Solid State Switching Control Methods: A Bibliometric Analysis for Future Directions

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Abstract: Recently, the development and controls of solid-state switching have gained significant popularity over the years especially in academic research. The development of control strategies in solid state switching applications to ensure fast switching in a protected distribution system has fueled a great deal of investigation and further developments. Therefore, a critical review and analysis in the field of solid-state switching for distribution systems are provided in this article. The Scopus database is used to compile a list of the most cited published papers in the field of solid-state switching control methods based on the identified criteria. The study explores 120 of the most cited articles emphasizing six keywords such as a solid-state breaker, solid-state transfer switch, static transfer switch, automatic transfer switch, automatic protection switches, and solid-state protection switch. The analysis was conducted using the Scopus database in the fourth week of January 2021. The 120 articles were collected from 24 different journals and 27 different countries. It is reported that 78% of the published papers outline the methodology based on control and test systems whereas 22% of articles are based on review surveys. From that, 73% of articles concentrate on the protection strategy in the system. The main objective of the article is to classify and define the highly cited published articles in the field of solid-state switching control methods as well as to provide direction for future research on fast switching in the distribution system. The analysis also highlights various factors, issues, challenges, and difficulties to identify the existing limitations and research gaps. This review will serve to strengthen the development concepts of solid-state switching control methods towards achieving improved operational performance, energy-saving, economic prosperity, and enhanced power quality. The authors believe that this bibliometric evaluation will allow academic researchers to identify opportunities for growth in the solid-state switching industry.

Keywords: solid state switching; fault; protection; control method; distribution network; highly cited articles; bibliometric

1. Introduction

The research on solid-state switching (SSS) has been growing enormously since the 19th century. The benefits of circuit breakers against fused switches were primarily focused at an early stage. In early 1970, it was found that solid-state controls offered much better protection, especially in motor testing than old breakers. It prevented step failure, sensed underload, and broke power when the system failed [1]. The solid-state circuit breaker (SSCB) uses power semiconductor technologies to achieve a faster-switching operation. The SSCB is structured using an auxiliary power supply, fault sensing system, voltage clamping circuit, gate driver, sense and trip electronics, and power semiconductor device.
During the normal operating phase, the suitable bias voltage or current from the gate driver is transferred to the power semiconductor to achieve a low resistance stable condition. When any fault or short circuit or overload issues are identified, the power semiconductor is turned off by the sense and trip electronics through a gate driver. Accordingly, a voltage is generated on the power semiconductor by residual energy in inductance. After, the voltage clamping circuit gets activated when the semiconductor voltage reaches a certain value. Next, a high impedance state is achieved in the voltage clamping circuit and power semiconductor once all the residual energy is absorbed by the voltage clamping circuit and current reaches zero, resulting in activating the circuit breaker to settle the system voltage. SSCB exhibits various advantageous features in comparison to conventional circuit breakers such as excellent fault detection capability without moving parts, shorter response time, fast current interruption capability, and extended lifespan [2,3].

The work by Alvarez et al. [4] addressed the solid-state switches and solid-state limiters technology to enhance the efficiency of the power supply using a 22 kW prototype. A voltage source converter (VSC) was proposed as a topology for solid-state transistors. In 2010, Prigmore et al. [5] proposed an Integrated Gate-Commutated Thyristor (IGCT) for a 12.47 kV distribution system. The switching of IGCT successfully identified the fault current behavior leading to secure the medium distribution level. The simulation results indicated fast transfer switching (in under microseconds) and greater overall protection, justifying the efficient operation of circuit breakers in the distribution system. Zhang et al. [6] introduced an electro-mechanical hybrid power controller (EMPHC) utilizing insulated gate bipolar transistors (IGBT) and a mechanical switch. They suggested that EMPHC can be used for electrical control, isolation, and fault protection in aircraft systems.

The investigations on SSS have risen since 2010 due to concerns about power quality issues related to residential and industrial sensitive loads [7,8]. The operations that include critical loads may be disrupted by voltage sags, swells, or other disturbances [9,10]. An effective way to enhance the network’s power quality is to employ a power electronic device based on SSS [11]. Several studies [12–14] reported that that SSS is a cost-effective solution to power quality. Switching power that disrupts the fault can allow the system to operate normally. SSS based on power electronic devices to protect against power quality disruption has become a common practice. Recently, researchers have focused on the impacts of power electronic switching in distribution systems using solid-state breaker topologies. Findings reveal that SSS provides a much quicker switching response time than electromechanical circuit breakers. The most recent developments in SSS over the last ten years focus on the protection system or controls system to ensure faster fault clearing, automatic, rapid recovery, and system stability. As a result, a secure, quick, cost-effective, less failure with improved long-term dependability interruption fault, current switching can be developed and proven with the application of SSS control. The design requirements of SSS control systems along with applicable fault detection techniques, fast switching, and efficient protection scheme are also taken into consideration towards ensuring safety, stability as well as improving power quality and achieving a satisfactory operation in the distribution system. Therefore, this study examines the most recent scientific literature highlighting control architecture and other strategic developments of SSS.

Bibliometrics is a sort of research method that delivers the information and analysis in different patterns such as statistics and the quantitative approach using the library and information science [15,16]. Bibliometrics is an important field of study because it offers some particular and historical findings that can be used to predict future research developments [17–19]. The bibliometric study is helpful for universities, teachers, researchers, and professors to evaluate the research quality through various key indicators including current standing, citation, impact factors, and h-index. Gingras [20] discussed the impact of bibliometric analysis on research direction and suggested some criteria to develop the appropriate evaluation process at a certain scale of research strategy and analysis. Andres [21] outlined the procedures to conduct the bibliometric analysis with numerous and real-world samples and interpretation. The authors also explained the value of Sciento-
metric studies in the bibliometric study. This article presents a bibliographic analysis of the current state of the publication activity in the field of SSS. In recent years, numerous bibliometric approaches have been employed to analyze research developments in specific different areas, such as software engineering [22], engineering nanomaterials [23], quantum electronics [24], Computers & Industrial Engineering [25], applications of artificial intelligence [26], climate engineering research [27], Industrial Ecology [28], Strategic Management [29], technological innovation [30], drug repurposing [31], Pediatric Surgery [32], and healthcare simulation [33].

To the best of our knowledge, no research works have been carried out for a bibliometric analysis on the topic of SSS. Thus, this study summarizes the first bibliometrics analysis of SSS that has been conducted over the past 10 years (from 2010 to January 2021) to examine its evaluation, research community, and current trends. The contributions of this paper are highlighted below.

- A brief overview of SSS is provided with respect to the number of papers published to date. The analysis is conducted on a year-on-year basis and includes the discussion.
- The rating of SSS is evaluated using the number of cited papers, the journal with the most reported papers, the most prolific authors, the most productive university, and the country dominating the publication.
- The interesting keywords and topics used for content analysis and gaps are examined.
- The document types of publications including conference papers, articles, books, and reviews are explored. An analysis of the number of document types is performed. Additionally, the impact factors and distribution publisher by the journals are studied.
- The extent of collaboration among researchers is identified. The team is evaluated using the number of authors in the papers and the cooperation between various universities and countries.
- The most prominent and influential authors, universities/institutions/companies, and countries contributing the most published work are determined. This is vital for discovering the productivity of authors, organizations, and countries in publishing as well as for increasing the production of research and collaboration between authors.

The purpose of this article is to identify the 120 most highly cited papers related to SSS research. Accordingly, the detailed report on the information, critical discussions, analysis, contributions, and shortcomings of these publications are delivered. The article will bring several benefits which are presented below.

- To provide an insight into the history and development of SSS research.
- To provide an overview of SSS that will extend the current knowledge and practice.
- To improve the understanding and ideas of SSS, recognize its research community and identify its trends.

The structure of the paper is organized as follows. Section 2 outlines the surveying methodology highlighting the selection process, research trend, data extraction, the criteria for inclusion and exclusion, and key findings. Section 3 presents the analytical discussion focusing on publication trends, citation structure, analysis of keywords and topics, document type of evaluation, and authorship evaluation. Finally, Section 4 narrates the conclusion and directions of the future outlook.

2. Surveying Methods

The strategy used for this review is based on Bibliometrics which is a statistical analysis of the Scopus database (www.scopus.com). The Scopus database is used as a source in the bibliometric analysis in this research because it has a larger number of papers than other databases, like the Web of Science [34]. Google Scholar is not assessed in this survey due to a lack of accurate results [35]. By the end of January 2021, the “solid-state switching” research had been tracked in the Scopus database. Figure 1 shows the techniques used in the Scopus database for bibliometric analysis. The process is diagrammed into three stages as shown in the illustration below:
Figure 1. Surveying methods in the Scopus database.

(1) Selection Process of Papers
- A total of 838 solid-state breaker papers were found, spanning the years from 1922 to 2021.
- 138 papers were collected based on application, control, protection switch, and limitations from 2010 to 2021.
- 112 papers were chosen based on Engineering and English subjects.
- 57 papers were obtained after screening based on abstracts, related subjects, and overlapped keywords.

(2) Record Identified Within 6 Keywords

The same process had to be done for each keyword: solid-state transfer switch, static transfer switch, automatic transfer switch, automatic protection switches, and solid-state protection switch. After all, this study re-sorted up to 120 papers (based on combinations of all keywords) by evaluating the appropriate title, abstract, keywords, relevant contents, and practical discussion contributions. The paper types were article, conference paper, book chapter, and review. Based on the citation counts, the papers were arranged from the highest citation to the lowest citation.

(3) Review Findings
- Surveying approaches were described in detail based on including or excluding data, the screening process, the research trend, data extraction, and study characteristics and outcomes.
- The analytical discussion focused on publication trends and citation structures, keywords analysis, topics analysis, document type, and authorship assessment.
• Identified the issues and suggestions on system failure by fault, control method, SSS implementation design, and system's protection for further advancement of SSS field.

2.1. Criteria for Inclusion and Exclusion
• The suitability of research techniques for analysis was considered in more detail, including or excluding data. Bibliometric analysis of papers was sorted from the Scopus database. The 120 papers were analyzed based on the following constraints:
  • The papers were based on the “solid state switching” which was used with six keywords separately during the search, including solid state breaker, solid state transfer switch, static transfer switch, automatic transfer switch, automatic protection switch, and solid state protection switch. The research investigated the terms of the application, control, and protection switch for each keyword.
  • The papers were selected in the limited years between 2010 and 2021.
  • Engineering is considered only for scientific fields and English was chosen.

2.2. Screening Procedures
  It was unfeasible to collate a single list of each article because of the distinction in output for every database. The screening method was conducted out of the Scopus database. The five screening processes were performed for each keyword, as depicted below.
  • In the Scopus database after primary search for “solid state breaker, solid state transfer switch, static transfer switch, automatic transfer switch, automatic protection switches, and solid-state protection switch”, a different number of articles was found. It covered a different period.
  • The first screening was limited to the “application”, “control”, and “protection switch”.
  • The second screening was carried out in a restricted time between 2010 and 2021.
  • The third screening involved the selection of the subject Engineering.
  • The fourth screening in English was limited to the Scopus database.
  • The last screening was conducted using all keywords by evaluating the appropriate title, abstract, keywords, relevant content, and contributions for practical topics and selecting 120 papers.

2.3. Research Trend
  All published papers were searched from the Scopus database under six search terms: solid-state breaker, solid-state transfer switch, static transfer switch, automatic transfer switch, automatic protection switch, and solid-state protection switch with keywords search for “application”, “control”, and “protection switch”. The publication trends for the papers in the list from 2010 to 2021 are presented in Figure 2. It is observed from Figure 2 that it has the highest number of papers under the search term “solid state breaker”, followed by terms solid state protection switch, automatic protection switch, automatic transfer switch, solid state transfer switch, and static transfer switch. The outcomes for several papers vary over different years. Overall, from the year 2010 to 2019, the trends show a rise in the number of published papers, then the number of papers decreases after 2019.
Figure 2. The number of papers per year in the research trend.

The growing trend in publications relating to “solid-state switching” indicates that it has become pervasive and endorsed in engineering research. The growth trend is expected to become a major deployment of the industry in the future. However, for 2021, it is early to predict since data was taken for January 2021. The research paper published in 2019 is at maximum for solid state breaker, solid state protection switch, automatic protection switch, and automatic transfer switch. The highest publication is identified in 2019 for solid state breaker which is 27 papers. However, for solid state transfer switch, the published papers show the highest number over the time frame of 2017 and 2018, and the highest published paper is recorded in 2018 for a static transfer switch. In the case of a solid state transfer switch, none of the research papers were published in 2010, 2011, 2012, 2014, 2016, 2019, and 2020. No publications in 2010, 2016, 2017, 2020, and 2021 are recorded for static transfer switches. In January 2021, only papers have been tracked for keywords: solid state breaker, automatic protection switches, and solid state protection switch.

2.4. Data Extraction

Using the Scopus database, data on papers were extracted on the list of variables: (1) author’s name; (2) paper DOI; (3) keywords; (4) paper’s publication year; (5) paper’s publisher; (6) paper’s type; (7) country of publication (based on the affiliation of the author for each paper); (8) number of paper citations; (9) average citation per year, (10) last-five years citation, and (11) impact factors for journals.

2.5. Study Characteristics and Outcomes

This review examines different search terms for the same disciplinary analysis in the Scopus database. We want to analyze “solid state switching” from the bibliometric analysis based on six keyword search terms. From the Scopus database, a total number of 120 papers was found from 2010 to 2021. All authors come from various backgrounds and countries of origin but still in similar engineering topics. Many bibliometric works of literature discuss SSS with different databases. From their analysis, it can be used as an option to broaden ideas for future empirical studies. Here we focus on the article information based on the number of citations, keywords, topic, publishing year, publisher, type of document, type of source, impact factor, author’s h-index, university’s h-index, and the most prominent authors, organizations, and countries. Finally, we conclude the bibliometric analysis.
3. Analytical Discussion

Our study uses “6 search terms keywords” focusing on “solid state switching” in the bibliometric database. The 120 articles for SSS were identified. The analysis of the time frame was conducted for the last ten years, between 2010 and 2021. The objective of this review is to define the 120 “solid state switching” to emphasize the characteristics of these papers:

- To study the publication trends and citations structure of papers
- Analysis of paper’s keywords
- Analysis of paper’s topics
- To study journal evaluation
- To study the authorship, universities, and countries evaluation.

3.1. Publication Trends and Citation Structures

The number of papers published between 2010 and 2021 is shown in Figure 3. A total of 308 papers were explored before scanning methods. As observed, the number of published papers increases gradually until 2019 with roughly 59 papers. The increase in research illustrates the acceptance and important potential deployment of the industry. Nevertheless, there is a slight reduction in the number of papers for recent years up to 2020. The published papers are fewer in recent years due to it being early to determine the article number for January 2021. Apparently, these data are dynamic and the trends are will change in the future if maturity is achieved.

The most important issue is to assess the most cited papers in the publication. Table 1 presents the evaluation data for 120 papers on solid state switching. The data classified is based on rank, author’s name, article’s DOI, keywords, publishing year, publisher, type of publication, country of origin, number of citations, average citation per year, average citation in last five years, and impact factor. As seen, the highest citation article is recorded by Li et al. [36] amounting to 310. The article’s title is based on the protection of nonpermanent faults on DC overhead lines in MMC-based HVDC systems. This article presents a protection scheme for non-permanent faults to decrease the DC connection current and improve modular multilevel converter (MVTC) reliability. The keywords for this research related to the DC fault, modular multilevel converter (MMC), fault clearance, and system recovery. The topics discussed are high voltage direct current systems (HVDC), converters, and static synchronous compensators. The paper is a journal article and published in IEEE Transactions on Power Delivery. The authors come from China. A paper by Park & Candelaria [37] is reported as the the-second-high citation article with a
number of 192. The title of the article is about fault detection and isolation in low-voltage DC-bus microgrid system with the keywords: Insulated Gate Bipolar Transistor (IGBT), over-current (OC), inverter, and optocoupler. The article provides fault detection, isolation scheme for the low-voltage dc-bus microgrid device and is tested using a prototype that can be applied to dc power system. The microgrid, DC-DC converter, and power-sharing topics were discussed. The article is based on a journal article and published in IEEE Transactions on Power Delivery. The author is from the USA. A third high citation article is reported by Wang et al. [38] in 2014. The title of the paper is the design and performance evaluation of overcurrent protection schemes for silicon carbide (SiC) power MOSFETs. The article introduces the overcurrent protection method under hard switching fault and load conditions for SiC MOSFETs. The conclusive evidence showed that the proposed protection can address the short-circuit fault in 200 nanoseconds. The keywords highlights are silicon carbide (SiC), metal–oxide–semiconductor field-effect transistors (MOSFETs), SSCB, and overcurrent protection (OP). The topics discussed are MOSFET, power module (SSTS), and JFET. The paper is based on journal articles and publishing under IEEE Transactions Industrial Electronics. The author is from the USA. Li et al. [36], Park and Candelaria [37], and Wang et al. [38] are top articles and have citation numbers as high as a hundred. These three journals have impact factors of 3.482, 5.589, and 2.341, respectively.

Among 120 numbers of papers, 2.5% of the papers have received over 100 citations, an estimated 4.2% have received more than 50 citations, 15% have received more than 20 citations, 13.3% have received more than 10%, 48.3% of the papers have received more than 1%, and 16.7% have none citation. However, the number of citations received by papers does not determine the best approach to the research quality [39]. Nonetheless, it expresses the readership of the specific paper and its influence in producing interventions, controversy, discussion, and some further research. This is a great indication of the acknowledgment of paper in its profession. Citation analysis has become a famous way to determine the impact of an article or author on a specific topic in a journal [40]. This paper was aiming for identifying the characteristic related to SSS research. Due to the reason that even the paper has a small number of citations, we have still included it in the research.

The review and discussion of the top 120 most cited papers were discussed, and it was discovered that the majority of the articles published in recent years focused on the development of protection schemes or control systems for fault detection to enable faster fault clearing, and automatic and quick recovery. Various approaches and methods have been developed for the implementation of solid state protection so that operation can be accomplished safely, quickly, at a lower cost and loss with increased long-term dependability interruption fault current switching [38,41–49]. Prototyping for interruption of faults has recently been completed and experimentally demonstrated the presence of interruptions [46,50–58]. The overall survey found that the feasibility of maintaining high levels of selectivity and quick fault detection by using a variety of security methods was proven. Fault-free elimination is configured in these articles survey at such limited time scales that has a significant impact on equipment capability, materials ratings, and results in lower fault insulation requirements. This opportunity is especially good for semiconductor switching devices in market opportunities.
Table 1. The 120 papers list for Solid State Switching keywords and publication detail.

| Ref. | Rank | Author's Name          | Article DOI                  | Keywords                                                                 | Year * | Publisher | Type * | Country | NC * | CPY * | FYC * | IF * |
|------|------|------------------------|------------------------------|-------------------------------------------------------------------------|--------|-----------|--------|---------|------|-------|-------|------|
| [36] | 1    | Li et al.              | 10.1109/TPWRD.2012.2226249  | DC fault, MMC, fault clearance, system recovery                         | 2012   | IEEE      | Article | China   | 310  | 25    | 199   | 3.482|
| [37] | 2    | Park & Candelaria      | 10.1109/TPWRD.2013.2243478  | IGBT, OC, inverter, optocoupler                                        | 2018   | IEEE      | Article | USA     | 192  | 16    | 140   | 5.589|
| [38] | 3    | Wang et al.            | 10.1109/TIE.2013.2297304    | SiC, MOSFETs, SSCB, OCP                                                 | 2014   | IEEE      | Article | USA     | 145  | 12    | 119   | 2.341|
| [59] | 4    | Shen et al.            | 10.1109/TED.2014.2384204    | GaN HEMT, SiC JFET, SSCB, WBG semiconductors                            | 2015   | IEEE      | Article | USA     | 75   | 6     | 58    | 3.13 |
| [42] | 5    | Emhemed et al.         | 10.1109/TPWRD.2016.2593941  | LVDC, SSCBs, DS, multiple IEDs, protection                              | 2017   | IEEE      | Article | UK      | 73   | 6     | 73    | 4.561|
| [60] | 6    | Magnusson et al.       | 10.1109/TPEL.2013.2272857   | DC breaker, MOV, OVP, SSCB, snubber circuit                            | 2014   | IEEE      | Article | Sweden  | 61   | 5     | 42    | 9.91 |
| [50] | 7    | Shen et al.            | 10.1109/ICDCM.2015.7152044  | SSCBs, DC MG, current status                                            | 2015   | IEEE      | Conf.   | USA     | 59   | 4     | 56    | -    |
| [43] | 8    | Qi et al.              | 10.1109/JESTPE.2016.2633223 | DC, SSCBs, distribution, fault protection                                | 2017   | IEEE      | Article | USA     | 55   | 4     | 55    | 4.321|
| [61] | 9    | Agostini et al.        | 10.1109/ESTS.2015.7157906   | SSCB, IGCT, RB-IGCT, power switch                                       | 2015   | IEEE      | Conf.   | Swiss   | 48   | 4     | 44    | -    |
| [51] | 10   | Cuzner & Singh         | 10.1109/JESTPE.2016.2638921 | DC distribution, SPS, DC fault protection                               | 2017   | IEEE      | Conf.   | USA     | 39   | 3     | 39    | -    |
| [62] | 11   | Li et al.              | 10.1109/TPEL.2018.2850441   | LVDC, SSCB, DC fault, distribution, fault current                      | 2018   | IEEE      | Article | China   | 38   | 3     | 38    | 2.510|
| [52] | 12   | Miao et al.            | 10.1109/JESTPE.2016.2558448 | SiC JFET, SSCB, DC power, WBG semiconductors                            | 2016   | IEEE      | Article | USA     | 38   | 3     | 38    | 3.219|
| [63] | 13   | Yazdanpanahi et al.    | 10.1109/TPWRD.2013.2276948  | DC, OP, compatibility, fault                                            | 2014   | IEEE      | Article | Canada  | 37   | 3     | 26    | 3.481|
| [64] | 14   | Costa et al.           | 10.1109/TPEL.2016.2585668   | DC–DC power converters, RC, SRC, fault diagnosis                       | 2016   | IEEE      | article | Germany | 37   | 3     | 37    | 7.151|
| [65] | 15   | Liu et al.             | 10.1109/TPEL.2016.2574751   | DC SSCB, OP, snubber, short circuit currents                            | 2016   | IEEE      | Article | China   | 31   | 2     | 31    | 7.151|
| [66] | 16   | Ji et al.              | 10.1109/TPEL.2018.2834463   | SiC MOSFET, short circuit, protection                                   | 2018   | IEEE      | Article | USA     | 28   | 2     | 28    | 7.224|
| [67] | 17   | Cuzner & Esamili       | 10.1109/ESARS.2015.7101536  | MVDC systems, SPS, DC fault protection                                  | 2015   | IEEE      | Conf.   | USA     | 28   | 2     | 22    | -    |
| [68] | 18   | Wang et al.            | 10.3390/electronics9020306   | DCCB, SSC, DC MG, bidirectional protection                             | 2020   | MDPI      | Article | China   | 27   | 2     | 27    | 0.303|
Table 1. Cont.

| Ref. | Rank | Author’s Name         | Article DOI            | Keywords                                                                 | Year * | Publisher | Type * | Country | NC * | CPY * | FYC * | IF * |
|------|------|------------------------|------------------------|--------------------------------------------------------------------------|--------|-----------|--------|---------|------|-------|-------|------|
| [69] | 19   | Rodrigues et al.       | 10.1109/ESTS.2017.8069314 | SSCB, fault protection, trip-curve, power semiconductor                  | 2017   | IEEE Conf. | USA    | 27      | 2    | 27    |      |      |
| [44] | 20   | Mobarrez et al.        | 10.1109/TIA.2016.2565458 | DC circuit breaker, dc fault, HVDC, protection                           | 2016   | IEEE Article | USA   | 25   | 2  | 24 | 3.72 |
| [70] | 21   | Song et al.            | 10.1109/TPWRD.2018.2815550 | VSC-HVDC, MVC, DC circuit breaker, DC fault clearance                    | 2018   | IEEE Article | China | 24   | 2  | 24 | 4.42 |
| [71] | 22   | Kennedy et al.         | 10.1109/PESGM.2012.6345729 | DC, ILS, STS, microgrids                                               | 2012   | IEEE Con. | Australia | 23 | 1 | 14 | -    |
| [72] | 23   | Hernandez et al.       | 10.3906/elk-1406-14     | DC power systems, STS, VSC, fault current                                | 2016   | TMC Article | Spain | 22   | 1  | 21  | 0.682 |
| [73] | 24   | Peng & Huang           | 10.1109/APEC.2014.6803800 | DC breaker, VSC, SSCB                                                  | 2014   | IEEE Conf. | USA | 22 | 1 | 11 |      |
| [74] | 25   | Song et al.            | 10.1109/TIE.2017.2786198 | ESS, STS, SC, DC microgrid, DC distribution                            | 2017   | IEEE article | China | 22 | 1 | 22 | 9.28 |
| [75] | 26   | Vodyakho et al.        | 10.1049/i.et-epa.2010.0258 | AFU, DESD, FID, IGBT                                                   | 2011   | IET Article | USA | 20 | 1 | 9  | 2.778 |
| [76] | 27   | Castellan et al.       | 10.1016/j.ijepes.2017.09.040 | MVDC, SST, DC circuit breaker, DC distribution                        | 2018   | Elsevier Review | Italy | 19 | 1 | 19 | 4.4    |
| [77] | 28   | Ahn et al.             | 10.1109/TPEL.2014.2352651 | SSPPM, protection circuit, pulsed power applications                   | 2015   | IEEE Article | Korea | 19 | 1 | 17 | 9.433 |
| [44] | 29   | Mobarez et al.         | 10.1109/ECCE.2015.7310254 | HVDC, DC circuit breaker, DC fault, protection                         | 2015   | IEEE Conf. | USA | 17 | 1 | 10 | - |
| [78] | 30   | Song et al.            | 10.1109/TPWRD.2018.2865226 | Fault, hybrid HVDC breaker                                            | 2018   | IEEE Article | China | 16 | 1 | 14 | 4.42 |
| [45] | 31   | Ilyushin & Suslov      | 10.1109/PTC.2019.8810450 | DG, ATS, transfer switch, relay protection                             | 2019   | IEEE Conf. | Russia | 15 | 1 | 15 | - |
| [79] | 32   | Suvorov et al.         | 10.1007/s00202-016-0464-4 | Synchronous motor, adequacy, operation                                 | 2016   | Springer Article | Russia | 15 | 1 | 10 | 0.264 |
| [80] | 33   | Munasib & Balda        | 10.1109/PEDG.2016.7527062 | DC microgrids, SCCBs, short-circuit protection                         | 2016   | Springer Article | Russia | 15 | 1 | 4  | 3.30 |
| [81] | 34   | Cairoli et al.         | 10.1109/ESTS.2019.8847815 | SSBC, DCSPS, RB-JGCT, fault protection                                  | 2019   | IEEE Conf. | USA | 13 | 1 | 13 | - |
| [82] | 35   | Mokhberdoran et al.    | 10.1016/j.epsr.2017.05.032 | DC circuit breaker, fault protection, HVDC transmission                | 2017   | Elsevier Article | Portugal | 13 | 1 | 13 | 2.7 |
| [83] | 36   | Song et al.            | 10.1109/TPEL.2016.2616841 | GTO, SOA, ETO, SiC, high voltage                                      | 2016   | IEEE Article | USA | 13 | 1 | 13 | 7.151 |
| [46] | 37   | Panetta                | 10.1109/ESW.2013.6509026 | SCR fast acting switch, switching transients                            | 2013   | IEEE Conf. | Canada | 13 | 1 | 9  | - |
| [84] | 38   | He et al.              | 10.2514/6.2018-5008      | HVDC, WBG, MEA                                                          | 2018   | IEEE Conf. | USA | 12 | 1 | 12 | - |
| Ref. | Rank | Author's Name       | Article DOI         | Keywords                                                                 | Year * | Publisher | Type * | Country | NC * | CPY * | FYC * | IF * |
|------|------|---------------------|---------------------|--------------------------------------------------------------------------|--------|-----------|--------|---------|------|-------|-------|------|
| [85] | 39   | Gu et al.           | 10.3390/en10040495  | SCCBs, HDC, semiconductor devices, protection                             | 2017   | MDPI AG   | Article | UK      | 12   | 1    | 12    | 2.676 |
| [47] | 40   | Pouresmaeil et al.  | 10.1002/etep.461    | Voltage disturbance, algorithm, sag, swell                                | 2011   | EREP      | Article | Spain   | 11   | 0    | 2     | 0.577 |
| [86] | 41   | Li et al.           | 10.1109/PEAC.2014.7038038 | SSDCB, Super UPS, DC protection                                           | 2014   | IEEE      | Conf.   | China   | 10   | 0    | 7     | -    |
| [87] | 42   | Bhat et al.         | 10.1109/APEC.2012.6166172 | SiC MOSFET, SSCB, reliability                                              | 2012   | IEEE      | Conf.   | USA     | 10   | 0    | 3     | -    |
| [88] | 43   | Zhou et al.         | 10.1109/PEDG.2018.8447563 | Digital-Controlled, SiC, SSCB, Soft-Start, DC Microgrids                  | 2018   | IEEE      | Conf.   | USA     | 9    | 0    | 9     | -    |
| [41] | 44   | Komatsu             | 10.1109/INTLEC.2016.7749138 | DC MG, DC circuit breaker, OCP, MOSFET, IGBT, SiC                        | 2016   | IEEE      | Conf.   | Japan   | 9    | 0    | 9     | -    |
| [89] | 45   | Liu et al.          | 10.1109/IEECC.2015.7361508 | MEA, HVDC, SCCB                                                           | 2015   | IEEE      | Conf.   | China   | 8    | 0    | 7     | -    |
| [54] | 46   | Nasereddine et al.  | 10.1109/IEEEGCC.2013.6705820 | SSCB, FCL, IGBTs, prototype                                               | 2013   | IEEE      | Conf.   | Saudi Arabia | 8 | 0 | 5 | - |
| [90] | 47   | Qi. et al.          | 10.1109/TIA.2019.2962762 | DC SPS, RB-IGCT, SSCB, fault protection                                   | 2019   | IEEE      | Article | USA     | 7    | 0    | 7     | 4.27  |
| [91] | 48   | Wei et al.          | 10.1109/APEC.2018.8341000 | STS, IGBT, HDCCB, MTDC, FEM simulation,                                   | 2018   | IEEE      | Conf.   | China   | 7    | 0    | 7     | -    |
| [92] | 49   | He et al.           | 10.1049/iet-pel.2017.0283 | SSCBs, SiC JFET, DC protection                                            | 2018   | IEEE      | Article | China   | 7    | 0    | 7     | 3.53  |
| [57] | 50   | Falaniappan et al.  | 10.1109/ECCE.2017.8096662 | SSCBs, DC fault protection                                                | 2017   | IEEE      | Conf.   | USA     | 7    | 0    | 7     | -    |
| [93] | 51   | Roshandeh et al.    | 10.1109/ECCE.2016.7854907 | SiC JFET, SSCB, WBG semiconductors                                        | 2016   | IEEE      | Conf.   | USA     | 7    | 0    | 7     | -    |
| [94] | 52   | Demetriades et al.  | 10.1109/IPECC.2014.6869742 | BESS, Solid-State DC-Breaker, VSC, protection                             | 2014   | IEEE      | Conf.   | Sweden  | 7    | 0    | 5     | -    |
| [95] | 53   | Marroqui et al.     | 10.1109/TPEL.2019.2893104 | SSCB, FCL, WBG Semiconductors, SiC cascade                                | 2019   | IEEE      | Article | Spain   | 6    | 0    | 6     | 6.373 |
| [96] | 54   | Liao et al.         | 10.1109/TCPMT.2019.2899340 | MOSFET, SSCB, SiC, MOV, snubber circuit                                  | 2019   | IEEE      | Article | China   | 5    | 0    | 5     | 2.31  |
| [97] | 55   | Wang et al.         | 10.1109/TASC.2018.2841918 | HDCCB, IGBTs, protection circuit                                         | 2018   | IEEE      | Article | China   | 5    | 0    | 5     | 1.755 |
| [48] | 56   | Pfitscher           | 10.1016/j.epsr.2013.07.003 | Smart grid supervisory system, transient analysis                        | 2013   | Elsevier  | Article | The Netherlands | 5 | 0 | 2 | 3.413 |
| [98] | 57   | Cramon et al.       | 10.1109/CPRD.2013.6822023 | ABTS, GOOSE application, protection                                     | 2013   | IEEE      | Conf.   | USA     | 5    | 0    | 4     | -    |
Table 1. Cont.

| Ref. | Rank | Author’s Name | Article DOI | Keywords | Year * | Publisher | Type * | Country | NC * | CPY * | FYC * | IF * |
|------|------|---------------|-------------|----------|--------|-----------|--------|---------|------|-------|-------|----|
| [99] | 58   | Kim et al.    | 10.1109/TIE.2019.2916371 | DC MG, SPS, protection coordination | 2019 | IEEE | Conf. | Swiss | 5 | 0 | 5 | 9.451 |
| [53] | 59   | Vodyakho et al. | 10.1109/APEC.2011.5744584 | FID, distribution systems, power electronics, prototype MVDC, SST, SSB, fault, overcurrent protection | 2011 | IEEE | Conf. | USA | 5 | 0 | 4 | - |
| [100] | 60   | Wang et al. | 10.1109/IECON.2019.8926684 | DC-Microgrid, SCCB, PV system, short-circuit protection | 2019 | IEEE | Conf. | China | 4 | 0 | 4 | - |
| [101] | 61   | Yaqobi et al. | 10.3390/app9040723 | Transmitter, amplifier, CMOS | 2013 | IEEE | Conf. | UK | 4 | 0 | 2 | - |
| [102] | 62   | Sa’ed et al. | 10.1109/IEEEIC.2017.7977785 | SSPC, SSCB, SiC, EMs, TVS, protection circuit | 2018 | IEEE | Conf. | USA | 3 | 0 | 3 | - |
| [103] | 63   | Mani & Naidu. | 10.1109/PEAC.2014.7038038 | SiC MOSFET, ICP integration, OCP, medium voltage | 2019 | IEEE | Article | USA | 4 | 0 | 4 | 6.373 |
| [104] | 64   | Valente & Demosthenous, | 10.1109/ICECS.2013.6815401 | Automation system, protection, line switch | 2012 | MDPI AG | Article | Taiwan | 4 | 0 | 3 | 0.852 |
| [105] | 65   | Zhang et al. | 10.1109/JESTPE.2019.2951602 | SSPC, SSCB, SiC, EMs, TVS, protection circuit | 2018 | IEEE | Conf. | Singapore | 4 | 0 | 4 | - |
| [106] | 66   | Zhang et al. | 10.1109/IECON.2018.8591242 | FID, distribution systems, power electronics, prototype MVDC, SST, SSB, fault, overcurrent protection | 2019 | IEEE | Article | USA | 4 | 0 | 4 | 6.373 |
| [107] | 67   | Qi et al. | 10.1049/cp.2016.0030 | DC, SCCB, shipboard, distribution | 2016 | IEEE | Conf. | USA | 3 | 0 | 3 | - |
| [108] | 68   | Zhang et al. | 10.1109/ICIT.2015.7125263 | Thyristor, low voltage, arc faults, bypass switch | 2015 | IEEE | Conf. | Sweden | 3 | 0 | 2 | - |
| [109] | 69   | Qi et al. | 10.1109/IAS.2019.8912385 | Power MOSFET, IGCT, SiC MOSFET, DC circuit breaker | 2017 | IEEE | Conf. | Japan | 3 | 0 | 3 | - |
| [58] | 70   | Komatsu | 10.1109/INTELECON.2017.8211688 | Power MOSFET, IGCT, SiC MOSFET, DC circuit breaker | 2017 | IEEE | Conf. | Japan | 3 | 0 | 3 | - |
| [110] | 71   | Rubino et al. | 10.15866/ieee.v125.13982 | Thyristor, low voltage, arc faults, bypass switch | 2015 | IEEE | Conf. | Sweden | 3 | 0 | 2 | - |
| [111] | 72   | Qi et al. | 10.1109/IEEE/IAS.2019.8912385 | Power MOSFET, IGCT, SiC MOSFET, DC circuit breaker | 2017 | IEEE | Conf. | Japan | 3 | 0 | 3 | - |
| [112] | 73   | Feng et al. | 10.1109/IEEE/IAS.2019.8912385 | Power MOSFET, IGCT, SiC MOSFET, DC circuit breaker | 2017 | IEEE | Conf. | Japan | 3 | 0 | 3 | - |
| [113] | 74   | Qi et al. | 10.1109/IEEE/IAS.2019.8912385 | Power MOSFET, IGCT, SiC MOSFET, DC circuit breaker | 2017 | IEEE | Conf. | Japan | 3 | 0 | 3 | - |
| [114] | 75   | Berg et al. | 10.23919/EPE.2019.8915142 | Power MOSFET, IGCT, SiC MOSFET, DC circuit breaker | 2019 | IEEE | Conf. | Norway | 2 | 0 | 2 | - |
| Ref. | Rank | Author's Name       | Article DOI                  | Keywords                                                                 | Year | Publisher | Type * | Country | NC * | CPY | FYC | IF * |
|------|------|---------------------|------------------------------|--------------------------------------------------------------------------|------|-----------|--------|---------|------|-----|-----|-----|
| [115]| 76   | Tapia et al.        | 10.3390/electronics8090953   | CB, FCL, DC power grids, DC circuit breaker                             | 2019 | MDPI      | Article | Spain   | 2    | 0   | 2   | 0.303 |
| [116]| 77   | Murugan & Prabu     | 10.1109/ICETEEEM.2012.6494451| SSCBs, power semiconductors, GTO, IGCT                                   | 2012 | IEEE      | Conf.   | India   | 2    | 0   | 2   | -   |
| [117]| 78   | Sărăcin et al.      | 10.1109/ATEE.2015.7133906   | ATS, electric power supplies, vital consumers                           | 2015 | IEE       | Conf.   | Romania | 2    | 0   | 2   | -   |
| [118]| 79   | Ma et al.           | 10.1109/ICEMS.2017.805596   | Thyristor, protection, distribution transformer                         | 2017 | IEE       | Conf.   | China   | 2    | 0   | 2   | -   |
| [119]| 80   | Pfitscher et al.    | 10.1109/INDUSCON.2012.6451396| Automatic reconfiguration, smart grids                                 | 2012 | IEEE      | Conf.   | Brazil  | 2    | 0   | 1   | -   |
| [120]| 81   | Tao et al.          | 10.1109/CECNET.2011.5768624 | HV double power, intelligent controller                               | 2011 | IEEE      | Conf.   | China   | 2    | 0   | 1   | -   |
| [121]| 82   | Jakka et al.        | 10.1109/IECON.2018.8592886  | SiC, SSTS faults, medium voltage, short-circuit                        | 2018 | IEEE      | Conf.   | USA     | 2    | 0   | 2   | -   |
| [122]| 83   | Prempraneerach et al.| 10.1109/ITEC.2017.7993304 | DC circuit breakers, thyristor, system protection                      | 2017 | IEEE      | Conf.   | Thailand | 2     | 0   | 2   | -   |
| [123]| 84   | Song et al.         | 10.1109/EPE.2016.7695558    | DC SSPC, short-circuit protection, loads                               | 2016 | IEEE      | Conf.   | China   | 2    | 0   | 2   | -   |
| [124]| 85   | Radmanesh.et al.    | 10.5370/JEET.2016.115.1070  | FCL, distribution network, protection                                  | 2016 | KIEE      | Article | Iran    | 2    | 0   | 2   | 0.67 |
| [125]| 86   | Ruszczyk et al.     | 10.1109/ISNCC.2015.7174699  | Hybrid switch, protection, semiconductor device                        | 2017 | IEEE      | Conf.   | Poland  | 2    | 0   | 1   | -   |
| [126]| 87   | Faisal et al.       | 10.3390/electronics9091396   | SSTS topologies, power quality,                                       | 2020 | MDPI      | Review  | Malaysia | 1    | 0   | 2   | 0.303 |
| [127]| 88   | Marroqui, et al.    | 10.23919/EPE17ECCEEurope.2017.8099083 | SiC, HVDC, Current limiter, protection                                | 2017 | IEEE      | Conf.   | Spain   | 1    | 0   | 1   | -   |
| [128]| 89   | Liu et al.          | 10.1109/ICEMPE.2017.7982174 | Hybrid DC contactor, SST, IGBT, MOV protection                         | 2017 | IEEE      | Conf.   | China   | 1    | 0   | 1   | -   |
| [129]| 90   | Tsyruk et al.       | 10.1109/Dynamics.2018.8601484| Fault detector, fast device, single-channel component                  | 2018 | IEEE      | Conf.   | Russian | 1    | 0   | 1   | -   |
| [55] | 91   | Pei et al.          | 10.1016/j.ijepes.2020.106004 | HDCCB, mechanical switch, semiconductor switch                        | 2020 | Elsevier  | Article | UK      | 1    | 0   | 1   | 3.588 |
| [130]| 92   | Lin et al.          | 10.1109/COGEN.2016.7728957  | DG, microgrid, network topology, planning island                       | 2016 | IEEE      | Conf.   | China   | 1    | 0   | 1   | -   |
| [131]| 93   | Ulissi.et al.       | 10.1109/TPEL.2020.3000855   | Fault protection, marine equipment, microgrids                        | 2020 | IEEE      | Article | Switzerland | 1 | 0 | 1 | 7.515 |
Table 1. Cont.

| Ref. | Rank | Author's Name | Article DOI | Keywords | Year * | Publisher | Type * | Country | NC * | CPY * | FYC * | IF * |
|------|------|---------------|-------------|----------|--------|-----------|--------|---------|------|-------|-------|-----|
| [56] | 94   | Xu et al.,    | 10.1109/TPEL.2020.2987418 | Circuit breakers, CS-MCT, microgrids, protection | 2020 | IEEE | Article | China | 1 | 0 | 1 | 7.515 |
| [132] | 95   | Ulissi et al. | 10.1109/TTE.2020.2996776 | Marine systems, power electronics, protection | 2020 | IEEE | Article | Switzerland | 1 | 0 | 1 | 5.79 |
| [133] | 96   | He et al.      | 10.1109/ECCE.2019.8913277 | Distribution system, SSCB, SiC JFET, inrush current | 2019 | IEEE | Conf. | China | 1 | 0 | 1 | - |
| [134] | 97   | Zhou et al.    | 10.1109/APEC.2019.8721869 | GaN, SSCB, heat dissipation, bidirectional | 2019 | IEEE | Conf. | USA | 1 | 0 | 1 | - |
| [135] | 98   | Zhou et al.    | 10.1109/TIE.2020.2972431 | CB, power system protection, thyristor | 2020 | IEEE | Article | China | 1 | 0 | 1 | 11.55 |
| [2] | 99   | Rodrigues et al. | 10.1109/TPEL.2020.3003358 | SSCBs, fault, power semiconductor devices breaker | 2021 | IEEE | Article | USA | 0 | 0 | 0 | 9.91 |
| [136] | 100  | Mehrotra et al. | 10.1109/ECCE44975.2020.9236347 | CB, SST, dc distribution, short circuit protection | 2020 | IEEE | Conf. | USA | 0 | 0 | 0 | - |
| [137] | 101  | Baradi & Xavier | 10.1109/CPRE.2018.8349819 | ATS, Boolean logic, task cycle | 2018 | IEEE | Conf. | USA | 0 | 0 | 0 | - |
| [138] | 102  | Qian et al.    | 10.1109/CICED.2014.6991653 | SSTs, custom power, sensitive load, voltage sag | 2014 | IEEE | Conf. | China | 0 | 0 | 0 | - |
| [139] | 103  | Maia Rodrigues et al. | 10.1109/COBEP/SPEC44138.2019.9065346 | SSTs, IGBT, UPS, passive standby | 2019 | IEEE | Conf. | Brazil | 0 | 0 | 0 | - |
| [140] | 104  | Cairoli et al. | 10.1109/ECCE.2019.8912246 | UPS, energy storage, medium voltage, power quality | 2019 | IEEE | Conf. | USA | 0 | 0 | 0 | - |
| [141] | 105  | Jiang & Yun    | 10.1088/1757-899X/533/1/012002 | OCP, STU, switching stations, GOOSE network | 2019 | IPP | Conf. | China | 0 | 0 | 0 | - |
| [142] | 106  | Hasanah et al. | 10.1109/IMCEC.2018.8469629 | ATS, LCD, contactor relay | 2018 | IEEE | Conf. | Indonesia | 0 | 0 | 0 | - |
| [143] | 107  | Makode & Joshi | 10.1109/ICCS45141.2019.9065408 | CB, relays, microcontroller, phase failure | 2019 | IEEE | Conf. | India | 0 | 0 | 0 | - |
| [144] | 108  | Choubey et al. | 10.1109/ICPEICES.2018.8897281 | IGBT, optocoupler, over-current, LV distribution, DER, microgrid, switches | 2018 | IEEE | Conf. | India | 0 | 0 | 0 | - |
| [145] | 109  | Gomes et al.   | 10.1007/978-3-319-96867-6_12 | CB, SST, DC distribution network, short circuit protection | 2014 | Springer | Book | Portugal | 0 | 0 | 0 | - |
| [136] | 110  | Mehrotra       | 10.1109/ECCE44975.2020.9236437 | CB, SST, DC distribution network, short circuit protection | 2020 | IEEE | Conf. | USA | 0 | 0 | 0 | - |
| [146] | 111  | Jose           | 10.1109/ICSSIT48917.2020.921472 | SCCB, short-circuit, IoT real-time monitoring | 2020 | IEEE | Conf. | India | 0 | 0 | 0 | - |
| [147] | 112  | Wang D.        | 10.1016/j.fusengdes.2020.111483 | SiC MOSFET, solid-state switch ECRH, snubber circuit | 2020 | Elsevier | Article | China | 0 | 0 | 0 | 1.692 |
| Ref. | Rank | Author’s Name  | Article DOI | Keywords | Year * | Publisher | Type * | Country | NC * | CPY * | FYC * | IF * |
|------|------|----------------|-------------|----------|--------|-----------|--------|---------|------|-------|-------|------|
| [148] | 113  | Wang et al.    | 10.1109/eGRID48402.2019.9092714 | DC microgrid, SCCB, bidirectional breaker | 2019   | IEEE      | Conf.  | China   | 0    | 0     | 0     | -    |
| [149] | 114  | Wang et al.    | 10.1109/ECCE.2019.8912780 | SCCB, SiC JFET, DC distribution system | 2019   | IEEE      | Conf.  | China   | 0    | 0     | 0     | -    |
| [150] | 115  | Komatsu       | 10.1109/INTLEC.2018.8612397 | CL, power MOSFET, IGBT, SiC MOSFET, OP | 2019   | IEEE      | Conf.  | Japan   | 0    | 0     | 0     | -    |
| [151] | 116  | Li et al.      | 10.1016/j.ijepes.2020.106550 | PSE, SCCB, Power electronic device | 2021   | Elsevier  | Article | China   | 0    | 0     | 0     | 3.588|
| [152] | 117  | Aaqib et al.   | 10.1109/ICECCE47252.2019.8940747 | SSTS, DC Systems, LVDC protection, bus bar | 2019   | IEEE      | Conf.  | Pakistan| 0    | 0     | 0     | -    |

Year * is the publication year, Type * is the type of publication, NC * is the number of citations, CPY * is the average citation per year, FYC * is the last 5-year citation, and IF * is the impact factor.
Table 2 summarizes the top ten most cited articles in the previous five years with detailed information including target, structure, validation, advantages, and limitations. A detailed technical comparative study is presented in Table 3 emphasizing topology, source, configuration, converter, control, method, frequency, power loss, type of load, fault detection time, and applications. The first article by Li et al. [36] is the most widely cited article over the last five years. Park & Candelaria [37] and Wang et al. [38] are the second and third most widely cited papers, respectively, over the last five years. It is noticed from Table 1; Table 2 that the popular keywords related to the SSCB switching are the fault clearance and fault protection (control method) compared to the general switching in the distribution system. This is due to the used of SSCB for fault protection (control method), which increases the reliability of power and the potential for survival. The high speed for SSCB switching can also reduce the stress on all the system components. This protection system is suitable for the distribution system.

Table 4 displays the distribution of published papers according to types of study based on the selected top-cited papers. There are four types of studies found in the survey. Experimental work, development, and performance assessment are the highest types of study among the published papers (44.17%). This approach is critical for the implementation of high performing system. The second highest type of study (34.17%) is based on problem formulation and simulation analysis which focuses on methods, approaches, and mathematical formulation. About 13.33% of articles focus on state-of-the-art technical overview which is based on general knowledge and the concept of switching studies while 8.33% of articles focus on reviews that explain topologies, control methods, strategies, and recommendations in solid states switching applications in detail. In general, the researchers have recently concentrated more on the operational theory, design requirements, and experimental findings which illustrate a unique market opportunity for solid-state switching.

Table 5 illustrates a more detailed knowledge of the subject related to research studies in the SSS field. This table describes the subject areas in which most papers were cited. The paper with the largest frequency (78%) is focused on a fault detection system. SCCBs implementation ranks second with 45.83%, followed by prototype testing with 24.17%. In the subject area of synchronous motors and power systems, a very small number of papers (less than 2%) was found. The topic of the fault has emerged as a major concern in the study. Many papers [36–38,42,43,50,51,60] discuss a fault detection or control system for SSS system. The proposed scheme’s objectives are to detect a system fault and then clear the faulted segment so that the system can continue to operate without being disconnected entirely. The trigger of the fault causes the machine to fail [37]. The fault can be easily cleared and restored power within the feeder by implementing switching. This is because the solid-state transfer switch (SSTS) role is a good solution to power quality issues. When a fault occurs, SSTS has a quick response time and can quickly reallocate resources. A quicker fault response time is often preferable to avoid damage [38]. Thus, it is essential to design fault safety on a SSS system to achieve fast fault clearance and quick system restarts. Some papers address the protection issue, the applicability of various control system strategies, and potential developments in protecting SSS systems from short circuits and other faults [36–38,42,43,45,50–52,60,61,63–70,72–74,78,80]. Such fault issues are likely to increase among researchers because of the need for a reliable and secure control system (fault protection system) that provides increased fault protection while decreasing risk and costs [42].
Table 2. Summary of top ten articles based on the highest citation in the past 5 years.

| Rank | Author’s Name | Ref. | Keywords | Year | Citation | Target | Structure/Configuration | Validation | Advantages | Limitations/Research Gaps |
|------|---------------|------|----------|------|----------|--------|-------------------------|------------|------------|-------------------------|
| 1    | Li et al.     | [36] | DC fault, MMC, fault clearance, system recovery | 2012 | 199      | - Develop a protection scheme to detect nonpermanent faults and execute automatic recovery in the modular multilevel converter (MMC) based—high-voltage direct current (HVDC) system. | - MMC is connected with single and double thyristor-switch submodules that are used to change the DC-link fault of an AC short circuit through MMC arms. | - Validation is carried out using PSCAD/EMTDC. | - Automatic and fast power transmission recovery is achieved. | - The proposed method has coordination issues relating to protection schemes among multiple HVDC ends. |
| 2    | Park & Candelaia | [37] | IGBT, OC, inverter, optocoupler | 2018 | 140      | - Detect and isolate the abnormal fault in low-voltage DC-bus microgrid systems | - A segment controller-based loop-type DC-bus-based microgrid system is designed. | - The solid-state bidirectional switches and snubber circuits are employed to construct a segment controller. | - Ability to detect faults on the bus despite amplitude of fault current or the feeding capacity of power supply. | - The proposed scheme has conduction loss in the solid-state CBs. |

- The scheme can be extended to a two-end MMC-HVDC system to achieve quick restart of the transmission system and fast clearance of faults. | - The fault current extinction time is 10 µs. | - Further exploration is required on fault-location methods and fault ride-through ability. |
| Rank | Author's Name | Ref. | Keywords | Year | Citation | Target | Structure/Configuration | Validation | Advantages | Limitations/Research Gaps |
|------|---------------|------|----------|------|----------|--------|------------------------|------------|------------|--------------------------|
| 3    | Wang et al.   | [38] | SiC, MOSFETs, SSCB, OCP | 2014 | 119      | • Detect and clear overcurrent faults in the SiC MOSFET-based converter.<br>• Two overcurrent protection approaches based on hard switching fault (HSF) and fault under load (FUL) conditions are introduced. | • A series-connected commercial gate driver IC and Si IGBT are used to design a solid-state circuit breaker (SSCB).<br>• A phase-leg configuration-based step-down converter is designed to examine the effectiveness of the proposed technique under various cases. | • A test board is developed with short-circuit control board, desaturation protection circuit, and power testing circuit, and SSCB. | • Improved design, cost-effective and excellent performance under decoupling capacitance, various fault types, and protection circuits.<br>• A short-circuit fault clearing time of 200 ns is obtained regardless of the temperature difference of SiC MOSFETs.<br>• The proposed design has limitations related to gate oxide reliability induced by poor interface quality.<br>• Further studies can be conducted under the negative influence such as overcurrent, lifetime, aging using the more mature Si-technology. |
| 4    | Emhemed et al. | [42] | LVDC, SSCBs, DS, multiple IEDs, protection | 2017 | 73       | • Build a fast-acting DC protection and safety scheme for low voltage direct current (LVDC) distribution systems | • The controllable solid-state circuit breakers along with multiple intelligent electronic devices (IEDs) are employed to identify the DC faults. | • The LabVIEW is used to execute the algorithm while experiments are performed to examine the DC faults at different conditions. | • A fast clearing DC fault time is achieved with less than 1 ms.<br>• Reduce the risk of fire hazard stress on the insulation's materials.<br>• Enable the use of equipment with lower ratings.<br>• Developing a reliable and safe protection scheme for complex AC-DC systems is challenging.<br>• A longer time is required to detect and clear DC faults.<br>• The sensitivity and selectivity issue of AC-DC converters need further attention due to small values of resistance and inductance in cables. |
Table 2. Cont.

| Rank | Author's Name | Ref. | Keywords | Year | Citation | Target | Structure/Configuration | Validation | Advantages | Limitations/Research Gaps |
|------|---------------|------|----------|------|----------|--------|-------------------------|------------|------------|--------------------------|
| 5    | Shen et al.   | [59] | GaN HEMT, SiC JFET, SSCB, WBG semi-conductors | 2015 | 58       | Propose a self-powered WBG SSCBs to detect current interruption during the short circuit failure of the DC system without requiring any external power supply. | The unidirectional SSCB is structured using SiC JFET, isolated DC–DC converter, blocking diode, two voltage sensing resistors, and a metal–oxide varistor. | Experimental tests are carried out using SiC JFET under DC voltage of 400 V and fault current of 125 A | • WBG switching devices are effective in terms of switching frequency, power efficiency, and operating temperature. • The turn-off fault current is very short, indicating 1 µs. • Further attention is needed to enhance the cost-effectiveness and reliability of WBG devices. |
| 6    | Shen et al.   | [50] | SSCBs, DC MG, current status | 2015 | 56       | Develop a short circuit protection scheme using a self-powered SSCB based on WBG transistor and isolated DC/DC converter | The bidirectional SSCB is configured using a current sensor, snubber, semiconductor static switch, signal processing unit, data communication unit, microcontroller, or DSP. | A prototype is designed using 1200V SiC JFET (UJN1205K from USCi). | • The new two-terminal SSCB can operate without requiring any extra wiring or external power supply. • A fast short-circuit fault clearing time within 0.8 µs is achieved under 400 V DC bus voltage at 180 A. • The lower loop impedance of DC system leads to a higher rate of increase in the fault current. • The efficiency of the proposed design can be examined under the mechanical and thermal stress related to cables and other circuit elements. • Further investigation is required to address against short circuits under low voltage distribution in microgrid applications. |
| Rank | Author’s Name        | Ref. | Keywords                                      | Year | Citation | Target                                                                 | Structure/Configuration                                                                 | Validation                                                                                       | Advantages                                                                                           | Limitations/Research Gaps                                                                 |
|------|----------------------|------|----------------------------------------------|------|----------|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| 7    | Qi et al. [90]       |      | DC, SSCBs, distribution, fault protection    | 2017 | 55       | Design an effective overcurrent protection scheme using Reverse Blocking IGCT (RB-IGCT) semiconductor for DC shipboard power systems. | The proposed circuit comprises HV low power supply, capacitor bank, air-core inductor, Two SSCBs. | Short circuit experimental tests are conducted using a DC capacitor bank, an adjustable air core inductor, and a low current power supply. | Enhanced design, low power loss, fast fault detection, and reaction time.                      | RB-IGCT exhibits low forward voltage blocking capability. Has a high gate triggering current as well as high latching and holding current. Has high Gate drive circuit losses. |
| 8    | Agostini et al. [61] |      | SSCB, IGCT, RB-IGCT, power switch            | 2015 | 44       | Construct a 1 MW bi-directional Reverse Blocking-IGCT (RB-IGCT) based DC SSCB to quickly identify the fault condition or high-level short circuit. | The bi-directional SSCB are integrated with Asymmetric (A)-IGCT, RB-IGCT, and Reverse Conducting (RC)-IGCT to improve the reliability, efficiency, and size-effectiveness. | The simulation and experiments illustrate that the proposed scheme is very effective in controlling the current capability with 6.8 kA against 1.6 kV, 400 K. | The scheme has very low on-state voltage drop and conduction loss. Has improved performance in terms of reliability, cost-effectiveness, and long lifetime. | IGCT has a clamp circuit that comprises clamp inductance and switching current, thus contributing additional losses during the switching operation. |
| 9    | Magnusson et al. [60] |      | DC breaker, MOV, OVP, SSCB, snubber circuit  | 2014 | 42       | Build an overvoltage protection strategy based on metal oxide varistor (MOV) to divide the voltage limitations into components and reduce the stress on power electronics switches. | The proposed scheme is designed using DC source, MOV, IGBT, and RC snubber circuits. | The performance of the proposed method is tested using experimental tests comprising resistance and inductance, MOV, and IGBT. | The simulations and experiment results demonstrate the suitability of the prospered design, consuming only 1–2% of the system energy if the voltage ratio between two varistors is optimized. | MOV lacks in detecting current surges during the startup of the device and can burn out if the powder flow stops. The performance of the proposed design can be further tested using large-scale experiments. |
Table 2. Cont.

| Rank | Author’s Name | Ref. | Keywords | Year | Citation | Target | Structure/Configuration | Validation | Advantages | Limitations/Research Gaps |
|------|---------------|------|----------|------|----------|--------|-------------------------|------------|------------|--------------------------|
| 10   | Cuzner & Singh | [51] | DC distribution, SPS, DC fault protection | 2017 | 39       | • Propose a short circuit protection method for medium-voltage DC (MVDC) integrated power systems to enhance reliability, efficacy, and cost-effectiveness. • The system architecture consists of power generation rectifier modules, power converter modules, pulsed power modules, and propulsion power modules. • The proposed scheme is validated on a shipboard distribution system with a capacity ranging between 4 k Vdc and 30 k Vdc • This topology has proven efficient with regard to survivability, efficiency, reliability of power, and cost-effectiveness. • The Solid-State protective device has a potential voltage drop in resistive loads. • Suffers from higher transient reverse recovery time because of the appearance of the diode. |
| Ref. | Topology       | Source                        | Configuration                                      | Converter                          | Control                                           | Method                  | Load       | Power Loss | Fault Detection Time | Applications                        |
|------|----------------|-------------------------------|----------------------------------------------------|------------------------------------|---------------------------------------------------|-------------------------|------------|------------|-------------------|--------------------------------------|
| [36] | Three-phase    | 150 kV                        | Thyristor-based transfer switches                  | Modular multi-level converter (MMC) | Voltage detection scheme and gating mechanism       | IGCT                    | Resistive  | Inductive  | High              | HVDC                                |
| [37] | Three-phase    | 1.5 kV                        | Solid-state bidirectional switches                 | Typical power-electronics converters| One master controller, two slave controllers       | IGBT                    | Snubber    | Circuit    | 10 µs             | Low-voltage DC-bus-based microgrid system |
| [38] | Three-phase    | 1200 V                        | Solid-state distribution switches                  | SiC MOSFET based step-down converter| Central logic control and gating mechanism         | IGBT                    | Inductive  | Low        | 200 ns            | DC-bus-based microgrid system          |
| [42] | Three-phase    | 320 kV                        | Solid-state distribution switches                  | 2 level AC-DC converter            | Intelligent electronic devices (IEDs)               | IGBT                    | Inductive  | Low        | Less than 1 ms.    | Industrial                          |
| [59] | Single-phase   | 1200 V                        | Solid-state distribution switches                  | Isolated DC/DC converter          | Voltage source converter (VSC)                     | SiC JFET                | Resistive  | Low        | 1 µs              | DC power distribution line            |
| [50] | Single-phase   | 1200 V                        | Semiconductor static switches                     | Isolated DC/DC converter          | PWM control                                        | SiC JFET                | Resistive  | Low        | 0.8 µs            | Transmission line                    |
| [90] | Single-phase   | 1 kV                          | Thyristor-based transfer switches                  | Bidirectional isolated DC/DC converter| Intelligent microcontroller system                | IGCT                    | Inductive  | Medium     | 180 µs            | DC grid, marine, battery protection Distribution line |
| [61] | Single-phase   | 2.5 kV                        | Solid-state bidirectional switches                | Bidirectional DC/DC converter     | Voltage detection scheme and gating mechanism       | Bi-directional Reverse Blocking-IGCT (RB-IGCT)| Resistive  | Medium     | Medium            | Distribution line                    |
| [60] | Single-phase   | 12 V                          | Solid-state distribution switches                  | Typical power-electronics converters| Metal oxide varistors (MOVs)                      | IGBT                    | Resistive  | Inductive  | 0.7 µs            | Transmission line                    |
| [51] | Single-phase   | 10 kV                         | Thyristor-based transfer switches                  | Non-isolated AC to DC converter   | Metal oxide varistors (MOVs)                       | Silicon super gate turn-off thyristors (SGTOs)| Resistive  | Low        | High              | Navy shipboard applications           |
Table 4. Distribution of Papers According to Types of Study.

| Types of Study                        | Frequency | Range of Years | Range of Citation |
|---------------------------------------|-----------|----------------|-------------------|
| Experimental work, development, and performance assessment | 53        | 2012–2021      | 0–310             |
| Problem formulation and simulation analysis | 41        | 2012–2020      | 0–13              |
| State of the art technical overview   | 16        | 2011–2019      | 0–75              |
| Reviews                               | 10        | 2014–2021      | 0–73              |

Table 5. Distribution of Papers in Different Subject Areas.

| Subject Area                              | Frequency | Citation Range | Frequency Weight (%) |
|-------------------------------------------|-----------|----------------|----------------------|
| Fault detection scheme                    | 94        | 0–310          | 78                   |
| SCCBs implementation                      | 55        | 0–245          | 45.83                |
| Prototype testing                         | 29        | 0–192          | 24.17                |
| Microgrid application                     | 19        | 0–192          | 15.83                |
| Power system overview                     | 19        | 0–75           | 15.83                |
| SCCB development system                    | 14        | 0–310          | 11.67                |
| SiC development for switching             | 11        | 0–28           | 9.17                 |
| Hybrid switches implementation            | 10        | 0–61           | 8.33                 |
| Power-sharing                             | 7         | 0–192          | 5.83                 |
| HVDC system                               | 6         | 1–17           | 5.00                 |
| DC shipboard power system                 | 6         | 1–13           | 5.00                 |
| Semiconductor device review               | 6         | 0–12           | 5.00                 |
| MVDC system                               | 5         | 0–28           | 4.17                 |
| VSC approach                              | 5         | 17–25          | 4.17                 |
| SCCB based design and optimization        | 4         | 1–2            | 3.33                 |
| Synchronous motors and power system       | 2         | 13–15          | 1.67                 |

SSCBs based on silicon IGBTs or IGCTs [41,46,58,64,73,77,83,84,91,101,126] and thyristors [41,46,58,64,73,77,83,91,101,126], as main static switches were reported. SCCB implementation is the second most frequently studied topic (see Table 4). A single SCCB unit has a current rating of several kA and power ratings up to tens of MW. The circuit breakers are connected in the system to achieve a high blocking voltage that can withstand any transient recovery voltage after a fast-current interruption [73]. The short circuit is normally detected by a current sensor. A control unit then ultimately processes the overcurrent signal to decide whether the switch is needed to be turned OFF. Therefore, many researchers recommended that the enhancement of the overall SCCB performance and speed to minimize the conducting losses in the device [73]. The major focus of most of the papers is to ensure the short circuit isolation and recovery of power transforming that are already in the system (functional isolation) or adding additional breakers as a part of the protective equipment. In addition, the papers outline the implementation of a novel control system (protection scheme) to shield the systems from faults evaluation [36,38,41,44,46,51,52,58,61,64,73,77,83,92,100,114]. SCCB, fault current assessment, and short-circuit control board are part of the main power testing circuit. SCCB is a universal protection framework that is used to defend against system failures. The SCCB can quickly react to a short circuit and fault current immediately using the main power testing circuit.

Extensive research is also conducted by researchers on the prototype. The prototype was built and tested for verification of the concept [64]. Thus, these experimental findings confirm the validity and effectiveness of the prototype solution [74]. Researchers use various types of prototypes to study the switching in the solid state field. Miao et al. [52] built unidirectional, bidirectional, and extended-voltage SCCB prototypes. The SCCBs are tested under various short-circuit conditions. It is shown experimentally that SCCB can break over to 200 A-currents in less than 0.8 µs at a 400 V bus voltage of interruption [52]. Next, the prototype with a capacity of 700–600 V is used to conduct experiments in which
10 kW of power is applied to the converter [64]. A test was performed on an IGBT SC using a 10 kW prototype and experimental results demonstrated the benefits and feasibility of the proposed fault-tolerant of SRC. An NDCT prototype built by [74] exhibits improved reliability, as well as added durability and voltage control. The results were promising in improving switching efficiency and reducing system cost. The implementation and verification of the proposed NDCT are presented in [74]. A fault isolation device (FID) prototype was built that prevented the short-circuit current from reaching its maximum value. A simplified prototype of SSCB as a fault current limiter (FCL) was proposed in [78]. A new 1200 V SiC MOSFET variant (iBreaker prototype) was proposed by [109]. The iBreaker technology can fit into a large variety of circuit applications using simple programming without complicated hardware configuration.

The researchers have discovered that model development and prototype validation methods are important for future studies. The validation system should be developed alongside a control system and an alternative system verification approach to strengthen model validation of the overall system. Moreover, it is crucial to upgrade the capabilities of the switching research methods and marketing limits as well.

From Tables 1, 3 and 4, it can be concluded that the researchers are more focused on developing SSS based on subject fault detection scheme (control system), solid-state circuit breakers (SSCBs) implementation, and prototype testing. The other subjects mentioned are also important to advance the research in the field of solid-state switching, as they can serve as ideas to understand and update the progress works of the researchers.

3.2. Analysis of Keywords and Topics

The co-occurrence map of the keywords for 120 papers searches in the Scopus database between 2010 and 2021 is depicted in Figure 4. The co-occurrence map is collated using VOS viewer, whereas the outcomes are collected from the Scopus database. This mapping approach using VOS viewer software is more advanced than the data counting technique because it is more sophisticated and allows for more interpretation [153–155]. The map covers the various items and links that refer to various keywords and the connection line. The stronger link points to the large frequencies in the item cluster. The network visualization map of the keywords represents different colors (for example: red, yellow, blue, green, and purple). The item’s colors are defined by the cluster in which the item is gained. For example, in the co-occurrence map of keywords in Figure 4, the green clusters have the strongest relationship connecting to insulated gate bipolar transistor (IGBT), silicon carbide (SiC), DC circuit braker, MOSFET, WBG semiconductor, power semiconductor, DC microgrid, electromechanical devices, etc. The second is the red cluster which represents the solid state transformer, failure analysis, control system, high voltage direct current (HVDC), etc. The purple clusters represent the strongest relationship related to the solid state circuit breaker (SSCB), overvoltage protection, short circuit, DC distribution system, etc. The blue clusters are solid state switch, mechanical switch, snubber circuit, thyristor, etc. Finally, the yellow clusters are power control, controllers, DC fault protection, etc.
Figure 4. Co-occurrence map of keywords for 120 papers on solid state switching.

Figure 5a shows the top-15 most used keywords in the last ten years. It is observed that the keyword SCCB is the most commonly used. The other notable keywords are SiC, IGBT, DC Circuit breaker, short circuit, DC fault protection, fault protection, SiC JFET, MOSFET, HVDC, OCP, WBG semiconductor, thyristor, power semiconductor, and DC microgrid. Additionally, Table 1 represents the relevant keywords over the entire paper. The findings in Figure 5a are consistent with Figure 4. It is worth recognizing the following keywords and outcomes:

- Today’s SCCB-system research requirements are more important than previous mechanical switches due to their suitability in DC systems and higher operating speed [38].
- Instead of using a mechanical switch, the researchers focused on using SCCB for high-efficiency switching applications. SCCBs are capable of achieving optimal quick switching times and power transfer to sensitive loads [12]. Several keywords, such as DC fault protection, fault protection for HVDC are suggested as alternatives to the SCCB scope analysis.
- The advent of WBG-type semiconductors, such as silicon carbide, as demonstrated by Shen, Z.J. et al. [59], have recently been proven to be particularly advantageous in the development of switching devices. WBG devices are used as drop-in silicon to enhance the power converter, which has been redesigned over decades. It provides a compelling growth opportunity in the future.
Figure 5. Common (a) keywords analysis and (b) topics for 120 papers.

The represented topics indicate what areas of study the paper explores. These necessities are further studied into these issues under various uses and applications that can affect the SSS sector. The study scrutinizes the top 15 most-cited papers from 120 papers to identify the most topic discussed in the SSS field. The findings shown in Figure 5b reveal that there is a high interest in the converter, power-sharing, microgrid, and circuit breakers. Some topics that attract the researcher’s attention including HVDC system, offshore wind, MOSFET, fault currents, power module (STS), JFET, IGBT, thyristor, distributed generation, OCP, and transformer. However, converter, power-sharing, microgrid, and circuit breakers are the hottest topics among them.
3.3. Document Type Evaluation

The number of papers depending on the type of document referenced in the Scopus database is shown in Figure 1. The Scopus database is not restricted to reviews, book chapters, conference papers, and conference reviews. However, Figure 1 shows documents that only include articles, conference proceedings, reviews, and books chapters for 120 papers. Figure 1 clearly reveals that the maximum contribution of documents is classified as conference papers and article journals with 68 (57%) and 49 (41%), respectively. It was followed by the review and a book with 2 (1.7%) and 1 (0.8%) paper reviews, respectively. All papers are published in English and the category of Engineering.

The study contributions from Table 1 related to the type of documents have been compiled. This category only focuses on contributions that lead to the journals which have received about 49 documents (41%) out of the total 120 documents as shown in Figure 6a. Figure 6a shows the lists of journal contributions each year (2010–2021) received in the Scopus database. According to Figure 6a, it presents that the journal of IEEE Transactions on Power Electronics has achieved the highest number of documents (12 publications). The second-largest journal is dominated by IEEE Transactions on Power Delivery with 6 publications. The third highest journal are IEEE Transactions on Industrial Electronics, IEEE Journal of Emerging and Selected Topics in Power Electronics, and International Journal of Electrical Power and Energy systems with 4 publications for each. It is followed by the Journal of Electronics with 3 publications, IEEE Transactions on Industry Applications, Energies, Applied Sciences with 2 publications for each, and Journal of IEEE Transactions on Electron Devices, Turkish Journal of Electrical Engineering and Computer, IET Electric Power Applications, Electrical Engineering, Electric Power Systems Research, European Transactions on Electrical Power, IET Power Electronics, IEEE Transactions on Components, Packaging and Manufacturing Technology, IEEE Transactions on Applied Superconductivity, Electric Power Systems Research, ARPN Journal of Engineering and Applied Sciences, International Review of Electrical Engineering, Journal of Electrical Engineering and Technology, IEEE Transactions on Transportation Electrification and Fusion Engineering and Design with 1 publication for each.

Through the journals, the impact factors can be analyzed. The quality of each journal based on impact factors can be seen in Table 1 and Figure 6b. International Journal of Electrical Power and Energy Systems, IEEE Transactions on Industrial Electronics, IEEE Transactions on Power Electronics, IEEE Journal of Emerging and Selected Topics on Power Electronics, IEEE Transactions on Industry Applications, and IEEE Transactions on Transportation Electrification have higher impact factor values in the range of 3.72 to 11.55 that indicate a higher quality content of their articles. Next, the review of the journal according to the publisher is examined in Figure 6c. As shown in Figure 6c, IEEE (64%) is recorded as the highest publisher amongst publications, followed by Elsevier (12%) and MDPI AG (10%). The remaining publishers involved in the SSS are Springer (4%), TUBITAK (2%), IET Electric Power Application (2%), Wiley Online Library (2%), Asian Research Publishing Network (2%), and Korean Institute of Electrical Engineers (2%).
3.4. Document Authorship Evaluation

The authors/writers are the backbones of every paper [26]. Initially, the publication is contributed by 537 inspired authors. As shown in Table 6, this study focuses on the most productive writers who contribute to the publication. From Table 5, the number of authors has risen steadily from 2011 to 2017, but the number declined by 2021. The average number...
of authors per paper (AU/TP) is 4.39. Among all the papers, 4 (3.33%) are single authors (SA) whereas 116 (96.7%) are collaborative (CA) authors.

Table 6. Characteristics by Year of Publication Outputs from 2010 To 2021.

| PY | TP | AU | AU/TP | SA  | CA  |
|----|----|----|-------|-----|-----|
| 2010 | 0  | 0  | 0     | 0   | 0   |
| 2011 | 3  | 13 | 4.33  | 0   | 3   |
| 2012 | 6  | 26 | 4.33  | 0   | 6   |
| 2013 | 5  | 16 | 3.20  | 1   | 4   |
| 2014 | 8  | 33 | 4.13  | 0   | 8   |
| 2015 | 11 | 44 | 4.00  | 0   | 11  |
| 2016 | 15 | 65 | 4.33  | 1   | 14  |
| 2017 | 17 | 103| 6.06  | 1   | 16  |
| 2018 | 20 | 90 | 4.50  | 0   | 20  |
| 2019 | 22 | 88 | 4.00  | 1   | 21  |
| 2020 | 11 | 49 | 4.45  | 0   | 11  |
| 2021 | 2  | 10 | 5.00  | 0   | 2   |
| Total | 120 | 537 | 48.33 | 4  | 116 |
| Average | | | 4.39 | | |

PY: published years, TP: total papers, AU: author number, AU/TP: author number per papers, SA: single author, and CA: collaborative authors.

The most prominent authors are explored in-depth. This approach is discovered by finding information-based one by one author at the top list for citation ranking. The study considers the 10 most prominent authors with a minimum article of 3 publications, as depicted in Table 6. The author rank is not dependent on citations but rather on the cumulative number of publications by such authors. In Table 6, Shen from the Illinois Institute of Technology, USA is the most active author in terms of citations and number of publications. Shen recorded 11 publications, 212 total citations, and received 39 $h$-index. Antoniazzi and Cairoli appear in the second place and have written 6 papers and achieved 125 and 51 citations, respectively. Antoniazzi from the Corporate Research Center, ABB Inc., USA, and Cairoli from the Research Center, ABB Inc., Raleigh, NC, USA. The $h$-index for Antoniazzi and Cairoli was 58 and 131, respectively. Additionally, Miao and Bhattacharya are in the third author place with 4 papers publication and total citations of 179 and 64, respectively. The $h$-index for Miao and Bhattacharya was 8 and 9, respectively. Song, Liu, Wang, Roshandeh, and Shuai have 3 papers published in the fourth author position. Their approximate number of citations are 356, 356, 155, 104, and 82, respectively. Their $h$-index, according to Table 6 was 49, 18, 43, 7, and 18, respectively. It is noticed that despite being in fourth position, authors Song and Liu have the highest CPP with a value of 118.67. Both authors, Song and Liu earned the highest citation article. Wang, Miao, and Roshandeh had CPP values of 51.67, 44.75, and 34.67, respectively. At present, authors Song from Tsinghua University, China and Bhattacharya from North Carolina State University, USA obtained the highest $h$-index; 49. That is followed by authors Wang (University of Tennessee, USA), Shen (Illinois Institute of Technology, USA), Liu (Tsinghua University, China), and Shuai (Illinois Institute of Technology, USA) with the $h$-index values of 43, 39, 18, and 18, respectively.

From Table 6, it can be inferred those prolific authors have varied approaches. Shen’s articles are almost entirely about the growing DC power systems for solid-state circuit breakers (SSCBs) in wide bandgap (WBG) semiconductors application. He also wrote a review article [50] on the DC SSCBs. His new idea discussed WBG self-powered SCB that used self-induced gap faults to turn and keep the switch closed. Additionally, new SSCB prototypes are constructed. Current and future trends to defend against shorts circuits and faults of microgrids systems were also presented. The author with the most citations and an $h$-index of 49, Bhattacharya published an article on the implementation of three different configurations of DC SCCB for protection in HVDC transmission systems. He proposed a hybrid fault current limiter in combination with the reduced time constant
of the inductor discharge to avoid DC fault. This results in a significant decrease in the overall multi-terminal VSC system’s cost [44]. Another author, Song with an h-index of 49 has published an article focusing on the modular multilevel converter (MMC) integrated with a DC circuit breaker modular multilevel converter (IDCB-MMC) responsible for a cost-effective DC isolation with a DC fault clearance module. Using the PSCAD software, the design parameters of the IDMC were proposed, where the IGBTs and capacitors were implemented in the power components [70]. Song also suggests an enhanced DC transformer (NDCT) based on the switched capacitor with reduced switches for the integration of low-voltage DC energy storage systems and medium-voltage DC power distribution grids in another article [74]. Additionally, topology, multiple phase shift, current, and voltage measurements, and the control technique of commutation and modulation are also been suggested and considered. NDCT prototype is designed to evaluate the performance of the proposed solution. Another author, Antoniazzi focused on the used SSCBs for DC shipboard distribution systems in the design of protection systems. He formulated the equations to design the SSCBs and the protected DC system in his work. An optimized SSCB-based DC protection strikes a balance between sufficient reliability, fast speed, low cost, and overall system efficiency [90]. For another article [43], Antoniazzi presents the design guidelines for a solid state circuit breaker, and MOV design equations to create a precise current interruption for high power density DC shipboard. He noted that the RB-IGCT system provides fast current interruption and high performance. The computer simulations and tests have been used to verify the proposed protection system.

In addition, as shown in Table 7, the most favorable authors are from the USA. These authors are from four different universities or institutions: Illinois Institute of Technology, Corporate Research Center, ABB Inc., North Carolina State University, and the University of Tennessee. China ranks second in producing favorable authors. These China authors are from Tsinghua University. English is the native language in the writers’ country of origin, and reviewers are English speakers.

Table 7. Top Ten Lists of Most Influential Authors.

| No | Author   | TP | TC   | CPP  | h-Index | University/Institute | Country |
|----|----------|----|------|------|---------|----------------------|---------|
| 1  | Shen     | 11 | 212  | 19.27| 39      | Illinois Institute of Technology | USA     |
| 2  | Antoniazzi| 6  | 125  | 20.83| 8       | Corporate Research Center, ABB Inc. | USA     |
| 3  | Cairoli   | 6  | 51   | 8.50 | 13      | Research Center, ABB Inc., Raleigh, NC | USA     |
| 4  | Miao      | 4  | 179  | 44.75| 8       | Illinois Institute of Technology | USA     |
| 5  | Bhattacharya| 4 | 64   | 16.00| 49      | North Carolina State University | USA     |
| 6  | Song      | 3  | 356  | 118.67| 49   | Tsinghua University | China   |
| 7  | Liu       | 3  | 356  | 118.67| 18   | Tsinghua University | China   |
| 8  | Wang      | 3  | 155  | 51.67 | 43    | University of Tennessee | USA     |
| 9  | Roshandeh | 3  | 104  | 34.67| 7       | Illinois Institute of Technology | USA     |
| 10 | Shuai     | 3  | 82   | 27.33| 18      | Illinois Institute of Technology | USA     |

Next, the study presents the top ten lists of prominent universities/institutions/companies based on compiling the lists from Table 1, as denoted in Table 8. Other performance data including country, TP, TC, and CPP are also mentioned. The research is contributed by 81 prestigious universities, organizations, and companies from all around the world which produced over 120 publications in the SSS field. To determine the top organizations producing the most papers, this research only considered those listed in the top ten lists. The Illinois Institute of Technology and Research Center ABB Inc. are the most productive organizations that published a total of 8 publications. Both institutes from the USA have received 195 and 107 citations, respectively. The rest top five lists for institutions are North Carolina State University, USA (7 papers), Tsinghua University, China (4 papers), University of Wisconsin, USA (3 papers), Xi’an Jiaotong University, China (3 papers), National Institute of Technology, Japan (3 papers), Miguel Hernández University of Elche, Spain (3 papers), University of Tennessee, USA (2 papers), and Wuhan University, China.
(2 papers). The TC values of all the institutions listed on the top five lists are 79, 363, 74, 31, 12, 8, 173, and 39, respectively. The highest CPP is presented by Tsinghua University from China with a value of 90.75. The next high CPP is followed by University of Tennessee from the USA, University of Wisconsin from the USA, Illinois Institute of Technology from the USA, Wuhan University from China, National Institute of Technology from Japan and Miguel Hernández University of Elche from Spain with the values of 86.5, 24.67, 24.38, 19.50, 13.83, 11.29, 10.33, 4.00, and 2.67, respectively. Based on the \( h \)-index analysis of the universities, North Carolina State University from the USA has the best position with the \( h \)-index value of 60.4. Both the University of Tennessee from the USA and Tsinghua University from China achieved the second and third positions with \( h \)-index values of 60.36 and 57.67, respectively. The \( h \)-index is very significant to represent a high level of a university’s success in the academic sector.

Table 8. Top ten list of influential universities/institutions/companies for publication.

| No. | University/Institutions/Companies            | Country      | TP | TC    | CPP  | h-Index |
|-----|---------------------------------------------|--------------|----|-------|------|---------|
| 1   | Illinois Institute of Technology           | USA          | 8  | 195   | 24.38| 45.50   |
| 2   | Research Center ABB Inc. Raleigh, NC        | USA          | 8  | 107   | 13.38| -       |
| 3   | North Carolina State University             | USA          | 7  | 79    | 11.29| 60.45   |
| 4   | Tsinghua University                         | China        | 4  | 363   | 90.75| 57.67   |
| 5   | University of Wisconsin                     | USA          | 3  | 74    | 24.67| -       |
| 6   | Xi'an Jiaotong University                   | China        | 3  | 31    | 10.33| 57.00   |
| 7   | National Institute of Technology            | Japan        | 3  | 12    | 4.00 | 48.00   |
| 8   | Miguel Hernández University of Elche        | Spain        | 3  | 8     | 2.67 | -       |
| 9   | University of Tennessee                     | USA          | 2  | 173   | 86.5 | 60.36   |
| 10  | Wuhan University                            | China        | 2  | 39    | 19.50| 44.50   |

To get a wider view, the publications at the top ten country level have been analyzed. Table 1 identifies 27 different countries that contributed to the SSS papers. Table 9 provides the productive countries that dominate the paper’s publishing (top ten countries). The USA produces the most papers and it is the most productive country. The USA contributes the highest of 36 TP with 882 of TC. China is the second productive country in which it contributed 28 TP with 534 of TC. It is interesting to note that Japan, Spain, India, Norway, United Kingdom, Switzerland, Russia, and Brazil are the top 10 countries to contribute in the papers with 6, 6, 5, 5, 4, 4, 3, and 3, respectively. In terms of TC, Japan, Spain, India, Norway, United Kingdom, Switzerland, Russia, and Brazil record 20, 43, 6, 80, 90, 54, 31, and 7, respectively. Additionally, the USA has the highest CPP of 24.50. The other countries (see in Table 1) from around the world have contributed to the publication of the solid-state switching paper. The outcome of the study clearly shows that the USA and China are leading the SSS research in the research community.

Table 9. Productive Country for Publication.

| R  | Country | TP | TC  | CPP  |
|----|---------|----|-----|------|
| 1  | USA     | 36 | 882 | 24.50|
| 2  | China   | 28 | 534 | 19.07|
| 3  | Japan   | 6  | 20  | 3.33 |
| 4  | Spain   | 6  | 43  | 7.17 |
| 5  | India   | 5  | 6   | 1.20 |
| 6  | Norway  | 5  | 80  | 16.00|
| 7  | UK      | 4  | 90  | 22.50|
| 8  | Switzerland | 4 | 54  | 13.50|
| 9  | Russia  | 3  | 31  | 10.33|
| 10 | Brazil  | 3  | 7   | 2.33 |
To explore the result attribute in Table 9, the map of the top ten countries that dominate the publication is shown in Figure 7. The map clearly shows the ten countries’ involvement in carrying out research. The different color signifies different countries: USA, China, Japan, Spain, India, Norway, UK, Switzerland, Russia, and Brazil.

According to Table 1 and Figure 7, the USA has the largest number of papers (36 papers). Considering the outcome of the United States (USA), the USA is a successful nation because it has highly active top-level universities (based on achievement in h-index) such as North Carolina State University, University of Tennessee, and Illinois Institute of Technology. The existence of a broad range of corporate research centers (ABB Inc. Raleigh) and the majority of active authors from the USA are also responsible for research as well as the attributes of the number of papers. This proof is shown in Tables 6 and 7. Additionally, a global research and development (R&D) area has arisen in the USA [154]. Normally, international corporate R&D will serve to promote scientific publications [155]. The highest number of papers contributions is from China (28 papers). This is possibly due to the economy’s growth in China. However, small numbers of the papers are from Japan, Spain, India, Norway, UK, Switzerland, Russia, and Brazil, perhaps these countries have poorer R&D teams compared to the USA. Both the USA and China are the countries with the highest number of papers in the SSS field.

4. Conclusions and Future Directions

Recently, SSS has undergone a rise in interest due to replacing mechanical switches. This research investigated the publication evolution of the SSS field using bibliometric methods. A total of six keywords were used and applied to the SSS field related to the solid state breaker, solid state transfer switch, static transfer switch, automatic transfer switch, automatic protection switch, and solid state protection switch. The articles were screened to the “application”, “control” and “protection switch” to define the research gap and potential developments for the applicable research scope. Ever since these articles started being published in 1922, 1963, 1965, 1947, 1948, and 1958 for every keyword, respectively, these articles have been concentrating up to date (2010 to 2021) with the category of “engineering” and are written in “English” only. The bibliometric analysis had been performed by searching in the Scopus database. Several bibliometric criteria have been discussed, including the total number of publications and citations, analysis of keywords, analysis of topics, evaluation of document type, and authorship evaluation (based on author, author’s university and country, author’s h-index, and university’s h-index list). The data presentations involved the performance analysis and VOS software’s data. This is
the first time bibliometric methods are applied to solid state switching. Bibliometrics is an important way to complete a profile for research analysis.

A rapid increase in the number of published papers occurred from 2010 to 2019, but the trend went down the next year. The anticipated growth is expected to put the industry into the mainstream. The pattern was significantly reduced up to 2020. But it can be changed for the next year with further growth. The article by Li [36] had 310 citations. Park & Candelaria [37] and Wang [38] outperformed the two top three cited reports in SSS with a number of citations of 192 and 415, respectively. IEEE publisher that concentrates on type subjects obtained the largest number of publications. Most papers have been published in “IEEE Transactions on Power Electronics”, “IEEE Transactions on Power Delivery”, “IEEE Journal of Emerging and Selected Topics in Power Electronics” and “International Journal of Electrical Power and Energy Systems”. The focused analysis with the high paper citation will help to explore the discipline of SSS and its relationship with the industry’s allied disciplines. The highly cited papers have highlighted areas of strength, analysis, and future directions. It can enrich the researcher and the academic world by helping them better understand the importance and achievements of the discipline.

Analysis of the keywords relevant to the research studies demonstrates the system’s real efficiency. Studies show interesting keywords with a special focus on SSCB, DC fault protection, and IGBT. The hottest topics that attract the researchers’ interest are converter, power-sharing, microgrid, and circuit breakers in recent last five years. These topics highlighted research directions in SSS focusing on research directions for the growing penetration of renewable energy resources, such as wind turbines and photovoltaic systems [37] It is also a good step for introducing renewable energy sources in the future while improving the operational, economic, performance, efficiency, energy-saving, and power quality [37,42].

The research also offers a summary of the authorship evaluation to analyze the work of the most productive and influential authors, universities, and countries. There are 560 authors contributing to the publications. Shen is the most active author who has published 11 papers and received 212 citations. Shen is the author of the Illinois Institute of Technology, USA. The highest h-index: 49, was attained by the author Song from Tsinghua University, China and Bhattacharya from North Carolina State University. Collaboration among researchers in the field of SSS is widespread in which 116 (96.7%) from collaborative authors. The Illinois Institute of Technology and Research Center ABB Inc. from the USA are the most productive organizations that published a high amount of paper publications. The USA is a globally successful nation in the SSS field because it has highly active top-level universities, corporate research centers, active authors, and advanced global Research and development (R&D). China is the second highest publication due to its rapid growth in the economy and industry sectors. Collaboration among researchers from various experienced authors, universities, and countries in the SSS field brought benefits such as an increase in productivity research, the use of costly equipment, the use of particular skills or information, and discoveries. The USA and China serve as a model to improve and lead the research in solid state switching, as well as the research in next-generation technologies that can open up and expand with substantial contributions from around the world.

The main goals of these articles are to critically review and comprehend the characteristics of frequently cited publications, as well as to provide insight into possible directions and developments in the field of research. This paper highlights many issues and possible solutions on system failure by fault, control method, SSS implementation design, and system protection. Based on the analysis and findings from the current literature, the main conclusions can be drawn about SSS which are explained below.

• The fault problem becomes the main issue in the system, which can lead to system failure [36]. Before the fault is cleared, the system has to endure considerable voltage surges. Voltage surges must be handled by the system to clear the fault. It takes time for the mechanical switches to clear the fault in the system. In the SSS system, solid state circuit breakers (SSCBs) can be a promising choice. Solid state circuit
breakers provide no reliability or lifetime issues as opposed to electromechanical circuit breakers. The study identified that SSS demonstrated the potential of power semiconductor technology used in distribution systems. SSS is receiving attention due to its quick response time and excellent operational advantages over conventional mechanical circuit breakers. The use of semiconductors in switching devices also can be developed in application areas such as high-voltage, high-frequency, and high-power applications [59]. Thus, solid state switch will greatly impact the industry moving forward.

- The papers evaluate the control method in the SSS area to protect design conditions, identify faults, and protect the system [43]. Hence, it is important to offer careful considerations to systems control in wide distributed DC networks. Conventional module circuit breakers (MCCBs) have a slow response time and are prone to damage the equipment in the DC system. To solve this issue, making use of solid-state circuit breaker (SSCB) based DC safety allows for much faster downstream speed (1 millisecond up to a microsecond range). For SCCB, insulated gate bipolar transistors and integrated gate-commutated thyristor are widely used as main static switches in SSCBs [92]. Instead of using an electromechanical circuit breaker, a solid state type of power switching circuit is being developed as a new power control system for DC power networks [58,103]. An article from [73] addresses the lack of control system for DC systems due to faults arise quickly and lower impedance in DC systems. For conventional AC systems, faults in VDC evolve ten times faster and need a faster response. The existing solid state circuit breaker switches are suggested to address this problem.

- The static transfer switch is composed of power semiconductor devices. In contrast to mechanical switches, it provides better characteristics such as high number in switching operation, lower arc forming, fast switching, and no audible ticking sounds [64,141]. Furthermore, an article [83] implies that thyristor has low forward conduction and it is not suitable for high-power applications. The high-power needs a considerable amount of localized heat dissipation in the semiconductor. This issue can be solved by improving the design of GTO technology, noticeably the integrated gate-commutated thyristor (IGCT). This significantly increases the dynamic efficiency of the GTO, increasing the overall efficiency of the system. Furthermore, the articles [76,91] imply that mechanical circuit breakers (MCB) do not follow the specifications in voltage source converter-based multi-terminal DC (VSC-MTDC) due to natural current zero-crossing and slow response. This can be solved by designation in the solid-state circuit breakers, such as IGBT, IEGT, and IGCT. The reliability offered by SSCB is ultrafast. Finally, HDCCB, which is MCB and SSCB, has low switching losses and fast switching can be regarded as a promising option for fixing DC faults.

- System protection is the most important for solid state switching, as it applies to all delivery modes [73]. The fault current distribution system is rapidly growing, so faster protection is required [43]. Therefore, SSS needs a protection scheme to avoid equipment failure due to faults [92]. For a reliable switching application, the protection fault identification and protection coordination programs and circuit breakers must detect faults to protect against abnormal conditions and initiate protection [43,56,66,137,138]. SSCBs should be examined in distribution networks to ensure that the SSS mechanism is safe. A preliminary test has been conducted on various lab prototypes and products with respect to fault identification and protection response [54–57,75,88,91,109,116,133].

Our analysis of the 120 cited papers in SSS might be worthwhile for a variety of reasons. The implications of this survey are highlighted below.

- A bibliometric analysis would provide researchers with a great deal of knowledge about which journals in the SSS areas are likely to publish research papers.
- This paper presents highly cited papers and other possible articles for useful characteristics and significant switching analyses. Awareness of the characteristics of the
highly cited papers can give some insights into significant developments in solid state switching. Citation review can be useful to the editorial board and potential writers, reviewers by offering some inputs on what kinds of papers tend to interest the researcher. It also gives writers clues about what creates a contribution to being one of the most cited papers.

- The keywords can help to find current research papers in the past. It also reflects the scope of relevant articles that have been published in SSS papers. It is expected that the promotion of research keywords will clarify the various phenomena in the switching field.
- This analysis provides the easiest way to examine and interpret the manuscript submitted to the journal publishers and editors.
- The growth of scientific collaborations and the performance of various authors, universities, and countries creates a huge mutual association. The authors and co-authors must make an innovative, descriptive, or empirical observation with the long-standing profession to get the article published. International collaboration encourages publications with higher citation counts in less advanced countries. Moreover, the developed countries often benefit from international collaboration.

In conclusion, the potential SSS studies and discoveries based on the 120 most frequently cited papers over the past ten years will not only play a crucial role in the advancement of evolving SSS technologies but also will create considerable effects on the energy market. We may be able to use this analysis, knowledge and information to overcome current power system limits, particularly when it is applied to next-generation SSS, which is expected to emerge in the next years.

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