrical power systems.	• Details experimental validation performance and comparison. • Provide test setup configuration for parameters measurement of SSCB.
68	[81]	10.1109/IECON48115.2021.9589056	DC power, current limiting, WBG, SSCB, SiC JFET.	IEEE	Article	United Kingdom	0	• Cascaded method of SiC JFET and Si MOSFET for current limiting and ultrafast SSCB on 400 V DC system. • Controllable fault current and simple implementation.	• Capable of interrupting current of 100 A within 55μs. • Suppressed the overvoltage below 800 V on the DC network system effectively.
69	[82]	10.1109/ISIE45552.2021.9576293	DCMG, Short-circuit protection, SSCB, Voltage clamping.	IEEE	Article	China	0	• An RCD-type snubber circuit approaches SSCB for fast disconnection speed and small voltage drop during short-circuit fault conditions.	• Achieved rapid release of transient energy in the fault line and successfully transferred to snubber capacitor with 14.3 A after 2 ms.
70	[83]	10.1109/TIA.2022.3156534	DC distribution system, hybrid DCCB, current limiting, MOV.	IEEE	Article	USA	0	• Faster fault isolation and peak reduction current magnitude-based MOV optimization and switching control for DCCB devices. • Optimized MOV structure to achieve near-uniform energy absorption during fault isolation with a progressive switching mechanism.	• Details of structure and model development are presented to evaluate the proposed approaches. • Experimental proved the effectiveness of the proposed approach by providing low fault current peak and uniform energy absorption.
71	[84]	10.1109/APEC42165.2021.9487219	Active injection circuit, CB, soft switching, SSCB.	IEEE	Article	USA	0	• An active injection circuit for SiC MOSFETs device in SSCB for fault current reduction during DC current interruption. • Simulated under 4 kV/100 A with experiment 380 V/150 A prototype.	• Fault current minimization to zero during DC current interruption that removes the parasitic effect of the main switch. • The breaker response time for fault clearance is 2.8μs.
72	[85]	10.1109/APEC42165.2021.9487155	GaN, overcurrent, SSCB.	IEEE	Article	USA	0	• 600 V GaN gate Injection Transistor for overcurrent capability under different time durations and temperatures. • Measured voltage from gate to source, drain to source and drain to current to evaluate the overcurrent capability of the devices.	• Maximum DC withstand current for GaN transistor under junction temperature between 25°C and 150°C and time duration between 10 ms and 3 s. • Applicable for DC SCCB that can handle overcurrent conditions with above 150°C temperatures.
73	[86]	10.1109/APEC42165.2021.9487057	DC distribution system, power system protection, CB, circuit design.	IEEE	Article	USA	0	• A novel surge voltage-free SSCB for fast current interruption without inducing surge voltage. • The current limiter capability in the proposed model does not affect the isolation speed of the breaker and surge voltage is not induced.	• Experimental validation was highlighted. • Surge voltage is not induced on its semiconductor switches. • Shorter-time fault clearance during operation. • Different scenario operations can potentially be considered.
74	[87]	10.1109/APEC42165.2021.9487393	Battery switching module, SSCB, SiC JFET.	IEEE	Article	USA	1	• Battery switching module-based SiC JFET semiconductor for fault current stress and improved lifetime operation. • Tri-mode operation concept integrated into module for the soft-start process of DC link charging.	• Less time taken for the BSM to trip the current reach 350 A at approximately 40nS. • The overshoot voltage at 1125 V does not exceed the voltage of the device rating of 1200 V.
75	[88]	10.1109/CPE-POWERENG50821.2021.9501076	SSCB, advanced clamping circuit	IEEE	Article	Germany	0	• A novel clamping circuit with a MOV capacitor is introduced to DC SSCB for breaker overvoltage reduction during protection operation.	• Reduce losses by 33 % for 1 kV/200 A system. • Experimental validation on the performance of overvoltage in DC SSCB during a fault condition.

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Table 1 (*continued*)

Rank	Ref	Article DOI	Keywords	Publisher	Type	Country	Citation	Methods and system	Scope and research gap/problem
76	[89]	10.23919/ICEMS52562.2021.9634601	DCCB, overvoltage suppression, snubber, current slope control, thermal network model.	IEEE	Article	China	0	• Novel gate driver method for SSCB-based soft-turn-off that reduces transient voltage during fault interruption conditions without additional snubber resistances.	• Experimental performance were highlighted. • Further research toward a closed-loop strategy for efficient overvoltage suppression detection.
77	[90]	10.11591/ijpeds.v12.i4.pp2322–2335	Current breaking, DCCB, fault current.	IEEE	Review	USA	0	• Critical review of the DCCB operation based on different topologies. • Different comparisons and issues on the DCCB were highlighted.	• Provide future scope and direction on the development new topology of the DCCB system for efficient operation.
78	[91]	10.1109/ITEC48692.2020.9161751	Power semiconductor, SSPC, electric CB.	IEEE	Article	USA	0	• GaN-based power semiconductor device for SSCB operation to isolate the fault current during short-circuit events in aircraft application.	• Detailed experimental analyses are highlighted. • The high current capability of GaN material in thermal effect.
79	[92]	10.1007/978–981–15–0206–4_3	DCCB, HVDC transmission, Fault protection	Springer	Book	India	0	• SSCB-based DC voltage system for fault current clearance during short-circuit events.	• Provide superior switching performance in fault clearance with less time required.
80	[93]	-	Electric CB, power electronic, SiC JFET.	IEEE	Article	USA	0	• Series connected SiC JFETs for the reverse current flow of inrush current limiter during a fault condition.	• Further experimental validation is required to verify the supercascode method.
81	[94]	10.1109/ICHVE.2018.8642190	MV breaker, fault current limiter, solid-state switching, MV network.	IEEE	Review	Poland	0	• Resonant-type fault current limiter for MV network for fast control circuit and minimized overvoltage stress during high short-circuit current level in a distribution network.	• Further detailed technical aspects such as control scheme and fault detection methods need to be addressed further to verify the efficient operation.
82	[95]	10.25728/assa.2019.19.1.647	Arc fault, time-frequency aggregation, Electric CB.	IEEE	Article	USA	0	• A Coupled inductor-based SSCB using IGBT for fault current limiting capability in an LVDC system.	• Detailed model development. • An enhanced experimental validation is needed.
83	[96]	10.1007/978–981–13–0212–1_76	CB, fault current, hybrid CB, SSCB	ICCCE	Article	India	0	• A hybrid topology of semiconductor devices in series and parallel for SSCB is presented to improve fault current reduction in short-circuit events for power grids.	• Provide wider integration of SSCB in existing power grids to isolate the fault current with below 100μs time. • Cost-effective nature.
84	[97]	10.1109/IFEEC.2015.7361570	Short-circuit level, fault current limiter, solid-state, transient stability.	IEEE	Article	Taiwan	0	• A single DC reactor fault current limiter with controllable resistive type is presented for short-circuit events to redirect power flow in high voltage.	• Transient stability enhancement during a short-circuit event with fault current suppression will absence extra controller.
85	[98]	10.1049/cp.2014.0135	DC power system, VSC, power system protection, fault current.	IET	Article	Spain	0	• Hybrid SSCB incorporating DC node of VSC and DC-DC converter for fast protection strategy in electric vehicle application power system.	• Optimal protection scheme with fault current isolation of milliseconds. • An experimental approach is necessary.

Based on Table 1, it can be analyzed that, the older paper received more citation numbers as evidenced by Mokhbedoran A et al. in 2014 with a citation number of 94 [16]. The papers were presented based on the review type of paper which has been published in the IEEE journal. The paper performed an analytical study based on the circuit breaker operation in the high voltage direct current application to highlight the technological improvement and circuit topologies. A comparative analysis towards different types of circuit breakers to achieve efficient fault current isolation is presented. This review will drive the reader to view the current topologies of different type of circuit breakers and their operation associated with the high voltage application that enables to determining the research gap toward stability system. The second top most cited paper were revealed by Z. John Shen et al. in 2015 with a citation number of 91 [17]. The paper was published in the IEEE journal with the article type of review paper. The paper reviews the state of the art of DC SSCB for low-voltage distribution systems. A new concept of self-powered SSCB-based advanced static switch of wide bandgap technological development was also highlighted. This analysis tends to provide a clear direction and enhance the SSCB device operation towards power quality and stability improvement on the distribution system network. Furthermore, Qi L.L. et al. published the third most cited paper recently in 2017, with a citation number of 76 in a similar IEEE journal [18]. The paper presented to development of the microcontroller switching technique on the SSCB for fast protection speed and fault current isolation in the DC shipboard system. Thus, this will enhance the SSCB operation for fault protection in low-voltage DC applications with low-cost and optimized operation. According to this review, the recent older paper received more citations number than the newer paper. The fourth most cited paper was also published in IEEE Journal in 2015 with the title "1 MW bidirectional DC solid-state circuit breaker based on air cooled reverse blocking IGCT". The paper was conducted by Agostini et al. and had a citation number of 74 [12]. This paper has developed the new switching strategy of SSCB that provides optimum conduction losses, and high turn-off current capability. The experimental and simulation were presented based on the system level to verify the proposed approach during the current interruption. This will enhance the state of the art of the SSCB operation, especially on the switching mechanism that can able to isolate the fault current optimally. According to Table 1, papers with a citation rate of 30 or more per year are considered hot papers in their respective field. This will enhance the understanding of the recent development of the current status in SSCB operation for distribution network system studies to achieve a stable and safe operation.

3.1. Publication trend and citations

The distribution of the top 85 most cited papers in the domain of SSCB devices to achieve a sustainable system and improve power quality issues in distribution networks over the years 2014 and 2023 is presented in Fig. 4. The figure presented the number of published papers over the year as well as the percentage of papers published. It is observed that the number of papers published that revealed in the years 2014–2015 was only 11 (12.9 %) and 6 (7.1 %), respectively. Furthermore, the highest number of published articles was revealed in the year 2021 which consisted of 16 (18.8 %) followed by the year 2019 which consisted of 15 (17.6 %) papers, respectively. Overall, the paper published between the years 2014 and 2023 shows an upward trend from 2016 to 2021 whereas it shows a dramatic fall from 2022 onward.

The analysis from Table 1 of the top 85 most cited papers collected shows that the highest citation number was revealed by Mokhberodan A et al. in 2014. The citation number was achieved by the author at 94 which focused on the review paper. This review was performed as an analytical study based on the circuit breaker operation in the high voltage direct current application to highlight the technological improvement and circuit topologies. The lowest number of citations that were achieved from the collected top 85 most cited papers is at

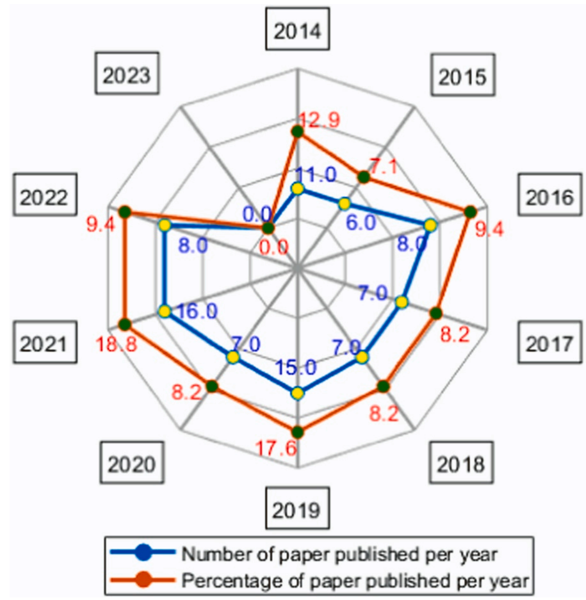

Fig. 4. Dissemination of selected papers with the most citations over the year 2014–2023.

0 citations which shows most of the papers were published recently. The potential reason for this lowest citation situation is because of the newly published paper may potentially require time to gain visibility from the reader.

3.2. Evaluation of Co-occurrence network keyword

The co-occurrence network is a method used to visualize the potential relationship between entities. Thus, in this study, the co-occurrence network analysis is implemented to examine the connectivity between each keyword used based on the top 85 most cited papers in the domain of SSCB devices. The connectivity network of all keywords is developed based on VOSViewer software that was shown in Fig. 5. This method reflects accumulated domain knowledge and aids in the extraction of essential information aspects and concepts based on the forms and strength of linkages between terms appearing in the study [99]. Hence, co-citation analysis is a highly effective and efficient method for mapping related information. The volume of the circle and label is obtained by the impact of the keywords, whilst the connecting line between the keywords is shown as the conjunctive connection which is represented in Fig. 5(a).

Depending on the field of study, different colours were utilized to significantly identify the different clusters of study and applications. From the VOSviewer dataset, 186 keywords are found with 2 or more interconnections which are classified into 5 categories that are denoted as 5 different colours such as red, blue, green, yellow and purple. The electric circuit breaker, SSCB, power electronic, fault detection, and power converter are in the red cluster which determines a strong bonding between them. Furthermore, the blue cluster contains an electric circuit breaker, SSCB, electrolysis, short-circuit protection, and DC circuit are in the blue clusters which are also connected with the red clusters. Mosfet devices, SiC, IGBT, and electric power system protection are in the green clusters which are also connected to the red and blue clusters through the electric circuit breaker. Among the colour-based clusters, the red clusters consist of 17 keywords, the blue and green clusters consist of 9 and 15 total keywords and the yellow and purple clusters consist of 7 and 4 keywords, respectively. These co-occurrence network analysis and keyword connectivity is obtained based on the top 85 most cited paper in the domain of SSCB device to achieve a sustainable system and improve power quality issues in the distribution

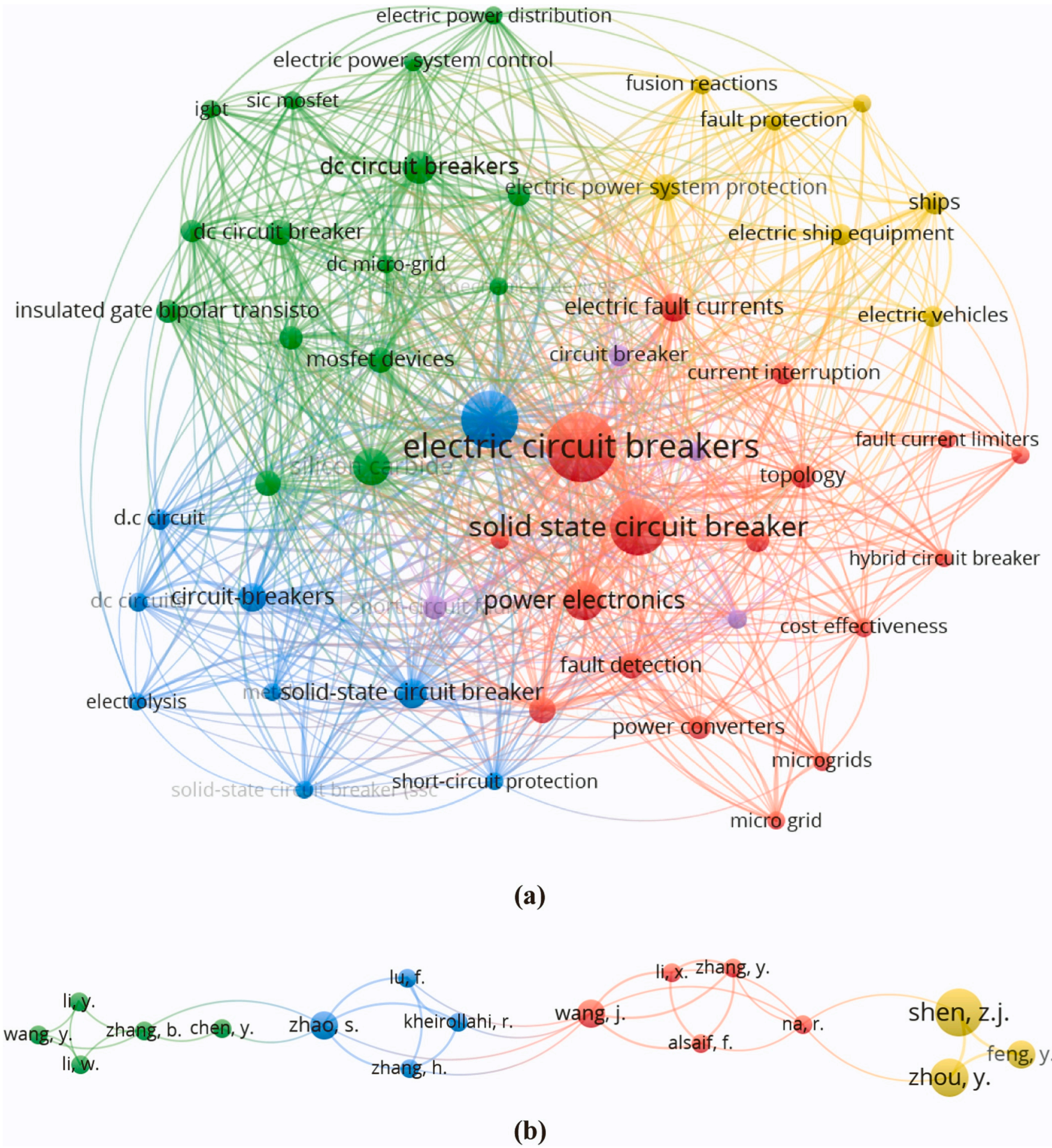

Fig. 5. Analysis of the selected top most cited paper (a) co-occurrence network keywords from the bibliometric analysis; (b) co-citation network analysis.

network.

Based on the selected top 85 most cited papers database, four different sets of clusters were formed in separate colour codes as shown in Fig. 5(b). This co-citation network analysis was obtained from the Scopus database that influenced the author's publication. The yellow cluster has shown a strong link between Shen Z. J and Zhou Y in which they are mainly focused on the technological development of switching mechanisms for SSCB devices. This subject is studied to develop the switching technology of semiconductors based on different materials to ensure the superior performance of the protection system. Moreover, the most prominent pair of authors in the red cluster is Wang. J and Li. X where the main research focus is the including the protection scheme using power electronic switch to improve the breaking capacity in HVDC network. In the blue cluster, a strong relationship between similar types of research was found between Zhao. S and Reza Kheirollahi in the similar year of 2021. Both authors recently studied the development of a fast-switching technique for SSCB devices for current interruption conditions in HVDC applications. Finally, distribution protection, MOSFET device technology development and DCCB application are the key research areas of Wang. Y, Zhang. B, Chen. Y, Li. Y and Li. W which indicates a solid bondage between the authors. The co-citation network analysis generates clusters that illuminate institutional tendencies in interdisciplinary research. This cluster network provides vital information regarding the research type, research speciality, and timeline that can lead to a better understanding of the research trends.

Based on Table 1, the highest 15 general keywords that have been used in several papers between 2014 and 2023 were presented in Table 2. It consists of 15 different keywords that were frequently used in the papers in the domain of SSCB devices for different applications towards power quality enhancement in the distribution network. This presented analysis can be analyzed to examine the research gaps and the current area of the research. It also can potentially able to obtain direction towards SSCB devices with different applications and provide a clear insight into the research area properly.

Based on the Table 2 analysis, the 3 most common keywords commonly used by the researcher for the years 2014–2023 are “SSCB”, “SiC device” and “DCCB”. The total number of keywords used for the “SSCB” and “SiC device” for the years are 41 and 15 whereas 14 for the “DCCB”, respectively. Both “SSCB” and “SiC” keywords are the top most common keywords used during the last 2 years reflect the trends of the study in the area of SSCB devices that are subjected to the technological development and control method to achieve stability and power quality enhancement in the distribution system. Fig. 6 illustrates the detailed graphical distribution of the top 15 keywords that were used in this area. The graphical presented the trends of the frequency of the keywords based on the Table 2 analysis. Thus, based on the co-occurrence keywords analysis, it can be concluded that:

- The presented co-occurrence network method-based study will describe the relationship between keywords, factors and development methodology in the field of SSCB devices toward technological development and control methods.
- A significant increase in SSCB devices and wide bandgap technological development to achieve high switching mechanism research is observed.
- The researcher is more focused on the development of switching technology by using different bandgap materials to improve the efficiency of the SSCB operations.

In Fig. 7, the evaluation of the top 15 keywords over the year 2013–2023 is presented based on MS Excell and MS Visio. The impact of each keyword is presented as the size of the rectangle and the size of the connected line denotes the number of keywords that belong to each category. The Sankey diagram presented the impact of keywords used over the year that is based on the country of origin and author’s name. “Solid-state circuit breakers” are the most commonly used from different countries in this domain with different types of study. For example, within these keywords, the authors Zhou Y et al. used only 1-time keyword “solid-state circuit breaker” that are from the country of USA. The total number of 21 times the keyword used by different countries. Thus based on this relation represented in Fig. 7, it can be concluded that the different counties have mentioned 21 times of “solid-state circuit breaker” keyword for improving the protection scheme to achieve a highly stable distribution network system. Furthermore, different aspect and control approaches were also focused on developing the switching mechanism of the SSCB device by using the keyword in order to improve the SSCB operation. Thus, the presented evaluation can potentially lead to determining the relationship and impact of keywords on the research area that provides insight into the domain of SSCB devices for the researchers.

3.3. Bibliometric Analysis research-based subject area and study types

The analysis research towards the SSCB device-based study types and subject areas in the last five years is presented to observe the trends of

Table 2
Top 15 keywords used in several papers for the year 2014–2023.

Rank	Keywords	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
1	SSCB	[21] [26] [27] [32,54]	[12] [17] [33,39,97]	[24,41] [52,53,56]	[18,22,36] [46]	[25] [30] [35,38] [42,96]	[20,28] [43,45,55,63,65,74] [75,76,95]	[51] [59]	[50] [72] [73,81] [82,84] [85,87] [88]	[69,70] [71] [80]	[78]
2	SiC Device	[21]	[17]	[24,31]	[36,46,48]	[35,36,38,42]	[65]	[93]	[50,81,87]	[68,70,79]	
3	DCCB			[31]	[48,49]	[30,47]	[74]	[92]	[50,57] [61] [62,83] [89,90]	[70]	
4	IGBT	[27,54]	[12]	[31,41]	[48]	[30]	[65]				
5	DCMG		[29,33]	[31]	[19]	[38]	[40,64]	[37]	[50,82]	[67,70]	
6	Fault protection	[21] [66]	[39]	[23]	[18,19,22]	[15,42,96]	[43] [64,76,95]	[37,51] [92]	[72,73]		[78]
7	Power semiconductor	[66]	[12,17]	[44]	[48,22]	[25]	[45,65]	[91]	[50]	[69]	
8	Current limiter	[54]	[97]	[31,52,53]		[94]	[65,74,75]		[62,81] [83]	[68,79]	
9	MOSFET		[12]	[31,44]	[46,48]		[65]		[84,85]	[68]	
10	JFET			[44]	[36]	[47]		[51]			
11	Hybrid CB	[21]	[39]	[52]		[30,96]			[61]		
12	VSC	[16,26,34] [98]	[29]	[41]	[36]		[40]		[88]		
13	DC power supply	[32,98]	[17,33]	[56,24]	[18,49]	[15,42]	[43,55] [63]		[81,83] [86]	[67,80]	[78]
14	CB	[16,34]	[29]		[49]	[96]	[95]	[91,93]	[61,72] [84,86]	[67,68,79]	
15	HVDC	[16,34,98]	[39]	[41]	[46]	[25,94]	[28]	[91,92]		[68]	

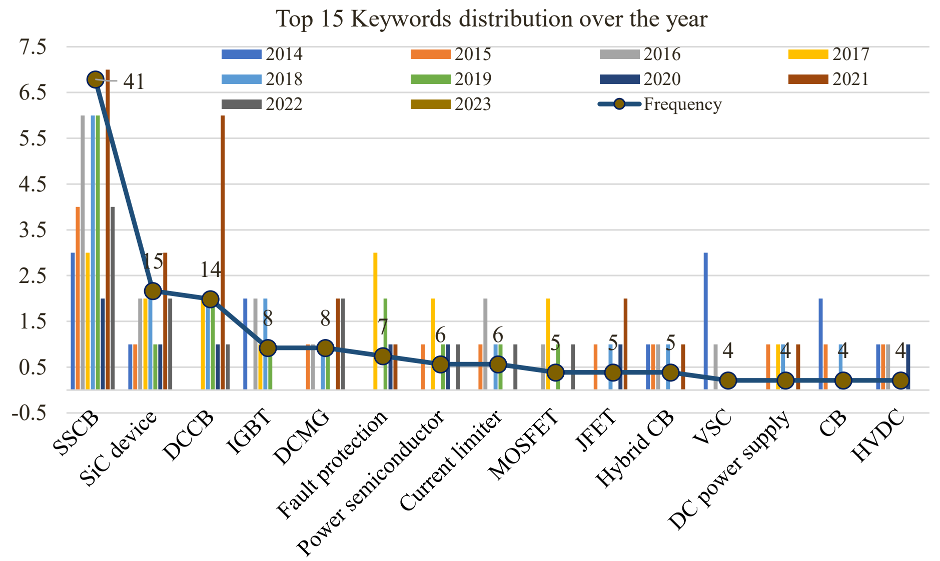

Fig. 6. Distribution of the topmost 15 keywords between the years 2014 and 2023.

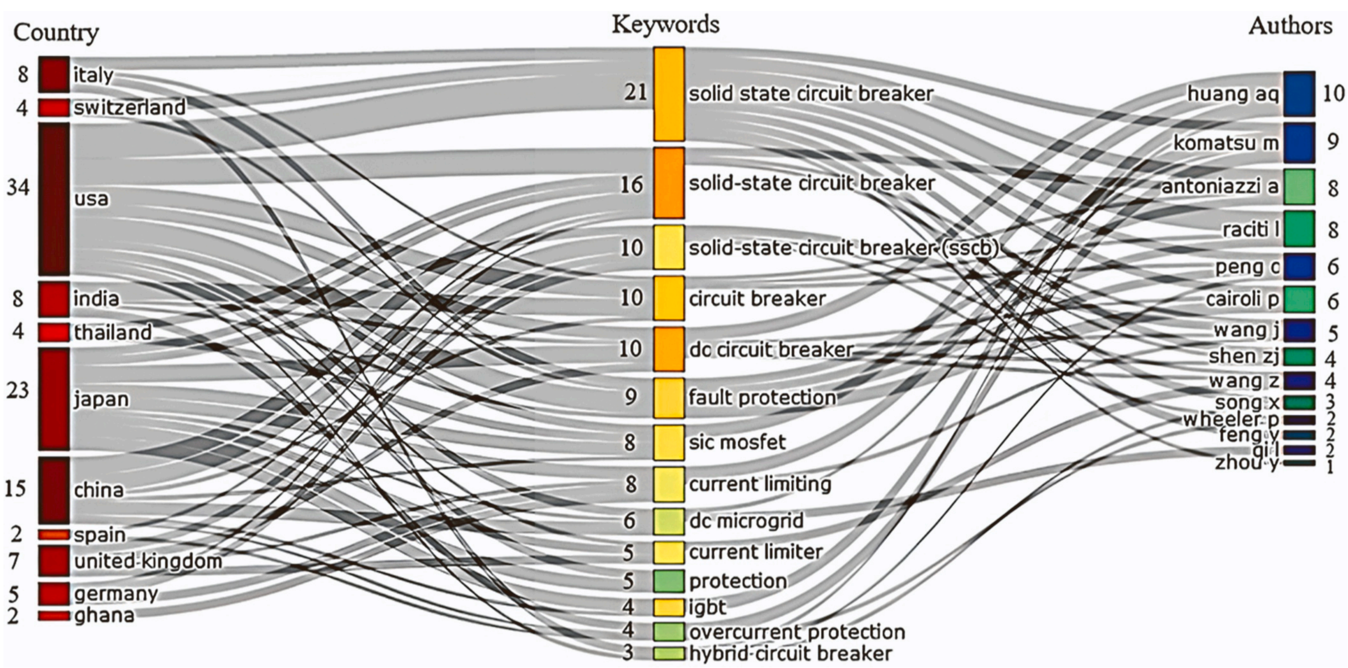

Fig. 7. Sankey diagram of the evaluation of the keyword in the domain SSCB device.

the publication with the highest citation. Table 3 summarises the top 10 papers published that included the highest citation, advantages, and validation and, aims to examine the impact of SSCB devices in different applications to achieve system stability. This study discovered the content included in the publication such as aim and validations in the domain of SSCB contributed to the research's benefit that is subject to improving the operation of SSCB for reliable and sustainable protection schemes. Qi L. L et al. [18], Z. John Shen et al. [17], Robert M. Cuzner et al. [19], Pietro Cairoli et al. [20], and F. Agostini et al. [12] published the top fives papers with average citation per year (ACY) count of 12.6, 11.62, 11.5, 11, and 9.37, respectively. The ACY is considered in this analysis to assess the yearly impact for a journal or the author of the publication. The detailed formulation of the ACY for each author to detrend the citation value across different years can be expressed as Eq. 1.

$$ACY = \frac{Number\ of\ citation}{Current\ year - Year\ of\ publication} \tag{1}$$

Qi L. L et al. [18] focused the research on the development of fast protective methods technology of SSCB devices for faults current situation in the DC shipboard power system. He also has presented and analyzed the current technologies, issues and challenges in this study to achieve desirable fast protection speed and full component protection. The research has advantages including providing an efficient operation and reliable protection scheme in DC power system applications with ultra-speed switching mechanisms. The research conducted by Z. John Shen et al. [17] aims to prove the concept of self-powered ultra-fast SSCB for DC distribution protection systems under low voltage levels of below 1000 V. The newly developed two-terminal of SSCB can be directly placed in a circuit branch without requiring an external power

Table 3
List of Top 10 papers with "highest average citation per year (ACY)" from 2013 to 2023.

Rank	Ref	ACY	Aim	Validation	Advantages
1	[18]	12.6	Modelling of the fast protective device of SSCB operation in DC shipboard power system for fault current issues. Analysis of the current trend and technologies of semiconductor topologies.	Protection coordination method, nominal rating, and fault interruption current of SSCB device fast switching strategy based experimental validation to achieve highly efficient operation.	The proposed model and analysis can provide efficient operation, reliable, and low-cost protection systems in DC power system applications with ultra-fast speed switching mechanisms.
2	[17]	11.62	Self-powered ultra-fast SSCB design concept and model development for low voltage system DC distribution application with different protection options.	Sense terminal voltage rises and holds off the wide bandgap semiconductor static switch without an external power supply needed.	New terminal SSCB can be directly placed in the circuit branch without requiring any external power supply and provide faster fault current isolation.
3	[19]	11.5	Development of MOSFET material-based SiC junction for SSCB switching mechanism in medium voltage level fault isolation for high reliability and device survivability.	Extensive comparative study towards protective topologies between electromechanical CB and SSCB device for fault current isolation in the shipboard distribution system.	High efficiency and survivability of SSCB operation-based SiC junction development of wide bandgap considering different topologies.
4	[20]	11	Limiting fault current scenario and energy dissipation of SSCB to provide protection selectivity, high survivability and reconfigurability devices.	SSCB-based RB-ICT semiconductor technology development with limit fault current and fault energy in 500 µs and clamp voltage of MOV at 2 kV under short circuit event	High-efficiency device operation, fast current interruption and wide range time constant with parallel MOV configuration.
5	[12]	9.37	Reducing conduction power losses and high turn-off current capability of SSCB for the current interruption. events with IGCT thyristor.	Development of thermal management-based DC SSCB with high turn-off current capability at 6.8 kA during current interruption conditions.	High-turn-off current capability and minimize the residual voltage by surge arrestor connected parallelly.
6	[15]	8.2	Extensive details comparative study towards MVDC grid system for SSCB operation in the protection scheme to achieve minimum short-circuit current, less time clearance of fault.	Different topology and conceptual methods of CB operation in MVDC application for fault clearance conditions including fault clearance time, residual energy dissipation and power losses.	Overview of the electrical characteristics of different conceptual analyses of CB in MVDC power system applications to achieve better protection system performance.
7	[22]	7.33	Comparative validation of SSCB with different topologies for protection devices in the power distribution system.	Advanced power semiconductor technology comparison and modelling for faster, more efficient, robust and reliable power devices of SSCB junction.	Overview of different topologies and SSCB performance for short-circuit interruption.
8	[25]	5.4	Emerging power electronic converter for MEA application to optimise aircraft performance that can reduce operating and maintenance costs.	An extensive comparison between different topologies of power electronic converter and SSCB to obtain a fast switching mechanism and high efficiency of system protection.	A different characteristic of the power electronic converter and SSCB topology is presented. A redundant power converter improves the fault-tolerant capability.
9	[23]	5.14	Development of high-power solid-state power controller for mitigating dynamical load management for MEA applications.	Modelling of SSPC high current 270 V for MEA application considering different topologies selection to achieve high reliability.	The development of high-power SSPC in MEA provides fast response time, lightweight, lower maintenance and eliminated arching events.
10	[28]	5	Cost-efficient model development of series connected IGBT switch of SSCB devices for fault isolation purposes in SST medium voltage distribution grid.	Experimental validation is presented to observe the performance behaviour of IGBT-based SSCB devices under short-circuit events.	Achieve voltage unbalance reduction from 80 % to 5 % by prolonging the detection process and thermal dissipation of the device.

supply to operate. It senses the terminal voltage rise and draws power from the fault condition itself to turn and hold off the wind bandgap semiconductor static switch to ensure a reliable protection system. Moreover, it should be highlighted that the review paper published by Z. John Shen et al. [17] in 2015 has garnered recent attention indicating the important concern in this field that highlighted the future direction towards SSCB device operation in protection systems. Robert M. Cuzner et al. [19] focus on the analysis of the development of MOSFET/junction barrier based on SiC of 10 kV 240 A SSCB for fault isolation in medium voltage application. A comparison study was also performed with voltage level rating of 4 and 30kVdc that contains protective topologies and scalability of each device towards fault isolation for the shipboard distribution system. This analysis presented the results of a wide bandgap SiC power semiconductor that achieved high system efficiency and survivability in limiting the fault current as compared to electromechanical CB. Furthermore, high current SSCB for DC shipboard power system-based RB-IGCT and optimized MOV is presented by Pietro Cairoli et al. to achieve ultra-fast reaction time, low conduction losses and high power density of SSCB protection system in [20]. This technical paper that were published by this author can potentially able to provide a bright insight to the development of semiconductor devices with WBG technology to achieve high efficient operation of protective device and enhance power quality of the distribution system. Thus, high current SSCB device development is very necessary for the distribution power system to ensure efficient operation in protection strategy, survivability and faster responses in limiting fault current.

F. Agostini et al. [12] study focuses on the thermal management of SSCB devices with RB-ICT junction to provide bidirectional current flow and low conduction losses during the current interruption. The proposed method is able to conduct current in both directions with two RB-ICT connected in the SSCB topology. This innovation proves the concept of current interruption in the distribution power system in which the SSCB is capable of providing high-turn-off current at 6.8 kA with minimal temperature. Additionally, the paper ranked 6 and 7 emphasised the fault detection methods in the MV distribution system protection for the development of the SSCB device's topology to achieve a high power density, fast protection scheme and low conduction losses. Meanwhile, the paper ranked 8, and 9, focused the study on the power electronic development of more electric aircraft (MEA) for solid-state protection to gain better system performance, high efficiency and reliability in electrical systems. Finally, the paper ranked in the 10 has presented the design of an IGBT series connected-based SSCB for fault isolation purposes in SST. A multi-pulse fault detection method is also presented to alleviate the thermal dissipation of the IGBT switch and achieve the voltage balance that contributes to the reliability improvement of SST.

Table 4 presented the information regarding the study type of the selected top 85 most cited papers that classified the research area based on the study type from each published paper. It is essential to identify the study type of the research while analyzing the structure of the top most cited papers. The study type is an integral part of the study design that helps to understand the nature of the study, the methodology employed and the strength of the evidence presented. It also can enable the researchers to evaluate the validity and generalizability of the findings and place the research within the broader context of evidence-based knowledge. Thus, this study presented Table 4 based on the study type of research from the top 85 most cited papers based on the Scopus

Table 4
Classification of study type of the 85 topmost cited papers in the Scopus database.

Study type	Publication Frequency	Range of year	Range of citation
Problem formulation and simulation analysis	21	2014–2023	1–26
Review	19	2014–2021	1–94
Experimental work, developments, and performance assessment	20	2014–2023	1–74
State-of-the-art technical overview	11	2014–2022	2–76
Observational and case study	14	2015–2022	4–18

database. The most frequently published type of study for the top 85 most cited papers is under the type of problem formulation and simulation analysis study with a publication frequency of 21. The next most frequently published paper was under the experimental work, developments and performance assessment study which consisted of 20 publication frequencies. The later study was published based on the review study with 19 publication frequency followed by observational and case study as well as a state-of-the-art technical overview which consisted of 14 and 11 publication frequency, respectively.

The distribution of published papers required a variety of years and citations but are all subjected to the Energy and Engineering field. This indicates that most research conducted the study based on problems and simulation, experimental analysis, methodology development, and performance evaluation account for 64.7 % of all studies compared to 35.3 % of the state-of-the-art technical overview and review papers. The problem formulation and simulation analysis receive great attention from the study type. The topic addressed includes mathematical models, numerical simulation, control strategy, switching technological developments and conceptual analysis. The researchers currently focused on the development of a control strategy on the SSCB device to achieve fast response, survivability, and reliable protection mechanism for fault isolation, and current interruption as well as the reduction in power losses. The method was presented and evaluated from low voltage level to medium voltage level in the distribution system application. The findings emphasise the important operation of the SSCB device in limiting the fault current that occurs in the network to improve power quality and stability system.

These bibliometric studies also examine the subject area presented by researchers from the selected top 85 most cited papers. It is essential to highlight this bibliometric study based on the subject area of the research that can gain a better understanding of the context, relevance and significance of the research. Also, assessing the relevant subject area helps the researchers prioritize their research question and objective that can potentially contribute to practical applications. Therefore, Table 5 elaborates on the classification of study type of research based on the subject area. It presented the different subject areas of research based on the publication frequency, range of citations and frequency weight factor, respectively.

The subject area of HVDC circuit breaker, SSCB short-circuit and wide bandgap power semiconductor earned the highest frequency percentage of 5.88 % from the selected top 85 most cited papers. The authors discussed the different technology developments of SSCB switches that can able to provide better short-circuit protection in different applications. Furthermore, the thermal management of semiconductor devices, fault protection and MOSFET technology current limiting of the subject area were also presented by the authors which consist of a publication frequency weight of 4.71 %. Similarly, the area of DC system protection and short-circuit interruption-based SSCB device development was also presented. Meanwhile, the other different subject areas of the research were presented to ensure the survivability and reliability of the SSCB device in power system applications which consist of 3.53 %

Table 5
Classification of the subject area of the 85 topmost cited papers in the Scopus database.

Subject area	Publication Frequency	Range of year	Range of citation	Publication frequency weight (%)
MVDC protection	3	2018–2019	1	3.52
HVDC circuit breaker	5	2014–2020	2–94	5.88
SSCB short-circuit fault	5	2014–2018	5	5.88
thermal management	4	2015–2022	1–74	4.71
SSCB protective device	5	2014–2022	1–69	5.88
SSCB limit fault current	2	2019–2021	1–46	2.35
SiC IGBT semiconductor	3	2014–2022	1–45	3.53
Fault protection	4	2015–2021	1–43	4.71
Power electronic converter protection schemes	3	2018–2021	1–42	3.53
DC fault current isolation	6	2014–2022	1–35	7.06
performance evaluation	3	2016–2019	1–30	3.53
wide bandgap power semiconductor	5	2018–2022	1–27	5.88
DC fault current protection system	3	2014–2019	10–26	3.53
hybrid DCCB	2	2018–2021	2–15	2.35
MOSFET technology current limiting	4	2016–2019	1–15	4.71
DC system protection	4	2015–2021	2–15	4.71
High inrush current	2	2018–2022	1–13	2.35
fault isolation	3	2017–2021	1–13	3.53
MG power converter	2	2020–2022	1–11	2.35
short-circuit protection	2	2016–2020	5–9	2.35
short-circuit interruption	4	2019–2021	1–7	4.71
voltage scalability	3	2019–2021	1–5	3.53
multi-function protection	2	2016–2022	1–5	2.35
Metal oxide varistor	3	2021–2022	1–2	3.53
phase shift control	3	2016–2021	1–5	3.53

Table 6
Circuit breakers (CBs) technologies.

CB Technology	Switch Type	Commutation part	Costs	Operating period (ms)	On-state loss
Mechanical	Mechanical breaker	Resonant LC circuit	Low	5–10	Low
Solid-state	Power semiconductor devices	Excludes the commutation line	High	1	High
Hybrid	Mechanical switch with power electronics	Power capacitor snubber or electronic breaker	High	2–5	High

and 2.35 % of publication frequency weight, respectively. Thus, the main observations of the subject area that were published by the authors for Table 5 are summarized as follows:

- The HVDC circuit breaker consists of different topologies namely mechanical HVDC circuit breaker and SSCB. In recent system infrastructure, the VSC based HVDC is utilized and considered the best option for realizing the future multi-terminal HVDC system to integrate the bulk amount of energy over long distances to the AC grid. Thus, a fast switching mechanism, lower weight and reliable device of semiconductor such as SSCB is needed to ensure a reliable protection scheme, safety, faster-switching response, and power quality enhancement.
- An SSCB inherently contains ultrafast turning-off speed and is capable of achieving the desirable fast protection speed. Based on the different applications, the SSCB used different semiconductor technologies that were subject to the different voltage and current ratings of the system [100]. The SSCB should be tested since much higher current derivatives exist in the DC distribution system than ac. Some aspects of SSCB such as topologies and different materials used have been discussed by many researchers. For example, the IGBT and IGCT are used in SSCB devices due to their wide commercial availabilities, high current ratings, and low power requirements to execute the gate drives [101]. An extensive control development towards SSCB operation-based RB-IGCT was implemented in a 1 kV 1 kA DC system. The ON-state losses of RB-IGCT are much lower than conventional IGCT and IGBT methods. Thus, with this advanced controller, the overall functionality of the SSCB can significantly improve and be fixed with the DC protection system [102].
- Although the conventional electromechanical CB is considered a mature technology with a proven record of cost-effectiveness, reliability, and long lifetime, slow breaking action and a limited number of switching operations as well as requiring an external arc distinguisher the major limitation of the device to isolate the faulty occurred on the distribution network system. Thus, the SSCB based on the power semiconductor switch eliminates these drawbacks with different control developments on the semiconductor switch to obtain a reliable and safe protection system. The recent development of IGCT is an ideal device that utilises a thyristor that provides inherent low-conduction losses and optimum plasma distribution in the conduction mode to achieve low on-state voltage drop as compared to IGBT technology [103].
- Achieving an ideal temperature for power semiconductors and electronic devices constitutes a continuous challenge for the heat transfer community. Thus, thermal management remains one of the pillars for the safe and reliable operation of power electronics semiconductor devices. Different controller approaches are developed on the semiconductor switch to provide superior protection performance with less complexity, safety and high reliability on the distribution network application. To strive for the optimum temperature, the air-cooled solution-based standard heat sink technology was chosen to enable the continuous operation of the semiconductor breaker system.

3.4. Publisher and country's bibliometric evaluation

The evaluation of the top 85 most cited published papers based on the different publishers is necessary to examine the quality of the research and the integrity of the publication. It is also able to provide insight into the research direction as it enhances the visibility and impact of the research, respectively. Fig. 8 shows the journal review based on the different journal publishers. Based on the figure, five distinct publishers were identified for the top 85 most cited papers. Among the selected paper, the highest proportion of papers has been revealed by IEEE which consist of 78 (n=78) published papers. Whereas, the Institute of Engineering and Technology (IET) published three

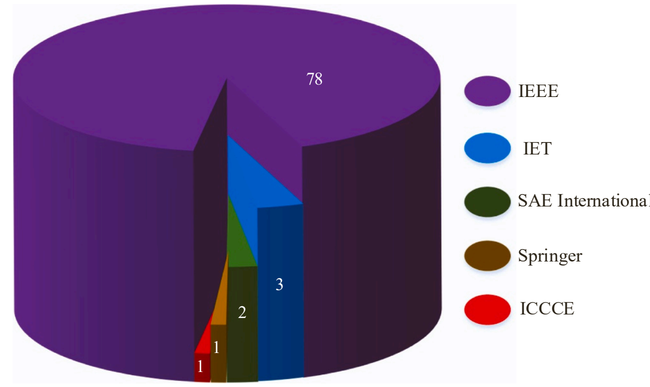

Fig. 8. Number of articles according to different publishers for SSCB device.

papers (n=3) followed by the Society Automotif Engineering Internation (SAE) with two publications (n=2). Finally, the Springer and ICCCE international journals consist of a similar number of published papers of one (n=1), respectively.

Due to the high potential and current trend of study mainly focus on the power quality and stability of the system, the researcher attempted to develop new technologies and approaches to the SSCB device operation which may be a substitute for the current electromechanical CB devices. The power semiconductor operation based on high-performance devices such as SiC IGCT, SiC JFET and SiC MOSFET has been presented as a valuable component for the SSCB [104]. It enables the SSCB devices to operate with low conduction loss, high voltage blocking capability, high thermal transient performance and fast protection speed in different applications [22,105]. Fig. 9 illustrates the location of the different countries that contributed to the publication in the domain of technological development and control methods of SSCB devices. According to the first authors' affiliation, the selected papers have originated from 16 different countries which revealed that reveled by United States as the highest number of publications (35 %). China is considered as the second highest of publications with (14 %) followed by the United Kingdom (8 %). Moreover, Japan and India contributed 5 % of the publication whereas Italy contributed 4 % of the total publication from the selected database. The remaining countries have contributed the number of published articles below 4 % of the selected highly cited papers.

4. Review of advanced SCCB technologies

As mentioned in Section 3, SSCB technology is advancing internationally. SSCB voltage ratings, speed of operation, breaking capacity, and other performance factors have improved significantly over electromechanical circuit breaker technology. The popularity of this device arises from its durability and ability to switch quickly or decrease fault currents. This section delivers an overview of advanced SSCB technologies, such as rapid-breaking mechanical devices, power semiconductor devices for SSCB, classification of power semiconductor technologies, and hybrid switch technologies.

4.1. Rapid-breaking mechanical device

In power distribution systems, a MCB is typically used for short-circuit prevention. The mechanical solution offers minimal conducting resistance but a lengthy turn-off time (60–100 ms) [106]. There are various types of classical MCB such as sulphur hexafluoride (SF6) CB, air-break CB, air-blast CB, vacuum CB, and oil CB. However, arcing, servicing, dimensions, expenses, switching conditions and dependability issues prompted engineers to replace conventional CB designs with semiconductor devices [107]. Arcs cause low lifespan, contact erosion, and expensive servicing costs [108]. For proper switching conditions, a

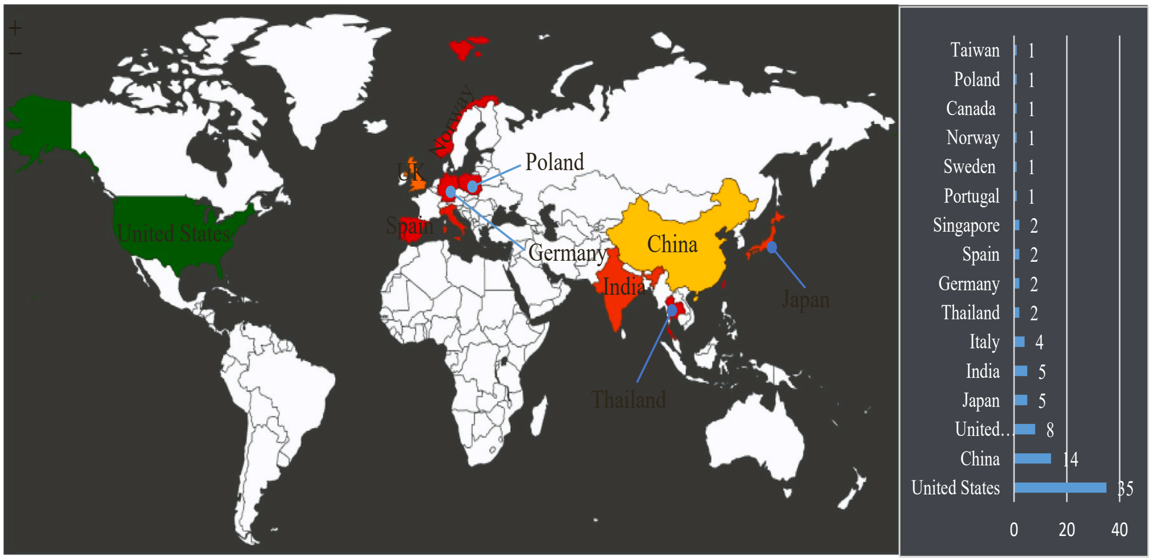

Fig. 9. number of article published according to originated country.

CB should switch quickly or depress the fault current [109]. Fast mechanical switches are commonly employed in contemporary MCBs that have the capability to rapidly detect and resolve fault problems within 10 ms [110]. Furthermore, the interruption time of an MCB is significantly shorter than that of an electromechanical counterpart (see Fig. 1 (b)). This enables the interruption of low-frequency AC of either 50 Hz or 60 Hz before it reaches its expected peak value [108].

4.2. Power semiconductor devices for SSCB

In recent years, power semiconductor devices evolved to carry thousands of Amps and block thousands of Volts [107]. Power semiconductor devices offer quick arc-free interruptions, significant dependability, and cheap maintenance [108], Various SSCB designs are influenced by power semiconductor device technology, which may be accessible on marketplaces or customized for the application. Power semiconductor technologies have unique qualities which influence their compatibility with other devices. Power semiconductor technologies have unique qualities which influence their compatibility with other devices [111]. These devices are used in power electronic systems including HVDC, electric traction systems, static VAR compensators, etc [107,16]. Low-power solid-state breakers for AC and DC applications have advanced recently. In [112] presented the advanced technological analysis model of LVDC system based on isolated phase busduct for better protection system. It include the advanced process of selecting protection parameters and assessing the sensitivity of magnetic fields that affect the reed switch through shielding coefficient techniques. The presented system enhanced its functionalities by providing smart device to enhance power electronic devices operation by increase their accuracy and reliability under stressful condition such as thermal stress, overvoltage, leakage current and electrical arc. Moreover, it tends to saving copper, steel and insulating amterials due to avoidance of using current transformers. The use of current transformer of 300–500 kg in mass inside the busduct can be eliminates.

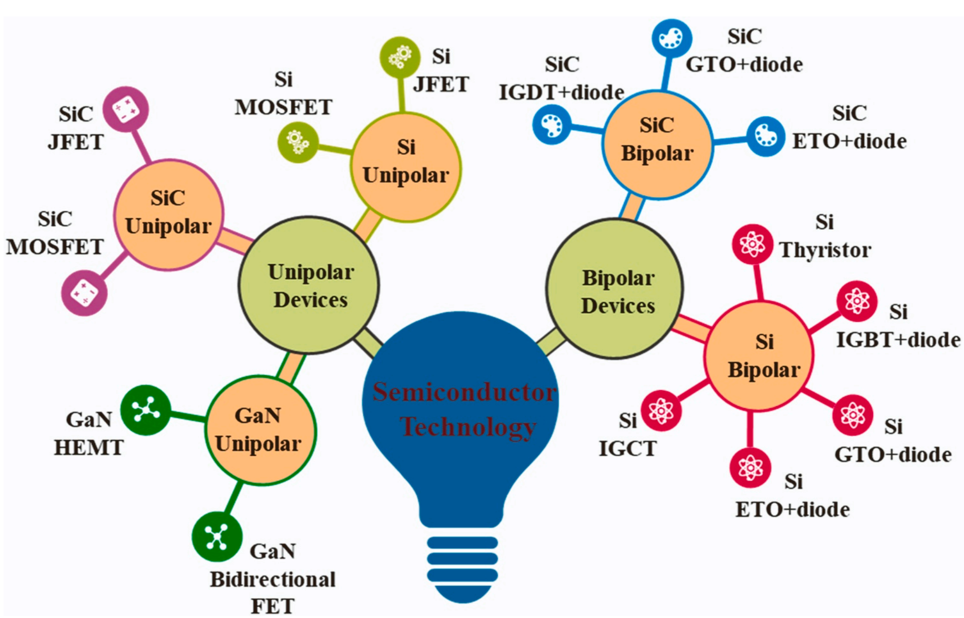

Fig. 10. Classification of the power semiconductor technology in SSCB devices to provide superior performance.

4.3. Classification of power semiconductor technologies

The classification of the power semiconductor technologies utilised in the power circuit of SSCBs or similar applications is shown in Fig. 10. A notable differentiation among semiconductor technologies involves the categorization of devices into bipolar and unipolar (first category). This differential significantly affects loss of power, current flow direction, excessive current capacity, and conduction feature sensitivity to operational temperature.

The main difference between devices with a major material of silicon (Si) and those with a dominating material of a WBG material (e.g., SiC or GaN) (a second category in Fig. 10). Silicon-based devices and those using a WBG material (e.g., SiC or GaN) differ most [113]. Commercially available Si devices are mature and have many current and voltage specifications. WBG semiconductors' superior material properties allow power devices to function at higher voltages, temperatures, and switching rates as sown in Fig. 11 [114].

Another notable differentiation (third category in Fig. 5) can be discerned in relation to the structural composition of the devices within each group. The basic device architectures have numerous implementations and manufacturing techniques that vary among manufacturers:

- Some research studies suggest employing Silicon bipolar devices including thyristors, IGBTs, GTO thyristors, ETO, and the IGCTs for SSCBs in medium-voltage distribution networks (as high as 4.5 kV and 4 kA) [106]. The components exhibit excellent short-circuit capability, overcurrent, and reliability [111].
- SiC bipolar includes GTO, BTO, and IGBT. SiC bipolar devices offer a great option for ultrahigh-voltage (>10 kV) power devices owing to their electrical conductivity modulation operation, which reduces the capacitance of the substantial voltage-blocking layer and has low dependence [115].
- Si unipolar devices encompass MOSFETs and JFETs. These devices are utilised in low-voltage and low-power applications. For example, Si MOSFETs were suggested as power semiconductor devices in SSCB aviation power distribution systems [24].
- The unipolar operation of silicon carbide (SiC) devices includes the utilization of MOSFETs and JFETs. These SiC unipolar devices have matured faster than other WBG technologies [111]. Commercialization of MOSFETs with blocking voltages of 600–1700 V resulted in an enormous decrease in the loss of power for different electrical power conversion systems [115]. SiC power MOSFETs with a higher voltage (15 kV) have been tested [116].
- The GaN unipolar consists of the Gallium Nitride High Electron Mobility Transistor (GaN HEMT) and the GaN Bidirectional FET.

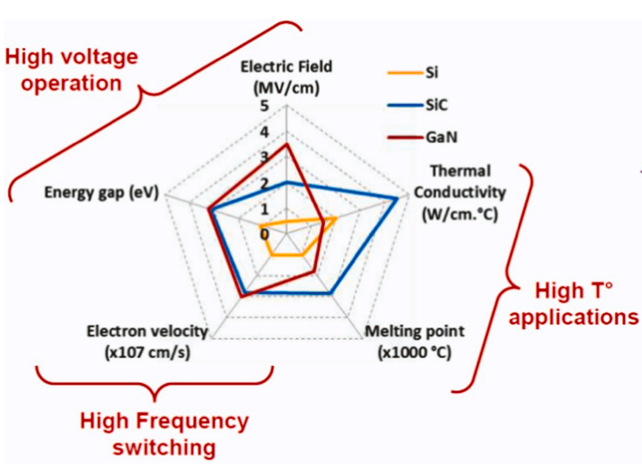

Fig. 11. Summary of relevant Si, SiC, and GaN material considering different properties.

Vertical GaN power semiconductor devices possess the lowest possible ON-state particular resistance and conduction losses over WBG unipolar devices. For example, monolithic bidirectional GaN FETs with 650 V blocking voltage and 200 mΩ room temperature ON-resistance have been examined as switching power for SSCB purposes [111]v.

4.4. Hybrid switch technologies

Hybrid switching technology involves combining controlled solid-state electronics with a mechanical breaker or disconnector. CBs use semiconductor switches as main interrupters due to their superior switching time, conduction losses, break-down voltage, and reliability. Solid-state switches commutate hybrid CBs, which activate only upon disruption. Electronic circuits control all switches [16]. In hybrid CB, control continuous current, while power semiconductor devices make and break processes with the breaker contact. Semiconductors fire first to carry inrush current to avoid an arc when turned on. Once main contacts close, contact resistance is lower than semiconductor resistance, hence current commutates to the contact path. Current flows continuously through the breaker with negligible loss. Upon disconnecting, semiconductor components ignite and current runs via them repeatedly since the current route possesses lower resistance than the arc path. Additionally, the arc will dissipate and semiconductors will block electricity [107].

There are a number of potential topologies for hybrid circuit breakers, but in practice, only two structures garner the most interest. Fig. 12 depicts the hybrid topology switches involving IGBT breakers. New performance criteria for the IGBT offer new perspectives in hybrid switching approaches [108]. The topologies are described below:

- Topology 1: This topology has parallel solid-state switches and a fast mechanical breaker. This architecture is speedier than traditional circuit breakers since the arc barrel is required to provide a sufficient voltage for the commutation, but not a present zero crossing point. The structure can be utilized in medium voltage grid applications.
- Topology 2: This structure has been introduced by Hafner et al. [117]. A speedy solid-state device in the main current path and a fast mechanical disconnector in series. Parallel paths are generated using series-connected solid-state switches (e.g.: IGBT). Conducting loss and voltage drops are typically reduced by interconnecting many IGBTs within a series.

Additionally, the CB technologies in HVDC transmissions are compared in Table 1 [118]. Despite high costs, hybrid CBs enhance operating speed and reduce losses compared to mechanical and solid-state CBs. The hybrid CB technology is the most promising for HVDC systems.

5. Issues and Challenges

The significant technological advancement of SSCBs in power system applications presents numerous challenges. Further investigation and advancement are required to offer more economically efficient alternatives. The subsequent study issues are deliberated upon in terms of their prospective outlook.

5.1. Uncertainties

Uncertainties parameter is significantly important in power semiconductor devices. It strongly influences the performance of the SSCB device during its operation especially the transfer switch condition [119]. For example, uncertainties of the load resistance, load inductance, and load capacitance need to be minimized by regulating the switching device of the converter. Although, various approaches have been undertaken to block the short-circuit current, response time, size of

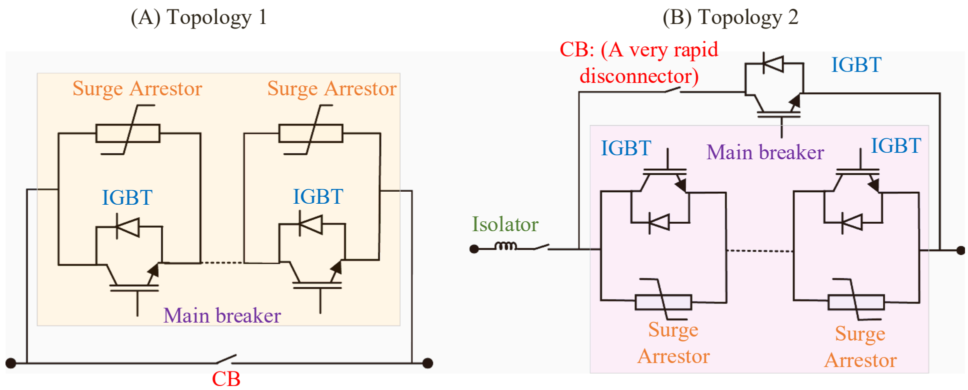

Fig. 12. Hybrid circuit breakers configuration for (A) topology 1 and (B) topology 2.

the device, and the switching losses can further be minimized by intelligent controller development. However, the effect of uncertainties of the environmental impact remains unsolved with the present development. Thus, an advanced approach is needed for the high capability to withstand the overvoltage, low weight, and increased performance of transfer switch with faster response time considering the uncertainties parameter to provide a reliable and safe device during operation. Furthermore, an optimal hybrid SSCB topology can potentially be a feasible solution in the future scope to ensure an efficient and reliable operation of the SSCB device for short-circuit current interruption in power system applications.

5.2. Selecting an appropriate transfer switch

Choosing the appropriate transfer switch is challenging due to a number of factors that engineers have to take into account throughout the installation. Several parameters are included: synchronization, switch delay, interface mechanical structure, and minimum electrical supply interruption during servicing and monitoring. Specify the appropriate transfer switch considering regional demands, sources qualification, as well as ground-fault current impact. Choosing a transfer switch also involves combining power disturbance time with hardware expense [120]. Adherence to standards such as IEEE, UL, NEC, CSA, and NFPA aids in the selection of appropriate equipment for tasks, particularly those involving voltages up to 1000 Vac. The presence of safety features has witnessed an increase in prevalence within the sector [121].

5.3. Gate terminal of thyristor

The SSCB topology category employs semi-controlled power semiconductor switches, including thyristors or SCRs. An SCR is a reversed blocking switching that is able to be utilized to operate a low-loss SSCB with the anti-parallel configuration. SCRs have affordable prices, low conduction loss, and suitability in large current usage. The second SSCB topology category employs semi-controlled power semiconductor switches, including thyristors or SCRs. SCRs with low conduction loss, affordable prices, and suitability in large current usage. An SCR is a reversed blocking switching that is able to be utilized to operate a low-loss SSCB with the anti-parallel configuration. A significant obstacle with thyristors is the fact that their gate terminal is unable to turn off the device. To create an SCR-based SSCB, another circuitry must be present for interrupting the electrical current [111].

5.4. Fault and Safety Operation in Power System

The faults will interrupt power systems [16]. The function of transfer switches is to identify defect locations prior to determining whether they must be transferred. Transfer actions should be immediately required for source issues and disallowed for burden issues [2]. Engineers have to comprehend power conversion, protection modes, operating scenarios, and system reactions to construct a reliable SCCB control system [122]. This issue demands rigorous modelling and experimental testing of SCCB technology. As an alternative to MCBs, SSCBs work without mechanical moving parts [113]. SSCBs have diverse uses, soundless, arc-free, quick operation, extended lifespan and reliability [123]. Various power semiconductor devices, such as the silicon IGBT, SSCB GTO, cathode metal oxide semiconductor controlled thyristor (CS-MCT), and IGCT have pros and cons. The switches are rapid but have high cost, high power losses, and need heat sinks making them unsuitable for some applications [108,124]. The WBG SSCBs include SiC MOSFETs, SiC JFETs, GaN HEMTs, SiC SITs, and GaN FETs and can handle blocking voltages, high temperatures and switching frequencies than silicon-based power devices. However, WBG technology is maturing and necessitates further extensive investigation [125].

5.5. SSCB Testing

Tests verify the analysis and suggested remedy for the SSCB application [126]. The testing did not significantly shorten the switch life. The testing of circuit breakers is essential for the reliability, safety, and efficiency of electrical systems. The built-in test switch selects the testing characteristic, drying contacting testing for remote evaluation, and automatic testing stores information in storage for either monthly or annual assessment [2]. The incorporation of safety protocols facilitates the mitigation of accidents, reduction of delays in operations, and compliance with company standards and regulations.

5.6. System protection issues

Recent DC SSCB technologies promote connected and centralized management of SSCBs for protection coordination. This approach improves certain DC microgrids. However, SSCBs are expensive and complicated rendering them unsuitable for commercial application [127]. In the framework of industrial DC microgrids, it is common practice to utilize standalone SSCBs for the purpose of power branch placement. These SSCBs are designed to operate independently, without the need for inter-module communication or additional wire. For the effective deployment of microgrids, it is imperative that every element, including SSCBs, adhere to a peer-to-peer architecture and possess plug-and-play capabilities. Protective SCCBs are incorporated to prevent failures from spreading throughout the system by detecting voltage and current waveforms [128].

5.7. Minimal interruption and maintenance

The concept of minimal interruption and maintenance refers to the process aimed at achieving optimal performance of the system through preventive measures. Without sufficient attention to maintenance throughout the planning and implementation phases, the device might swiftly grow unstable as well as fail in fulfilling its intended purpose. For maintenance to be performed, a bypass valve is required. While the transfer switch is isolated, power is maintained through a bypass switch [121].

6. Potential technological development and future directions

Drawing upon a thorough examination and analysis of existing literature pertaining to technological development and the method of SSCB devices for efficient protection, the subsequent sections delve into specific opportunities for potential technological advancements in SSCB devices and explore future directions in this field. These developments collectively contribute to more robust and dependable power electronics systems across various applications that enable to enhance reliability and safety of the entire system [129].

6.1. Parallel connection of the power semiconductor

High performance of the DCCB is necessary to achieve high reliability in the DC distribution system or MG application. Unlike AC systems, DC distribution networks can effectively improve power quality, reduce energy conversion steps, decrease power loss and running costs, and maximize the value and benefits of distributed energy resources. Generally, DCCB is always one of the important prerequisites for the extensive adoption of DC power [130]. Due to rapidly increasing DC fault currents caused by low short-circuit impedance in DC systems, fast protection and reliable switching devices are necessary to prevent damage to power electronics equipment [131]. Although SSCB has several advantages and is able to compensate for these issues within (ranging from several microseconds to <1 ms), large energy burden, avalanche breakdown, and overvoltage is part of the limitation of the devices. DCCB plays two roles simultaneously: incurring conduction losses during the steady-state operation state and dissipating the energy during the current interruption operation state. Thus, SSCB in the DCCB application should be connected parallel to share the current to reduce on-resistance loss and improve avalanche tolerance. Power semiconductor technology such as SiC MOSFET and SiC diode is potentially can be implemented as they exhibit excellent characteristics of low-on resistance and high avalanche tolerance [132,133].

6.2. power semiconductor device with optimization approaches

Recently, WBG semiconductor technologies have emerged widely in SSCB devices such as SiC, SiC MOSFET, and SiC JFET that can provide superior switching performance and rapid protection speed over conventional MCCB [134]. These features with low on-resistance and safe operating areas have emerged and been implemented in the DC distribution network system that can control overvoltage without extra suppressing circuits. Generally, a swift response of the SSCB to a short-circuit fault implies a quick activation of the gate driver from its idle state. Consequently, the optimal design of gate driver topologies and parameters plays a crucial role in enhancing the rapidity of the SSCB. Recent research has developed a novel bidirectional DC SSCB to realize the bidirectional flow of energy to ensure the higher operating efficiency of the MG system [7,135]. This approach tends to provide an advanced control strategy in SSCB operation that can be applied as the protective circuit and improve the power quality of the system. Furthermore, a novel control topology-based single gate driver for cascaded SiC MOSFETs was also developed by other researchers to optimise the operation of SSCB device and fast operating IGBT switch to limit the fault current during short-circuit events. These approaches can potentially able to provide a superior switching performance of the SSCB device with improved control topology on the semiconductor switch that can gain a better performance of protection scheme and increase stability in a distribution network system.

6.3. Thyristor technology-based SSCB devices

A significant challenge associated with the SSCB is the high conduction losses, primarily due to the considerably higher voltage drops across power semiconductor devices compared to the traditional electromechanical contacts. Consequently, the precise selection of semiconductor technology and devices for an SSCB is of essential importance. Recent advancements in technologies of WBG semiconductor devices such as SiC, static induction transistors (SITs)SiC MOSFETs, and SiC JFET can provide superior switching performance and are notably superior to their mechanical counterparts in addressing power quality issues [2]. This WBG material shows superior properties enabling power device operation at higher temperatures, voltages and switching speeds. Furthermore, it also provides low on-resistance and high avalanche tolerance during operation that leads to compatibility in SSCB operation for energy dissipation [136]. However, an effective cooling system is often necessary for these technologies as they generate significant heat during operation due to the complex gate drive circuit and unique characteristics. Thus, effective thermal management and robust gate drive circuit and protection are necessary to prevent overheating and ensure device reliability. Recent research reported that power semiconductor devices such thyristors, gate turn-off thyristors, IGCT and IGBT allow the transfer time within a quarter of a cycle (equivalent to 5 ms). It offers several advantages such as low costs, low conduction loss, high current carrying capability, and rapid interruption as compared to other technologies [137,138]. A comparative study was presented that employed different types of technology in an SSCB device that was subjected to voltage and current rating capability as shown in Fig. 13. The Si thyristor achieves the highest voltage and current rating capability among other power semiconductor devices with up to 12 kV with 1.5 kA due to an excellent bipolar conduction mechanism. This indicated that the power semiconductor-based thyristor technology for SSCB devices can potentially provide a superior switching performance and fast protection speed during short-circuit events and fault current condition to provide a reliable protection system in high-voltage power applications.

7. Conclusion and recommendation

Citation analysis serves as a powerful tool for gauging the influence of an article within a specific academic field. By quantifying the number of citations an article receives, an extensive future direction of the subject area can potentially able to gain insight into its scholarly impact and glean valuable information. In this paper, an in-depth examination of the most frequently cited articles sourced from the Scopus database is

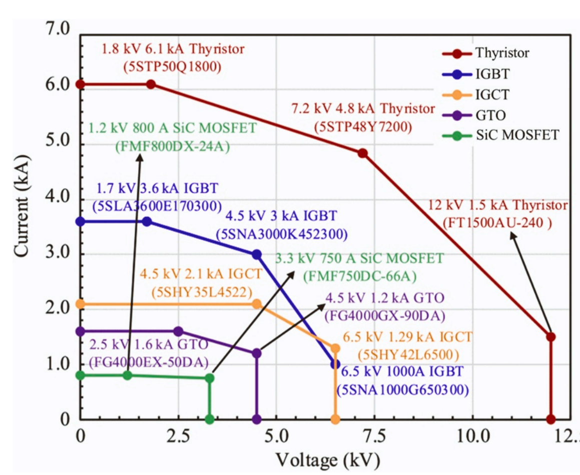

Fig. 13. State-of-the-art controllable power devices comparison based on different power semiconductor technology in SSCB devices.

conducted specifically focusing on the realm of the advanced technological development and control method of SSCB power system applications. A set of predefined criteria is employed to properly select these articles in order to compute the extensive analysis. This rigours evaluation encompassed several key aspects, including categorizing articles by their publication year, identifying those with the highest citation counts over the preceding five years, classifying them by subject area, study type country of origin, noting the highly regarded journals in which they were published, along with their respective publishers. Through this meticulous analysis, the objective is to illuminate the evolving landscape of SSCB with advanced technological development and control methods in power system applications. Thus, the aim of this study is to provide valuable insights to researchers and contribute to shaping future developments in this field to enhance their operation and ensure power quality improvement.

The main goals of this article are to critically review and comprehend the characteristics of the most frequently cited articles as well as to provide bright insight into possible direction and developments in the field of research. Thus, in terms of power quality, efficiency, stability, reliability, protection and safety, this paper highlights many issues and provides recommendations on the control methods and technological improvement in SSCB operation.

- Enhancements to the current DC breaker topology can be achieved through the optimization of component sizes, including inductors, capacitors, varistors, and more. The objective is to minimize downtime while simultaneously reducing the overall size and cost.
- Medium-voltage DC breakers can be adapted for high-voltage applications through technological advancements, series connections, or by integrating DC breakers across various medium-voltage levels in multilevel converter topologies.
- Hybrid DC breakers are recommended for their ability to combine features of both mechanical and solid-state breakers while utilizing switches with reduced ratings. These results can potentially reduce in size, cost, and interruption time of the devices.
- New WBG power semiconductor devices such as SiC, JFET, GaN, and Si are recommended to have negligible on-state losses and provide fast switching operation.
- The complete multi-terminal-HVDC system should undergo integrated optimization to align with the requirements of breaker control and protection.
- Integration of protection functions such as short circuit faults, grounding faults, arcing faults and other fault detection including mechanical isolation switches is necessary to prevent system failure on the distribution network as well as cost reduction and space availability.
- The use of MOV in the SSCB is recommended to dissipate the energy in the anti-series connection of IGBT devices. This method can be employed to reduce the overvoltage of the IGBT devices caused by high stray inductance between MOV and IGBT.
- An optimization strategy method can potentially be considered in the development of a converter-based IGBT device circuit to suppress the voltage oscillation and voltage drop during operation. This optimization might give accurate outcomes and provide an efficient operation that can reduce switching losses and ensure the safe operation of SSCB without affecting the dynamic performance of the devices.

The influence of highly cited papers in this field is significant. This article examines the top 85 most cited articles, along with recent influential papers, to offer future researchers a comprehensive perspective on technological development and control methods of SSCB power semiconductor devices, as well as insights into current trends and challenges. Researchers will acquire a well-defined insight into future directions and advancements by analyzing the characteristics of articles in the field of SSCB power system application and protection.

- The highly cited paper with the ability to coordinate research scope can inspire a large number of enthusiastic researchers to contribute to newly emerged technologies and innovation in the field.
- This overview and analysis can help identify potential research collaborators as to enhance the scope of the study.
- A bibliometric review can offer valuable insights into publications that are more likely to accept research papers in the technological development and control method of the SSCB power semiconductor device field.
- Facilitate the manuscript review process for journal editors and reviewers.
- This study will also assist government leaders and policymakers in formulating a long-term energy strategy, as well as identifying potential directions for energy research that align with the country's economic and political goals.

Furthermore, this review identifies the most influential and widely cited papers from the past decade, providing a foundation for future research and advancements in the technological development and control methods of SSCB devices. This paper is poised to make a substantial contribution to shaping the future development strategy within the power semiconductor device domain, which is set to play a pivotal role in the evolving electricity market. Ongoing and future research in this field has the potential to address the current limitations in the technological and control development of SSCBs, ensuring they meet the demands of long-term usage.

CRediT authorship contribution statement

M F Roslan: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation. **M S Reza:** Software, Investigation, Formal analysis. **M S Rahman:** Project administration, Methodology, Formal analysis. **A Z Arsad:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **M Mansor:** Writing – review & editing, Visualization, Supervision, Project administration. **Pin Jern Ker:** Writing – review & editing, Visualization, Validation, Resources. **Vigna K. Ramachandaramurthy:** Writing – review & editing, Supervision, Funding acquisition. **M Hannan:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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