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Research trends on microgrid systems: a bibliometric network analysis

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ABSTRACT

The numeral of academic publications in the microgrid system field has rapidly grown. A microgrid system is a group of interconnected distributed generation, loads, and energy storage operating as a single controllable entity. Many published articles recently focused on distributed generation, system control, system stability, power quality, architectures, and broader focus areas. This work analyzes microgrid: alternating current (AC), direct current (DC), and hybrid AC/DC microgrid systems with bibliometric network analysis through descriptive analysis, authors analysis, sources analysis, words analysis, and evolutionary path based on the Scopus database between 2010 and 2021. The finding helps find out the top authors and most impact sources, most relevant and frequently used in the research title, abstract, and keyword, graphically mapping the research evolved and identifying trend topic.

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1. INTRODUCTION

A microgrid system comprises interconnected loads and the distributed generation that perform as a single controllable system concerning the grid [1]. One or more types of distributed power energy (solar panels, wind turbines, micro-hydro, diesel engine, or other generation), load, and energy storage (usually batteries) are contained within a microgrid system. A microgrid system may connect or disconnect from the distribution grid, permitting it to function in the grid-connected or island-mode operation [2]. Furthermore, whether there is a blackout or a problem on the primary grid, the microgrid system can detach from the grid and serve its local demands in islanded mode [3]. The microgrid system is an alternative to the conventional electrical power system to supply demand. Microgrid systems also can be applied in streets, residential, neighborhoods, campuses, hospitals, communities, localities (towns and villages), small islands, organizations, military, and business centers [4]–[8]. A microgrid generally comprises three major components: distributed generators, loads, and storage elements. It can run independently or connect to the main network, either low- or medium-voltage [9]. Electricity supply for islands and isolated places is developed by exploiting local energy potentials, especially renewable energy sources (RES) [10]. Due to their flexibility, quick operation, and low complexity, most islanded microgrid power systems rely on diesel generators for their electrical source. However, diesel generators have significant running expenses [11].

The hybrid device setup for a typical microgrid system is shown in Figure 1. The direct current (DC) bus connects the DC supply, battery energy storage, and the load to the inverter. The load can be an alternating current (AC) or DC load located close to the power source or distant (external load) from the microgrid system. The charging regulator is connected to the battery using a two-way DC to DC converter. The DC to DC

converter connects the batteries to the DC bus. Next, the AC bus connects the load (AC or DC load), grid-tied inverter, and DC power source. Finally, the bidirectional inverter connects the AC and DC buses, with the AC bus connecting to the external grid [12]. Energy resource planning recreates a considerable function in clean energy's geopolitics and the global economy to achieve global commitment toward net zero emission [13]. Several studies have shown that microgrid systems can assist rural electrification, especially in developing countries. Historically, rural areas have had difficulty obtaining power sources. They are not connected to any main power networks and are typically smaller and less populated, resulting in lesser demand. Rural areas can utilize microgrid systems in this situation due to the heightened expense of grid expansion and lesser demand [14]–[16].

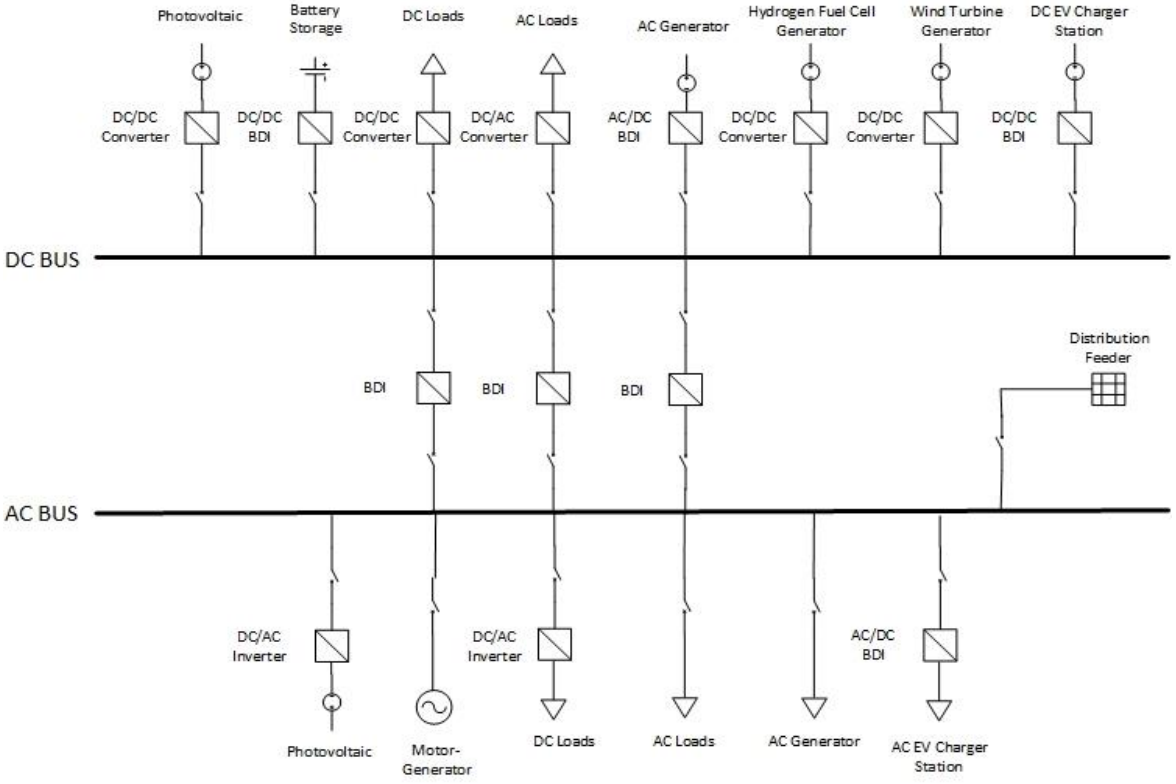

Figure 1. Typical hybrid microgrid system

Microgrid fields have been the topic of many studies around the world. Guerrero and colleagues discussed decentralized power generation, distributed generation, hierarchical control of the islanded systems and grid-connected, power quality, AC/DC hybrid microgrid, and distributed-energy-storage systems [17], [18]. According to Vasquez *et al.* [19] the microgrid system will soon become more intelligent and flexible. It may work in a grid-connected or island mode and provide voltage and frequency stability, black start, reactive and active power flow regulation, storage energy management, and dynamic power filter capabilities. Moreover, another article shows the critical concepts in intelligent microgrid systems: configuration, control, and energy management. Blaabjerg *et al.* [20] looked into distributed generation and protection. The high penetration capacity of variable renewable energy resources (i.e., wind or solar photovoltaics) into the grid is critical in developing a sustainable and resilient microgrid system. In order to accommodate the integration, power electronic converters with enhanced control techniques. Wang *et al.* [21] propose a management approach for the dependable autonomous procedure of a hybrid microgrid system that incorporates power-sharing in separate networks, the energy exchange between AC and DC networks, and network energy management.

In recent decades, there have been many thorough review papers on microgrid systems from the viewpoint of technology, control, system stability, power quality, and architecture. Hartono *et al.* [22] examines a variety of technological advancements in microgrid systems and grid-tie inverters (GTI). Power-sharing between the microgrid system and the grid is a design feature. GTI can transfer excess power from the

microgrid system to the external grid, and can also provide power in times of power shortage. Kaur *et al.* [23] focus on microgrid control with varied features for appropriately coordinating distributed energy resources (DERs) to service critical and non-critical loads. Shuai *et al.* [24] identify and evaluate the system stability of microgrid systems with DERs, taking into account microgrid system forms of disturbance, operation mode, physical characteristics, and time frame. Banerji *et al.* [25] agreed to evaluate the viewpoint on a microgrid system integrated with DERs that deals with power quality issues. Mariam *et al.* [26], different microgrid system architectures based on the current electrical transmission and distribution system, geographical regions, load demand, and resource availability. Because it maximizes the use of accessible DERs, the combination of diverse DERs and storage has a promising future. Al-Saadi *et al.* [27] provide a detailed assessment of centralized, decentralized, multiagent, and intelligent microgrid control systems developed to manage and control distributed energy storage. They also illustrate the possible degree of services this storage can provide, the challenges of maintaining them, and recommended solutions. This review focuses on management strategies based on reinforcement learning and multiagent communication, echoing recent breakthroughs in artificial intelligence and digitalization. The paper comes to a close with an assessment of emerging topics and a list of possible future approaches.

Bibliometric analysis is a statistical analysis of published journal papers or other scientific articles. It is a helpful method of determining the impact of publications, researchers, or organizations in the scientific community [28]. Bibliometrics can synthesize the most recent research on a specific topic, define the quantitative development process, and compare research outcomes and dynamic evolution using bibliometric analysis and macro development perspectives. Sakata and colleagues used journal information analysis, citation network analysis, and visualization to identify the structure and geographical distribution of knowledge and expose the form of research collaboration in an interdisciplinary domain like the power grid. The results show that "Control of Microgrid" is one of the citation networks of the smart grid and power grid's major clusters [29]. Smart grids offer straightforward control over consumer consumption to execute demand-side management, whereas utilities have excellent control over consumer load [30]. Woon and colleagues look at the bibliometrics on distributed generation, which covers issues and challenges. The progression of research through time aids in identifying significant patterns in developing distributed generation-related technologies. Microgrid systems have recently attracted much interest as one of the dimensions in analysis groups [31]. According to Gao and colleagues, genetic algorithms and simulated techniques are the most often utilized optimization algorithms for microgrid operations. This literature bibliometric analysis suggests that microgrid operation optimization has attracted more attention recently, and developing nations have shown more interest in this field than industrialized countries [32]. Gao *et al.* [33] highlighted future research challenges for microgrid operation optimization. There is not much literature that examines bibliometrics specific to microgrid systems fields from the literature observation.

Bibliometric network analysis can be built and visualized using various software tools. Barra *et al.* [34] employ a VOSviewer for bibliometric analysis, representing a significant increase in publications on adaptive microgrid protection. Ante *et al.* [35], BibExcel to examine blockchain technology concerning peer-to-peer (P2P) microgrids and energy. The findings show a high degree of similarity in this field of study, with several streams focusing on blockchain technology. Carbon or green certificate trade on the blockchain could become a reality shortly. Using Cite Space, Dai *et al.* [36] conducted a bibliometric investigation on energy consumers. The findings show that digital technology will substantially impact future prosumer engagement in energy market trades, distribution network processes, microgrid functions, peer-to-peer contact, and demand response. This technology will fundamentally transform the current energy supply chain model. David *et al.* [37] and colleagues uses biblioshiny (R-package) to assess scientific publications in photovoltaic solar energy management. Compared to all other groups of words, the findings indicate that the microgrid system is one of the most frequently used.

Although many studies and reviews have been published on microgrid systems fields, the lack of systematic publications regarding research trends and evolutionary paths in this subject is not well recognized. This work can help researchers and the scientific community understand the study field's knowledge foundation more rapidly. This research employs descriptive analysis, authors analysis, sources analysis, words analysis, and topical evolutionary methods to research the map of the microgrid system from the Scopus database, combining the advantages of two bibliometric analysis tools (bibliohiny R-package and VOSviewer). The remainder of this study is structured as follows. The typical microgrid system, data collection, and research methodology are all covered in section 2. The descriptive analysis consists of general information and annual science publication, authors analysis: co-authorship, top relevant authors, and top author production, sources analysis: most relevant sources, source growth, three fields plot, and Bradford's law, word analysis: word cloud, most relevant words, word growth, word co-occurrence, and treemap of keywords, and evolutionary path analysis: thematic evolution, thematic map, and trend topic are all covered in section 3. Section 4 is a result discussion and research outlook, while section 5 is the conclusion of the work.

2. METHOD

The bibliometric network analysis's initial stage was to explore the Scopus database for all published works on microgrid systems to compile a data set. Scopus is a peer-reviewed literature abstract and citation database that includes scientific journals, books, and conference proceedings—providing a comprehensive picture of research output in the domains of science, technology, medicine, social sciences, and the arts and humanities around the world. The bibliometric network analysis interval was between the timespan 2010 and 2021. Scopus data sets are collected yearly using Harzing's Publish or Perish (PoP). PoP is software that finds and analyzes scientific citations [38]. It gathers raw citations from various sources, analyzes them, and displays a variety of citation metrics, such as the total citations, number of papers, and h-index. PoP software imported the meta-data for these documents through the Scopus application programming interface (API) into research information systems (RIS) or BibTeX format files to examine the data. The PoP software analyzes the Scopus parameter structure, then processes it into several statistics.

As stated in Table 1, there are three codes among the data gathering keywords in PoP. The search terms are combined using Boolean "OR" operators, employed as conjunctions in searches to incorporate keywords, resulting in more focused and productive results. Microgrid system bibliometric network analysis focuses on three technologies: AC microgrid system, DC microgrid system, and AC/DC hybrid microgrid system. The information from the PoP data collection then adds to the Mendeley library. There is a possibility that some information will be missing or incorrect, regardless of the source. Mendeley software supports the detailed updating of these data sets. Mendeley can occasionally find missing or incorrect details. Biblioshiny for bibliometrix provides a web interface method created by Massimo Aria from the University of Naples Federico [39]. Biblioshiny, based on Java software, combines the bibliometrix package capability with the convenience of web apps built with the shiny package environment. Furthermore, it helps researchers efficiently use the primary features of bibliometrix, such as data gathering using raw files from Scopus, Web of Science (WoS/WoK), Dimensions, Lens, and Cochrane Library database), data importing and conversion to data frame collection.

VOSviewer software completes the analysis of the co-citation network of authors and top keywords with the strongest link related to microgrid system fields. VOSviewer, created by Nies Jan van Eck and Ludo Waltman from the center for science and technology studies at Leiden University, frequently uses network map analysis software, particularly regarding authors and keywords [40]. VOSviewer works based on bibliographic, network, or text data to create a keyword co-occurrence, co-authorship, bibliographic coupling, citation, or co-citation metric. In this study, Biblioshiny and VOSviewer combined to complement each other to obtain research trends on the microgrid system fields with selected and relevant metrics. The research flow chart for bibliometric network analysis is shown in Figure 2 (see in appendix). The limitations of the chosen technique should be considered when reading this study: the Scopus database was the only database used to acquire bibliographic data. The other scientific databases, such as Web of Science (WoS/WoK), Dimensions, Lens, and the Cochrane Library database, could have revealed more publications and increased the sample size to be evaluated. The data was examined without the use of any manual modification.

Table 1. The code of keywords

Code	Keywords
A	"microgrid" OR "AC microgrid" OR "alternating current microgrid" OR "microgrid system"
B	"DC microgrid" OR "direct current microgrid"
C	"hybrid microgrid" OR "AC/DC microgrid" OR "AC-DC microgrid" OR "acdc microgrid"

3. RESULTS AND DISCUSSION

3.1. Descriptive analysis

Descriptive analysis is a type of data analysis that focuses on the data's characteristics and explains, shows, or summarizes general information constructively. The critical information about the initial data set is shown in Table 2. The Scopus database resulted in 5,668 research works relating to the microgrid system from 2010 to 2021. Data processing stages removed duplicated documents, unrelated topics, retracted papers, erratum, and books/chapters from the data set to fit the subject of the microgrid system, as shown in Table 3. Zotero software supports avoiding relying on the retracted document from data sets based on the online database. The final data set resulted in 4,747 research studies relating to the microgrid system in 2010 and 2021. Figure 3 shows the number of documents published each year, indicating that the number of publications relevant to the microgrid system has generally increased. Furthermore, the annual growth rate is 8.23%.

Table 2. General information about data sets from the Scopus database

Description	Results
Timespan	2010 to 2021
Documents	5,668
Author keywords	8,393
Authors	7,415
Single-authored documents	130
Authors of multi-authored documents	7,285
Documents per author	0.64
Authors per document	1.56
Co-Authors per documents	3.84
Collaboration index	1.59

Table 3. General information about the document collection

Description	Results
Code A	2,200
Code B	2,067
Code C	1,401
Total Document (“A” AND “B” AND “C”)	5,668
Duplicate documents	852
Book/chapter	17
Unrelated topics	51
Retracted document	1
Erratum	1
Total data	4,747

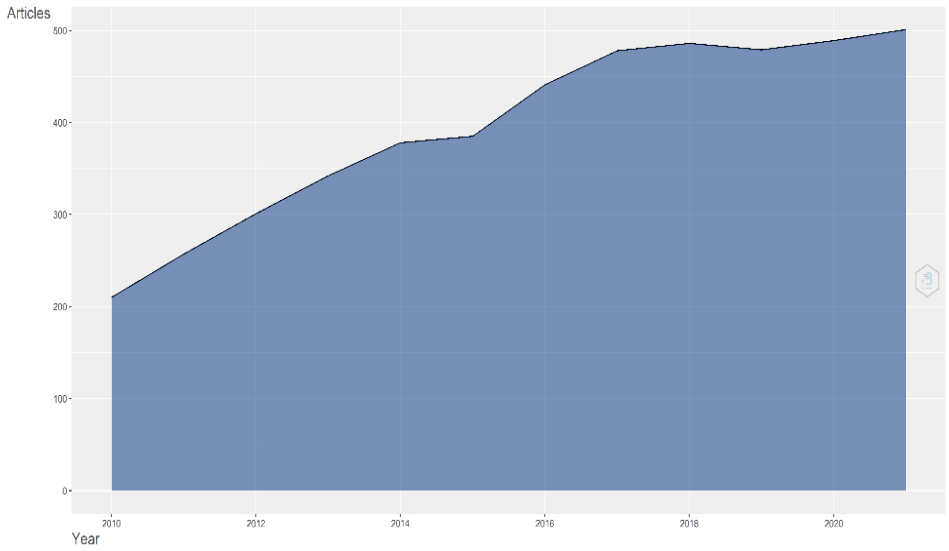

Figure 3. Scopus’s annual science publication activities were related to the microgrid system from 2010 to 2021

3.2. Authors analysis

The performance of the top twenty productive authors on microgrid system fields during 2010 to 2021. The publication counts revealed Joseph M Guerrero from Aalborg University, Denmark, with 223 publications on Scopus ranked first in the list. The second and third rank also comes from Aalborg University, Denmark. Juan Carlos Vasquez Q and Frede Blaabjerg as shown in Figure 4. Figure 5 depicts the top writer’s output in recent decades, with most authors publishing annually. The map of the co-authorship collaboration network is shown in Figure 6. Co-authorship is a type of collaboration in which two or more researchers report their findings on the same publication document. The main goals of co-authorship networks are to help understand scientific collaboration patterns, collect collaborative statistics, and propose accurate and reliable methods for recognizing prominent authors [41]. The nearest circles show the researcher’s close scientific collaboration, and the related items show social cooperation. Simulation output shows collaborative research is more common than single authorship in microgrid system issues. The results show Joseph M Guerrero has the most significant research collaboration with a solid social partnership.

3.3. Sources analysis

The top twenty influential sources on microgrid system fields from 2010 to 2021 were analyzed and represented in Figure 7. It shows that seven journals had more than 100 publications related to microgrid systems. IEEE Transactions on Smart Grid reached first place with 409 relevant documents. The Institute of Electrical and Electronics Engineers (IEEE) publishes the most appropriate top sources. The source growth of IEEE and other major journals is shown in Figure 8.

Bradford’s law describes the spread of citations for a specific subject or field [42]. Bradford's law has been used to make a case about building collections, choosing journals to be indexed in bibliographies, measuring bibliography coverage, solving practical problems related to information seeking and retrieval, organizing bibliographical work, and documentation [43]. Therefore, it can find the most referenced journals

in a particular area or issue. This research identified essential publications in microgrid system domains using currently recognized formulations of Bradford's law. The result shows that the cluster of sore sources in the microgrid system constituted only nine journals, as shown in Figure 9.

3.4. Word analysis

After observing and analyzing the relevant author and sources, the three-field plot analysis is performed. The left field contains the pertinent authors, the center field contains the journal (sources), and the right includes the keywords. Figure 10 shows the distribution of authors and representation of the sources contributing the most to the worldwide most representative keywords. The authors contribute to several relevant journals with various keywords related to the microgrid system.

The word analysis subsection includes the research title, keyword, and abstract related to the microgrid system employed. In the broad field of microgrid systems, publication keywords might provide helpful indications of research subjects and interests, thereby indicating the most explored issues. Figure 11 depicts the top ten themes regarding overall occurrences, as stated in the research title. The word "microgrid", "system", "DC", and "hybrid" are at the top rank because of part of the primary keyword code. In addition, the selection word "droop control", "distributed generation", "energy management", "renewable energy", "smart grid", "energy storage", "hybrid AC/DC microgrid", and "distributed control" are frequently used in the research title on microgrid system.

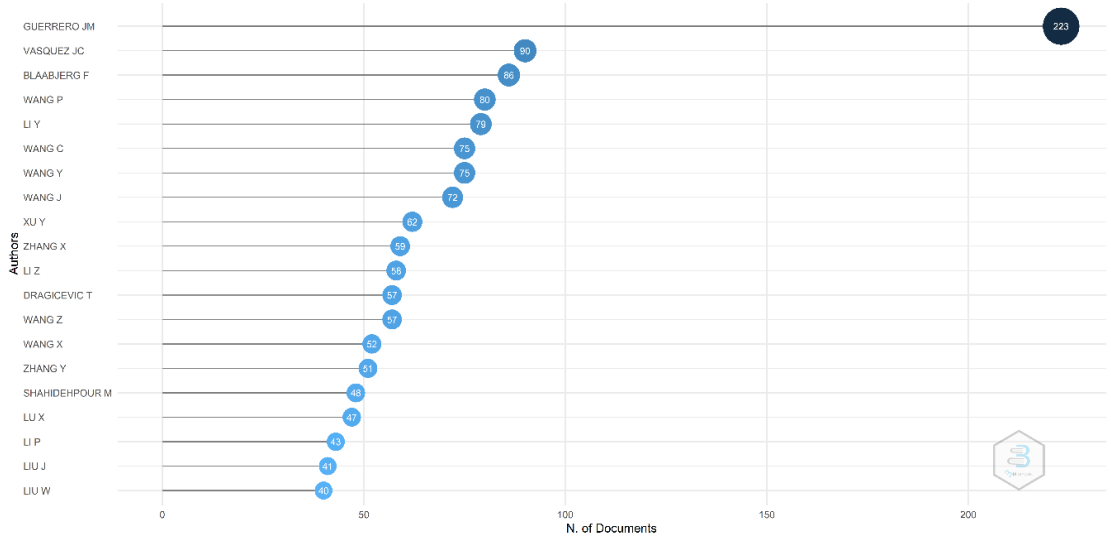

Figure 4. The top twenty relevant authors who research the issues of a microgrid system

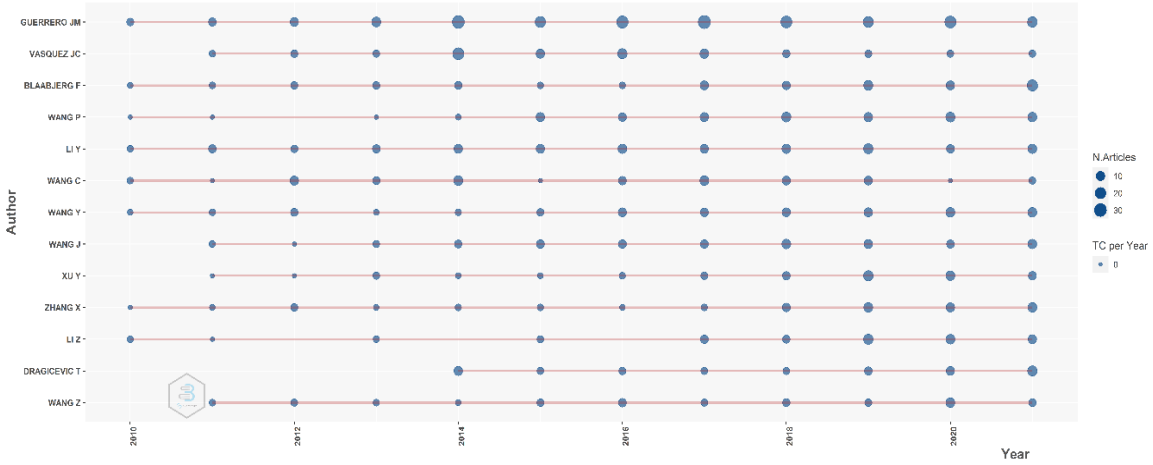

Figure 5. The top-authors production in the field of microgrid from 2010 to 2021

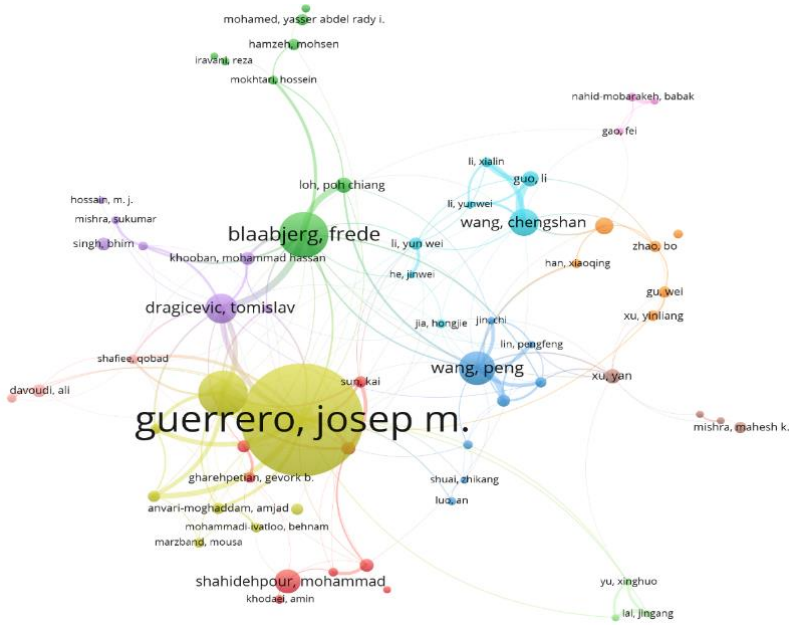

Figure 6. The co-authorship collaboration network in Scopus related to microgrid from 2010 to 2021

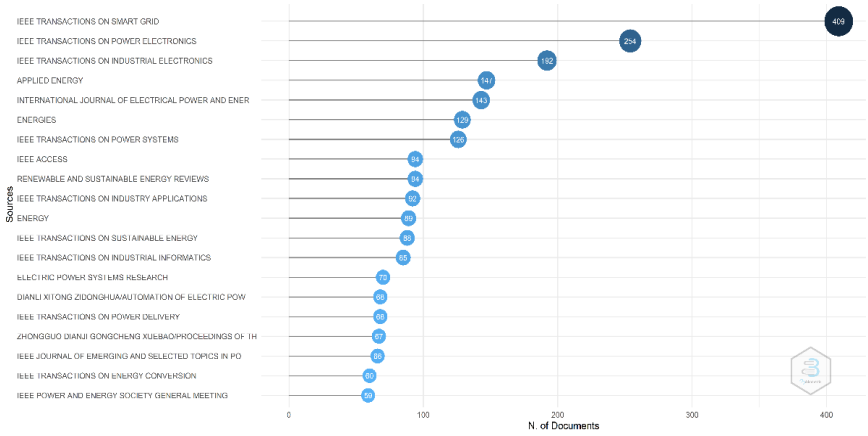

Figure 7. The most relevant sources in microgrid systems are from 2010 to 2021

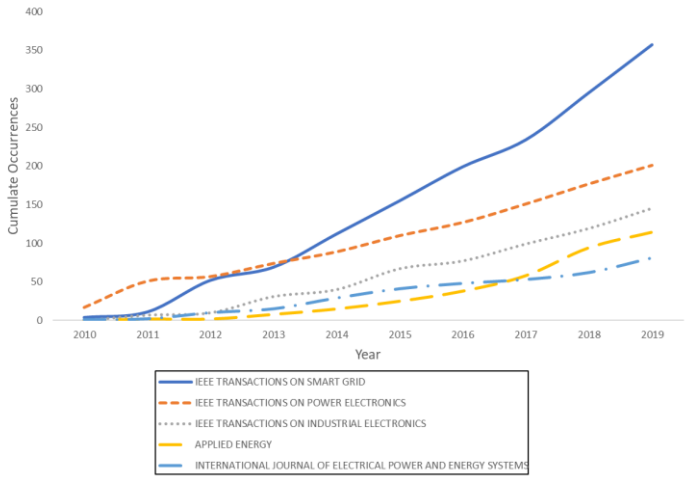

Figure 8. The top source of growth in microgrid systems from 2010 to 2021

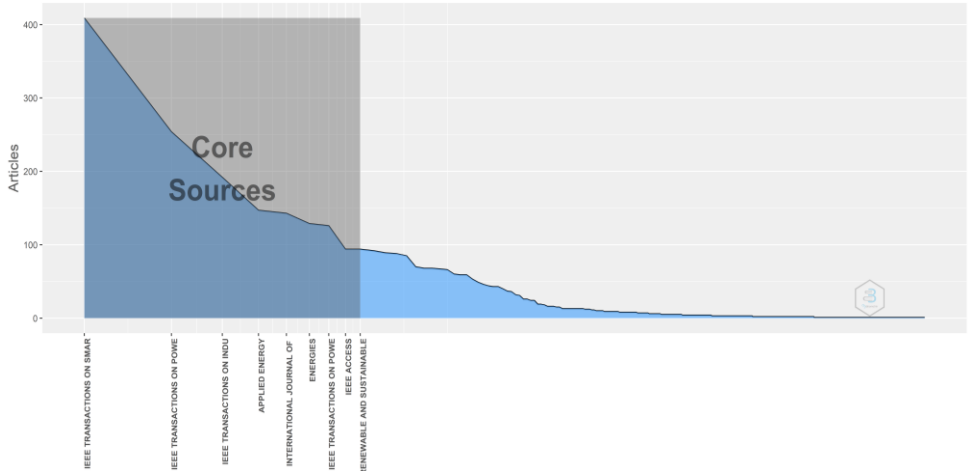

Figure 9. The Bradford's law analysis in Scopus related to microgrid system from 2010 to 2021

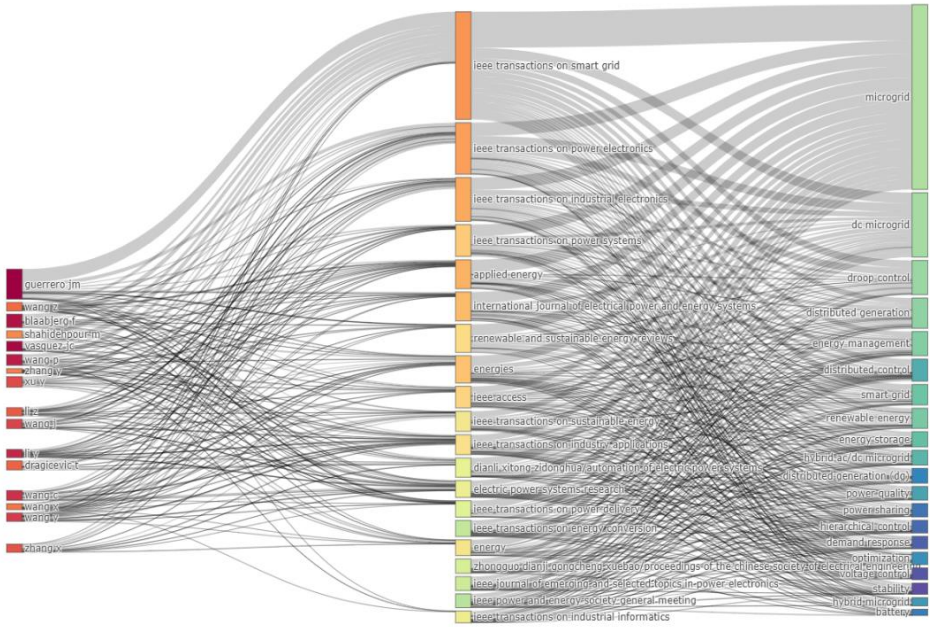

Figure 10. The distribution of authors (left) and the representation of the sources (center) with the most significant contributions to the globally most representative keywords (right)

Depending on its frequency and relevance, a word cloud is a visual representation of words (a tag cloud, wordle, or word collage) [39]. The most globally representative keywords related to the microgrid system topic using word cloud are shown in Figure 12. The keyword "DC microgrid", "distributed control", "distributed generation", "droop control", "energy management", "energy storage", "hybrid AC/DC microgrid", "microgrid", "renewable energy", and "smart grid" are the most frequently used in microgrid system fields. The top keyword dynamic from 2010 to 2021 is shown in Figure 13.

For the research areas of interest represented using keywords, a treemap was created with the 50 most used keywords, as shown in Figure 14. Treemap visualization employs and integrates numerous different layout principles [44]. Treemap is excellent for displaying enormous amounts of hierarchically organized data (tree-structured). The visualization's space is divided into rectangles sized and sorted according to a quantitative variable. This map is helpful for quickly understanding the critical terms and comparing the topic. For example, the keyword of "DC microgrid", "droop control", "distributed generation", "energy management", "renewable energy", and many more are the most exciting research areas in the fields of a microgrid system.

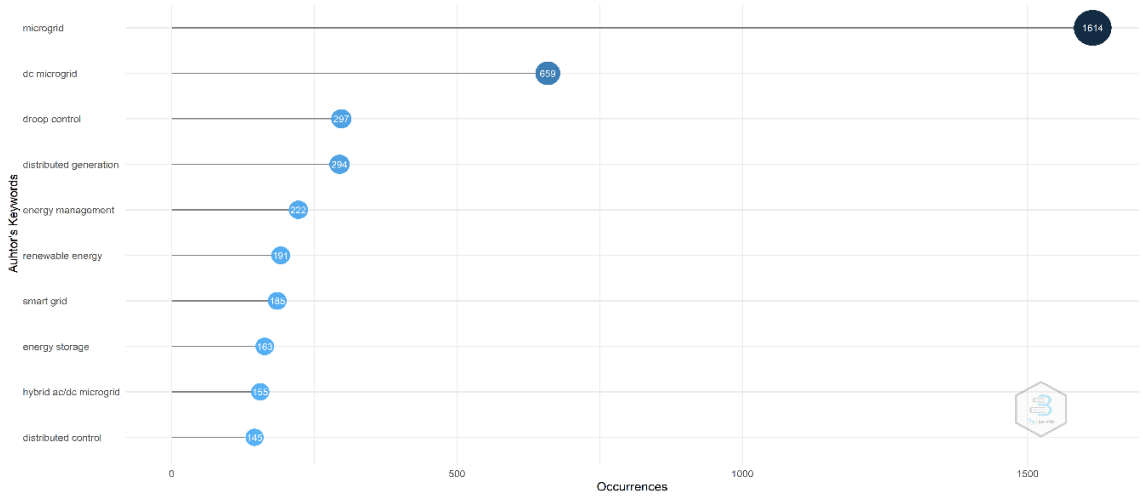

Figure 11. Most relevant research title in microgrid systems from 2010 to 2021

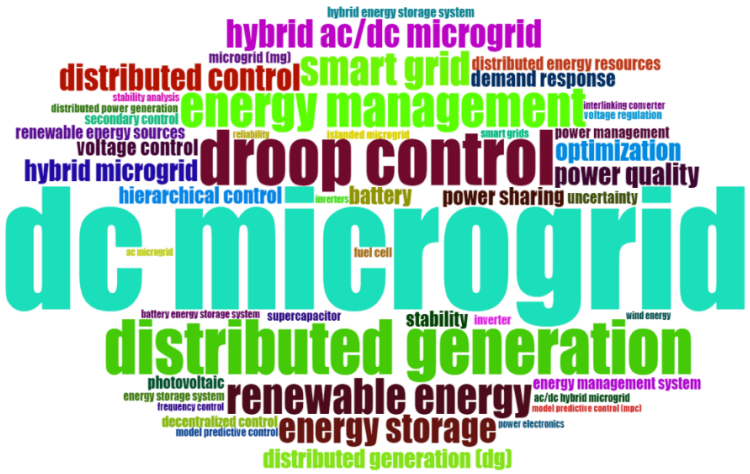

Figure 12. Scopus's most globally representative keywords related to microgrid systems from 2010 to 2021

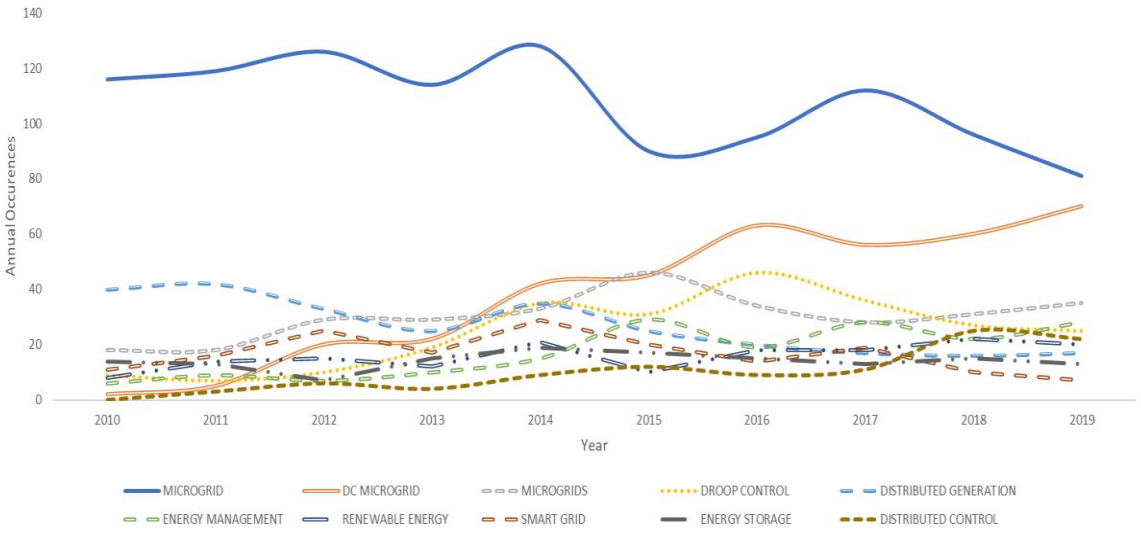

Figure 13. Word growth in the microgrid system field in the microgrid system from 2010 to 2021

Figure 14. Research areas of interest in Scopus related to microgrid systems from 2010 to 2021

Figure 15 presents a network visualization map of co-occurrence combinations of title and abstract in the microgrid system research domain in the following simulation results. The frequent words are shown by the items (circles). The weight of an item determines the item's size (label, ring, or frame). The wider the circle or structure of an item, the greater its weight (importance). The links between the elements are represented by the lines connecting them (keywords) [45]. The microgrid system field of research can observe in three main word clusters (red, green, and blue). The most critical being in the central point (red) consists of "microgrid", "model", "generation", "cost", "renewable energy source", "integration", and others. The second cluster consists of "control", "converter", "DC microgrid", "frequency", "voltage", "stability", "power quality", and others. The last cluster (blue) consists of "battery", "stage", and "charge". The words "microgrid" and "control" have the most comprehensive abstract and title related to microgrid system research.

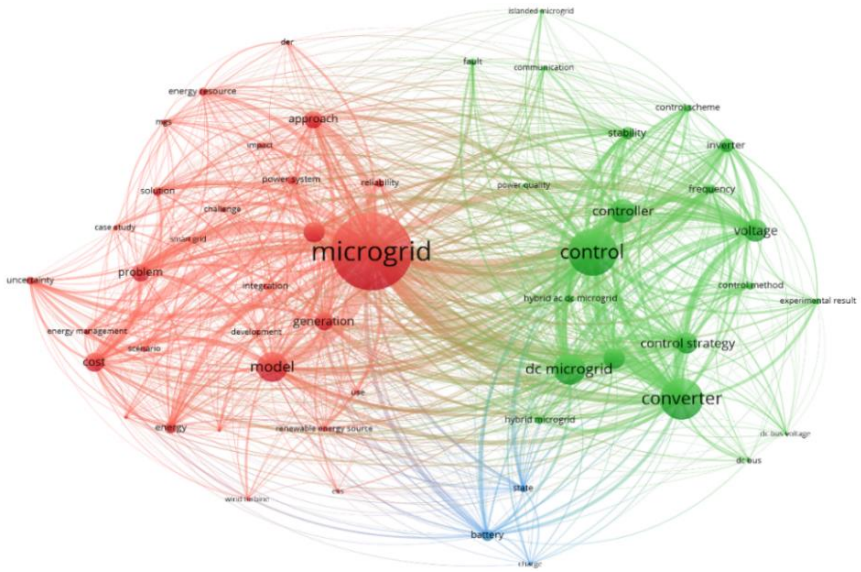

Figure 15. The title and abstract fields with the strongest link in Scopus related to the microgrid system from 2010 to 2021

3.5. Evolutionary path of research analysis

The evolutionary path of microgrid system research consists of three primary analyses: thematic evolution, thematic map, and trending topic analysis. Moreover, the evolution study reveals the content's changing laws, evolutionary relationships, routes, and trends through a statistic. This analysis also depicts the subject's intensity and structure over time. A subject evolution study helps determine a field's development environment, define its direction, and forecast future trends [46]. According to the thematic evolution of research keywords Figure 16, the term "microgrid" was integrated with "power quality" and "model predictive control (MPC)" issues in the 2010 to 2017 period. In the same way, "distributed power generation", "battery", and "voltage control" were included in microgrid research in the 2018 to 2021 period. The term "DC microgrid" in the 2010 to 2017 period is integrated with "hybrid AC/DC microgrid" and "MPC" from 2018 to 2021.

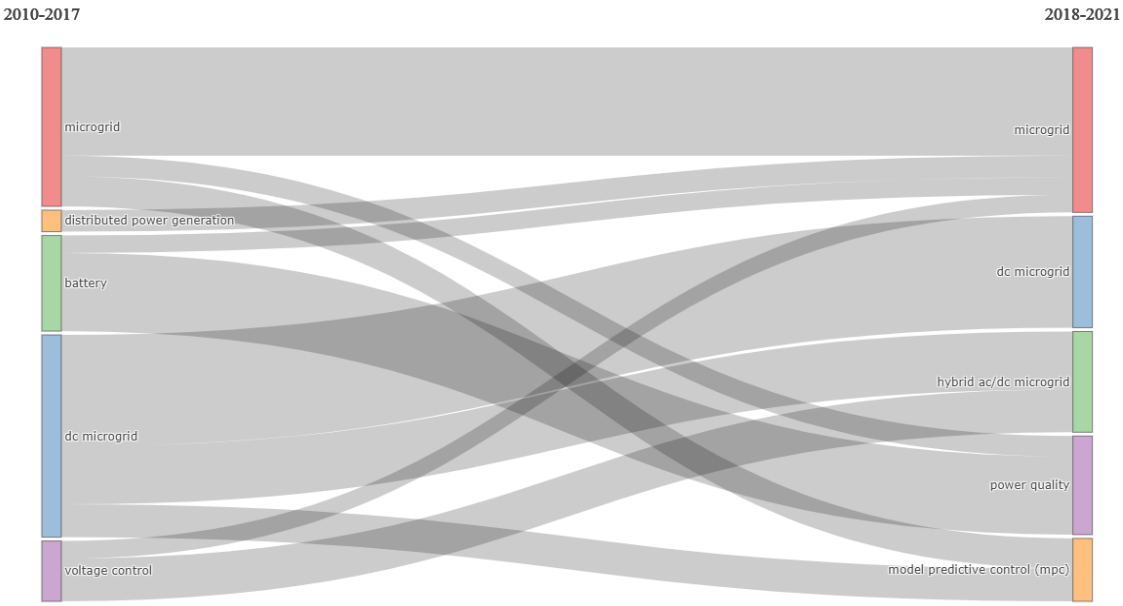

Figure 16. Thematic evolution in the field of microgrid systems from 2010 to 2021

The thematic evolution in microgrid systems is research results in evolutionary statistics and structure over time. Thematic evolution in microgrid system research is integrated with distributed power generation, battery, and voltage control. Most distributed power generators system (DPGS) in the microgrid are powered by renewable energy resources. This condition could be disconnected from the primary grid and operate in islanded mode [47]. The DPGS connected to converters parallel to the grid is distinguished by their contribution to forming the grid voltage and frequency. This condition changed the traditional structure of the electric distribution grid [48]. A study from [49] investigates the modeling and control of a battery management system used in a microgrid for both grid-connected and autonomous modes. The higher renewable energy penetration level may create challenges like unstable frequency voltage and complicated power management and interaction with the utility grid. The recent experiment from [50] results in good performance instability under a variation in production and consumption.

The thematic evolution in DC microgrid is integrated with MPC and hybrid DC/AC microgrid. Predictive control has much potential in microgrid applications because of its fast transient reaction and flexibility to suit diverse restrictions. The study from [51] comprehensively reviews MPC in individual and interconnected microgrids, including converter-level and grid-level control strategies. As a result, in frequency control, voltage regulation, economical operation optimization, and power flow management, MPC use in microgrids appear as a viable alternative to conventional approaches. The DC microgrids may be more beneficial than AC microgrids. This system eliminates the need to synchronize generators, minimizes the need for converters, simplifies the connection of various types of renewable energy resources and loads to the microgrid common bus, and minimizes the losses associated with AC/DC energy conversion [52]. The study from [53] shows a hybrid DC/AC microgrid with central and distributed battery energy storage systems (BESS), applying a power-sharing mechanism between the different devices in the system. An adaptive power-sharing mechanism between the DC and AC bus for voltage control based on distributed BESSs.

In the thematic map (also known as a strategic diagram) based on keywords, see Figure 17, four zones consider two variables: relevance degree (centrality) and development degree (density). Centrality refers to the degree of interaction of one cluster with another, and density refers to internal cohesion. In other words, the higher centrality, the higher relevance of the term, and the higher density, the higher development of the time [54]. The cluster keyword of "microgrid", "distributed generation", and "energy management", and the cluster keyword of "DC microgrid", "droop control", and "hybrid AC/DC microgrid" categorize on motor themes. These themes are well developed and vital for the structure of the microgrid research field. The cluster keyword of "distributed generation (dg)", "voltage control", and "microgrid (mg)" are categorized in emerging themes. These themes in the lower-left quadrant have low density and low centrality and mainly represent emerging or declining themes. The cluster keyword of "power quality", "battery", and "photovoltaic" categorize basic and emerging themes. Pieces in the lower-right quadrant are neutral for a research field but are not well developed. The cluster keyword of "power electronics", "microgrid control", and "fault detection" are categorized between emerging and niche themes. These themes have neutral developed but marginal importance for the field.

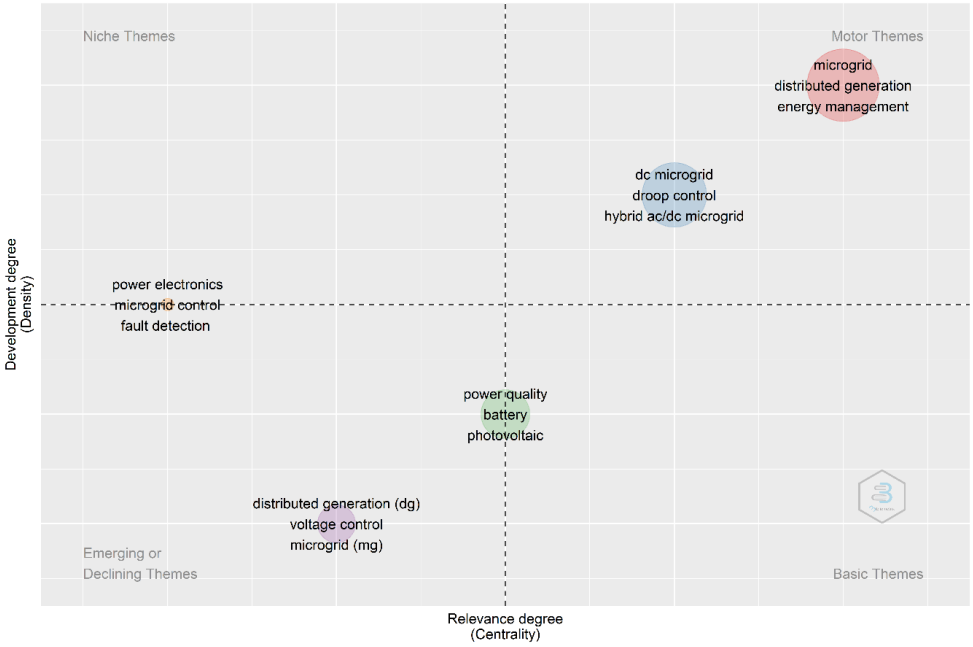

Figure 17. Thematic map based on density and centrality in microgrid systems from 2010 to 2021

The cluster (DC microgrid, droop control, and hybrid AC/DC microgrid) categorize as motor themes. Without relying on vital communication channels, linear droop control can provide power-sharing across generators in a DC microgrid. However, with uncertainties and disturbances from renewable sources and loads in the DC microgrid, the droop connection between output power and voltage magnitude of renewable power generating systems is nonlinear. The sliding mode droop controller is intended to compensate for uncertainties and disturbances to obtain accurate power-sharing results [55]. The second cluster (microgrid, distributed generation, and energy management) is the motor theme in the thematic map. The rapid development of distributed generation makes microgrids connect with multiple microgrids to provide a regional power supply. Microgrids should be managed by an energy management system (EMS) that facilitates the minimization of operational costs, economical operation of the interconnected power system, reliability, emissions, and peak loads while satisfying the microgrid technical constraints [56], [57].

The trending topics based on keywords in microgrid system research from 2010 to 2021 are shown in Figure 18. The research keyword of "power-sharing control", "electricity market", and "multiagent system" are trending topics throughout the decade but have low term frequency. Today's research keywords related to microgrid systems are "cyber attacks", "mathematical model", "machine learning (ML)", and "sliding mode control (SMC)".

Recent microgrid systems research is cyber attacks, mathematical models, ML, and SMC. Distributed control in microgrids is known for reliability and scalability. However, the absence of a global monitoring entity makes it highly vulnerable to cyber-attacks. Furthermore, the accuracy in detecting the compromised

link becomes critical due to the dynamic relationship between the cyber-physical entities in the microgrid [58]. The mitigation is accomplished with the help of a novel event-driven attack-robust controller for N cooperative grid-forming converters, which ensures resilient synchronization for up to N-1 attacked units [59]. Study [60] derives a mathematical model of a DC microgrid consisting of photovoltaic arrays, BESSs, and grid-tied converter, employing a distributed control algorithm. The mathematical model focus on converters with their voltage, current, and droop controllers to ensure stability in all operating modes. A study from [61] utilizes machine learning in real-time using cloud resources in a virtual server for microgrid control and setting the EMS. SMC is employed as additional input as an energy reshaping mechanism [62]. Another work focuses on the load frequency control (LFC) for a multi-area interconnected microgrid power system with communication networks. A robust SMC strategy based on the adaptive event-triggered mechanism is proposed against the frequency deviation caused by power unbalance or time delays [63].

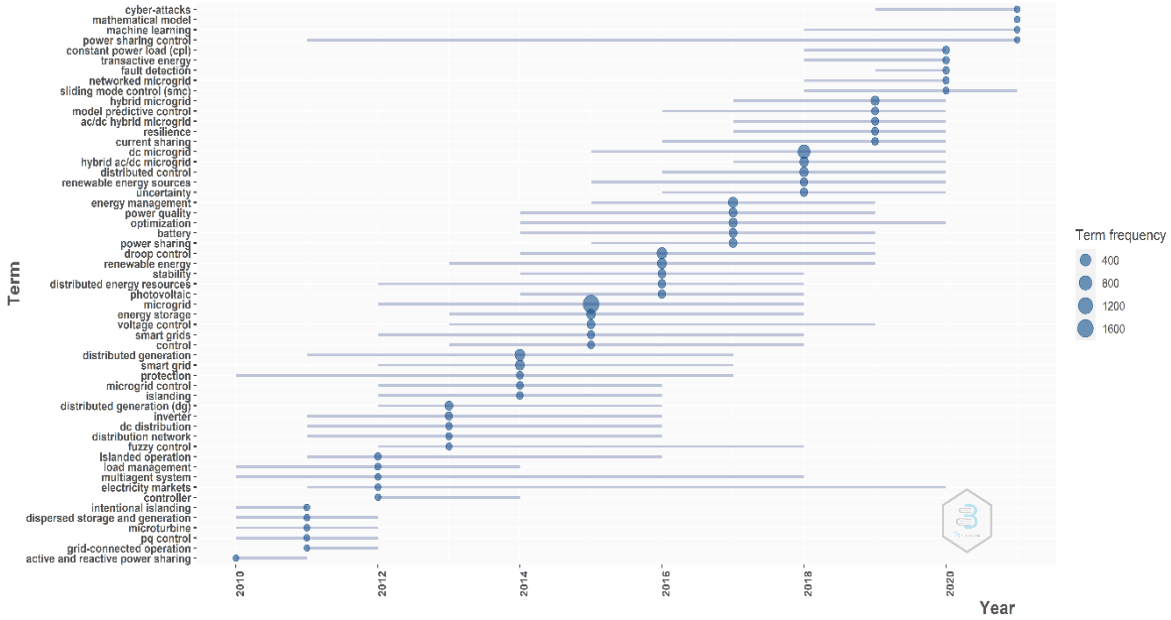

Figure 18. Trending topics in Scopus related to microgrid systems from 2010 to 2021

4. CONCLUSION

This study has researched microgrid system fields through descriptive analysis, authors analysis, sources analysis, word analysis, and evolutionary path of research analysis from 2010 to 2021. The research's limitations are related to the bibliometric analysis, which was conducted solely utilizing the Scopus database, which has a high academic and scientific reputation and extensive coverage of scientific articles. The descriptive analysis results show that the number of scientific publications related to microgrid systems has continued to increase from publication trends, where the annual growth rate is about 8.23%. The author analysis shows that the significant author contribution to this research topic predominates from Aalborg University, Denmark, and many top authors on the statistical results. The authors have solid social networks and collaboration. From the sources of publication perspective, seven journals had more than 100 publications related to microgrid systems, whereas IEEE Transactions on Smart Grid reached first place with 409 relevant documents. The word analysis shows DC microgrid is most appropriate and frequently used in the research title and keyword. The co-occurrence network based on combinations of title and abstract indicates the field of research with a solid link divided into three main words clusters: microgrid, control, and battery. The evolutionary path of research analysis shows that the term DC microgrid from 2010 to 2017 was integrated with hybrid AC/DC microgrid" and MPC issues in the 2018 to 2021 period. The cluster keyword of microgrid, distributed generation, and energy management, and the cluster keyword of DC microgrid, droop control, and hybrid AC/DC microgrid are categorized on motor themes, which are vital and well developed for the structure of the microgrid research field. The research keywords of power-sharing control, electricity market, and multiagent system have been trending topics throughout the decade but have a low frequency. Today research keywords move to cyberattacks, mathematical models, ML, and SMC.

APPENDIX

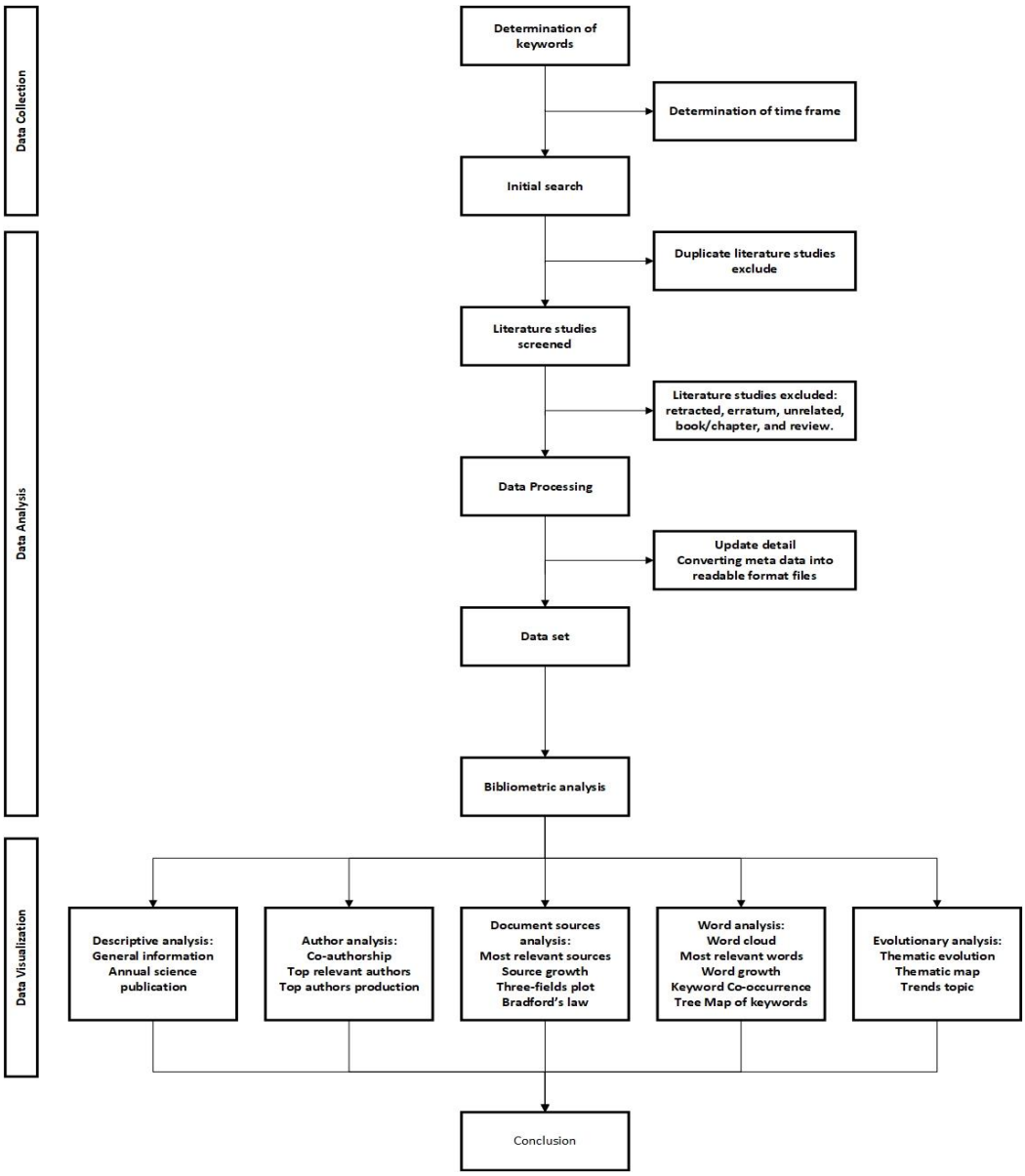

Figure 2. Research flowchart

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