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Review

Progress of Photovoltaic DC Fault Arc Detection Based on VOSviewer Bibliometric Analysis

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Abstract: This paper presents a review of research progress on photovoltaic direct current arc detection based on VOSviewer bibliometric analysis. This study begins by introducing the basic concept and hazards of photovoltaic DC arcing faults, followed by a summary of commonly used arc detection techniques. Utilizing VOSviewer, the relevant literature is subjected to clustering and visualization analysis, offering insights into research hotspots, trends, and interconnections among different fields. Based on the bibliometric analysis method of VOSviewer software, this paper analyzes the articles published in the last 10 years (2014–2023) on photovoltaic DC fault diagnosis. We analyzed the specific characteristics of 2195 articles on arc failures, including year of publication, author, institution, country, references, and keywords. This study reveals the development trend, global cooperation model, basic knowledge, research hotspots, and emerging frontier of PV DC arc. Future research directions and development trends for photovoltaic DC arc detection are proposed which provides valuable references for further studies and applications in this domain. This comprehensive analysis indicates that photovoltaic DC arc detection technology is expected to find broader applications and greater promotion in the future.

Keywords: photovoltaic DC arc; fault detection; research progress; bibliometric analysis

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1. Introduction

Photovoltaic (PV) DC arc fault detection is a crucial research area in modern PV power generation systems [1]. Due to the severity and complexity of DC arc faults in PV systems, the effective detection and localization of these faults are paramount for ensuring the safety and reliable operation of PV power generation systems [2]. Typically, a PV system consists of a PV array, DC/AC inverters, and a distribution network. The DC generated via the PV array is converted to AC with inverters and injected into the distribution network for power consumption [3]. However, due to various factors such as aging of PV cell components [4], temperature fluctuations [5], dust, and corrosion [6], DC arc faults may occur in PV-powered hybrid energy systems [7]. DC arc faults exhibit characteristics such as high temperature [8], high energy release [9], and relatively long durations [10], making them prone to severe consequences like fires and explosions [11]. Moreover, PV power generation systems are often installed outdoors, facing harsh environmental conditions, making fault detection more challenging. Thus, accurately and timely detecting and localizing PV DC arc faults has become a focal point and challenge in current research [12].

In recent years, researchers have conducted extensive studies on PV DC arc fault detection. Primary research methods include current feature analysis [13], voltage feature analysis [14], frequency domain analysis [15], and time domain analysis [16]. By monitoring the current and voltage signals generated by DC arc faults and utilizing signal processing and pattern recognition techniques, fault detection and localization can be achieved. Simultaneously, advanced detection technologies such as infrared imaging [17], acoustic detection [18], and fiber optic sensing [19] have been introduced into PV DC arc fault detection. These technologies provide real-time information on the temperature, sound, or light signals at the location of the fault, offering more precise information for fault localization. However, challenges persist in PV DC arc fault detection. Firstly, due to the unique nature of DC arc faults in PV power generation systems, existing fault detection methods still require improvements in terms of accuracy, sensitivity, and real-time performance [20]. Secondly, current and voltage signals in PV power generation systems are subject to various disturbances, such as noise and harmonics, posing challenges to fault detection [21]. Additionally, experimental conditions and standardization methods for PV DC arc fault detection need further refinement [22] due to the reason that PV DC arc fault detection is a significant and challenging research area. By studying the characteristics and principles of DC arc faults in PV power generation systems and employing effective detection methods and advanced technologies, the safety and reliability of PV power generation systems can be enhanced, contributing to the advancement of PV power generation technology [23].

Photovoltaic DC arc faults pose a significant safety hazard in photovoltaic systems due to their unique characteristics and severe consequences [24]. These faults often occur in the DC combiner box or DC distribution box, where the large number of photovoltaic cell strings increases the energy density of any arc fault [25]. As a result, they are highly prone to causing fire accidents that threaten the safety of the entire photovoltaic power plant. A fire safety guideline for PV system installation systematically evaluates 40 publicly accessible publications, and provides design considerations and installation practices for fire protection of residential rooftop PV systems [26]. A checklist is suggested to address the lack of emphasis on fire hazards involved in installation, which could contribute to the top cause of PV fires—DC isolators. The inclusion of this guideline can improve awareness and prevention of fire hazards during PV system installation. However, the key characteristic of photovoltaic DC arc faults is that their current waveform changes only slightly, making them difficult to detect [27]. This difficulty in detection renders traditional protective devices unable to respond accurately, allowing the arc faults to persist unnoticed for long periods. The limited variation in the current waveform of photovoltaic DC arc faults presents a significant hurdle in their detection. Traditional protective devices, engineered to respond to sudden fluctuations in current, often fail to accurately identify these subtle changes. Consequently, these unnoticed arc faults can persist for prolonged durations, posing potential safety risks and compromising the overall efficiency of the PV system [28].

The formation of a DC arc involves the ionization of electrode materials [29], current overload [30], and gas ionization [31]. When the circuit in a solar photovoltaic system is disconnected or poorly connected, intermittent interruptions in the current lead to the creation of an arc [32]. The ionization of electrode materials is crucial for the formation of a DC arc and depends on factors such as temperature, current density, and properties of the electrode material. Current overload is a significant cause of DC arc formation, as high current density can raise the surface temperature of the electrode and initiate the arc. Gas ionization is another key factor, closely linked to gas pressure, electrode spacing, and gas type.

DC arcs possess several characteristics. Firstly, they are characterized by high temperature, brightness, and energy, producing intense light radiation and thermal radiation [33]. Secondly, DC arcs display instability and complexity, with their parameters varying according to changes in environmental conditions and fault types [34]. Moreover, DC arcs have significant impact and destructive power, capable of damaging equipment and components in photovoltaic systems. Lastly, DC arcs generate harmful gases and pollutants, posing potential risks to the environment and human health [35].

DC arc faults in photovoltaic power plants are a significant problem that can lead to unpredictable hazards, including system damage, energy loss, and fires. Therefore, research on detecting DC arc faults is crucial. DC arc faults occur when arcs form during current interruption or switching processes [36]. In photovoltaic power plants, these faults primarily result from equipment malfunctions, insulation breakdowns, or external environmental factors. They can happen in key components such as battery banks, inverters, and connectors.

The hazards of DC arc faults include energy loss, reduced equipment lifespan, decreased operational efficiency, and increased safety risks. Therefore, accurately and promptly detecting and eliminating DC arc faults is vital for ensuring the normal operation of photovoltaic power plants [37].

Although existing methods for detecting DC arc faults in photovoltaic systems have made some progress, they still have limitations. Firstly, monitoring methods based on voltage and current signals are greatly affected by noise interference in practical applications, resulting in higher false positive rates [38]. Secondly, although infrared thermography techniques can effectively detect the presence of arc faults, their ability to distinguish between fault types is limited, making it difficult to determine the specific location and severity of faults accurately [39]. Additionally, some machine learning algorithms require ample sample data for training and are sensitive to parameter selection and model optimization, heavily relying on data quality and algorithm performance [40]. Lastly, existing detection methods often struggle to meet the complex and ever-changing environmental conditions in practical engineering applications, lacking adaptability and stability for actual photovoltaic power plant scenarios. Therefore, future research should address these limitations and explore more comprehensive and effective solutions to improve the accuracy and reliability of DC arc fault detection in photovoltaic systems.

The contribution of this research can be summarized as follows: (1) A comprehensive analysis of the research progress in PV DC arc detection is presented using VOSviewer bibliometric analysis. The results highlight key research hotspots, trends, and interconnections within different fields, revealing the increasing number of publications on PV DC fault diagnosis and the growing global collaboration. (2) Future research directions and development trends, which focus on the in-depth study of arc failure mechanisms, development of new detection methods and equipment to enhance practicality and efficiency, and strengthening international cooperation to advance PV DC arc detection technology are identified. (3) The findings of this research contribute significantly to advancing PV DC arc detection technology, providing valuable references for future research and applications in this field.

2. Bibliometrics Analysis of PV DC Arc

The burgeoning interest in PV DC arc events necessitates a comprehensive bibliometric analysis to understand the evolution, trends, and contributions within this field. Through systematic literature review and bibliometric methods, key insights into the research landscape surrounding PV DC arc events are uncovered.

2.1. Methodological Framework Using VOSviewer

Bibliometrics is a branch of information science that utilizes scientific and quantitative analysis methods to study academic literature and explore emerging trends and knowledge structures in a particular research field [41]. This approach is considered an effective tool for objectively assessing the current status and reflecting on the development of a discipline [42]. VOSviewer is a software tool used to construct and visualize bibliometric networks, known for its ability to handle large-scale data and provide clear and intuitive visualizations, supporting multi-dimensional analysis [43].

To effectively analyze the bibliometric data related to PV DC arc studies, VOSviewer is utilized for constructing and visualizing bibliometric networks. This methodological framework facilitated a systematic review and visual analysis of the data retrieved from the Web of Science (WoS) database, as exhibited in Figure 1. The methodological framework using VOSviewer enabled us to conduct a thorough and insightful bibliometric analysis, laying a solid foundation for identifying the research hotspots, understanding the evolving trends, and mapping the intricate network of research activities within the field of PV DC arc detection.

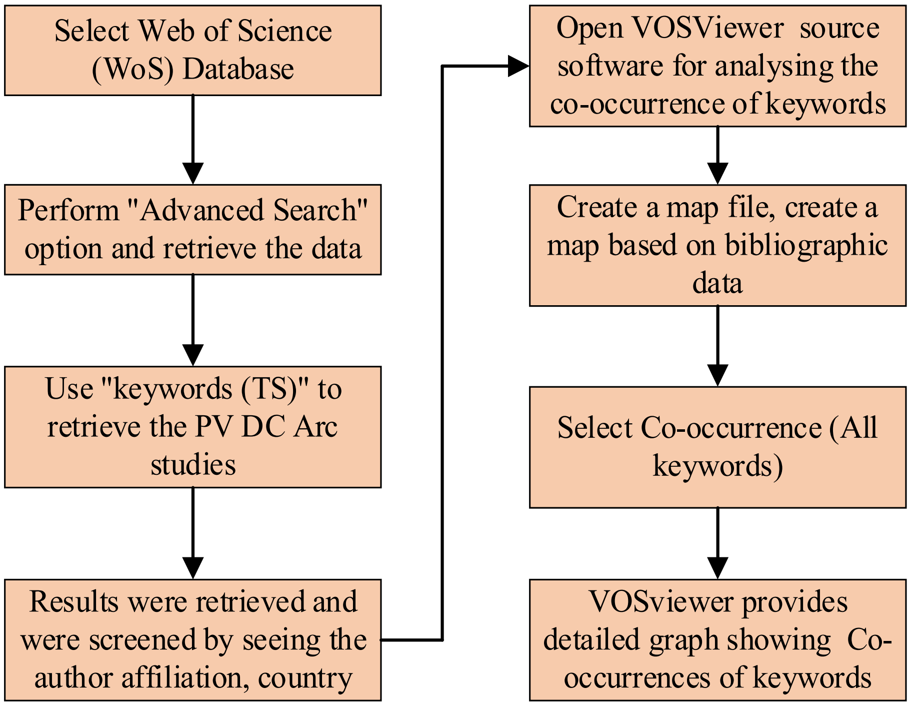

Figure 1. Flowchart of methodological framework using VOSviewer.

The flowchart in Figure 1 describes the methodological framework for using VOSviewer to analyze the co-occurrence of keywords based on bibliographic data from the WoS database. The steps involved in the VOSviewer methodological framework as depicted in the flowchart are as follows:

(1) Select WoS Database: Start by accessing the WOS database, which serves as the primary source for retrieving scholarly articles;
(2) Perform 'Advanced Search': Use the 'Advanced Search' option in the Web of Science to precisely locate relevant articles. This step focuses on filtering and collecting data that will be pertinent to the analysis;
(3) Use Keywords: Employ specific search keywords (TS = Topic Search) to refine the search further. In this context, the keywords target studies related to PV DC arc, ensuring that the retrieved data are highly relevant to the research focus;
(4) Retrieve and Screen Results: After conducting the search, the results are retrieved and then screened based on criteria such as author affiliation and country, which helps in identifying the most relevant and significant studies for further analysis;
(5) Open VOSviewer Source Software: Launch the VOSviewer software, which is utilized for analyzing and visualizing bibliometric networks. VOSviewer is capable of handling large sets of bibliographic data;
(6) Create a Map Based on Bibliographic Data: In VOSviewer, create a new map file that will visually represent the bibliographic data. This map is crucial for understanding the relationships and patterns within the data;
(7) Select Co-occurrence (All Keywords): Choose the co-occurrence analysis option in VOSviewer, focusing on all keywords. This step involves analyzing how frequently different keywords appear together in the same articles, which helps in identifying key themes and trends in the literature;
(8) Detailed Graph Showing Co-occurrences of Keywords: VOSviewer then generates a detailed graph or network map showing the co-occurrences of keywords. This visual representation allows researchers to easily identify and interpret the main research hotspots, trends, and the interconnections among various fields within the dataset.

2.2. Global Annual Publication Trend of Photovoltaic Direct Current Arc Fault

Based on bibliometric analysis, one can uncover the development trends in the field of photovoltaic direct current arc fault detection, as well as identify authors and research institutions with high quality and productivity in this field [44]. Moreover, it enables rapid identification of high-quality and highly credible research topics in the field. Building upon this foundation, this paper provides a review and discussion on the current status and future development trends in the research field of photovoltaic direct current arc fault detection. Visual analysis of annual publications, countries, institutions, authors, and keywords using the WoS is conducted.

A total of 2195 literature articles related to PV DC arc fault detection were retrieved, as seen in Table 1, from the WoS core collection from 2014 to 2023. As shown in Figure 2, the number of publications on photovoltaic arc fault detection exhibited an increasing trend from 2017 to 2020, while the quantity has declined in the past two years.

Table 1. Top 10 most-cited papers.

Article Title	**Source Title**	**Times Cited**	**Publication Year**
A Comprehensive Review of Catastrophic Faults in PV Arrays: Types, Detection, and Mitigation Techniques	*IEEE JOURNAL OF PHOTOVOLTAICS*	1218	2014
Fault detection and diagnosis methods for photovoltaic systems: A review	*RENEWABLE AND SUSTAINABLE ENERGY REVIEWS*	315	2016
A comprehensive review on protection challenges and fault diagnosis in PV systems	*RENEWABLE AND SUSTAINABLE ENERGY REVIEWS*	259	2019
Fault Detection and Location of Photovoltaic Based DC Microgrid Using Differential Protection Strategy	*IEEE TRANSACTIONS ON SMART GRID*	254	2018
The Detection of Series Arc Fault in Photovoltaic Systems Based on the Arc Current Entropy	*IEEE TRANSACTIONS ON POWER ELECTRONICS*	240	2014
Arc Fault and Flash Signal Analysis in DC Distribution Systems Using Wavelet Transformation	*IEEE TRANSACTIONS ON SMART GRID*	201	2014
A comprehensive review on DC arc faults and their diagnosis methods in photovoltaic systems	*RENEWABLE AND SUSTAINABLE ENERGY REVIEWS*	199	2018
A Comparative Evaluation of Advanced Fault Detection Approaches for PV Systems	*IEEE JOURNAL OF PHOTOVOLTAICS*	199	2017
Artificial intelligence and internet of things to improve efficacy of diagnosis and remote sensing of solar photovoltaic systems: Challenges, recommendations and future directions	*RENEWABLE AND SUSTAINABLE ENERGY REVIEWS*	193	2016
DA-DCGAN: An Effective Methodology for DC Series Arc Fault Diagnosis in Photovoltaic Systems	*IEEE ACCESS*	193	2015

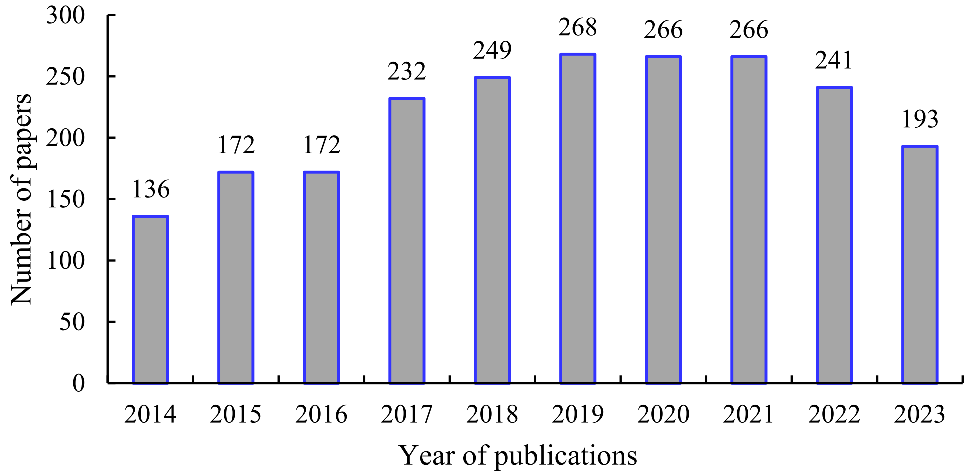

Figure 2. Statistics collection of photovoltaic DC arc literature during 2014–2023.

2.3. Distribution of Author Cooperation by Country/Region

VOSviewer is a tool used for analyzing national/regional co-authorship to reveal international cooperation in a field. Figure 3 shows the co-authorship network of countries/regions, which includes 59 countries/regions grouped into eight different colored clusters. The largest cluster (in red) is centered around China and consists of 10 countries/regions.

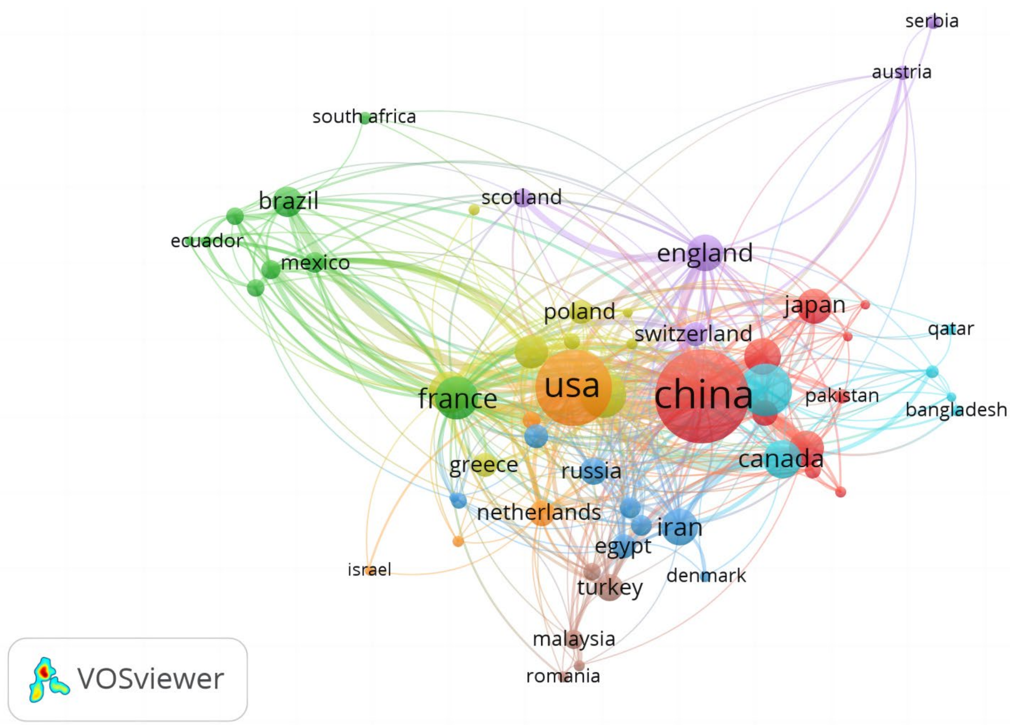

Figure 3. Distribution of author cooperation by country/region.

Table 2 lists the top five countries with the highest production capacity. In terms of national scientific research strength, China published 553 papers with a citation frequency of 5890, while the United States published 382 papers with a citation frequency of 6438. From the perspective of standardized citation impact, the United States has an advantage over China. Both countries lead in terms of paper quantity and quality.

Table 2. The top 5 productive countries/regions.

Rank	Country/Region	Publications	Citations	Category Normalized Citation Impact
1	CHINA	553	5890	0.94
2	USA	382	6438	1.36
3	INDIA	174	1997	0.91
4	GERMANY	133	1782	1.10
5	FRANCE	119	1484	0.99

2.4. Analysis of Institution Cooperation

A total of 1534 institutions worldwide participated in research related to photovoltaic DC arc fault detection as exhibited in Figure 4. Table 3 lists the top five most productive institutions, with Xi'an Jiaotong University publishing 77 related papers, the highest number of publications. Next are the French National Center for Scientific Research (Centre National de la Recherche Scientifique, CNRS) and the Chinese Academy of Sciences. The author cooperation network between these institutions is shown in Table 3. The cooperation network between institutions includes 150 institutions divided into 15 clusters, each represented by a different color. Xi'an Jiaotong University has the largest volume of papers, but the institutional cooperation is not significant. CNRS has more partners for cooperation.

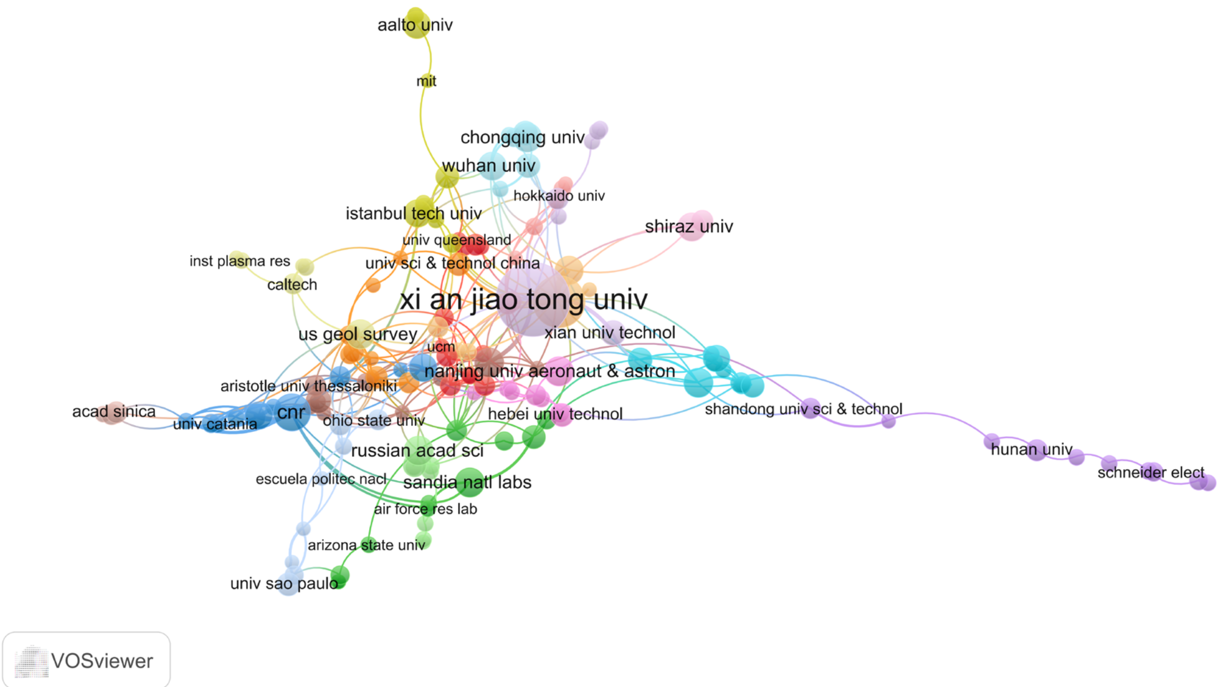

Figure 4. The map of institution cooperation.

Table 3. Top 5 productive institutions.

Rank	Institution	Publications	Citations	Category Normalized Citation Impact
1	Xi'an Jiaotong University	77	865	0.98
2	Centre National de la Recherche Scientifique (CNRS)	75	1085	1.09
3	Chinese Academy of Sciences	42	764	1.51
4	National Institute of Technology (NIT System)	37	415	1.15
5	Indian Institute of Technology System (IIT System)	36	330	0.73

2.5. The Most Productive Author

Utilizing VOSviewer for Author Collaboration Analysis is displayed in Figure 5. Table 4 presents the top 10 most productive authors. Among them, six authors are affiliated with Xi'an Jiaotong University. Ranking first is Schweitzer, Patrick from Universite de Lorraine with 15 papers and a citation frequency of 214. The author collaboration network is depicted in Figure 5, encompassing 91 highly productive authors grouped into nine clusters represented by distinct colors. The red cluster comprises 18 authors, with He Hailong, Wu Yi, and Wu Yifei situated in the center.

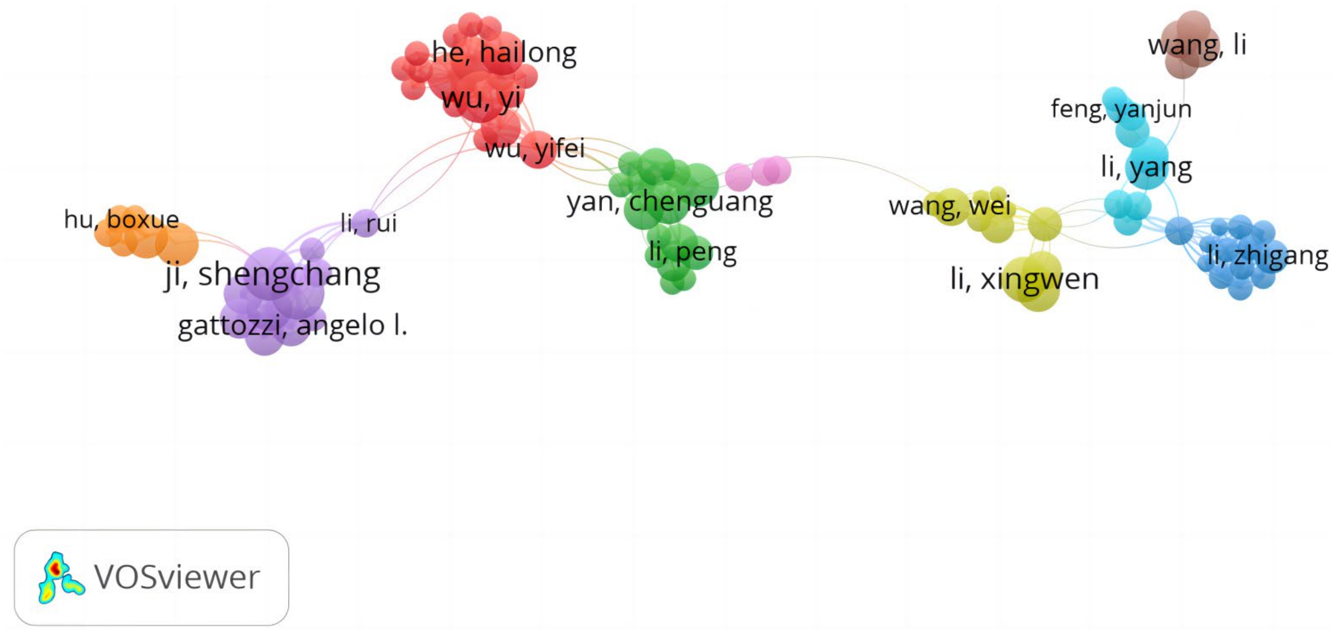

Figure 5. The most productive author.

Table 4. The top 10 productive authors.

Rank	Author	Publications	Citations	Affiliated Institution
1	Schweitzer, Patrick	15	214	Universite de Lorraine
2	Liu, Zhiyuan	13	93	Xi'an Jiaotong University
3	Geng, Yingsan	13	93	Xi'an Jiaotong University
4	Wang, Jianhua	13	93	Xi'an Jiaotong University
5	Ji, Shengchang	11	317	Xi'an Jiaotong University
6	Xiong, Qing	11	173	Xi'an Jiaotong University
7	Weber, Serge	10	104	Universite de Lorraine
8	Lehtonen, Matti	10	68	Aalto University
9	Kwak, Sangshin	10	67	Chung Ang University
10	Wu, Yi	10	61	Xi'an Jiaotong University

2.6. Keyword Cluster Analysis

In Figure 6, the co-occurrence analysis of the top 100 keywords provides insights into the main themes covered in the publications, making it suitable for analyzing the co-occurrence of high-frequency keywords. VOSviewer was used to extract and cluster the top 100 keywords of this study (Table 5). Figure 5 presents a visual network map of the top 100 keywords and their contributions within five clusters. The node labels indicate the keywords, and the size of each node represents the frequency of the keyword. The links connecting two nodes signify the co-occurrence relationship between the keywords.

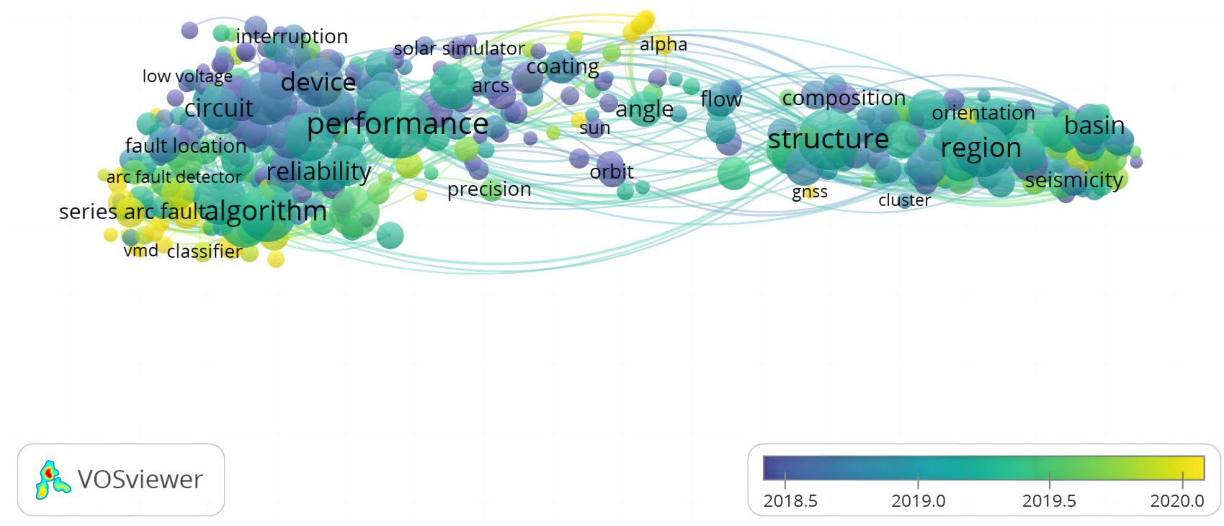

Figure 6. VOSviewer automatic classification of all the keywords.

3. Materials and Methods

As PV systems continue to proliferate globally, ensuring their safety and reliability becomes paramount. Arc faults pose a significant threat to PV system integrity, potentially leading to fires and equipment damage. Therefore, developing effective detection methods is imperative to mitigate the impact of arc faults in PV systems.

3.1. Feature Extraction and Classifier-Based Fault Detection

Traditional methods employ feature extraction and classifier-based techniques for arc fault detection in photovoltaic systems [45]. These methods extract feature parameters from current and voltage signals in the photovoltaic system and train and classify these features using various classifiers to determine the presence of arc faults.

Feature extraction methods include time-domain features, frequency-domain features, and wavelet transform features. Time-domain features analyze parameters such as amplitude, peak value, and mean value of current and voltage signals [16]. Frequency-domain features extract spectral characteristics like frequency and amplitude through Fourier transforms or spectrum analysis [46]. Wavelet transform features combine information from the time and frequency domains to enhance the representation capability of fault signals [47].

Classifiers, such as support vector machines, artificial neural networks, and decision trees, are commonly used [48]. They establish classification models by learning feature data from known faults and normal states, enabling accurate detection of unknown data. However, traditional methods still face challenges. Feature selection and parameter settings during extraction significantly influence the results, and classifier performance is limited by the dataset's size and quality.

3.2. Data-Driven Fault Detection

Machine learning algorithms, including support vector machines, decision trees, random forests, and neural networks, are used for fault detection [49]. These algorithms learn and process input data from photovoltaic systems to classify different fault states and detect arc faults. Support vector machine algorithms construct nonlinear classification hyperplanes to identify different fault states [50]. Decision tree algorithms use a tree structure to classify fault signals. Random forest algorithms improve accuracy and robustness through an ensemble of multiple decision trees [51]. Neural network algorithms extract fault features through layers of neurons, achieving precise detection of arc faults [52].

Machine learning-based fault detection methods demonstrate high accuracy and adaptability, effectively handling complex fault patterns in different photovoltaic systems.

Additionally, they possess strong generalization capabilities, accurately classifying and recognizing different datasets, enhancing fault detection reliability and stability.

However, these methods also face challenges. Large-scale photovoltaic systems require more training data and computational resources to improve algorithm performance. Algorithm interpretability and stability need further improvement to meet practical application requirements. Future research can explore techniques like feature selection and model optimization to propose more efficient and reliable machine learning algorithms, driving the development and application of photovoltaic DC arc fault detection methods.

3.3. Artificial Intelligence-Based Fault Detection

Advanced methods utilize artificial intelligence algorithms for fault detection in photovoltaic systems. These methods employ machine learning and deep learning techniques, learning and training on extensive data to achieve accurate arc fault detection. Artificial intelligence-based fault detection methods include neural networks, convolutional neural networks, and recurrent neural networks. Neural networks construct network structures with multiple layers of neurons to learn and process input data, enabling fault state judgment [53]. Convolutional neural networks extract spatial features through convolutional and pooling layers, effectively classifying fault signals [54]. Recurrent neural networks consider time series characteristics through memory units and time feedback structures, detecting time-related faults [55].

Artificial intelligence-based fault detection methods exhibit high accuracy and robustness [56]. They automatically learn and adapt to different photovoltaic systems, effectively identifying complex fault patterns. Additionally, they possess strong generalization capabilities, handling incomplete or noise-disturbed data to enhance fault detection reliability. However, these methods also face challenges. Large-scale photovoltaic systems require more training data and computational resources to improve algorithm performance. Algorithm interpretability and stability need further improvement to meet practical application requirements. Future research can explore the optimization of deep learning network structures and model interpretation techniques to propose more efficient and reliable artificial intelligence algorithms, driving the development and application of photovoltaic DC arc fault detection methods.

With the advancement of research on photovoltaic DC arc fault detection, image processing-based advanced methods have emerged in this field [57]. This method utilizes high-speed cameras to capture images of arc faults and accurately monitor their morphological characteristics through image processing techniques, thereby opening up new possibilities for improving detection accuracy and efficiency.

Firstly, the image processing-based fault detection method achieves precise monitoring of arc behavior by capturing arc morphology with high temporal resolution [58]. The processing and analysis of instantaneous image sequences of arcs enable researchers to accurately locate and classify arc faults, providing more detailed fault features. Secondly, this method exhibits strong adaptability and robustness, addressing issues faced by traditional methods such as the complexity of arc morphology and variations in environmental lighting. Image processing-based methods demonstrate higher stability, being unaffected by the complexity of arc morphology and changes in environmental lighting, thus providing more reliable solutions for practical applications. However, image processing-based fault detection methods also face challenges, including the efficient processing of a large amount of image data and the requirement for real-time performance. Future research will focus on optimizing image processing algorithms to improve systems' real-time performance and stability, meeting the high demands of power systems for arc fault detection. This advanced method injects new vitality into the field of photovoltaic DC arc fault detection and is expected to make greater breakthroughs in practical applications. The detailed comparison of different operational strategies of photovoltaic DC detection is exhibited in Table 5.

Table 5. Literature reviews of operational strategies of photovoltaic DC detection.

Detection Method	Key Techniques	Pros	Cons	Applicability	Hardware/ Software	Numerical Accuracies	References
Feature Extraction- and Classifier-Based Fault Detection	Frequency-domain features	Captures frequency variations	May require advanced processing	Detailed frequency analysis	Moderate	High	[15]
	Time-domain features	Simple implementation	Limited in capturing frequency	Real-time monitoring	Basic	Moderate	[16]
	Wavelet transform features	Excellent time-frequency resolution	Complex implementation	Non-stationary signal analysis	Advanced	High	[47]
Data-Driven Fault Detection	Support vector machine	Effective for classification	Sensitive to parameter tuning	Fault pattern classification	Moderate to advanced	High	[50]
	Decision tree	Simple interpretation	Prone to overfitting	Decisionmaking	Basic to moderate	Moderate to high	[51]
	Random forest	Handles high-dimensional data	May require large training set	Classification tasks	Moderate	High	[51]
Data-Driven Fault Detection	Neural network	Complex patterns recognition	Requires large training data	Pattern recognition	Advanced	High	[53]
	Convolutional neural networks	Effective for image processing	Requires large datasets	Image-based fault	Advanced	High	[54]
	Recurrent neural networks	Captures temporal dependencies	Complex architecture	Time-series data analysis	Advanced	High	[55]
	Image processing-based advanced methods	Effective for visual analysis	Requires specialized algorithms	Image-based fault detection	Advanced	High	[57]

4. Challenges and Prospects of Photovoltaic DC Arc Fault Detection Technology

As the PV installation in distribution systems continues to grow, DC arc faults pose significant safety and reliability concerns. The myriad challenges encountered in developing robust DC arc fault detection technology range from the inherent complexity of PV systems to the diverse operating conditions and environmental factors.

4.1. Technical Challenges and Bottlenecks

The complexity of arc faults is the primary challenge faced by current research. The working environment of photovoltaic systems is variable, and the mechanisms for arc fault formation are complex and diverse, making the accurate identification and localization of arc faults a highly challenging task [59]. Improving the detection accuracy under various interference conditions is a core issue that needs to be addressed in current research. Traditional methods consume excessive computational resources when dealing with large-scale data. As the amount of data continues to increase, traditional parameter-based methods are limited in terms of real-time performance and efficiency [60]. Therefore, researchers need to seek more efficient algorithms and processing strategies to meet the demands of future large-scale photovoltaic systems.

There is a lack of unified standards and specifications in the field of photovoltaic DC arc fault detection, making it difficult to compare and reproduce different research results effectively. Establishing unified evaluation standards and testing methods is an urgent issue to promote the systematic and sustainable development of this field. The reliability and stability in practical engineering applications need to be given special consideration. The robustness, anti-interference capability, and operational feasibility of the detection system in different environments require further research and validation [61]. To overcome these technical challenges and bottlenecks, researchers will continue to drive innovative development in photovoltaic DC arc fault detection technology, making greater contributions to improving the safety and reliability of power systems.

In the future, the field of photovoltaic DC arc fault detection will witness several notable trends and research directions that will play a crucial role in enhancing system safety, detection efficiency, and practical applications [62].

4.2. Future Trends and Research Directions

Firstly, with the continuous maturation of artificial intelligence technology, future photovoltaic DC arc fault detection will focus more on machine learning- and deep learning-based methods. This includes using neural networks and deep learning algorithms for arc feature extraction and identification, thereby achieving higher accuracy and faster fault detection. The introduction of machine learning will provide the system with more powerful data processing and analysis capabilities, enhancing the automatic perception and response to arc faults in photovoltaic systems [63]. Secondly, researchers will tend to engage in interdisciplinary collaborations, integrating image processing, sensing technology, and intelligent algorithms to comprehensively improve the performance of photovoltaic DC arc fault detection systems [44]. By fusing multiple sources of information, comprehensive and accurate identification and localization of arc faults can be achieved, thereby improving the comprehensiveness and practicality of the detection [64]. On the other hand, future research will also focus on establishing more comprehensive standards and specifications to promote the healthy development of this field [65]. The establishment of unified testing methods and performance evaluation standards will facilitate the comparison and validation of different research results, promote the commercial application of the technology, and foster consensus within the industry regarding photovoltaic DC arc fault detection.

Furthermore, expanding the application areas will be a key direction for future research. In addition to photovoltaic power generation systems, researchers will explore the extension of arc fault detection technology to a wider range of power systems, including power transmission and distribution grids, electric vehicle charging stations, and other fields, to meet the practical requirements in different scenarios [66]. Overall, future photovoltaic DC arc fault detection will experience deeper development in areas such as artificial intelligence, interdisciplinary collaboration, standardization, and application expansion, providing more advanced and comprehensive solutions for the safety and reliability of power systems.

DC arc detection technology is expected to find broader applications and greater promotion in the future. Notably, studies such as those by Omran et al. [67] provide an extensive review of the models, detection methods, and ongoing challenges in the field, suggesting that as these challenges are addressed, the technology will become more viable across various applications. Similarly, Dang et al. [68,69] introduce advanced learning techniques for fault diagnosis in DC systems, demonstrating significant advancements in detection capabilities, which are crucial for broader adoption. Moreover, new market analysis forecasts, such as the report on the Direct-current Arc Detector Market, project a robust growth in the demand for these technologies, driven by increasing safety requirements in photovoltaic systems and other applications reliant on DC power [70]. The study by Zhang et al. [71] also supports this view by presenting a novel DC arc detection method tailored for PV systems, underscoring the sector-specific advancements that contribute to the technology's broader applicability and market readiness.

5. Conclusions

In this research, an analysis of the advancements in PV DC arc detection through a comprehensive bibliometric review using VOSviewer is presented. Our clustering and visualization analysis has provided deep insights into the pivotal research areas, evolving trends, and the dynamic interconnections among various domains involved in this field. This study reveals a consistent annual increase in publications over the past decade, underscoring the rapid evolution and heightened interest in photovoltaic direct current fault diagnosis. The global collaboration patterns in this field are strengthening, which significantly bolsters the technological advancements in PV DC arc detection. From the analysis, it is evident that the most frequently discussed topics in the literature include fault diagnosis, arc characteristics, and detection methodologies. These focal points highlight the scholarly community's dedication to understanding arc failure mechanisms and advancing detection technologies under diverse environmental conditions.

Future research will encompass enhanced studies into arc failure mechanisms to boost the accuracy and reliability of PV DC arc detection systems. There is also a pressing need to develop innovative detection techniques and devices that improve both the efficiency and applicability of these systems. Additionally, fostering international collaboration will be crucial for driving forward the research and application of this technology on a global scale. The expected broader application and promotion of PV DC arc detection technology point towards a promising future for this field. The insights garnered from this study serve as a valuable resource for further research and practical applications in photovoltaic direct current arc detection, potentially accelerating technological progress in this vital area.

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