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Review

A Systematic Literature Review on AC Microgrids

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Abstract: The objective of this work is to analyze and compare AC microgrid (ACMG) solutions to introduce the topic to new researchers. The methodology used to achieve this goal is a systematic literature review using five questions: (1) How have ACMGs evolved in five years? (2) What are the standards for ACMGs? (3) What are the different schemes for connecting MGs to the utility grid? (4) What are the different control schemes in ACMGs? (5) What is an appropriate way to compare results when working with ACMGs? The articles were published in Q1/Q2 journals as based on either the Scimago Journal Rank (SJR) and/or the Journal Citation Report (JCR) between 2018 and 2022 and were from three databases: (1) Web of Science (WoS), (2) Scopus, and (3) IEEE Xplore. Publications not describing pure ACMGs, review papers, publications not related to the questions, and papers describing work that did not meet a quality assessment were excluded, resulting in 34 articles being included in this review. Results show: (1) the energy sources and AC bus nature of microgrids over five years, (2) the identification and quantification of cited standards for microgrids, (3) the pros and cons of different schemes for connecting an AC microgrid to the main grid, (4) the control schemes, classified in a hierarchical control structure, and (5) the simulation tools and experimental benches used in microgrids. Most studies considered a generic energy source and a low-voltage three-phase AC bus, 16 standards were found, and the most cited standard was IEEE Standard 1547. The most common connection scheme to the utility grid was a direct connection, most of the works proposed a modification to a hierarchical control system scheme, and the most common simulation tool was MATLAB. The preferred experimental setup consisted of parallel inverters for testing a control scheme, a prototype when proposing a power electronic system, and a laboratory microgrid for testing fault detection methods.

Keywords: AC microgrid; experimental microgrid; grid-tied microgrid; microgrid control systems; microgrid standards; simulation tools; systematic literature review

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1. Introduction

With the advent of renewable energy, the paradigm in electrical systems has shifted from centralized to distributed generation. This has given birth to the concept of microgrids. Although the concept of a microgrid varies between different authors and has been changing over the years, a good definition of a microgrid is "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode". Microgrids can enable grid modernization, allow the integration of renewable energies, reduce peak loads and losses by locating generation near demand, ensure power availability for critical loads, and may support the main grid [1].

Microgrids are often classified according to the nature of the common bus to which the generators, loads, and storage elements are connected. If the bus works in alternating current (AC), the microgrid can be called an AC microgrid, if the bus is direct current (DC), the microgrid is known as DC microgrid, and if it has both AC and DC buses, it is known as a hybrid microgrid. Microgrids can be connected to the main electrical system (so-called grid-connected MGs) or they can be independent of the grid, so-called off-grid MGs. Nevertheless, the imcrogrid must be able to operate independently of the grid, which it is known as island mode [2]. This last requirement makes it necessary to include systems that allow continuous and controlled generation of power. Controlled generation sources are generally based on non-renewable and polluting energy, so they should be avoided if possible. However, the variability of renewable energy production usually requires operation with the addition of an appropriate storage system. Currently, bidirectional converter technologies are crucial for efficient energy management in microgrids, as they allow users to store renewable energy and release it when necessary [3,4].

Matrix converters are bidirectional AC/AC converters that have been studied for over 50 years, during which time researchers have acquired mature knowledge for applications in grid operations, sustainable transportation, and electrical drives [5]. Papers have proposed the inclusion of matrix converters in microgrids, but they are usually focused on the modulation or control scheme and do not consider distributed generation [6,7]. The motivation of the work described in this paper is to consider the state of development of microgrids to evaluate the inclusion of matrix converters, taking into account the current problems of microgrids and their required functionalities. Given the nature of matrix converters, which are bidirectional AC/AC converters, only AC microgrids (ACMGs) are considered. Matrix converters have applications in grid-tied microgrids as the interface between the microgrid (MG) and the main grid [5,8] for bidirectional power flow, so grid-connected microgrids receive more points than islanded microgrids in the evaluation process.

There are related reviews on ACMGs, but they tend to be very specialized, whereas more general approaches are presented in this paper. Some review articles discuss protection schemes for ACMGs [9–13]; other works center on control and management systems [14,15]. In addition, none of the related papers developed a systematic literature review (SLR). The main objective of this work is to summarize the current information on ACMGs in order to introduce the topic to new researchers in a simple way.

This paper is organized into five sections. This section introduced the paper. Section 2 shows the material and methods employed for developing the review. Section 3 shows the findings of this review. Section 4 discusses the results, and Section 5 presents conclusions.

2. Materials and Methods

This systematic literature review (SLR) follows the structure suggested by the PRISMA 2020 statement [16] as much as possible, considering this journal's requirements. The workflow starts by formulating the following five research questions (RQs):

1. Research question 1 (RQ1): How have AC microgrids (ACMGs) evolved over five years? This question aims to find the most common structures of microgrids (MGs) and the tendency for the next years. It is too wide, so just two characteristics were considered: the nature of every distribution generation unit (DGU) employed and the nature of the AC bus.
2. Research question 2 (RQ2): What are the standards for ACMGs? This question is intended to compile the current requirements of ACMGs.
3. Research question 3 (RQ3): What are the different schemes for connecting MGs to the utility grid? This focuses on the method for grid connection. It may be direct with possible connecting relays or through different power converters.

4. Research question 4 (RQ4): What are the different control schemes in ACMGs? The control system design depends on the source of energy, filters, and power converter employed.
5. Research question 5 (RQ5): What is an appropriate way to show results when working with ACMGs? This question will be helpful in investigating ACMGs, so it can introduce the equipment required to lead an investigation.

These questions are the basis of the work, and every decision made during the development of the work has been taken to answer these questions successfully. A general scheme of the paper selection procedure is shown in Figure 1. The different steps in the process are detailed in the following subsections.

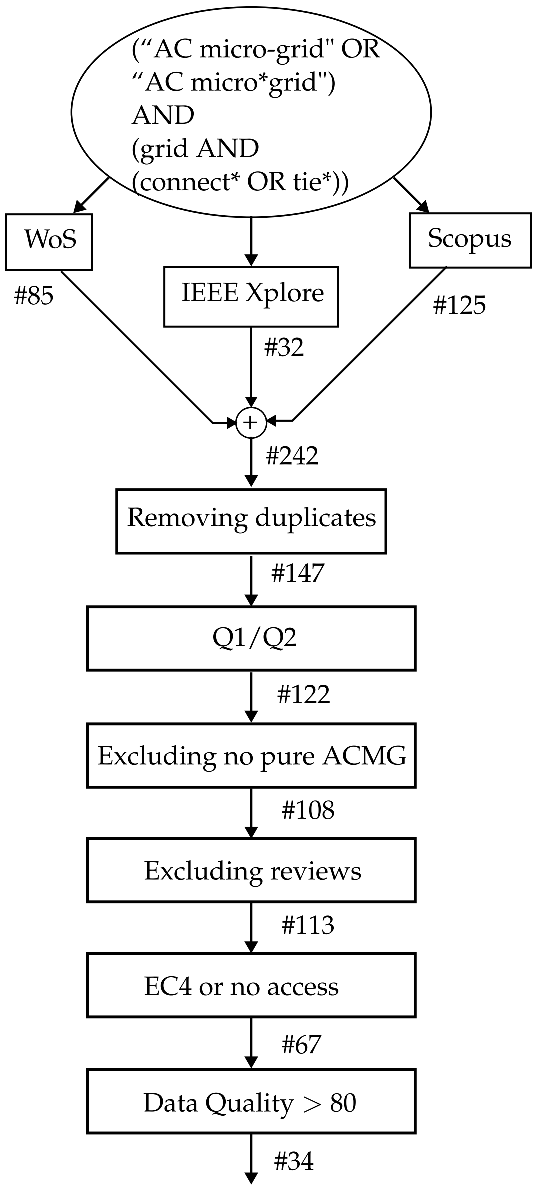

Figure 1. Selection process.

Tools employed to organize and evaluate the papers were:

- Mendeley reference manager: for reading, taking notes, and organizing papers along the process;
- Microsoft (MS) Excel: for arranging, evaluating, and extracting data.

2.1. Inclusion and Exclusion Criteria

2.1.1. Inclusion Criterion (IC)

- IC1: articles from journals written in English and that included ACMGs, especially if they are grid-tied, published between 2018 and 2022.

2.1.2. Exclusion Criteria (EC)

- EC1: not being in a Q1/Q2 journal—this is a guarantee of quality;
- EC2: abstract showing that it does not study a pure ACMG;
- EC3: the paper is a review—only primary sources were considered;
- EC4: lack of information to answer more than three research questions. The objective of this criterion is to reduce the number of articles included and to keep those with more information related to the study. It was included for three main reasons: (1) publications that include a real system or at least an experimental MG are considered more important to answer RQ1 than those that only have theoretical formulations (equations) or simulations of non-real systems; (2) RQ5 only makes sense when the study answers RQ1 and RQ3 or RQ4; (3) most of the works are high-quality papers, so they get a high score even when not answering any question.

2.2. Information Sources

The databases employed for the research were Web of Science (WoS) and Scopus due to their reputation and reliability. IEEE Xplore was also consulted to recover newer papers that might not yet be available in the aforementioned databases.

2.3. Search Strategy

The main query used for the research was: `(‘‘AC micro-grid’’ OR ‘‘AC micro*grid’’) AND (grid AND (connect* OR tie*))`. The search query was obtained in an iterative process, as we tried to obtain only works related to the research questions. This search command is understandable in all three databases, simplifying the reproducibility of the work. Other concepts such as “active distribution network”, “parallel converters”, and “distributed generation” can also be intimately related to MGs, but the authors preferred a short, simple query instead of trying to cover the whole universe. As initial search queries such as “microgrid” resulted in thousands of works, it was not considered necessary to capture more papers; instead, our purpose was to reduce the number of resulting papers and to keep those that could help answer the research questions. As the term “microgrid” involves not only the most popular DC MGs but also other topics such as heat systems, policies, economic aspects, stability studies, and communication systems, the employed term “AC microgrid” could filter the results more successfully. It was not an easy task to establish a search query because the research questions were too general and the results too numerous. Moreover, the following filters were considered:

- Only journal papers, which have passed through a more rigorous revision process than other sources;
- Only articles published between 2018 and 2022 to ensure that the information used in the study was up to date;
- Only papers in English because English is considered to be the more extended language for scientific research;
- In Scopus, the query was applied to the title, abstract, or keywords to reduce the high number of articles presented without this restriction (3768 articles).

2.4. Selection Process

2.4.1. Q1/Q2 filtering

The search process was performed by the first author, who also defined the eligibility criteria, so the work might be biased based on his criteria. However, the rest of this section tries to explain in great detail all the reasons for the different choices the author made during the review process. To guarantee trusted sources, only articles in the first or second quartile (Q1/Q2) were included, reducing the number to 122 studies from 45 different journals, which may be found in Appendix A. Two rankings were considered: SJR (Scientific Journal Ranking) in the categories *Energy* or *Engineering* and JCR (Journal Citation Report) in the category *Engineering, Electrical and Electronic*. These categories were chosen in order for us to focus on research on the electrical and electronic aspects of MGs. Nevertheless, in practice, the categories chosen in SJR were much more inclusive than the categories in JCR. As SJR has more journals, most of the papers that appear in JCR also appear in SJR with a better percentile. Only the journals: *Electronics*, *IEEE Transactions on Smart Grid*, and *IET Renewable Power Generation* were included by the JCR side and not by SJR. The first exclusion criterion (EC1) is: not belonging to a journal that has been Q1 or Q2 in at least one of the aforementioned rankings in the included five years.

2.4.2. Title and Abstract Screening

Titles and abstracts were screened, and some articles were excluded:

- EC2: abstract shows that the study does not include a pure ACMG but instead studies a DC MG, hybrid MG, or other type of MG [17–30].
- EC3: the article is a review—review articles are excluded as they are not primary sources [31,32].

Thereafter, exclusion criterion 4 (EC4) (explained in the Section 2.4.3) was applied.

2.4.3. Excluding Criterion 4 (EC4)

To reduce the number of works studied while keeping the more relevant ones for answering the research questions, it was decided to exclude works that do not satisfy at least two of the three following requirements:

- Includes a grid-tied MG;
- Has real or experimental results (not just theoretical or simulation results);
- Answers three or more research questions.

This rule reduced the number of works to 67. In this step, one article could not be verified because access was not possible, so it was also excluded [33]. Emulation platforms were considered experimental setups. The electrolyzer found in one article is only used for hydrogen generation, so it does not count as a distribution generation unit (DGU), and its scheme is not considered an MG [34].

2.4.4. Quality Evaluation

Finally, these 67 works were evaluated with the criteria shown in Table 1, resulting in 34 articles included in this review. Articles with a score greater than or equal to 80 points out of 100 were included. The evaluation was done in an MS Excel sheet.

Table 1. Quality evaluation criteria.

Paper		Weight
Title	<15 words	3
	Keywords in the title	3
Abstract	Presents a logic structure	3
Introduction	Context	3
	Implicit or explicit hypothesis	3
	Problem	3
	Explicit objective	3
Theoretical framework	State-of-the-art in a logical order	3
	Appropriate content	3
	Detailed methodology	3

Table 1. *Cont.*

Paper		Weight
Results	Available data	3
	Results match objectives	3
	Shows results with standardized metrics	3
	Information in figures complements the text	3
Discussion	Findings related to the objectives	3
	Results are compared to those from the state-of-the-art	3
Conclusions	Correspond to the objectives	3
	Show future work	3
References	References match	3
	Complete references	3
EC4	Includes a grid-tied MG	14
	Real or experimental application	13
	Answer three or more research questions	13
	Total	100

The first 60 points relate to the quality of the article, while the last 40 points relate to the research questions. The threshold of 80 points was selected to reduce the sample size to a manageable number.

2.5. Data Collection Process

The first author gathered data. Some data were tabulated in the same MS Excel Version 2496 sheet used for evaluation, and some information was directly inserted into this document.

2.6. Data Items

Included studies are summarized in Table 2, where excluded works and the exclusion reasons are also shown. Many areas are included, such as the design of a power converter for solving a specific problem, the simulation and emulation of control systems for ACMGs, optimization of MG parameters, techniques for noise reduction, and fault detection and protection systems.

Table 2. Included and excluded works.

	Articles
Included	[35–68]
Excluded—reviews	[31,32]
Excluded—no pure AC	[17–30]
Excluded—EC4	[33,69–106]
Excluded—<80	[34,107–138]

2.7. Study Risk of Bias Assessment

As for all search queries, evaluation and data extraction were performed by one author; the authors recognize the possibility of introducing bias in the process. However, as this is not a quantitative study, it is difficult to evaluate bias, and the best that can be done is to show the work and explain the method as transparently as possible.

2.8. Synthesis Methods

2.8.1. RQ1a

For RQ1a, the number of articles using each type of DGU was counted. Only DGUs used in the main work were counted. Energy storage systems were also counted, as they can act as DGUs.

2.8.2. RQ1b

The information was searched in the text and figures.

2.8.3. RQ2

The requirement was to explicitly include the name of the standard in the document. On the first read of the articles, the standard was remarked on if found. Then, in a second phase, the word *standard* was searched for with the text finder in Mendeley. In this way, some standards included in the references were also found. A problem this last search may have is the separation at the end of the line, as was found in some articles, so the first compilation was kept, and the second procedure was only to complement and could not replace the full reading of an article.

2.8.4. RQ3

The connection scheme of the ACMG to the main grid was first searched for in the figures of the developed work. The text was then read if any information was missing. When not all the necessary information was found, the work was excluded based on.

2.8.5. RQ4

The control scheme was first searched for in the figures, and then the text was read again for missing information. As was found during the work, there are different approaches to controlling a microgrid. The first time, all control systems were extracted, including their function and the level of hierarchy control (if this existed). In a second round, after gaining more knowledge on the topic, it was decided to classify the different control schemes to answer this question. The modulation stage is not considered a control system. In HMGs, only the control system involved in AC bus control was considered, but sometimes it was difficult to separate the control system, especially when the system had interleaved converters that worked between the AC and DC buses.

2.8.6. RQ5

The simulation and experimental sections were read to find this information. The results consisted of simulations or experimental results, so all the simulation tools and experimental platforms or benches were compiled.

3. Results

3.1. Research Question 1 (RQ1): Evolution of AC Microgrids (ACMGs) over Five Years

This research question is very wide, so in this study, two aspects are considered: the source of energy of the distributed generation units and the characteristics of the AC bus—in other words, the level of voltage, number of phases, and frequency of the AC bus.

3.1.1. RQ1a: Evolution of Distributed Generation (DG) in ACMGs over Five Years

To answer this question, the number of articles that contained each DG source was counted and tabulated. Data were drawn using MATLAB and are shown in Figure 2.

Most of the works used a hierarchical control scheme for microgrids. Defining the type of energy source was mainly necessary for the control of the tertiary level for optimal dispatch [62]. Modeling the different sources of energy is another case when the nature of the DG unit is important [35]. Furthermore, designing a specific system based on one DG unit is another case in which the energy source of the DG unit is mentioned [43,44,61].

In other cases, such as proposing solid state transformers or interlinking devices for AC and DC buses [64], modifying the primary level [53,56,59,60,65,68], dealing with the secondary level [58], seamless operation [39,46,48,55], grid feeding [38,41], grid support [45,50,54,57,63], detecting faults [36,47,49,67], dynamic response enhancement [51], measurements [52], and communication improvements [66], energy sources were not important.

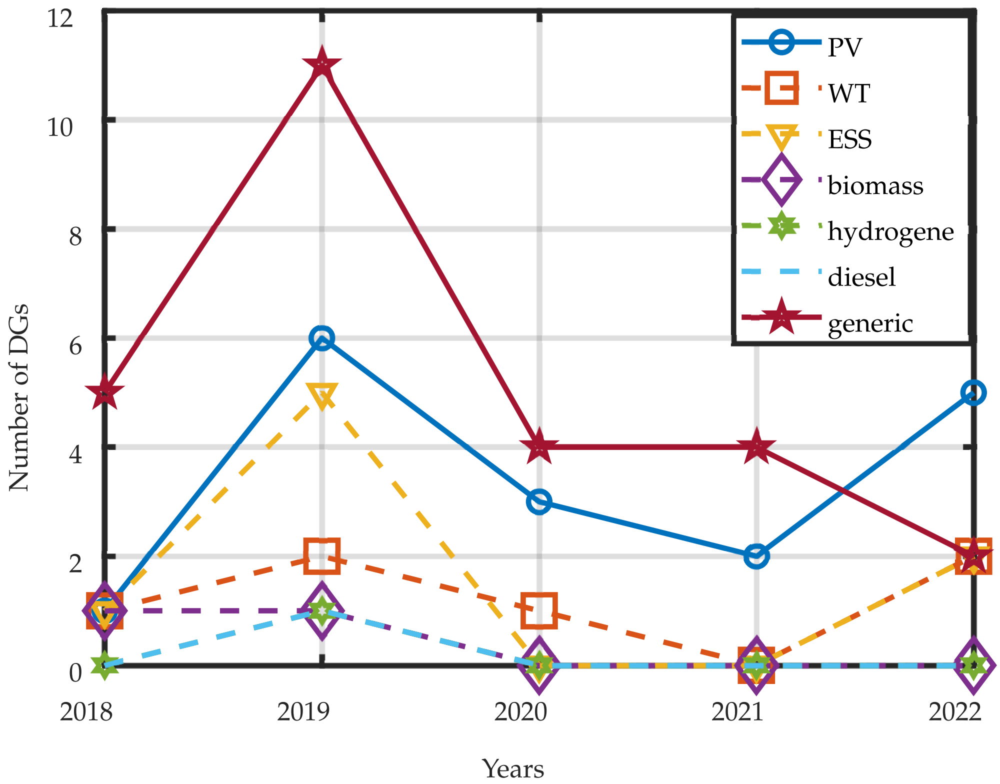

Figure 2. Evolution of the number of sources of DG included in the literature over five years (RQ1). We can see a decline in research on the topic after the peak in 2019. Numbers show that photovoltaic (PV) systems are the most popular DG source. The data also reflect that energy storage systems (ESSs) are one of the most popular topics, given the problem of the variability of renewable energy sources (RESs). Sometimes, this variability is compensated for with other sources of energy, such as diesel or biomass, and, of course, the main grid supply. Nevertheless, most of the works do not care about the energy source and use a generic DC voltage to feed the inverters, given that they work on another issue such as a control scheme, a power converter, or solving an optimization problem.

DG units (DGUs) are assumed to use generic DG when DG is mentioned but not used in the main work [57,58]. Superconducting magnetic energy storage is considered an ESS [44]. PV emulators used in the experimental setup were also considered as PV DGUs [37,40,61]. In [62], the DDGs mentioned were considered generic DGs, as they can came from diesel, hydro, thermal, or other sources. The difference the author claims is that DDG power is programmable, whereas renewable sources such as PV or WT are not always available. In [64], the source was considered to be a PV system, because even though it uses an ideal DC link, the power-decoupled current source inverter (PD-CSI) was designed taking into account PV systems.

3.1.2. RQ1b: Evolution of AC buses in ACMGs over Five years

The results for the different AC buses found are summarized in Table 3. The nature of the AC bus is classified as: low-voltage single-phase and high-frequency (LV 1-ϕ HF), low-voltage single-phase (LV 1-ϕ), low-voltage three-phase (LV 3-ϕ), and medium-voltage three-phase (MV 3-ϕ). The works are arranged by publication year. For the voltage level, we considered:

- Low-voltage (LV): up to 1000 V;
- Medium-voltage (MV): between 1000 V and 45 kV.

Table 3. AC bus scheme in the included works (RQ1).

	2018	2019	2020	2021	2022	Sum
LV 1-ϕ HF					[37]	1
LV 1-ϕ	[52]	[35,57,63]	[59]	[64]		6
LV 3-ϕ	[44–46,48]	[40–43,50,54–56,61]	[36,66]	[38,47,53,65,67,68]	[39,62]	23
MV 3-ϕ		[60]	[49,51]			3
Sum	5	13	5	7	3	33

Some remarks regarding the data extraction include: the voltage operation level is not mentioned, but it was assumed to be low-voltage due to its experimental setup [45]. The voltage level is not shown, but this is assumed to be MV because of the power levels [51]. An article included an unusual AC bus frequency of 400 Hz, so it was separated from the others [37]. The article shows a low voltage, but it is not clear whether it is single-phase or three-phase, so it was not included in answering this part of the question [58]. The voltage level is not mentioned, but it is assumed to be low-voltage because the power levels are within the range of generators with low voltages [62]. The MG does not have an AC bus but is connected to a single-phase grid [63].

3.2. Research Question 2 (RQ2): Standards for ACMGs

Standards found in the included works are tabulated in Table 4. Many works do not mention any standard [35–37,41,42,45,46,48,49,53,55,56,62,63,65–67]. Some of them refer to *IEEE Standards* [48,53,54] or *IEC Standards* [54] but do not mention anything specific. It is important to note that VDE 0126-1-1 is a German standard for which the current status is "withdrawn".

Table 4. Standards for microgrids (RQ2).

Standard	Name	Mentioned by
IEEE Standard 1547-2018 [139]	Standard for interconnection and interoperability of distributed energy resources with associated electric power system interfaces	[17,44,51,58–60]
IEEE Standard 519-2014 [140]	IEEE recommended practices and requirements for harmonic control in electric power systems	[39,52,57,61]
EN-50160 [141]	Voltage characteristics of electricity supplied by public electricity networks	[38,50]
IEEE Std C37.118.1 [142]	IEEE standard for synchrophasor measurements for power systems	[38]
IEEE 1159-1995 [143]	IEEE recommended practices for monitoring electric power quality	[50]
IEEE 2030.7-2017 [144]	IEEE standard for the specifications of microgrid controllers	[40]
IEEE 1459-2010 [145]	IEEE standard definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, and unbalanced conditions	[43]
EN 61000-2-2[146]	Electromagnetic compatibility (EMC)–part 2-2: environment—compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems	[50]
EN IEC 61000-3-2 [147]	Electromagnetic compatibility (EMC)–part 3-2: limits—limits for harmonic current emissions (equipment input current <= 16 A per phase)	[50]
IEC 61727 [148]	Photovoltaic (PV) systems—characteristics of the utility interface	[51]

Table 4. *Cont.*

Standard	Name	Mentioned by
IEC 60831-1 [149]	Shunt power capacitors of the self-healing type for AC systems having a rated voltage up to and including 1 kV–part 1: general—performance, testing, and rating safety requirements guide for installation and operation	[52]
IEC 60831-2 [150]	Shunt power capacitors of the self-healing type for AC systems with a rated voltage up to and including 1kV–part 2: aging test, self-healing test, and destruction test	[52]
IEC 60255 [151]	Measuring relays and protection equipment–part 1: common requirements	[47]
IEC 61850 [152]	Communication protocols for intelligent electronic devices at electrical substations	[47]
IEC 62040-2 [153]	Uninterruptible power systems (UPSs)–part 2: electromagnetic compatibility (EMC) requirements	[68]
VDE 0126-1-1 [154]	Automatic disconnection device between a generator and the public low-voltage grid	[64]

3.3. Research Question 3 (RQ3): Schemes for Connecting MGs to the Utility Grid

The direct connection scheme can be through a filter, a circuit breaker, or a combination of both. The schemes we found for connecting ACMGs to the main grid with their respective pros and cons are tabulated in Table 5. The information extracted is only from the main work the papers include and does not include information about grid connections that is present in the introduction.

There were some considerations when collecting information. The article involving the high-frequency AC bus is considered an islanded solution [37]. Another article included two schemes, but the laboratory grid scheme uses an autotransformer [41]. Some MGs are considered islanded because the work does not show a clear connection of the AC bus to the main grid; also, the work focuses on distributed generation and does not consider the grid connection [56]. A photovoltaic unified power quality conditioner (PV-UPQC) connects to the grid at two points through an isolation transformer—on the primary and the secondary—which is why it is put into another category [43]. One article does not have only one AC bus: instead, three AC buses with their AC sources are interconnected through inverters connected to the same DC bus [50]. A paper used TRIAC to connect the AC bus to the grid, but this is considered to be a type of direct connection [55].

Table 5. Pros and cons of different schemes for grid connection (RQ3).

Connection Scheme	Pros	Cons	Works
Direct	Easy connection and low cost	Little control	[35,38,41,44–46,48,51–53,55,57–60,66,67]
Isolation transformer	Galvanic isolation	High cost	[40,42,47,49,50,62]
Autotransformer	Efficiency and cost	No isolation	[39,41]
Grid-tied inverter	Simple, quality of the AC bus voltage	High cost	[54]
PV-UPQC system	Power quality of the grid	Depends on PV system	[43]
Energy storage system	Palliates the intermittence of RESs	Highest cost	[63]
H-bridge, active power decoupler	Power quality	Complex control and high cost	[64]
Islanded			[36,37,56,61,65,68]

3.4. Research Question 4 (RQ4): Control Schemes in ACMGs

Before answering this question, note that there are many control system schemes for different purposes among the different subsystems inside a microgrid. Commonly controlled variables can be power (active or reactive), voltage (magnitude and frequency), and current. Some works pretend to improve the quality of the electrical variables with their control system by controlling reactive power, reducing harmonics, and seeking seamless transitions between modes of operation. Other problems must also be resolved with control systems, such as the capability of working in an islanded and grid-tied mode and delays in the communication systems of centralized or distributed control.

Taking into account the results, hierarchical control is a promising approach to controlling a microgrid; it defines three levels for controlling different variables. Primary-level control is responsible for controlling active and reactive power, and this level is usually decentralized. Secondary-level control is responsible for correcting the steady-state deviation of the primary level and can be centralized, decentralized, or distributed. Finally, tertiary-level control is in charge of energy dispatching, i.e., establishing the power references. Again, control schemes can be found for a seamless transition from islanded to grid-tied mode or vice versa. Decentralized droop-based control schemes are the most popular at the primary level for power sharing. Secondary control may be centralized, decentralized, or distributed. Some authors prefer to avoid communication and propose decentralized secondary control, while others prefer to include a communication system to have more information in a centralized or distributed secondary control system. Tertiary control is centralized. Taking into account the results, the authors recommend using hierarchical control for a matter of organization. The authors consider that the most organized way to divide this multipurpose control system is hierarchical control, so the control schemes we found were classified into the hierarchical scheme structure when possible, as shown in Table 6. Some works did not explicitly show a control system [47,49,67], and some used only pulse width modulation [52].

After this classification, it can be seen that most of the works accept the hierarchical control scheme, as this scheme facilitates the design of a specific part of the control system. This classification shows the (highest) level that each control system occupies (or might occupy) in a hierarchical control scheme. For example, a control system occupying the secondary level may replace the secondary control or both the secondary and primary levels. The first 0-level is for control systems that could be employed in the inner loops of the primary level for controlling the voltages and currents.

Table 6. Control schemes in ACMGs (RQ4).

0-Level	PI-resonant for current control [36], PI-resonant for voltage control [36], PI-resonant for voltage control [36], model predictive current control [41], active damping and LCL output current control [41], PR for voltage control [37], negative-sequence voltage elimination [38], negative-sequence current sharing [38], deadbeat current control [50], PI current control [51,55], PI voltage control [55], and hysteresis current controller [61]
Primary level	Classic droop [48,58], PI for reactive power control [41], bilinear PI controller based on passivity-based formulations [44], bilevel functional-rotation-based active damping control [45], improved droop controller [53], repetitive and state feedback control combined with droop control [56], optimal direct control method (FCS-MPC current and voltage control for active power filter) [57], classic droop modification [59], linear quadratic Gaussian control [60], efficiency-prioritized droop control strategy [65], model-predictive-control-based virtual synchronous generator (VSG-MPC) [103], 3-phase improved-magnitude phase-locked-loop control [61]
Secondary level	Microgrid central controller [40], distributed droop-based [46] distributed leader–follower control, fuzzy multitask secondary controller [58], droop [62], decentralized passive dynamic PI controllers [42]
Tertiary level	MPC for optimal dispatch [35], supervisory control [46], master–slave configuration [39], PI power control [51,58]
Hard to classify in hierarchical control schemes	Current and voltage control of PV-unified power quality conditioner [43], quasi-proportional-resonant-integral (PRI) current controller (grid-tied inverter with MPPT for PV) [63], quasi-proportional-resonant (PR) current controller (grid-tied inverter with MPPT for PV) [64], composite controller (internal model controller + quasi-PR controller with multiple resonance compensation) for grid-tied inverter [66]

3.5. Research Question 5 (RQ5): Tools and Experimental Setups for ACMGs

The answer to this question is classified into two categories: simulation and experimental results. The proposal of each article can be also arranged into five groups, and the results shown depend on this proposal. Proposals found among the works are (1) control schemes, (2) systems involving power converters, (3) fault detection methods, (4) optimization methods, and (5) power quality monitoring indexes. Depending on these classifications, the results and experiments, as well as the tools employed, were different. The information on the simulation tools used is summarized in Table 7. Most of the works involving MG control systems employ simulation tools to test their proposed schemes. Some of the works go further, with real-time simulation of MGs. Works proposing power converters for a specific application in MGs usually test their platform experimentally [36]. Some works do not specify the simulation tool [42,46,53]. In some of the articles, the plots seem to be made in MATLAB, but it is not clear, so they are not included in the table. MATLAB/Simulink was the most popular tool for simulations. PLECS can be used in a MATLAB environment [65], which suggests that authors perform simulations in MATLAB before PLECS implementation.

The experimental results were also classified with the same organization, but in this case, instead of the simulation tools, the type of experimental bench is considered, as shown in Table 8. The most common experimental method to test the control in MGs is through parallel converters. Only five works employed full experimental MGs with emulated or real generation units [39,49,61,67]. Another interesting approach is emulating an MG in real-time [40,41,53].

Table 7. Results shown and simulation tools.

Proposal	Results	Simulation Tool	Works
Control scheme	Works commonly show figures of merit and figures of physical variables to show the tracking capability and response time	MATLAB PLECS PSCAD PSIM	[39,41,44,48,50,54,59,66,68] [65] [56] [55]
Power electronic system	Experimental prototype of their proposal	MATLAB PLECS	[21,43,62,124] [37]
Fault detection method	Works show tables of delay times for fault detection	MATLAB PSCAD	[47,49] [67]
Optimization method	Figures of physical variables	MATLAB	[51]
Power quality monitoring index	Comparison to other indexes	MATLAB	[52]

Table 8. Experimental results.

Proposal	Experimental Setup	Works
Control scheme	2-parallel VSI 3-parallel VSI 1-VSI OPAL-RT simulated MG Control in FPGA + dSPACE RT simulated scheme Typhoon HIL emulated MG	[39,54,58,60,61,65,68] [38,45,66] [40,50,56] [40] [41] [53]
Power electronic system	Solid state transformer Other converter	[43] [36,37,63,64]
Fault detection method	Laboratory MG	[49,67]

4. Discussion

4.1. Limitation of Evidence

In general, the search query could have been more extensive given other synonyms found in the current literature: nanogrid, picogrid, minigrid, smart grid, distributed generation, and parallel inverter; however, the term microgrid (MG) is the most common. Similarly, not including hybrid microgrids in the search query omits related information, as AC microgrids are present in hybrid microgrids. Nonetheless, limiting the search query to ACMGs is a price that must be paid to obtain a more selective sample, as the ultimate goal was not to consult all the literature but to answer the research questions. Distributed generation and parallel inverters are general terms that may or may not describe microgrids. Distributed generation is the basis for the development of microgrids and typically is related to renewable energy sources (RESs) in an MG; likewise, parallel inverters typically function in MGs. The main difference between the other concepts is the levels of power they manage, and only MGs are normally connected to the grid [155], so the employed term is considered correct. However, choosing only grid-connected MGs was an important cut of information, but it was one of the purposes of the work to review the different connection schemes.

More databases could have been included, but the choice of these databases does not represent a significant risk of bias in the posterior quality assessment because it is considered that the more qualified works and journals are present in these databases.

Taking into account the SLR technique, the research questions were too general, and they were modified during the process. They could have been defined more precisely if the knowledge of AC microgrids (ACMGs) was deeper. It is necessary to have closely related research questions, maybe fewer, to define a unique search query; otherwise, it could be better to define multiple search queries, but again, multiple queries can result in multiple articles with fewer questions. Moreover, the systematic literature review (SLR) technique was developed for resolving conflicts (different numerical results) between different sources, so PRISMA 2020 recommendations are best suited for solving conflicts or contradictory statements between different sources.

4.2. Interpretation

4.2.1. Research Question 1 (RQ1)

It can be seen that the distributed generation units (DGUs) are not of importance for many authors, given that they use generic DGUs in their studies. In any case, the most studied DGUs are photovoltaic (PV) systems along with a proper energy storage system, which should be of no surprise for DC or hybrid microgrids (HMGs), but they also occur in ACMGs.

PV systems as renewable energy sources have gained more interest than others given their high scalability and easy installation. PV efficiency has also increased over the years. Another reason PV systems are interesting is that solar irradiance is less unpredictable than other energy sources. These factors have produced a fast decline in costs, which makes PV systems less expensive than all of the other renewable energy sources. Evidence suggests that PV systems will continue to be the fastest growing renewable energy source for the coming years [156].

Concerning the AC bus, the most popular is the three-phase low-voltage. Works including medium-voltage buses were rarely included because they are difficult to implement experimentally. The fact that low-power distributed generation units usually work at low-voltage promotes the preference for low-voltage ACMGs. Another factor that drives the preference for low-voltage microgrids is local consumption, which does not require the voltage elevation that is necessary to reduce transmission losses. Three-phase systems are preferred over single-phase systems because the power is constant: they can transmit three times more power with just one more conductor, and they can supply three-phase loads as well as single-phase loads. One article presented an unusually high-frequency AC bus [37], and more works of this type are expected because this can help in high-frequency applications and allows reducing the number of components required for the filters; however, their usage is expected for specific islanded microgrids, like space applications, and not for the main utility grid. In conclusion, current facts and evidence imply that low-voltage three-phase AC buses will be preferred in the future.

In particular, the studied aspects were not the most interesting, but the work unveiled others that could be considered for the evolution of ACMGs. It is considered that the most relevant topics given the change of paradigm from centralized to distributed generation in ACMGs will be: (1) Control systems need to be modified, given that distributed generation has changed the usual control schemes and different standards and protocols have different requirements. (2) Energy storage systems need to be developed due to the variability of the energy sources. This will consist of enhancing the energy and power capacity of the energy storage systems. It includes appropriate energy conversion systems for storing and recovering electrical energy (fuel cells, flywheels, etc.) as well as the power electronics for adequate electrical energy delivery [3,4]. (3) Interconnection systems can help to connect DC and AC buses in microgrids and also interconnect different microgrids in the electrical system. (4) Communication systems can reduce package loss and allow faster and more reliable data transmission. (5) Measurement systems can provide appropriate power management and control. (6) Protection systems need to be updated, as current devices are not designed for distributed generation. (7) Optimization in terms of costs, losses, efficiency, etc., needs to be performed, and self-adaptive tuning methods for control parameters need to be formulated given the current developments in artificial intelligence and self-learning and self-adapting systems.

It is also shown that the number of included publications decreased since 2019; however, the first set of 147 articles did not show this decrease. Other search queries like "microgrid" show an increasing number of publications over time. This means that the selection process is likely to be responsible for the observed decrease. This could imply that the ACMG tied to the grid, which is the studied system, is less relevant for researchers than other topics like energy storage systems or DC and hybrid microgrids. In the future, one may expect a reduction in ACMGs and a dominance of DC microgrids since energy storage systems (ESSs), PV systems, and most household devices work with DC voltage. Today, HMGs lead this transition.

4.2.2. Research Question 2 (RQ2)

Standards from the IEEE Standard Association, which is an American institution, and the International Electrotechnical Commission (IEC) from Europe are the most popular. The standard to be adopted depends on the specific topic of study in the MG and regional and national regulations. As MGs are diverse, many standards on different topics were found. The reader should define the problem and select the standard according to their region and purpose.

The most frequently mentioned standard was IEEE Standard 1547, which is a series of standards for the connection of distributed energy resources with associated electric power system interfaces, with IEEE Standard 1547-2018 being the basis of the series [139]. Other standards of the series complement the first in other aspects like details, schematics, cybersecurity, island mode operation, secondary network systems, distribution impact studies for distributed generation interconnection, and storage systems. This standard has been fully adopted in 8 states and 25 utilities in the USA. It is also in the process of being adopted by other USA states and utilities [157]. The IEEE 519-2014 standard is the second-most cited standard and defines the voltage and current harmonic distortion criteria for the design of electrical systems [140].

The IEC is an international standards organization that prepares and publishes international standards for all electrical and electronic technologies; the IEC consists of 170 countries: 60 full members, 23 associate members, and 87 affiliates. IEC standards cover a vast range of technologies from power generation, transmission, distribution to home appliances and office equipment, semiconductors, fiber optics, batteries, solar energy, nanotechnology, and marine energy, as well as many others. EN 50160 is a standard from the IEC that defines the voltage characteristics for the electricity supplied by public electricity networks. IEC 61000-4-30 is another standard of interest that defines measurement procedures for applying the previous standard correctly.

Standards reference other standards, and nowadays, efforts are put into making them all compatible. For example, IEEE 1547 refers to IEEE Standard 519 and IEC 61000.4.15 [158] regarding flicker and fluctuation. Another example is IEEE Standard 519, which was purely an IEEE standard with no references to the IEC standards in its version from 1992, but its updated version from 2014 includes all of the measurement methods referenced to IEC standards.

Information on potential gaps and areas for improvement of standards has not been found in the included literature. However, standards will continue evolving, with every revision searching for global compatibility (as far as possible) for electric specifications; IEEE 1547 is a good option to adopt given its current state of development, its current permeation in the utilities, and its periodic revisions and improvements every 10 years by the IEEE Standard Association.

4.2.3. Research Question 3 (RQ3)

The most usual option is direct connection: letting the AC bus be directly connected to the main grid, perhaps with a current filter and a circuit breaker for protection. Transformers or auto-transformers are also based on passive elements and are also simple and more secure, but they are more expensive. One implication of using these passive schemes is that the AC bus voltage inside the microgrid is regulated by the main grid. Another implication is that microgrids change their mode of operation from island mode to grid-connected mode when the microgrid is connected to the main grid. This is how real-world microgrids are normally connected to the main grid [159,160].

Other, more complex systems like solid-state transformers are attractive as they allow a controlled interconnection of the MG and provide ancillary services. Practical implications include a more complex and expensive interface. They are preferred in DC or hybrid microgrids since they provide a DC stage, which serves as a DC bus [17]. However, a real-world application of this configuration has not been found. In the future, we expect more research on bidirectional grid/MG power interfaces, such as solid-state transformers, and devices that can provide ancillary services to this interface, such as unified power quality conditioners, active power filters, dynamic voltage restorers, and static synchronous series compensators.

One thing to bear in mind is the concept of MGs that different authors may have. Some works considered a grid-tied AC bus that only considered the grid-tied mode of operation, which lacks the autonomy of MGs. In this context, the stability and inertia of the MG are not taken into account, and some other problems, such as power quality or optimal dispatch, are approached. Some authors may consider a grid-tied electrical system with one generator alone as an MG, and some others define an MG as an autonomous electrical system with distributed generation that may or not be connected to the grid. We prefer the definition of IEEE Standard 1547 [139].

4.2.4. Research Question 4 (RQ4)

Control systems in microgrids are too wide, but in general, hierarchical control is taking over and promises to be the first option in the coming years as it provides an organized framework to establish a multipurpose control scheme. Central control is more effective but is not scalable like decentralized control [42,60]. Centralized control also requires good and fast communication, which represents more cost. However, central control can be applied to critical systems that do not change over time. Distributed control occupies a midpoint between centralized and decentralized control: being scalable but requiring a communication system among all (or some) of the converters [46,161].

The most popular recent trend in ACMG control systems is to look for a more robust control system and to improve the stability by appropriate voltage and frequency control systems [162–167]. Taking this trend into account, potential future directions would be to test and validate non-linear control as well as to include artificial intelligence in the control system. Another innovative trend is handling cyberattacks in the control system [168–170]. Other topics included in ACMG include the optimization of the energy management system (EMS) [171] and the seamless transition between grid-connected and island modes of operation [39,55]. Considering the need for energy storage systems, appropriate control systems for further developing energy storage technologies are also expected.

4.2.5. Research Question 5 (RQ5)

Many papers describing different proposals validated their work through simulations. MATLAB/Simulink has proven to be the first choice for simulation and is complemented by equipment like dSPACE for experimental applications. Other options are not very common. Moreover, MATLAB allows for an easy way to plot results and is widely used to show results.

The experimental microgrids found are mainly laboratory prototypes, and the results show only one-time operation, which does not tell about continuous operation. Most of the included works propose a control scheme for the MG, and the best choice for testing a control scheme is to have parallel inverters connected to the same bus. However, these experiments should include, if possible, the generation unit to test the controller response to the variability of renewable energy sources. When proposing a converter or system, it is almost a rule that an experimental prototype supports the proposal.

5. Conclusions

This work presents a systematic literature review on AC microgrids (ACMGs) based on five research questions, all of which have been addressed and discussed. The article serves as an introductory overview of ACMGs; it focuses on five key aspects and acts as a hub for accessing related research papers. These points include: (1) the evolution of ACMGs, (2) standards applicable to ACMGs, (3) grid connection schemes, (4) control systems within ACMGs, and (5) findings from articles on ACMGs.

According to the literature reviewed, the typical ACMG configuration involves distributed generation units connected via power converters to an AC bus that supplies AC loads. When connected to the grid, this AC bus is typically linked to the main grid through breakers and passive components. ACMGs commonly employ hierarchical control systems, facilitating operation in both grid-connected and island modes.

It is noteworthy that the development of microgrids is closely linked to the advancement of standards, with IEEE Standard 1547-2018 being particularly prominent.

Considering the trend towards autonomy achieved through batteries and the rising popularity of DC loads alongside the dominance of photovoltaic systems, the adoption of hybrid microgrids appears more pragmatic than relying solely on ACMGs.

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Abbreviations

The following abbreviations are used in this manuscript:

APF	Active power filter
AC	Alternating current
ACMG	AC microgrid
DDG	Dispatchable distributed generation
DG	Distributed generation
DGU	Distributed generation unit
EC	Exclusion criterion
ESS	Energy storage system
FCS-MPC	Model predictive control with finite control set
FPGA	Field programmable gate array
HF	High frequency
HIL	Hardware in the loop
HMG	Hybrid microgrid
IC	Inclusion criterion
JCR	Journal Citation Report
LV	Low voltage
MG	Microgrid
MPPT	Maximum power point tracking
MS	Microsoft
MV	Medium voltage
PD-CSI	Power decoupled current source inverter
PI	Proportional-integral
PR	Proportional-resonant
PRI	Proportional-resonant-integral
PV	Photovoltaic
PV-UPQC	Photovoltaic unified power quality conditioner
PWM	Pulse width modulation
SG	Synchronous generator
SJR	Scimago Journal Rank
RES	Renewable energy source
RQ	Research question
VSG-MPC	Model-predictive-control-based virtual synchronous generator
VSI	Voltage source inverter
WoS	Web of Science
WT	Wind turbine

Appendix A

A summary of the journals included in the study is presented in Table A1.

Table A1. Journals (Q1/Q2) in SJR or JCR and the number of works obtained from each one.

Journal	Article
Applied Sciences (Switzerland)	3
Computers and Electrical Engineering	2
Electric Power Systems Research	4
Electricity Journal	1
Electronics	5
Electronics Letters	1
Energies	9
Energy Conversion and Management	1
Energy Reports	3
Heliyon	1
IEEE Access	7

Table A1. *Cont.*

Journal	Article
IEEE Canadian Journal of Electrical and Computer Engineering	1
IEEE Journal of Emerging and Selected Topics in Power Electronics	3
IEEE Systems Journal	4
IEEE Transactions on Circuits and Systems I: Regular Papers	1
IEEE Transactions on Control Systems Technology	1
IEEE Transactions on Industrial Electronics	7
IEEE Transactions on Industrial Informatics	2
IEEE Transactions on Industry Applications	6
IEEE Transactions on Power Delivery	1
IEEE Transactions on Power Electronics	5
IEEE Transactions on Power Systems	2
IEEE Transactions on Smart Grid	11
IET Generation, Transmission and Distribution	4
IET Power Electronics	2
IET Renewable Power Generation	3
International Journal of Electrical Power and Energy Systems	9
International Journal of Energy Research	1
International Journal of Hydrogen Energy	1
International Review of Electrical Engineering	1
International Transactions on Electrical Energy Systems	6
Inventions	1
Iranian Journal of Science and Technology-Transactions of Electrical Engineering	1
Journal of Energy Storage	1
Journal of Engineering	1
Journal of Intelligent and Fuzzy Systems	1
Journal of Modern Power Systems and Clean Energy	1
Protection and Control of Modern Power Systems	1
Renewable and Sustainable Energy Reviews	2
Renewable Energy Focus	1
Sustainable Cities and Society	1
Sustainable Energy Technologies and Assessments	1
Sustainable Energy, Grids, and Networks	1
Systems and Control Letters	1
TOTAL	122

Appendix A.1. Registration and Protocol

This review is not registered and no protocol was prepared for this work.

Appendix A.2. Additional Data from This Work

The first author can supply more data related to this work.

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