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RESEARCH ARTICLE

Recent Development of Grid-Connected Microgrid Scheduling Controllers for Sustainable Energy: A Bibliometric Analysis and Future Directions

M. MANNAN[1], M. MANSOR[2], M. S. REZA[3], M. F. ROSLAN[2], PIN JERN KER[3], (Senior Member, IEEE), AND M. A. HANNAN[4,5]

[1]Department of Electrical and Electronic Engineering, Universiti Tenaga Nasional, Kajang 43000, Malaysia
[2]Institute of Power Engineering, Universiti Tenaga Nasional, Kajang 43000, Malaysia
[3]Institute of Sustainable Energy, Universiti Tenaga Nasional, Kajang 43000, Malaysia
[4]School of Engineering and Technology, Sunway University, Bandar Sunway 47500, Malaysia
[5]School of Electrical Engineering, Korea University, Seongbuk-gu, Seoul 02841, South Korea

Corresponding authors: M. A. Hannan (hannan@sunway.edu.my) and M. Mansor (muhamadm@uniten.edu.my)

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ABSTRACT This study presents a comprehensive bibliometric analysis of grid-connected microgrid (MG) scheduling controller techniques. An extensive search was done in the Scopus database using preset parameters to extract articles relating to the MG scheduling controller. The selection of the most cited paper involved careful keyword filtering on grid-connected MG scheduling controllers over the period from 2013 to 2024. Within the timeframe, a total of 115 top-cited articles were extracted, focusing on the scheduling controller algorithms applied to the grid-connected MG system. These highly cited articles originated from a diverse source, encompassing 49 distinct journals, spanning 28 different regions, and representing the publications of 7 distinct publishers. This paper seeks to identify and analyze the highly referenced published articles in the relevant area to yield an in-depth analysis of advanced controllers and optimization strategies in MG energy management systems. The key challenges such as power electronic interface, quality, controller, safety and optimization were also highlighted to provide the clearest insight on the recent MG development. Valuable recommendations for future research directions are also provided, aimed at promoting the sustainable growth of MGs. A substantial total of 63.56% articles were published based on simulation while 18.6%, 13.95% and 3.87% of total articles were published on the experimental setup, critical analysis and review-based study. Therefore, it can be inferred that ongoing research and development efforts continually seek to improve the sustainability of MG systems within the electric power sector. The bibliometric analysis was employed to identify pivotal research publications concerning grid-connected MG scheduling controller technique. This analysis aimed to delineate the multidisciplinary nature, illustrate trends, and outline areas warranting further research in the field. Thus, to ensure an effective, economical, reliable, and sustainable power supply, this analysis will broaden the scope and offer context for the development of MG scheduling controller integrated grid systems.

INDEX TERMS Energy management system, grid-connected, microgrid, optimization, scheduling controller.

I. INTRODUCTION

A microgrid is a unified entity comprising distributed energy resources (DERs) such as renewable energy sources (RESs), energy storage, and loads and it is capable of localized operation under centralized control [1]. MGs exhibit diverse configurations based on their size and functions, existing in both grid-connected and isolated modes. Grid-connected MGs are linked to a broader power network through a Point of Common Coupling (PCC), requiring seamless transition

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capability into an islanded mode [2]. During grid-connected operation, the MG can either provide power to or adopt power from the adjacent grid, depending on the system's generation and load demand [3]. MGs are key players in the field of grid resilience and reliability [4]. They are essential in supporting the stability of electricity networks [5]. However, integrating multiple DG within an MG system introduces challenges in controlling the system, causing issues in power quality, security, stability, resilience and reliability [6]. Inadequate MG control can lead to instability in the overall grid's dynamic and transient responses due to power-sharing procedures that arise, particularly during islanded mode operation in the event of power disruptions [7]. Therefore, it is essential to implement an energy management system (EMS) in an MG, encompassing controllers and optimization techniques, that aim to minimize power consumption, improve energy storage system efficiency, and enhance the quality of services offered to consumers [8].

For MGs, a scheduling controller is crucial for managing power exchange with the main grid and distributing energy from various sources to meet load demands [9]. However, the intermittent nature of renewables like solar and wind makes this challenging due to weather-related fluctuations in power generation [10]. Optimization is extensively studied for energy management scheduling controllers, as it offers significant benefits such as high accuracy, adaptability, computational intelligence, and improved exploration and exploitation capabilities [11]. However, implementing optimization algorithms presents various challenges, encompassing numerous variables, intricate computations, time-intensive processes, early convergence, and difficulties in achieving global optimal solutions [12]. Hence, deeper investigation is essential to advance the development of enhanced controllers and optimizations for energy management systems within MGs. In this context, the study aimed to analyze existing scholarly articles to investigate the trends in the field of ''Grid-connected MG scheduling controller'' and optimization techniques and assess potential connections between published studies and advancements in integrating MG energy management systems to achieve sustainable development based on bibliometric analysis.

Various techniques have been employed to perform analysis, including traditional analytical methods, main path analysis, and bibliometric analysis. Bibliometric analysis is essential for its ability to offer specific historical insights, which can be utilized for predicting forthcoming research trends. Bibliometric provides a key benefit by enabling scholars to conduct comprehensive analyses on specific research areas. This includes evaluating factors like citations, analyzing authorship, geographic location, evaluating university affiliations and administrators, and extracting immensely valuable insights. However, evaluating highly cited articles can aid in recognizing notable positions within the research domain and indicating directions for further investigation. Employing bibliometric methodologies, this study offers novel empirical perspectives on academic publication and impact assessment. To ensure impartiality, certain limitations are necessary when choosing the most highly cited articles in a field. For instance, individual citation practices can influence citation rates, and older publications may accumulate citations over time, potentially distorting the selection process.

In various fields, this phase of bibliometric analysis has identified the most frequently cited literature. For instance, research fields like microgrid systems [13], LIBs in electric vehicle [14], power systems [15], cost assessment for EV [16], area in sustainability committee [17], ES optimization and controller scheme [18], Energy optimization tendencies [19], Blockchain and energy [20]. However, there has been no prior investigation employing bibliometric analysis to examine published papers concerning research on scheduling controllers for MG EMS. Emerging from limited academic exploration and resources, this article serves as a valuable resource for researchers engaged in grid-connected scheduling controller studies, aiding in generating novel insights, expanding scientific knowledge, and identifying unexplored research directions.

This study explored scientific literature by examining highly cited articles, prominent authors, leading countries, co-occurring keywords, study types, subject areas, and the affiliations of the top 10 profiled authors. The key contributions of this research encompass the following:

- Enhance researchers' comprehension of the historical background, evolutionary progress, present advancements, and contemporary trends within the field of MG scheduling controllers for energy management.
- Provides a comprehensive examination of contemporary controllers and optimization strategies within MG energy management systems. The analysis focuses on the goals, advantages, and limitations of the top cited 115 papers chosen for study.
- A thorough analysis is conducted on the variety of existing concerns and challenges related to power electronic interface, power quality, energy management, safety concerns, scheduling, and optimization and controller execution problems.
- Contributes valuable recommendations for future advancements, offering effective suggestions to explore potential directions and promote the growth of MGs.

The paper is arranged as follows: The second section outlines the analyzing procedure and the bibliometric approach employed to analyze extensively cited publications. This encompasses criteria for inclusion and exclusion, the selection process, identification of research trends, and data extraction from the Scopus database. The third section describes a comprehensive analytical discussion including research, citation analysis, article distribution across journals, publishers and countries, authors and co-authors, keywords co-occurrence, types of study, and subject areas. The fourth section presents a discussion of the most frequently used controller and optimization techniques. In section five, issues and challenges are described related to grid-connected

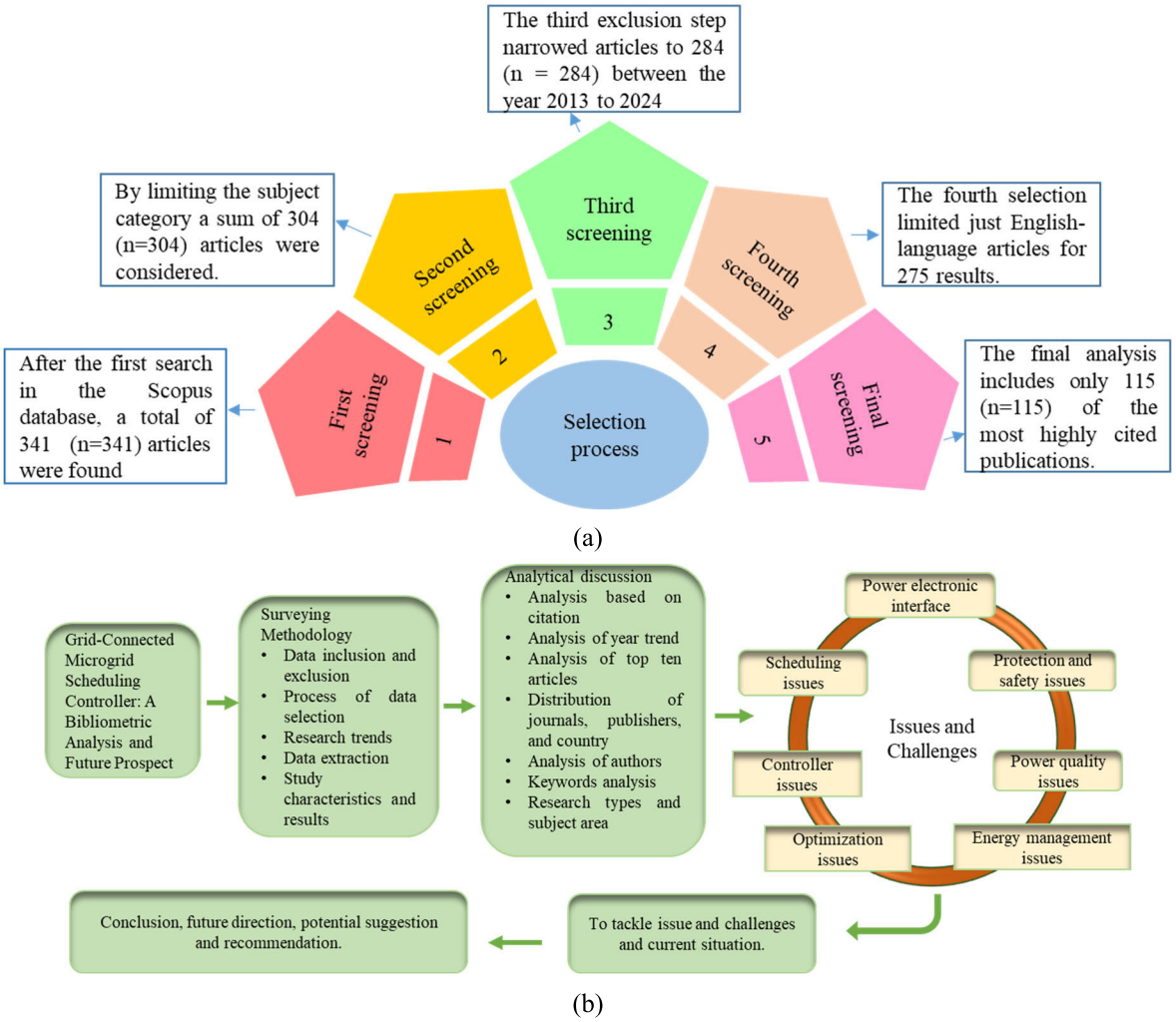

FIGURE 1. Overall methodology in grid-connected MG scheduling (a) selection process of the top 98 articles and (b) analyzing process.

MG EMS. Section six includes useful recommendations as well as concluding thoughts for future research.

II. SURVEYING METHODS

This research employs a widely accepted scientific methodology called bibliometric technique to evaluate it. This research aims to extract the main characteristics of highly cited publications to enhance the analysis of grid-connected MG scheduling controllers. To learn about the current state of scientific research in this large field, searches were executed in the final week of March 2024 for the years 2013 to 2024 based on the Scopus database. The date of the search was set for the final week of March 2024 since the number of publications may have varied as more items were published in the meantime. The initial search was done based on the keywords ''Microgrid'', ''scheduling controller,'' and ''grid-connected''. The ''Subject filter'' was chosen to find related articles. Due to limited resources, the filter called ''English Language'' was one of the options. To arrange the articles in a specific order, some sorting criteria were utilized, including ''Times cited highest to lowest'' and two of them are the ''excluding self-citations'' filter. There were multiple articles discovered, but only the significant articles were recognized by analyzing the manuscript's title, topic area, abstracts, intense focus, and references. Figure 1 illustrates the overall analyzing process in the field of grid-connected MG scheduling.

A. DATA INCLUSION AND EXCLUSION

The process of gathering and analyzing Scopus publications involves applying various criteria, as described before in this study. The following are the specifics of the inclusion and exclusion criteria used to select the 115 most cited published works in grid-connected MG scheduling controllers:

- The collecting process includes all articles addressing MG, scheduling control, and grid-connected systems. The study's exclusion criteria would be to limit the subjects of papers published to only ''Engineering'', ''Energy'', ''Environmental Science'', ''Mathematics'' and ''Materials'' subjects, which would narrow down the number of publications available.

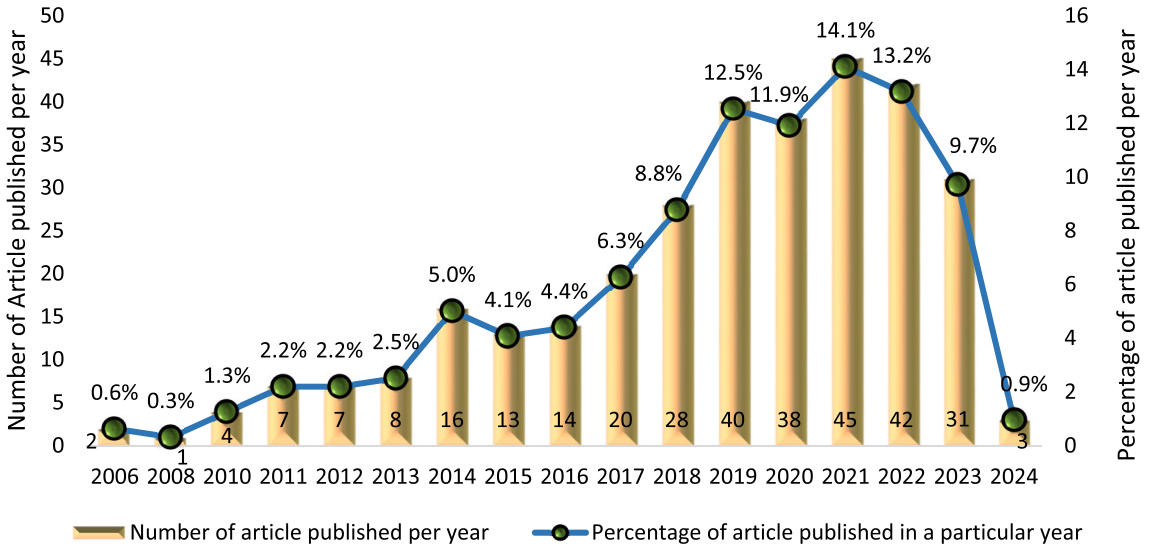

FIGURE 2. Research trends in the field of grid-connected MG scheduling from 2006 to 2024.

- To be considered for the analysis, the papers must be published from 2013 to 2024.
- Only articles published in English are included in the data collection and selection process.

B. PROCESS OF DATA SELECTION

- Following the initial search, 341 articles (n = 341) were chosen.
- The second step reduces the number of publications available to 304 (n=304) by focusing on the subjects like ''Engineering'', ''Energy'', ''Environmental Science'', ''Mathematics'' and ''Materials''
- The third exclusion step limited articles to those published between 2013 and 2024, resulting in 284 (n = 284) articles.
- The fourth screening further reduced the available published papers to 275 (n=275) by considering only English language articles.
- Lastly, only 115 (n=115) of the most highly cited publications are chosen for the study's final analysis and commentary.

Bibliometric analysis serves as a widely adopted method for domains and examining the interconnections among various disciplines. However, it's important to acknowledge several limitations in our analysis. Firstly, we relied solely on the Scopus database for article selection, suggesting the inclusion of other platforms such as Web of Science, Google Scholar, Science Direct, and IEEE Explore in future studies. Secondly, the articles lacking mention of the research area were excluded. Thirdly, the analysis was confined to publications spanning the past 12 years (2013 to 2024). Fourthly, only top-cited articles from the database were considered. Additionally, a specific subject category was applied, focusing on publications containing keywords such as Microgrid, Scheduling, Controller, EMS, and Grid-connected. Despite these constraints, bibliometric analysis remains a valuable tool worldwide for gaining insights into specific research areas and historical trends within a particular field of study, assessing current advancements, scrutinizing specific research.

C. RESEARCH TRENDS

Throughout the selection process, it becomes evident that an ever-growing community of scholars holds a keen interest in controllers for scheduling grid-connected MG. Figure 2 presents a visual representation of the analysis spanning from 2006 to 2024, showcasing the annual publication trends. The first article in this field was found in 2006 according to the Scopus database. Since then, the volume of publications has exhibited a consistent upward trend. Figure 2 shows that the number of researchers interested in grid-connected MG scheduling controllers has also increased over the years to 2024. Between 2019 and 2024, a substantial total of 199 articles delved into various aspects of grid-connected MG scheduling controllers. However, the earlier 13-year period, spanning from 2006 to 2018, there were 120 articles published. This earlier period contributed 37.7% to the overall body of work, while the subsequent six years accounted for an impressive 62.3%. It is noteworthy that 2021 stood out as a particularly prolific year, with 14.1% of the total articles published. Based on last year's trend, an increasing number of publications is expected.

D. DATA EXTRACTION

For comprehensive and rigorously curated data of the research, the Scopus database is choose as the primary source, and each data was extracted and selected according to predefined criteria. The following are details about the data collected from the chosen publications:

- Documents title and digital object identifier (DOI).
- Author's information
- Keywords designated by the author

- Year of publication
- Source title
- Publisher
- Methods and systems
- Research gap
- Document type
- Study type
- Subject area
- Author's country
- Citation number
- Impact factor

Further analysis has been done and given based on the extracted information to illustrate the current stage of research work related to grid-integrated MG scheduling controller.

E. STUDY CHARACTERISTICS AND FINDINGS

In this research a total of 341 publications were identified through the initial screening of the Scopus Database. After carefully selecting the top 115 papers, the cumulative number of citations for these 115 highly regarded articles amounted to an impressive 4329 citations, with individual articles garnering ranging from 0 to 631 citations. The most recent year's innovative publications attracted a greater number of citations compared to the total citations of the previous year. It is observed that the top cited publication is "IEEE Transactions on Sustainable Energy" which is published by IEEE and has an impact factor of 8.8. The United Nations and China have published a total of 35 papers among 115 highly cited papers, which shows the greatest interest among the researchers in that region. Overall, the rising number of cited articles focused on grid-connected MG scheduling controllers indicates a high level of growing research enthusiasm within the relevant academic community.

III. ANALYTICAL DISCUSSION

To gain a comprehensive understanding of a particular field, it is essential to categorize and analyze the prevailing research trends. The fundamental objective of this paper is to provide a clear overview of the current research direction and to explore the most influential research publications within the expansive field of grid-connected MG scheduling controllers and EMS. An extensive and recognizing analysis is conducted to clarify the current state and to serve as a valuable resource for prospective researchers, providing them with a more complex and significant understanding of the field of MG scheduling controllers.

A. ANALYSIS OF YEAR TREND

From Figure 3, it can be observed that the highest number of articles were published in both 2019 and 2020 which have the same number of 18 articles published. On the other hand, 3 articles were published in the year 2013 which is the lowest publication. The average citation per year (ACY) in 2013 was the highest followed by 24.4. We have considered the base of ACY as 2 for the fair selection of the most influential

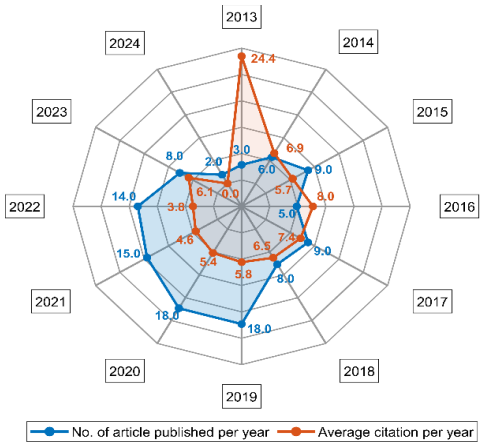

FIGURE 3. Top 115 articles distribution from the year 2013 to 2024 and ACY per year.

articles because earlier articles get more time to cite. The number of articles published between the years 2019 to 2021 was 51, whereas 40 articles were published in the last 6 years from 2013 to 2018. It shows the greatest interest among researchers in recent years except in 2024. As we select the top highly cited articles, the number of articles published in 2022 and 2023 could be higher.

B. CITATION ANALYSIS

The citation is an alphabetic expression that acknowledges the significance offered by the author to the contribution of others regarding a topic being discussed in the context of the citation. Citations are used primarily to give original writers credit for their published work and concepts. In general, an author's credibility in their field increases as their citation history grows. Citation analysis is a bibliometric procedure that entails the analysis of the citation pattern of published data.

According to Table 1, the top 10 reference articles were determined to be the most prominent works in the field of grid-connected MG scheduling controller research to date, making them a good indicator of general trends and interests in the broader field. It can be observed that from the selected Scopus database the most highly cited article was by Zhang et al. [21]. The article was published in 2013 in the journal IEEE Transactions on Sustainable Energy with citation number 631. The article's title is "Robust energy management for MGs with high-penetration renewables" and a revolutionary scheduling strategy is proposed. The target comprised conventional generation, adjustable load utilities, DS, and worst-case transaction costs. The essential issues of this article were optimal power flow and unit commitment. The second most cited article was "Impact of communication delays on secondary frequency control in an islanded microgrid" by Liu et al. [22]. The citation of the article was 343 and published in 2015 in the "IEEE Transactions on Industrial Electronics". The research is aimed at how the communication delays in a MG with several distributed generators affect

TABLE 1. A list of the top ten most-cited publications from 2013 to 2024.

Rank	Ref	Author name (Year)	Citation	Method and system	Research gap
1	[21]	Zhang *et al.*(2013)	631	A novel power scheduling approach for renewable energy sources.	Problems in the unit commitment (UC) and the optimal power flow (OPF).
2	[22]	Liu *et al.*(2015)	343	Gain scheduling approach for communication delay.	Non-linear load and randomly time-varying delay should be included.
3	[23]	El-Hawary *et al.*(2014)	288	Real-time energy control approach for smart grid.	The development of a smart grid has not been addressed regarding its issues, challenges, and optimization techniques.
4	[24]	Tulpule *et al.*(2013)	243	An optimal charge scheduling strategy for energy economic analysis.	The methodology is applied in limited locations. It can be applied in electricity rate structures, and finance.
5	[25]	Díaz *et al.*(2017)	174	Centralized Control Architecture for Islanded MG.	Inaccuracies in predicted data compared to renewable energy generation.
6	[27]	Zhao *et al.*(2015)	170	Linear circuit model and decentralized droop control for DC MG.	More complicated process.
7	[26]	Chen et al (2015).	168	Distributed economic dispatch algorithm for multiple generators.	Lack of information control scheme.
8	[28]	Petrollese *et al.*(2016)	161	Model predictive control strategy for hydrogen-based MG.	MPC should be exploited.
9	[29]	Sarkar *et al.*(2019)	155	The smart hybrid microgrid, integrating solar PV, wind, biogas, and VRFB storage, is optimized for its design.	Replacement cost and MPPT were not considered.
10	[30]	Marzband *et al.*(2016)	131	Hierarchical bi-level control scheme for multi-MG system.	Less computational complexity and multiple smaller problems.

the secondary frequency control. A small-signal model-based approach is presented to determine delay margins and a gain scheduling strategy is used to adjust the influence of communication delay. Time-varying delays and non-linear load were not considered in the article. The third-ranked article according to citation was "The smart grid-State-of-the-art and future trends" written by El-Hawary [23]. It was a technical overview paper published in the Electric Power Components and Systems journal in 2014, receiving 288 citations. This paper talks about the smart grid and its technical, environmental, socioeconomic, and other non-tangible benefits to society. It also talks about the necessity of the idea and the fact that it is a dynamic, proactive, real-time infrastructure that interacts with the difficulties of designing and constructing the power system of the future. Tulpule et al. [24] introduced an optimal charge scheduling technique to compare an uncontrolled charging case for economic analysis. The findings highlight the effects of PV-based workplace charging on grid emissions and profitability. Additionally, the articles ranked 5 and 7 were published by Diaz et al. [25] and Chen et al. [26] focused on distributed economic dispatch algorithm and centralized control approach respectively. A linear circuit model and decentralized droop control for DC MG were proposed by Zhao and Dörfler [27] and the proposed controllers were demonstrated in a simulated environment. However, it is a complicated process Petrollese et al. [28] proposed a model predictive controller (MPC) for hydrogen-based MGs. The controller reduces the optimization cost of the MG.

C. ARTICLES DISTRIBUTION AND COUNTRY

Another important aspect of the bibliometric study of the area of grid-connected MG scheduling controllers is the distribution of selected articles among journals, publishers, and countries of origin. This helps to point future scholars in the appropriate paths. All this data about prestigious journals, publishers, and nations within the relevant field of study may be useful for collaborating with upcoming scholars and the scientific community to advance the topic. Figure 4 depicts the top 20 journals based on the number of articles published and the impact factors of the respective journals. The top 20 journals published the most papers, accounting for 70.43% of all papers published in this research area, while the remaining 29.56% of papers were published in other journals. Among them, nearly one-third of the total number of articles are published in the top five journals followed by Energies and IEEE Access each with 9 articles, Applied Energy with 8 articles, International Journal of Electrical Power and Energy Systems with 7 articles and IEEE Transactions on Sustainable Energy with 6 articles respectively.

It can be observed that from Figure 4 the number of articles published in journals with higher impact factors is typically lower. Figure 5 displays the different publishers of the 115 highly cited articles chosen from the Scopus database. Notably, the majority of articles (77.4%) were published by IEEE or Elsevier. IEEE holds the record for the most percentage of articles published, with 46.1%, followed by Elsevier with 31.3% publication. In addition to these, MDPI has 13% of publications and IET has 5.2% from the selected database. The other publishers including Taylor & Francis, Springer, and ISA contributed a total of 4.4% of published articles.

The geographical data provided by various research organizations were studied to gain a better understanding of the distribution of countries and article publications. By looking at the country of origin of the first author, it is observed

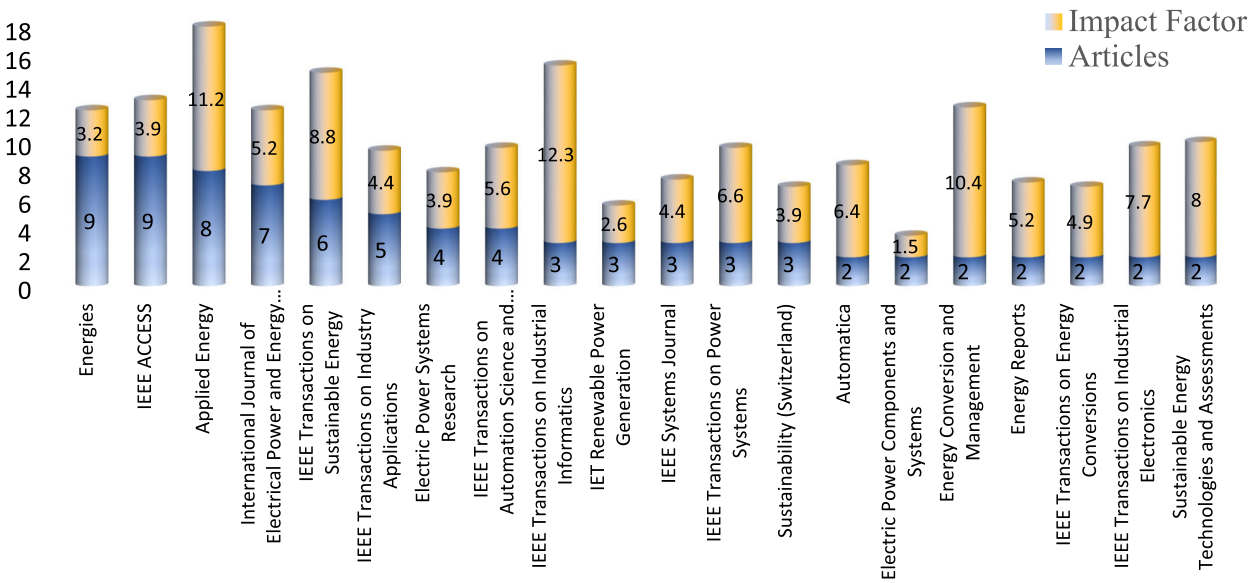

FIGURE 4. Top 20 journals based on publication and journals' impact factors.

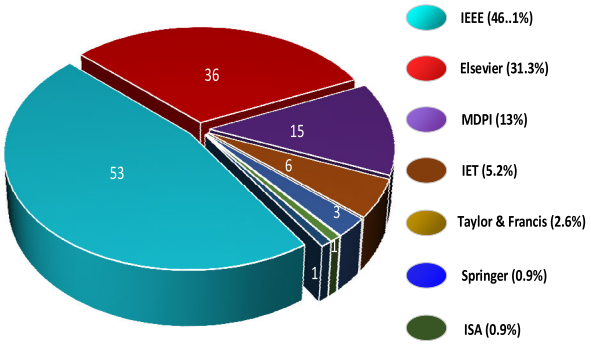

FIGURE 5. Different publishers for the 115 highly cited articles.

that the research articles come from 28 different countries represented in Figure 6. According to the data, China has published highest 19 articles which making it top contributor and the United States stands for the second most contributor published with 16 publications. In addition, Iran has published 12 articles followed by Italy, India, Malaysia, Canada, and Australia. Figure 7 displays the network of bibliographic coupling between the 115 nations that published the selected articles through Vosviewer software. The various colors represent the several clusters that were connected more frequently. The United States has the strongest links with other countries followed by China. Australia, Iran, and Canada are also among the countries that collaborate with a great number of other nations. According to the chosen database, Portugal, Croatia, and France have the weakest collaborative networks.

D. ANALYSIS OF AUTHORS WITHIN MG SCHEDULING

Table 2 and Figure 8 provide the top authors' contributions from the Scopus database in the field of grid-connected MG scheduling controllers based on the frequency of publication. The leading contributor's profile area was analyzed by using Google Scholar to learn more about their areas of expertise. Guerrero J.M, a researcher from Denmark's Aalborg University who specializes in MG controller, power system research, and development, has made the most contribution to the study of the MG scheduling controller. His work has been cited a total of 112833 times, and he has contributed eight articles in the year 2015 to 2022. His work focuses on centralized control architecture [25], hierarchical bi-level control schemes [30], multiagent-based distributed control [31], and noise-resilient economic dispatch [56]. The second author who has made a significant impact on relevant studies is M.A. Hannan, originally from Malaysia with affiliation with

TABLE 2. Top seven authors and co-cited authors that contributed publications on grid-connected MG scheduling controllers.

Rank	Authors name	Present Institution	Country	Citation	H-index	Article
1	Guerrero J.M.	Aalborg University	Denmark	112833	149	8
2	Hannan M.A.	Sunway University	Malaysia	22063	73	6
3	Ouammi A.	Qatar University	Qatar	2704	28	4
4	Abdolrasol M.G.M.	Universiti Tenaga Nasional	Malaysia	885	15	3
5	Begum R.A.	University of Technology Sydney	Australia	11703	50	3
6	Faisal M	University of Wollongong	Australia	671		3
7	Ker P.J	Universiti Tenaga Nasional	Malaysia	5052	32	3

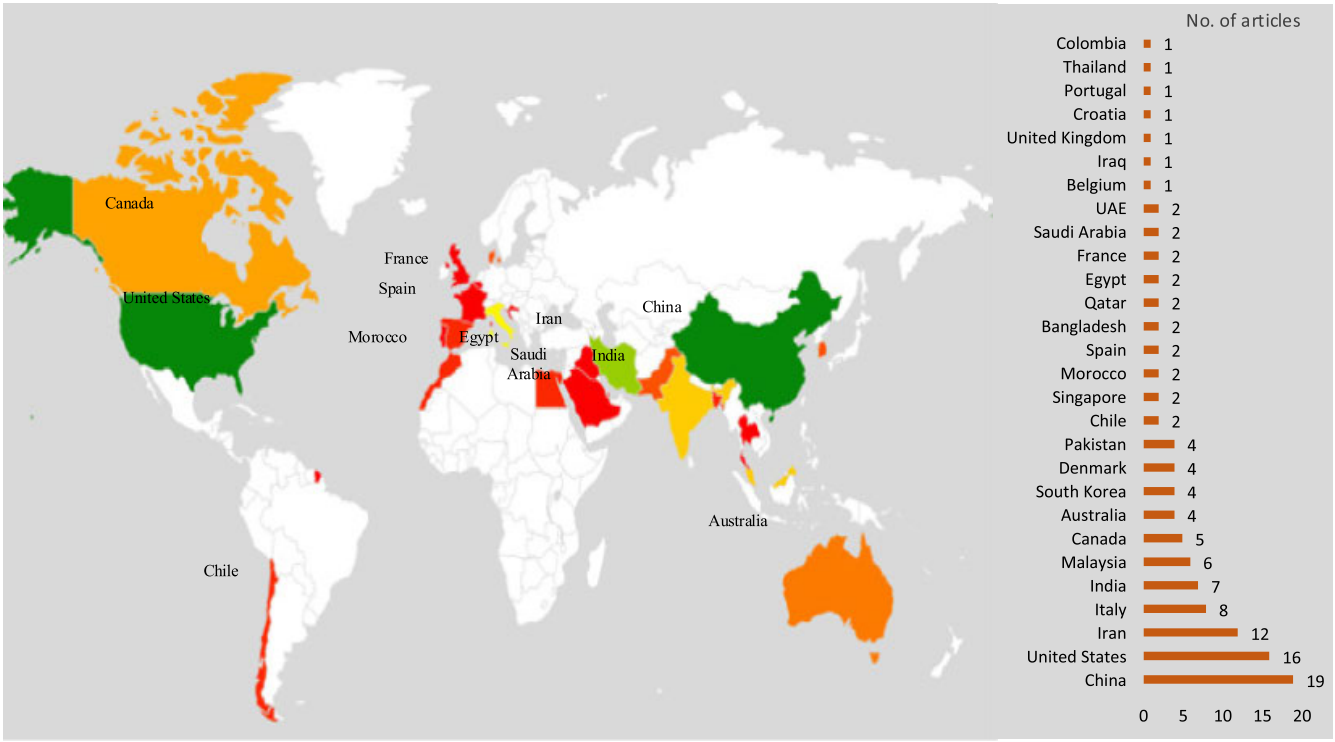

FIGURE 6. Geographic country analysis.

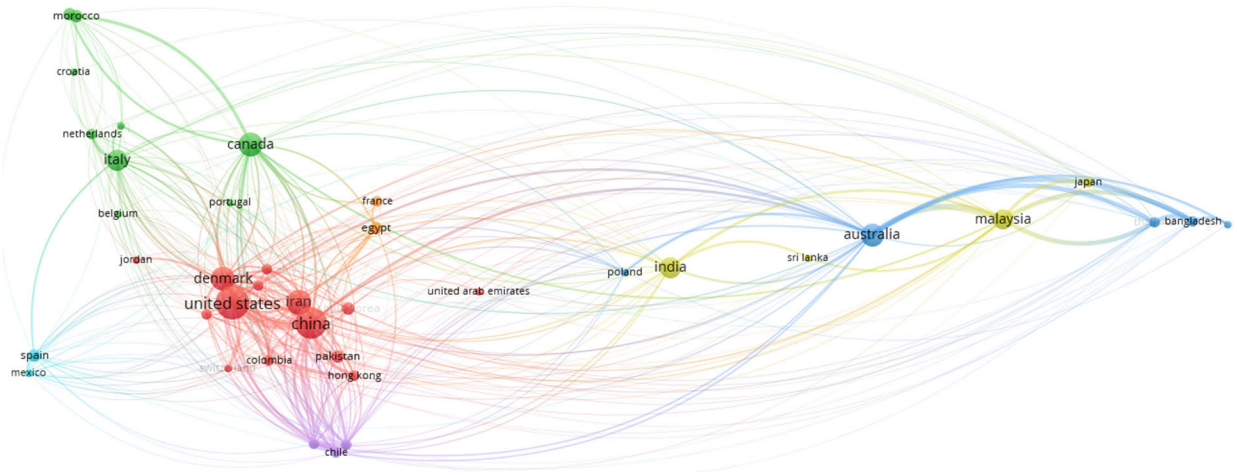

FIGURE 7. Bibliographic country coupling network.

Sunway University (School of Engineering and Technology), who published 6 articles and received a total of 22063 citations. M.A. Hannan et al.presented various optimization techniques related to integrated MG systems and scheduling controllers such as binary backtracking search algorithm (BBSA) [32], binary particle swarm optimization [33], lightning search algorithm [34], fuzzy logic controller [35] to manage renewable energy sources, energy and power saving, increasing stability, reduce operating cost. The third author Ahmed Ouammi from Qatar University focused on model predictive control (MPC), Scheduling optimization, and multi-objective integrated optimization for Smart Greenhouse.

The co-authorship network is shown in Figure 9, which shows the collaboration among authors selected from the chosen articles who worked together within the field of grid-connected MG scheduling controller research. In this representation, each node corresponds to an author's publication count, while the thickness of connecting lines between two authors reflects the number of collaborative articles they have produced together.

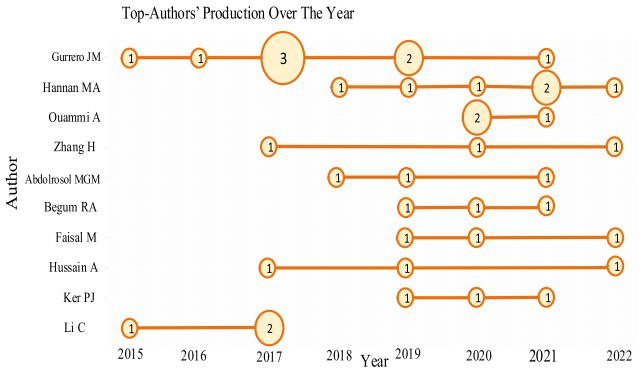

FIGURE 8. Top author's production over the year.

E. ANALYSIS OF KEYWORD CO-OCCURANCE NETWORK

Keywords are one of the most important aspects of any research to determine the precise area of the study. The KCN analysis shows the relationships between keywords, their weights, and their occurrences, revealing the field's overall research. A co-occurrence keyword network is presented in Figure 10, which was constructed using the 115 most referenced papers. Figure 10 depicts the software VOSviewer's creation of an interconnected network of authors' keywords. The impact of the keywords is represented by the circular pattern and its label, and the connection between the keywords is reflected by the connective line that runs through each of the keywords. The network was divided into four clusters according to the relative strengths of the links formed by the occurrences of items that occurred simultaneously. The red cluster represents the most significant keywords: microgrid, scheduling, renewable energy resources, and electric load dispatching. Distributed power generation and various control systems like adaptive control systems, power control, co-operative control, distributed parameter control, and distributed control were also represented in cluster 1(red).

The green cluster represents microgrid, energy management, optimization, energy, power generation, energy efficiency, energy utilization, electric power transmission, smart grid, smart power grids, and renewable energies. The storage battery energy storage systems and charging of batteries. MG controllers such as fuzzy logic, scheduling controllers and particle swarm optimization are interconnected in the blue cluster. Finally, the yellow cluster presents stochastic systems, integer programming, energy storage, electric power distribution, and costs.

According to the KCN structure presented in Figure 10, the top 11 keywords implemented in the field of grid-connected MG systems were illustrated in Figure 11 by word cloud. The frequency and rank of keywords are indicated by various font sizes and colors. Among the top 11 keywords scheduling is the most extensively used keyword with a frequency of 57. Scheduling is used to control renewable energy resources for sustainable development [36]. The second most frequently utilized keyword is microgrid. MGs consist of different distributed renewable energy sources such as wind, PV fuel cells, and various small-scale generation [37]. MGs are now becoming more popular research among researchers. Additionally, scholars are currently concerned with the efficiency of energy management and are equally focused on the controllers and optimization techniques with MG EMS. Electric load dispatching has been another focused area in recent years.

F. BIBLIOMETRIC ANALYSIS OF RESEARCH TYPE

It is vital to distinguish the different types of studies while analyzing the structure of highly cited publications. As shown in Table 3, the chosen publications have been divided into four different study categories. It is observed that, with a frequency of 82, most papers fall into the category of problem formulation and simulation analysis. Observational and case study studies come next, with a frequency of 24. Furthermore, there are 18 articles categorized as experimental work, development, and performance assessment. Three articles fall under the ''state-of-the-art and technical overview'' category. Finally, there are just five publications that fall under the ''state-of-the-art, technical overview, and analyze'' category, with citations ranging from 3 to 288.

These studies typically cover subjects like models for MG scheduling systems, mathematical models, computer simulation, control tactics, and best operating strategies. The researcher's current research interests for grid-connected MG scheduling controllers are their design, modeling, proposed controller methods, optimal energy utilization, and energy management strategies. The results highlight the critical significance of reducing the cost of distributed energy.

1) SUBJECT AREAS

To gain a comprehensive overview of this bibliometric research in the field of MG scheduling controllers, the articles have been classified within different subject areas presented in Table 4. Notably, the highest number of articles was 39 articles in the ''cost analysis and economic aspect'' category. Additionally, a sizable portion of 30 articles fall under the ''Energy management system development'' category. Followed by ''Grid-connected and smart grid'' and ''MG integration and development'' with the figures of 22 and 20 articles, respectively. However, only 4 articles are categorized under the ''State of charge (SOC)'' and ''Power system studies'' categories. The subject's findings in Table 4 are summarized as follows:

As the power sector experiences significant advancements in Microgrid (MG) development, effective supervision and control have become increasingly crucial for the successful management and operation of MGs. An integral aspect of this control management process involves the utilization of a power converter, which serves as an interface connecting the MG to the main grid. Numerous study's has been conducted on supervisory control as well as strategies to enhance the reliability of MG system supply [27], [53], [124], [135]. The primary focus of supervisory control within the MG system centers on the control structure and

TABLE 3. Types of study in the highly cited 115 articles.

Type of Study	Article Rank	Reference	Year of Publication	Citation Range	Frequency
Problem formulation and simulation analysis	1,2,4,5,6,8,9,10,13,15,16,17,18, 22,25,27,28,29,30,33,34,35,36, 37,38,39,41,42,43,44,45,47,48, 49,50,51,52,53,56,59,60,61,62, 63,64,67,71,73,76,77,79,80,83, 84,85,86,87,88,89,90,91,92,93, 94,96,97,99,100,101,102,103,1 04,105,106,107,108,109,110,11 1,112,113,114,115	[21],[22],[24],[27],[26],[28],[30],[29],[38],[39], [32],[40],[41],[42],[43],[34],[33],[44],[45],[31], [46],[47],[48],[49],[50],[51],[52],[53],[54],[35], [55],[56],[57],[58],[59],[60],[61],[62],[63],[64], [65],[66],[67],[68],[69],[70],[71],[72],[73],[74], [75],[76],[77],[78],[79],[80],[81],[82],[83],[84], [85],[86],[87],[88],[89],[90],[91],[92],[93],[94], [95],[96],[97],[98],[99],[100],[101],[102],[103] ,[104],[105],[106],[107]	2013-2024	0-631	82
Observational and case study	4,14,19,21,23,24,26,39,40,54,5 5,57,65,66,67,70,72,75,76,77,7 8,102,104	[24],[108],[109],[110],[111],[112],[113],[51],[1 14],[115],[116],[117],[118],[119],[70],[120],[1 21],[122],[73],[74],[123]	2013-2023	10-243	24
Experimental work, development, and performance assessment	7,8,10,11,31,32,46,47,51,58,63, 64,68,69,74,79,81,82,98	[25],[28],[29],[31],[124],[125], [126],[56],[60],[127],[68],[69],[128],[129],[130],[75],[131],[132],[133]	2015-2022	2-168	18
State-of-the-Art, Technical Overview, and analysis	3,12,20,50,95	[23],[134],[59],[135],[136]	2014-2022	3-288	5

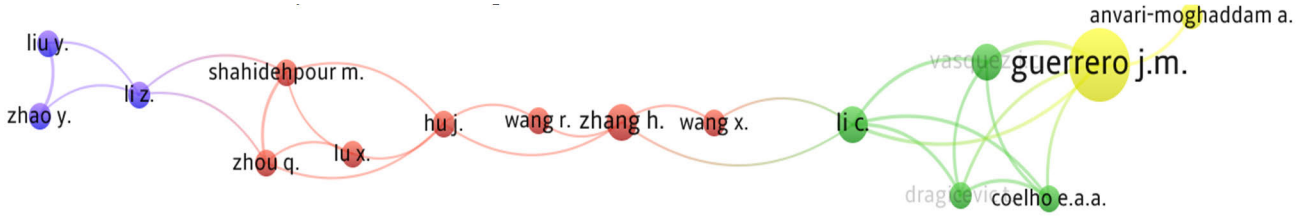

FIGURE 9. Co-authorship network.

implementations, particularly concerning power converter (inverter) methods. Various contemporary control approaches have been widely employed to assure the stable operation of MG system, particularly in islanded mode [25]. Droop control, voltage ride-through, multi-agent systems (MAS), and optimization-based approaches are among them.

Researchers have extensively explored the EMS of MG, with a particular focus on the tertiary-level control structure. Such an EMS holds significant importance as a controller to guarantee the seamless operation of the MG system. The challenge arises due to the inconsistent nature of distributed sources like WT and PV systems, making it difficult to maintain a consistent power supply to meet load demands. Consequently, the implementation of an EMS becomes imperative to ensure the efficient generation, transmission, and distribution of energy while minimizing costs. To attain an efficient and optimal operation for ensuring a sustainable energy supply, multiple solutions have been proposed to address energy management strategies within MGs [43], [67], [72], [119], [123].

Battery energy storage systems (BESSs) are commonly used in MGs in conjunction with renewable energy sources (RESs) to supply backup power and maintain peak load operations during extended grid disruptions. They additionally assist in maintaining grid stability by regulating voltage and frequency, as well as enabling demand responses when operating on the grid. Numerous efforts have been made to address challenges like as BESS sizing, optimal scheduling, energy management strategies, and MG control in grid-connected modes, all aimed at achieving efficient power generation [44], [125]. Galván et al. [128] present a method for using a battery energy storage device on a MG generating to its full potential.

An energy storage system (ESS) is critical in MG applications for maintaining and improving frequency and voltage stability within acceptable limits. It also has the potential to undergo several charge and discharge cycles, as well as recharge with low energy input in a short period. Storage units can be converted into dispatchable resources by combining them with non-dispatchable DER units such as solar energy and wind. Various energy storage technologies have been presented in different aspects including hybrid energy storage systems (ESS) for uses in transportation, recent advancements, design and control methods, and life cycle analysis applications [45], [109], [110].

Among the various areas of research, "Cost analysis and economic assessment" stands out as the most prevalent and extensively studied field. Approximately 37.75% of the chosen articles over the past 10 years focused on cost optimization and economic evaluation in this field. Numerous methodologies have been developed by researchers to reduce

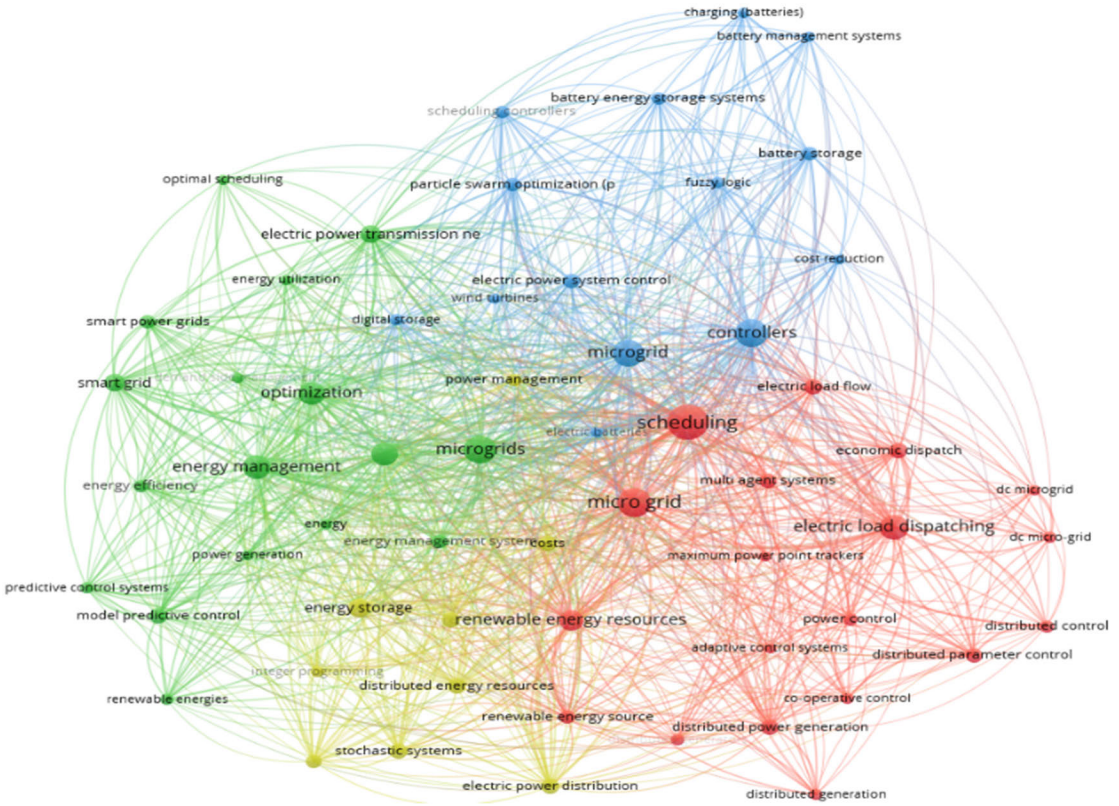

FIGURE 10. Keyword Co-occurrence network analysis.

FIGURE 11. Top 10 keywords by word cloud.

the overall system cost using the scheduling controller [45], [63], [109], [110], [111], [124].

IV. DISCUSSION ON FREQUENTLY USED CONTROLLER STRATEGIES AND OPTIMIZATION TECHNIQUE

Numerous controller strategies and optimization approaches are proposed in MG scheduling. Tables 5 and 6 represent the advantages and disadvantages of the most frequently used controller and optimization methods in the MG scheduling field.

A. CONTROLLER STRATEGY

Microgrid systems offer a versatile platform for the implementation of a wide range of control strategies, all aimed at enhancing microgrid performance, optimizing the utilization of RESs, and maximizing the economic advantages and other associated benefits of microgrid deployment. Many control strategies are discussed for managing MG operations with regard to voltage, current, frequency deviations, and harmonic distortion. These include advanced controllers, model predictive control, scheduling control, hierarchical control, proportional-integral (PI) control, fuzzy logic control, neural networks, sliding mode control, and droop controller. These controllers are utilized for MG control based on MG architecture, applications, and specific requirements.

Model Predictive Control (MPC) is the most utilized controller in the field of MG scheduling. MPC obtains control signals and directives by optimizing a variety of targets using a range of control approaches. MPC achieves acceptable outcomes in terms of operating cost reduction while adhering to optimization and financial restrictions. Recently, Ouammi et al. [40] presented an innovative control strategy for MG-based MPC controllers. The proposed supervisory controller model is formulated to optimally control the operation of the MG to achieve efficient energy management. The outcome shows that the proposed MPC method can deal with a variety of RES and load-related uncertainties that provide a sustainable system structure. Furthermore, extensive research toward real-time scheduling of MG systems with integrated RES and hydrogen storage is presented in [28]. This study indicates a significant improvement in

TABLE 4. Articles distribution based on subject area.

Subject areas	Articles rank	Range of citation	Frequency
MG integration and development	1,5,11,16,20,21,23,26,28,33,38,40,45,48,57,60,70,87,91,96	3-574	20
Supervisory control research	5,7,8,9,17,18,20,31,42	24-153	9
Energy management system development	1,8,9,10,13,14,23,24,25,27,35,40,46,52,54,55,57,62,63,66,69,70,73, 78,82,83,84,90,91,106	5-574	30
Battery energy storage system	29,32,44,68,89,92	4-31	6
Droop control technique research	5,18,74,85,90,105	5-153	6
DG controls	6,12,18,34,36,41,43,49,50,61,79,81,94	3-138	13
ESS development	7,11,19,21, 24,30,33,37,51,52,68,71,75,104,108	11-137	13
DER and generation	7,16,19,31,67,75,80	10-137	7
Renewable energy development	1,8,15,7,39,51,78,79,93,97	3-174	10
Grid-connected and smart grid	1,3,13,17,21,27,31,32,45,47,49,50,52,55,59,68,73,81,82,86,88,99	8-174	22
Power system studies	16,49,63,96	3-64	4
Cost analysis and economic aspect	4,12,13,14,19,22,23,25,27,28,30,31,32,35,39,41,44,49,53,54,56,59, 62,65,66,68,70,71,72,73,74,77,80,81,83,84,98,99,105	2-211	39
Environmental perspective	3,4, 27,28,31,54,55,66,77,95	3-246	10
PV and Wind power	11,6,19, 21, 31,38,42,48,68,84,88,89,90,101,107,108	5-104	16
Economic dispatch	26,34,41,56,58,65,72,74,76,82,85,86,88,92,100,107	4-36	16
State of charge (SOC)	33,44,68,92,104,109	4-29	6

lowering MG's operating cost. The study in [71] introduces an Economic EMPC algorithm tailored for a two-layer control framework suitable for systems with storage devices like MGs and hybrid electric vehicles. It extends existing EMPC theory to ensure the stability of optimal steady states and demonstrates superior performance in a simulation of a hybrid solar photovoltaic (PV) / battery system, showing improved economic efficiency and convergence to optimal states. However, limitations may arise in practical implementation due to complexity and dynamic cost functions. In [77] presents a modular hierarchical MPC strategy for building energy management, utilizing three control levels: building zones, central conditioning, and MG subsystems. By integrating price-consumption information exchange, it achieves substantial demand response capabilities, reducing building operation costs by 9-24% compared to rule-based control, while improving indoor comfort. However, practical implementation may face challenges due to computational complexity and maintenance requirements. In the study [116] presents a cooperative control framework utilizing MPC for interconnected MGs with smart greenhouses, aiming to optimize power flow and ensure high service quality within a smart grid context. Through bidirectional communication and centralized control, the framework effectively manages power flows, leveraging renewable energy sources and facilitating exchanges between MGs. Results demonstrate effective management of HVAC operation, balancing of renewable generation and power loads, and achievement of net zero energy greenhouse objectives, although with potential limitations in scalability and system complexity.

MAS-based control techniques are extensively utilized in MGs [84]. A MAS can regulate and stabilize output power, voltage, and frequency in the presence of an uncertain atmosphere and load with uncontrolled RESs. In a MAS-based MG, the agents placed on the MG components communicate with one another to operate as efficiently as possible. The paper in [118] proposed a fully distributed economic dispatch method for MGs, utilizing a multi-agent hierarchical control architecture and a modified diffusion algorithm. It aims to minimize operation costs while optimizing power generation and demand-side flexibility. Simulation results demonstrate the method's effectiveness in achieving economical and stable microgrid operation, with the potential to reduce reliance on communication networks and enable plug-and-play integration of distributed power units. The study in [125] focused on the MAS-based MG operation approach consisting of intelligent load and BESS for demand response. In the DR program, the agent operation method incorporates a scheduling algorithm that utilizes day-ahead pricing and a real-time operation that makes use of emergency demand response (EDR) in case of an emergency. A decentralized MAS architecture has been proposed in [46] which is more adaptable and scalable to manage MG's dynamic properties. The advantages include being able to identify the best control inputs to reduce the cost within a short period, deal with uncertainty disruption, and improve decentralized information-sharing efficiency.

Hierarchical control strategies address complex scenarios like voltage, frequency, and power quality regulation, load power-sharing, striking a balance between centralized and decentralized control. This approach involves three levels: primary, secondary, and tertiary control. The hierarchical approach in MGs enhances the control, reliability, and security of the distributed system. In [22] analyzed communication delays on secondary frequency control in islanded MGs with inverter-based generators, using a small-signal model to

TABLE 5. Summary of most frequently used controller methods in the field of MG scheduling controller.

Reference	Controller	Application	Advantage	Disadvantage
[32],[34], [33], [57]	scheduling controller	Energy balance, load management, power exchange	• Enhance system reliability. • Minimize the operation cost.	• Need a lot of computational resources. • Time-consuming.
[22], [30], [52], [118], [122], [79]	Hierarchical control	Power flow, economic dispatch, voltage regulator, power-sharing	• Lowering the expenses of generation. • Control the transfer of power between MGs and the grid. • The converter controls local voltage and current. • Increase system flexibility, and reliability. • It is feasible to make the most suitable decision.	• Failure to convey data or energy if a higher layer fault. • For generation balance, an intelligent system needs to predict demand.
[28], [40], [47], [116], [117],[129], [71], [74], [123], [77], [90], [95], [101]	Model Predictive Control	Energy management, demand side management	• Improve transient responsiveness. • Can handle RES/load uncertainties. • Cost-effective. • Power saving and optimal control.	• Complex method • High computational requirements
[125], [46], [87]	Multi-agent system	Power balance, power generation, multi-MG network	• Resistant to restrictions and multi-objective control. • Able to identify the best control inputs to reduce the cost within a short period.	• Complicated and slow-convergent. • The agent's specifications shouldn't differ from others.
[43], [44], [50], [35], [75]	Fuzzy logic controller	Frequency and voltage response, EMS, power management,	• Improved ability to control frequency and voltage. • Capable of preserving battery life and cost. • Able to meet energy demand, and maintain SOC.	• Slow speed and time-consuming system. • Requires huge data. • Lack of fast response.
[57], [127], [131]	PID controller	Temperature control	• Easy implementation. • Simple structure and is easy to design. • Reduce steady-state error. • Cheaper than other control methods.	• May not be suitable for non-linear or complex systems. • The tuning process is complex and time-consuming.
[27], [122], [84]	Droop control	Load sharing, DC MG system	• Easy to implement. • Does not need a complex algorithm. • Can operate without a central controller. • Power-sharing is high.	• Provides a limited amount of frequency and voltage control. • May not be appropriate for complicated or nonlinear dynamics in MG systems.
[48]	Robust controller	AC/DC MG, power flow, current sharing	• Increase the system's resistance to uncertainty. • Reduce voltage error. • Decrease in circulation current	• Require sophisticated mathematical techniques to design and execute. • More expensive.
[87]	sliding mode control (SMC)	Power sharing, SOC balance, voltage, and frequency control	• Fast response. • Can control nonlinear systems. • Accurate tracking.	• Chattering problem. • Tuning difficulties.

determine the delay margin for stability. Results indicate that increasing proportional gains improves delay margin, while integral gains decrease it. A gain scheduling method mitigates delay effects, validated through simulations on a Canadian urban distribution system. Future research should address synchronous machines, nonlinear loads, and time-varying delays. A hierarchical control system for real-time energy management in multiple electrically coupled MGs, utilizing primary and secondary level controllers to optimize generation resource dispatch is presented in [30]. It minimizes information exchange between MGs and operators, handling uncertainties through Taguchi's orthogonal array testing. Simulation results demonstrate effective optimization of generation resources with minimized computational complexity, though the simplified formulation may overlook certain system complexities and require further refinement for broader applicability. A hierarchical distributed control scheme is proposed by Babazadeh-Dizaji and Hamzeh [52] to achieve optimal power dispatch within multiple DC MGs. The proposed control scheme demonstrates significant achievements based on simulation results, including optimal power dispatch, improved voltage regulation of DGs, simultaneous voltage regulation and economic power dispatch, resilience against failures, robustness against physical breakdowns, and efficient management of renewable source intermittency and load fluctuations. In [122], the study proposed a hierarchical predictive controller for large-scale PV MGs to optimize PV usage, minimize power flow variability, and manage grid connection fluctuations. Utilizing load and PV predictions, coupled with energy storage and diesel resources, the controller compensates for prediction errors, demonstrating successful operation across various scenarios. However,

TABLE 6. Summary of the most frequently used optimization algorithm in the field of MG scheduling controller.

Optimization technique	Objective function	Advantage	Disadvantage	Reference
MILP optimization	-Cost minimization -Scheduling	• Convergence of solution is globally optimal and guaranteed. • Economically available solvers are incredibly quick and efficient in handling MILP problems.	• Non-linear effects cannot be considered. • It is necessary to consider the entire time horizon at once.	[109], [129], [72], [78]
Robust optimization	-Minimize economic cost -Energy flow to the main grid	• Simple execution • Various alternatives exist to address the problem.	• Complexity in model formulation. • Robust optimization strategies are typically conservative.	[21], [47], [65]
Scheduling optimization	-Energy management -Control of MG systems	• Enabling effective resource allocation. • Tackle various uncertainties.	• Sensitivity to the input data. • Model intricacy, and real-time implementation.	[28], [40], [116]
Particle swarm optimization	-Scheduling -Cost optimization	• Simple. • Easy to implement. • Less computational time. • Possesses effective memory capacity.	• The challenge lies in the identification of the primary design parameter. • Inferior approach.	[43], [45], [35], [116], [128]
BBSA	-Reduce power loss and generation cost -Scheduling	• Increase reliability. • Reduces the complexity of the optimization problem. • Delivers high-quality power.	• High computational time. • Limited precision.	[32], [128]
Linear programming	-Load sharing -Economic dispatch	• Can manage a variety of restrictions. • Guaranteed Optimality • Real-time usability.	• Unable to precisely capture nonlinear behavior. • Limited ability to manage uncertainty.	[27], [38], [62]
Dynamic programming	-Charge scheduling	• Can effectively handle uncertain parameters. • Empowering robust decision-making in the presence of uncertain conditions.	• Computational complexity. • Discretizational error and scalability. • High memory and storage needed.	[24]
Energy management algorithm	-Energy management -Load management -Maximize the utilization of RES	• Reliable operation. • Effective use of energy resources. • Enhancing grid stability.	• Require extensive computational resources and effort. • Results can be significantly impacted by the quality and accuracy of the input data.	[29], [60], [61]
Two-step optimization	-Demand and supply management -Energy management system	• Faster convergence. • Provide flexibility in integrating several optimization techniques for each step. • Reducing the complexity of the design and execution.	• It can be difficult to combine the results from the two steps. • The accuracy of the initial solution produced by the global optimization in the first stage may impact the eventual outcomes.	[39], [126], [69]
Multi-objective optimization	-Energy management -Frequency security	• Permits an extensive trade-off analysis between competing objectives like cost reduction, emission reduction, and system reliability. • Can handle multi-objective constraint	• Time consuming • Solution of Pareto set can be challenging • Multi-objective optimization issues can be computationally difficult to solve.	[115], [117]
Genetic algorithm (GA)	-Voltage and frequency regulations -Scheduling	• Outstanding performance • Easy to implement and operations are simple. • Able to deal with various objectives and uncertainties.	• Unpredictable behavior produces diverse outcomes. • The calculation requires a long time.	[89], [43]
Lightning Search Algorithm (LSA)	-Scheduling, power management, voltage stability, cost.	• Accurate optimization structure and fast convergence speed. • Employ step leader propagation. • Wide search space solution to solve the objective and constraints.	• Complex formulation. • Huge variable declaration. • Complex structure.	[34]

limitations may arise in scalability and adaptability to different grid configurations, warranting further investigation.

Fuzzy logic controllers are used to choose appropriate distributed controller parameters for MG system operation in distributed control management. An optimized fuzzy logic energy management system is presented in [43] for a standalone DC MG serving residential loads, incorporating solar PV, wind, battery storage, fuel cell, and diesel generator. Controlled by a low-complexity fuzzy system, optimized with an artificial bee colony technique, the system improves energy saving efficiency by 10.89% and reduces generation costs by 11.19% compared to conventional methods. Limitations include reliance on specific environmental data and potential challenges in generalizing results to other regions. The study in [44] proposed a mathematical framework to enhance hybrid MG resilience using a fuzzy logic-based

Battery Energy Storage System (BESS) controller, determining BESS operation modes based on event occurrence probability. Simulation results show a slight increase in operation cost in normal mode but a significant reduction in load shedding during emergency operation, validating the effectiveness of the proposed strategy. However, limitations may include the reliance on event occurrence probability estimations. In [50] a fuzzy-based gain scheduling power management scheme is proposed for parallel connected PV systems in MGs. The fuzzy controller modifies the gain of each inverter module using fuzzy rules and input and output membership functions. Bisht and Sathans [57] proposed a fuzzy gain scheduled PID (FGSPID) controller for frequency regulation in response to rapid changes in load or generation power. The performance of the controller demonstrates an enhanced ability to rapidly eliminate system frequency deviations stemming from all three disturbances. Furthermore, the proposed controller is characterized by reduced oscillation and time and overshot. Recently, the study in [106] introduced an adaptive PID controller using the DDPG RL algorithm for LFC in an AC MG power system with renewable resources. The controller, trained offline, dynamically adjusts PID gains online based on MG system conditions. Comparative simulations with the FGSPID controller demonstrate superior performance, particularly in scenarios with data transmission delays, highlighting the efficacy of the proposed method in dynamic and steady-state conditions.

Numerous droop control approaches have been proposed to ensure the consistent distribution of loads within a MG [27], [122]. Droop control in MG systems enables load sharing, stable voltage, and fault tolerance while promoting efficiency, reliability, and renewable energy integration. It enhances energy resilience and cost savings. Despite their benefits, they are restricted by their inadequate transient response. This limitation requires the use of a low-pass filter, leads to imbalanced harmonic current sharing, and involves an inherent trade-off between voltage and power sharing. In the standalone framework, the inherent uncertainty in the initial phase values among individual units leads each unit to utilize frequency as a means of governing power flows within the droop control method, rather than relying on power or phase angles. In [27] presented decentralized voltage droop control strategies for DC MGs, aiming to achieve fair load sharing and economic dispatch of generation. It introduces primary droop control and secondary integral control strategies, along with a consensus filter to compensate for steady-state voltage drifts and recover optimal injections. Limitations include assumptions of constant loads and resistive network models, with future work focusing on robustness and inclusion of diverse load and network models. In [84], a novel droop control technique for the standalone DC MG is proposed to improve the system's dependability and efficiency.

B. OPTIMIZATION ALGORITHM

From the selected 115 articles it can be observed that various optimization methods have been addressed to solve the scheduling problem. These methods include deterministic, stochastic, and heuristic ones. MILP (Mixed-Integer Linear Programming) is a modified version of standard integer programming. MILP treats the goal and constraint functions as continuous functions, whereas certain variables are denoted as integers. MILP is employed to capture the discrete nature of certain decisions, offering it several advantages, such as reduced computational time and the ability to terminate algorithms early upon discovering an integral solution. However, a lack of algorithm capabilities and complex search space leads to the failure to discover the objective that is raised by the uncertainty condition and the inability to determine the optimal solution. In [109], the MILP method is used to formulate the MG short-term scheduling problem aiming at reducing the operating cost. A mixed-integer nonlinear programming (MINLP) is proposed in [72], aiming at minimizing total operational cost. This objective considers both the grid's technical limitations and the individual preferences of customers. The study in [103] proposes a model predictive control (MPC) approach to solve optimal power flow (OPF) in unbalanced MGs, optimizing active and reactive power flows. The formulation, modeled as a mixed integer non-linear programming problem, incorporates voltage control and capacitor banks. Results demonstrate fast convergence (<5 min), renewable energy utilization for reactive power, and storage optimization based on market prices. Commercial solvers enable real-time application, though future research could focus on scalability.

PSO stands as the most commonly utilized heuristic method for addressing the MG scheduling problem, and it finds applicability in global optimization problems characterized by nonconvex or improper objective functions. The method exhibits the capability to achieve high-quality solutions within relatively shorter computational times and its convergence characteristics are notably more stable compared to other stochastic methods [35], [128]. The simplicity, ease of implementation, adaptability, global exploration and efficiency of PSO have made it an attractive choice for researchers. Its simple implementation and rapid convergence make it accessible and effective for solving a wide range of optimization problems. Despite its advantages, the Particle Swarm Optimization (PSO) method faces several limitations such as obtaining low-quality solutions, the necessity for memory to update velocity, being trapped in local optima, and the persistence of early convergence. The study in [128] proposed a PSO algorithm to optimally use the PV generation and ESS to minimize the main grid cost including a power peak cost and energy cost. The BBSA optimization algorithm offers an exceptional binary fitness function, specifically a global minimum fitness function, which proves instrumental in identifying the optimal cell for generating the most optimal schedule. Abdolrasol et al. [32] presented a novel BBSA within a controller to facilitate the optimal scheduling of generators within a MG. The results demonstrate that the BBSA-optimized controller can produce a priority-based optimum schedule for MG integration.

An MPC-based scheduling optimization is developed in [40] to optimally control the NGIM's operation. The presented numerical results establish the validation of the proposed model in effectively tracking reference signals, which represent the optimal desired climate data for each greenhouse. This is achieved while adhering to the necessary operational constraints. The study [38] used a linear optimization approach to maintain the stability of the demand-supply curve, establish a price decision process, and enhance overall grid efficiency. An integrated multi-objective optimization framework is presented in [117] to comprehensively manage the complete operation of the smart greenhouse. The framework considers both forecasts and updated data derived from the existing wireless sensor network. A multi-objective dispatching model is proposed in [99] to address the instability between renewable power and load demand in MGs, focusing on maximizing revenue, load reliability, and effective energy storage utilization. The model employs a multi-series exponential iterative optimization approach and integrates peak load regulation and valley filling strategies for grid connectivity. Simulation results demonstrate improved economic benefits and capacity utilization, yet further hardware-level considerations and deeper studies on loss of power supply probability are warranted. In [89] a multi-objective Genetic algorithm is employed to attain scheduling for the gains of the STATCOM controller. The algorithm aims to achieve optimization without introducing any delay in the control signal. The simulation results conducted using MATLAB show that the MG's performance is enhanced, leading to a reduction in voltage, frequency, and power oscillations. Furthermore, a decentralized and coordinated scheduling method for interconnected multi-microgrids using a virtual energy storage model to ensure information privacy is presented in [96]. It employs a two-level optimization model to optimize tie-line power and virtual energy storage, utilizing analytical target cascading for independent optimization. Case studies demonstrate the model's effectiveness in reducing operation risks and costs while enhancing overall system reliability and flexibility, despite limitations in addressing complex conditions and ensuring privacy. In [91] proposed an online energy management algorithm based on the Lyapunov optimization technique for a sustainable smart home with HVAC load and unpredictable occupancy. The algorithm aims to minimize overall energy and thermal discomfort costs by regulating indoor temperature, EV charging, and energy storage system queues. Simulations show a 20.15% reduction in average energy cost, demonstrating the effectiveness of the proposed approach in real-time energy optimization despite uncertain system inputs. The recent work in [107] introduced a customized approach for coordinating voltage regulation and voyage scheduling in seaport MGs, aiming to balance economic benefits while ensuring system security. By optimizing voyage schedules and voltage regulation, the method minimizes power losses and operation costs. Utilizing mixed-integer linear programming and a satisfactory index, the proposed approach achieves significant reductions in power losses and operation costs, demonstrating effective coordination between voyage scheduling and voltage regulation.

V. ISSUES AND CHALLENGES

It is crucial to recognize several limitations while discussing this bibliometric survey. Firstly, the selection of the topmost cited 98 manuscripts is based on the Scopus database. Compiling a comprehensive list of these highly referenced papers becomes a challenging task, especially when considering the incorporation of additional datasets like Google Scholar or Web of Science, which could potentially serve as avenues for future research recommendations. Secondly, the compilation of the most cited manuscript list focuses on publications from 2013 to 2023, aiming to understand current research trends. Furthermore, the search is limited to English publications, potentially excluding globally impactful works in other languages. The analysis considers articles meeting specific criteria, acknowledging the challenge of assessing subjects due to interdisciplinary complexity. Therefore, the integration of MG scheduling control strategies is crucial to managing fluctuations caused by various sources. However, the MG field faces challenges such as power quality, power electronics, protection and safety, energy management, controllers and optimization issues, and scheduling problems. These issues impact the strategies within integrated MG systems, influenced by internal and external factors. Further details about these challenges are discussed in the following section.

A. POWER ELECTRONIC INTERFACE

Power electronic interfaces play a crucial role in the operations of MG scheduling controllers. Devices that are interconnected with the main grid voltage are developed and incorporated to manage the interfaces between Distributed Energy Resources (DER) units, Direct Current (DC) links, Alternating Current (AC) links, and the surrounding power systems that operate in both MG modes. Given that most MGs significantly rely on power electronics, this component is crucial to MG operations because it could lead to serious system failures. Furthermore, as a single aggregate system, this component allows for flexible regulated operations [137]. Every energy resource and storage system possess the capability to generate and supply power based on their intrinsic characteristics, irrespective of the efficiency and optimal voltage and current supply. Nevertheless, when control operations and distribution management are insufficient, it can lead to a range of issues such as decreased performance, diminished power quality, reduced reliability, power loss, misutilization, unforeseen storage-related incidents, various forms of damage, restricted functionality, and a decrease in equipment lifespan. In MG applications, the power electronic interface is indispensable for managing power conditions, regulating power flow, facilitating power conversion, energy management, maintaining charge equilibrium, and ensuring safe operations, thereby optimizing system durability and efficiency [138].

B. POWER QUALITY ISSUES

Power quality assumes paramount significance in grid-connected mode due to the adverse consequences of improper control strategies on grid electricity pricing, particularly in terms of market sensitivity [139]. The occurrence of sporadic operations in DG units, the presence of sensitive nonlinear loads and the use of switching devices within MG exerts a substantial influence on power quality, significantly impacting overall system performance [140]. Consequently, the adoption of advanced control technologies becomes imperative to effectively mitigate the intermittent elements, particularly in DG-connected grids. Extant literature addresses the management of intermittency issues in MGs, proposing a scheme to enhance power quality and maintain system reliability [6]. MGs must have the capacity to function effectively despite unbalanced and nonlinear load variations, which can result from voltage and frequency fluctuations in the utility grid. These challenges can lead to power quality issues.

C. PROTECTION AND SAFETY ISSUES

Protection and safety concerns are essential factors that must be considered during the planning, construction, and operation of MG scheduling controllers. In an MG, faults can arise for a variety of causes including ground faults, over-currents, and short circuits [141]. MG scheduling controllers need to be built with quick fault detection and system protection features. Various factors including overvoltage, low voltage, overloading of power, and overheating of equipment can cause equipment damage and increase the likelihood of power outages [142]. To mitigate this hazard, scheduling controllers should be developed with suitable control algorithms and be able to alter power schedules in real time to maintain sustainable voltage and frequency levels and prevent overloading. Furthermore, to avoid electrical shocks and lower the risk of electrical hazards, adequate isolation, and grounding are crucial for the safety of employees and equipment in a MG.

D. ENERGY MANAGEMENT

In recent times, researchers have shown significant interest in centralized control architecture for MG energy management. However, with the growing integration of DGs into power systems, the centralized approach faces challenges such as high computational demands, limited scalability, and vulnerability in case of system failures. Consequently, decentralized architectures have emerged as an appealing solution to address these concerns. Nonetheless, they require the constant presence of bidirectional communication network connecting various MG components, along with the need for synchronization. These factors can result in heightened system expenses. Furthermore, optimizing the expenses associated with upgrading these communication systems is imperative. Additionally, energy management challenges often manifest as optimization problems. For example, the constraint that is considered in the optimization process can affect the operation of energy management in the MG system. The limitation of each constraint should be satisfied to achieve the desired objective. Non-compliance with these constraints can potentially impact the longevity and efficiency of the MG component which may result in physical damage to the devices. In MG systems, technical limitations encompass various aspects, including frequency stability, feeder currents, bus voltage, as well as constraints related to startup, shutdown reserves, and ramping.

E. OPTIMIZATION EXECUTION ISSUES

Utilizing an appropriate optimization algorithm can enhance scheduling controller performance by optimizing relevant parameters during execution, thereby contributing to overall improvements in the MG system's efficiency. Furthermore, the optimal scheduling controller achieves a suitable equilibrium among distributed sources, supply, and grid-connected MGs, while considering factors such as load demands, storage capacity, and battery energy availability [143]. However, the utilization of optimization for scheduling controllers in the MG system remains considerably constrained. Furthermore, the incorporation of optimization introduces numerous issues such as extensive parameters, intricate execution procedures, slow convergence, substantial computational load, and difficulty in achieving global optimal solutions [144]. Consequently, a comprehensive investigation is essential to strike a balance between computational complexity and precision.

F. CONTROLLER ISSUES

The precision of distinct scheduling controller strategies within MGs exhibits a significant level of sensitivity to the appropriateness of their structure and parameter choices. Despite the existence of numerous controllers developed for MG scheduling, the adjustment of parameters often relies on the trial-and-error method, resulting in inefficient utilization of time and human effort [145]. Furthermore, conventional controllers tend to involve intricate computations and are unsuitable for maintaining satisfactory performance during substantial load fluctuations. Thus, the proper execution of the algorithm is crucial to EMS techniques, which are mainly intended to ensure smooth functioning and avoid becoming trapped in local minima. As a result, it is essential to investigate additional research to address the aforementioned issues.

G. SCHEDULING ISSUES

The MG scheduling challenge aims to reduce the operational costs of the power exchange between the MG and the utility grid as well as the local distributed energy resources (DERs) while fulfilling the MG load within a specific period [34]. Several operational restrictions affect the MG scheduling challenge, including energy balancing, load management, and DER limiting. Appropriate management of load shedding and minimization of overall system losses are prerequisites for efficient MG scheduling. These measures are crucial in ensuring sufficient reserve capacity for future demand and

optimizing the efficiency of MG. Additionally, scheduling for loads or renewable energy sources (RES) can be used to control power fluctuations. As a result, the MG application can be improved, ensuring stability and dependability while also raising general effectiveness and lowering overall expenses. The study in [32] presents a scheduling strategy to efficiently control and coordinate MGs' power flows reduce generation cost, conserve energy, and enhance overall system reliability.

VI. FUTURE DIRECTION

The examination of grid-connected MG scheduling controllers through a bibliometric analysis has shown issues and challenges that warrant further exploration in this rapidly evolving field. Future research directions in the following areas emerge, building on the current state of knowledge:

- While Scopus served as the foundation for our bibliometric analysis, future research should consider incorporating additional data sources such as Google Scholar and Web of Science. These platforms might provide insightful information about current worldwide research directions, which would improve our knowledge of MG scheduling controllers. Additionally, efforts should be made to include non-English publications to ensure inclusivity and catch works published in different languages that have a global impact.
- It is impossible to overestimate the importance of power electronic interfaces in MG scheduling controllers. To improve the performance and reliability of MG systems, research should concentrate on optimizing these interfaces. For these interfaces to function safely and avoid system failures, problems with power quality, flow control, and energy management must be addressed.
- Power quality in grid-connected MGs continues to be a major challenge. To reduce the negative effects of intermittent operations, nonlinear loads, and voltage and frequency deficiencies on power quality, future research should investigate improved control methods. It's crucial to develop cutting-edge methods to improve power quality while preserving system dependability, especially in grids connected to distributed energy resources.
- MG scheduling controllers need to be designed, built, and operated with strong security measures. To protect MG components, research should concentrate on the creation of quick fault detection systems and adaptive control algorithms. To reduce electrical risks and equipment damage, adequate isolation and grounding solutions should be investigated.
- Future studies should investigate decentralized designs to handle scalability and communication concerns in energy management in MGs, which is a complex topic. To ensure effective and dependable MG operation, emphasis should be placed on optimizing energy management algorithms while considering restrictions such as bus voltage, feeder currents, and frequency stability.
- There are advantages and disadvantages of using optimization algorithms in scheduling controllers. Striking a balance between computational complexity and precision should be the goal of research. To maximize the effectiveness of MG systems, it is crucial to investigate cutting-edge optimization strategies that solve problems including slow convergence and extensive parameter adjustment.
- Metaheuristic optimization algorithms, like genetic algorithms and particle swarm optimization, are essential for solving intricate optimization problems in MG system operation. These algorithms, along with swarm intelligence techniques such as ant colony optimization, and PSO contribute to improving power quality, tuning controller parameters, and minimizing costs for optimal MG operation. However, there remains a wealth of unexplored metaheuristic algorithms and potential hybridizations of these algorithms to enhance control and energy management systems, aiming to achieve sustainability and efficiency in MG operations.
- MG scheduling is a significant issue that affects system effectiveness and operational costs. Future studies should investigate sophisticated scheduling techniques that maximize the transfer of electricity across utility grids, distributed energy resources, and MGs. To increase the effectiveness of MG scheduling, energy balance, load control, and DER utilization must be prioritized.
- In grid-connected mode, the grid regulates network frequency and voltage, while distributed energy resources (DER) manage their power outputs, with the grid compensating for any mismatches. In islanded mode, DER units must maintain feeder voltage and frequency within acceptable ranges, necessitating suitable control and communication schemes for each DER unit's local controller to update information and system parameters accordingly in the MG system.
- Further research into MG data management is imperative to guarantee the stability of MG operations through effective control management. Attention should be given to remote data transfer mechanisms and the potential expansion of reliable MG systems to serve both utilities and customers.

In conclusion, there are many prospects for cutting-edge research in grid-connected MG scheduling controllers. In addition to assisting in the creation of more dependable and effective MG systems, addressing these future research directions will be essential in furthering the more general objectives of sustainable energy integration and grid resilience.

VII. CONCLUSION

Analyzing the citations to a report is a wonderful technique to determine the significance of an article within its respective field. By identifying the topic area's future direction and accounting for the constraint during the analytic phase, an article's citation status might indicate its scholarly significance. The main goal of the bibliometric analysis used in

this study is to provide a thorough analysis of the most recent academic study trends while identifying the unique traits and evolutionary path of the most highly cited papers related to the scheduling controller algorithm in grid-connected MG systems. A total of 115 articles that represent the top-cited in the field of grid-connected MG scheduling controllers have been extracted from the large volume of literature present in the Scopus database. It has been shown that many analyses have been performed, including distribution of articles by year, categorization by type of study, research area, co-occurrence keyword analysis, journal analysis, country of origin, publishers, and others. The primary outcomes of this analytical assessment show that experiments, simulations, case studies, problem formulation, and the development of algorithms are present in 96.1 % of the articles, while reviews, state-of-the-art, and technical overviews make up only 3.87% of the manuscripts. This article's primary objectives are to critically evaluate and comprehend the traits of commonly referenced works as well as to offer insight into potential paths and advancements in the field of grid-connected MG scheduling controllers. Additionally, this paper outlines the specific benefits and drawbacks associated with each optimization and controller technique. It also delves into a range of challenges and potential solutions pertaining to MG scheduling controller strategies and optimization schemes Thus, this study addresses several challenges and offers suggestions on control approaches for grid-connected MG applications in terms of power efficiency, protection and safety, sustainability, cost-effectiveness, optimal management, power quality, and so on.

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