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Review

A Review of Advanced Control Strategies of Microgrids with Charging Stations

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Abstract: In the context of the global drive towards sustainability and rapid integration of renewables, electric vehicles, and charging infrastructure, the need arises for advanced operational strategies that support the grid while managing the intermittent nature of these resources. Microgrids emerge as a solution, operating independently or alongside the main grid to facilitate power flow management among interconnected sources and different loads locally. This review paper aims to offer a comprehensive overview of the different control strategies proposed in the literature to control microgrids with electric vehicle charging stations. The surveyed research is primarily categorized according to the employed control algorithms, although distinctions are also made based on defined microgrid architecture, utilization of specific power sources, and charging stations configurations. Additionally, this paper identifies research gaps in the current research. These gaps encompass the use of oversimplified models for charging stations and/or renewable sources operation, limited simulation time periods, or lack of experimental testing of proposed approaches. In the light of these identified shortcomings, this manuscript presents recommendations for guiding future research.

Keywords: microgrid control; charging station; renewable energy resources; control strategies

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1. Introduction

Top topics of our lives nowadays include decarbonization and environmentally friendly lifestyles. This movement towards sustainability also impacts the operation of electrical power systems, presenting various challenges for their efficient management and control. As the world strives to integrate a growing proportion of renewable energy sources and reduce reliance on fossil fuels, traditional power grids encounter stability issues due to the fluctuating nature of renewables. Moreover, changes in energy consumption patterns among consumers introduce added complexity to the equation.

To ensure a seamless and sustainable integration of renewable energy sources into the power grid, addressing these challenges is of paramount importance. Innovative approaches, such as demand-side management and advanced grid control algorithms, hold the key to adapting power systems to the dynamic nature of renewable energy generation and consumer demand. In this regard, the concept of the smart grid has emerged, aiming to create a reliable, efficient, and sustainable energy infrastructure by leveraging modern communication, automation, and information technologies [1].

Microgrids, as a specialized form of smart grid, have gained popularity in recent years. These autonomous and localized energy systems operate independently or in coordination with the main grid to generate, distribute, and manage electricity for specific geographic areas of interconnected consumers [2]. With their ability to function as self-contained entities, equipped with their own energy resources, control mechanisms, and often energy storage capabilities, microgrids offer promising solutions for energy resilience and sustainability.

Managing microgrids effectively is critical to realizing their full potential. By ensuring efficient coordination of energy resources and controlling energy flow, microgrids can effectively balance supply and demand, minimize energy waste, and optimize energy consumption patterns. Furthermore, advanced control strategies and tools are required to guarantee the reliability and resiliency of microgrids, especially in light of their growing association with the electric vehicle (EV) revolution.

The rising popularity of electric vehicles as a means to reduce carbon emissions in the transportation sector introduces a new dimension of complexity to the energy landscape [3]. The increasing number of EVs and the time windows of their charging sessions significantly impact the operation of power systems, necessitating more sophisticated control strategies to align the charging patterns of EVs with grid conditions. This close interplay between electrical power systems and the transportation sector underscores the need for advanced control measures to ensure the seamless integration of EVs into microgrids, safeguarding stable and resilient power supply to consumers.

Numerous literature reviews address the charging of electric vehicles. In Savio Abraham's work [4], the authors present connector types, architectural configurations of charging stations, and control algorithms proposed for charging control. However, the role of the charging station in the electric power systems or microgrids is usually absent. There are also reviews for specific control algorithms. Nimalsiri [5] undertakes a comprehensive evaluation of decentralized control algorithms, while [6] focuses on hierarchical control algorithms. However, both [5,6] neglect the critical influence of the charging station on grid operation—be it conventional or microgrid.

There are also reviews that deal with the role of EV charging stations within the electrical grid. The review in [7] focuses on EVs and their charging stations in energy and transportation systems. That review also addresses market-driven charging station management. However, [7] fails to address the effects of charging stations on microgrid stability and operation. Similarly, the study in [8] deals with the optimal management strategies in grids with electric vehicles, but the specifics of microgrids with EV integrations are omitted.

There are also reviews that focus on the microgrid's operation but most of these studies neglect the effects of EV charging stations. Vadi's work [9], for instance, critically evaluates control optimization methods for transient stability in microgrids, yet this work sidesteps exploration of how EV charging stations affect microgrid operations. Likewise, [10] dissects reinforcement learning methods in the power management of grid-tied microgrids as a tool more adaptive to stochasticity in such grids. However, there is no information about the effect of EV charging stations on microgrid operation or on the islanded microgrids' control algorithms. On the other hand, the review in [11] studies the role of EVs in the microgrid. The authors in [11] deal with design, control, energy management, and protection in DC microgrids for EV charging. A review of AC or hybrid microgrids is missing, and even more so, the primary focus of these microgrids is to supply required power to the charging station and coverage of other loads is neglected. There is also a review in [12] that studies the role of the so-called fleet operator that can control charging groups of EVs. However, independent usage of personal EVs is neglected.

This review aims to discuss the role of EV charging stations in microgrid operation more generally. This paper presents studies with different microgrid architectures and various control algorithms, as well as the different roles of EV charging stations in microgrid operational strategies. The main contribution of this paper is the definition of the current research shortcomings and the research gaps that should be addressed in future research to enable the implementation of such advanced operational strategies in real-world applications.

The rest of this paper is organized as follows: Section 2 presents the review methodology and statistics of the presented research studies. Next, Section 3 presents the research studies that focus on power control in the microgrids with charging stations. Similarly, Section 4 discusses the studies that deal with voltage control and Section 5 focuses on the research papers covering the economic operation control of microgrids. The studies with other control strategies than the previous ones are presented in Section 6. Section 7 discusses the research gaps in presented manuscripts and defines recommendations for future work. Section 8 concludes the paper.

2. Review Methodology and Statistics

The compilation of scientific papers for this review article was based on searching for certain keywords within scientific databases. The keywords applied for the search in scientific databases were "microgrid", "control", "charging", and "station", thereby ensuring the inclusion of articles that incorporated any of these terms. The scientific databases used for the search included Web of Science, Scopus, and IEEE Xplore with the selected articles discussing the topic of microgrid control with charging stations for electric vehicles. During the selection of relevant literature, we followed a similar process to the one presented in [13], with the literature selection going through several steps. In the initial step, the aforementioned keywords were utilized for search in the scientific databases. The second step involved reading the titles and abstracts of the articles obtained from the search in the scientific databases. This process led to a compilation of a set of literature for each scientific database. Subsequently, the individual sets of literature were merged into a single set from which duplicate papers were removed. The final step in the literature selection process entailed the full-text reading of the articles, based on which the final set of literature utilized for this review article was compiled. The final set of publications presents, from the author's perspective, the most relevant articles to the topic discussed in this review article. To help with the discussion and division of reviewed literature, a number of statistics were made and are shown in this section.

2.1. Reviewed Publications

The final set of publications consists of 70 papers which were published in journals as well as papers from conferences. The publications selected for this review span from the year 2010 to the present day. In recent years, there has been an increase in the frequency of publications related to microgrid control with charging stations for electric vehicles. This recent increase in interest in this topic may be caused by the increase in the number of EVs as well as in the number of corresponding charging stations, or as a response to many initiatives planned as a tool to reduce greenhouse gas emissions. The frequency of selected publications through the years is shown in Figure 1. The graph representing the distribution of journal papers and conference papers among the final set of papers is shown in Figure 2 where it can be seen that the majority of papers discussed in this review are from journals. Figure 3 shows the distribution of different publishers among the selected set of papers, as well as between journals and conference papers. From this graph, it is apparent that most of the journal papers in our selection are from ELSEVIER and MDPI, while almost all conference papers are from IEEE. It is important to note that the paper selection was conducted at the end of the second quarter of 2023.

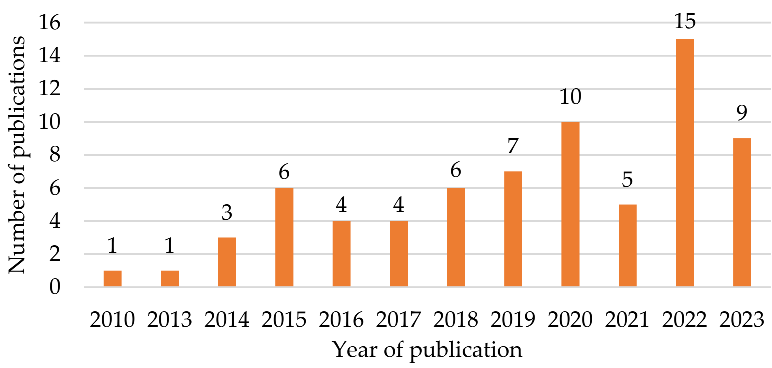


Figure 1. Publications by years.

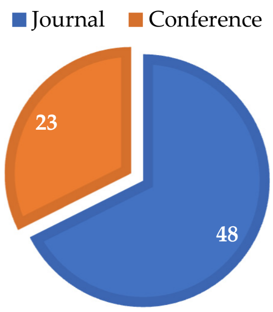


Figure 2. Type of publication.

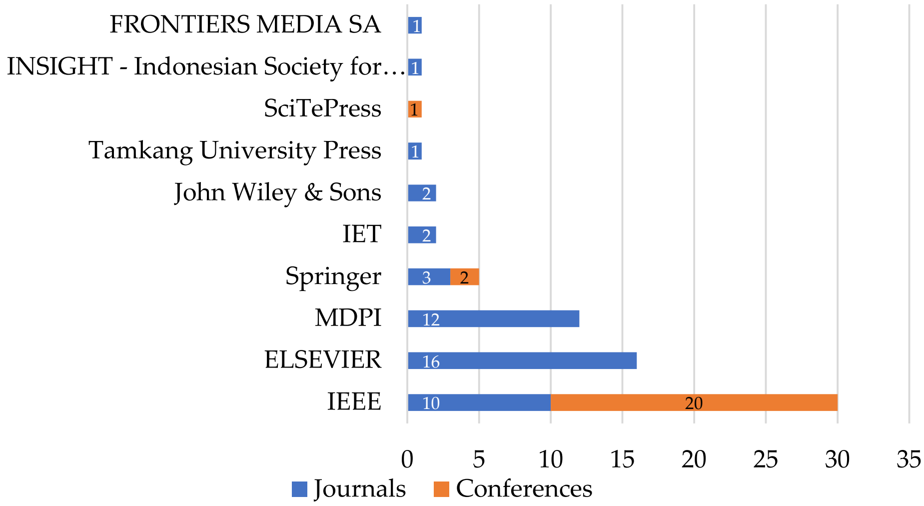
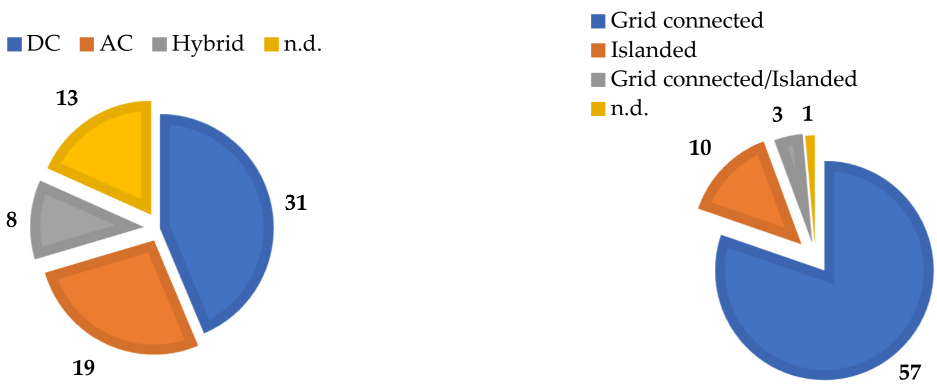


Figure 3. Distribution of different publishers.

2.2. Types and Architectures of Microgrids

Research in the utilization of microgrids has in recent years gained more interest due to the development and utilization of renewable energy sources (RESs), as well as electric vehicle charging stations. Utilization of microgrids provides a flexible solution for the implementation of these facilities and at the same time provides space for the implementation of novel control structures. Microgrids are typically divided into three types based on the characteristic of currents and voltages used by the loads in the microgrid. These types are AC microgrid, DC microgrid, and Hybrid microgrid. The architecture of a microgrid is based on the interconnection between the distribution network and the microgrid. The most common architectures in literature are grid-connected microgrids and islanded microgrids. The distribution of the different types and architectures of microgrids in our final set of papers is shown in Figure 4.

In the case of microgrid types (Figure 4a), the majority of microgrids were operated as DC microgrids, and in the case of microgrid architectures (Figure 4b), the majority of microgrids were operated in grid-connected mode. In a few of the papers [14,15], the authors tested their control mechanisms in grid-connected as well as in islanded mode to prove the reliability of their systems. During the full read of some papers, it was not clearly stated or defined what type of microgrid or architecture of microgrid was used in these papers. Therefore, in these cases, we used the abbreviation of the phrase "not defined (n.d.)" to visualize these papers in graphs.

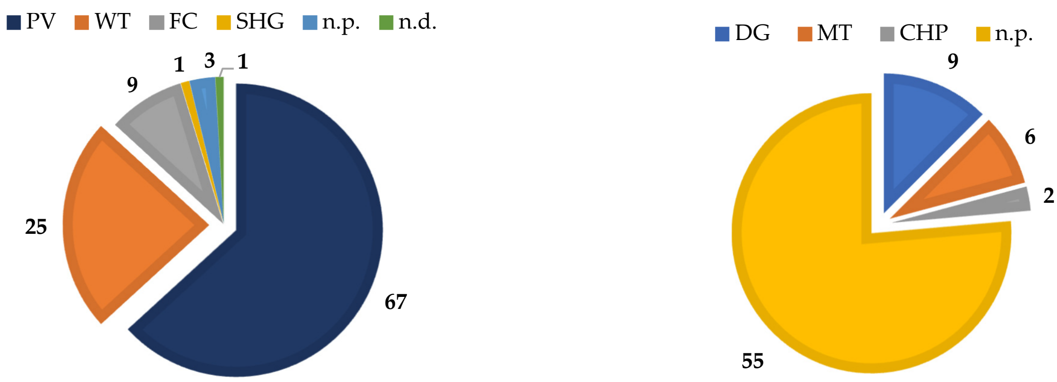


(**a**) (**b**)

Figure 4. Distribution of types (**a**) and architectures (**b**) of microgrids.

2.3. Energy Generation and Storage in Microgrids

One of the advantages of microgrids is the possibility for implementation of complementary power sources to enable the independent operation of the microgrid system from the utility grid. This possibility has enabled increased research in the area of microgrid implementation. Complementary power sources used in microgrid systems are either renewable energy sources such as photovoltaic systems (PV), wind turbines (WT), fuel cells (FC), and small hydro generators (SHG), or conventional energy sources powered by fossil fuels such as diesel generators (DG), microturbines (MT), and combined heat and power (CHP). The utilization of renewable energy sources is the most common method utilized for independent energy generation where solar and wind power are most commonly used. RESs also provide a possibility to reduce greenhouse gas emissions associated with energy production. The distribution of different energy sources used in the final set of review papers can be seen in Figure 5. From the final set of papers, only three papers did not utilize RESs, as it is possible to see from Figure 5a representing the distribution of individual RESs among the final set of papers. On the other hand, conventional energy sources (CESs) were not utilized in 55 papers from the final set. The rest of the papers either had one or more RESs or CESs. In the case of one paper, the authors have not stated clearly the type of RES, so therefore to represent this case in a graph we used the same abbreviation "n.d." as in the previous section. To represent a situation when no RESs or CESs were used in a discussed paper, the abbreviation of the phrase "not present (n.p.)" is used to visualize these papers in graphs.



(**a**) (**b**)

Figure 5. Distribution of renewable energy sources (**a**) and conventional energy sources (**b**).

Another important part of microgrids in combination with RESs is the use of energy storage systems. Energy storage systems (ESS) are used primarily for the storage of excess power produced by the RESs and the subsequent use of this energy to support microgrids themselves, or individual loads placed in microgrids, or to provide support to the utility grid. In addition to the power flow exchange, the storage system can be used for power quality or microgrid stability control. The most common storage system is the battery storage system (BSS) which was used in 48 papers as shown in Figure 6. Other storage systems used in the literature are hydrogen storage systems (HSS), supercapacitors (SC), and fuel cell energy storage (FCES). Similarly, for complementary power sources, not all review papers have energy storage systems implemented in their respective microgrids. Therefore, to represent these papers in graphs, we used the abbreviation "n.p." as defined in a previous section.

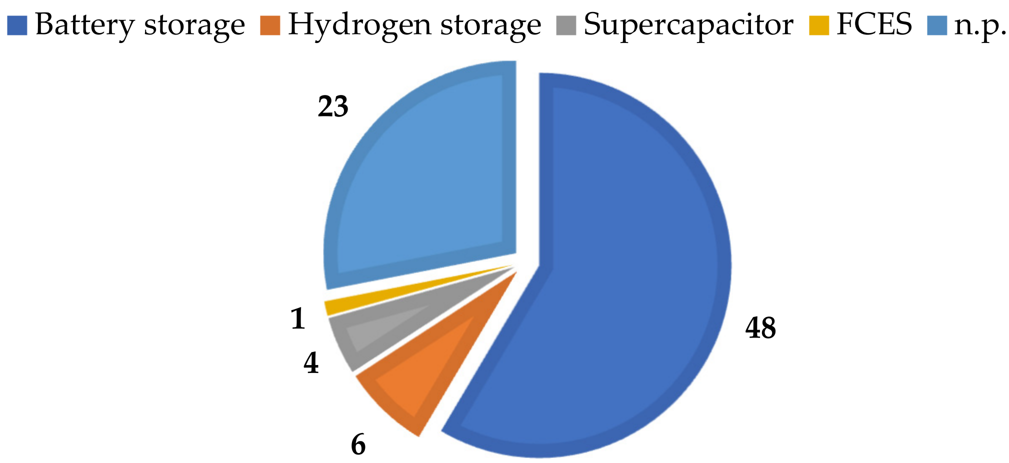
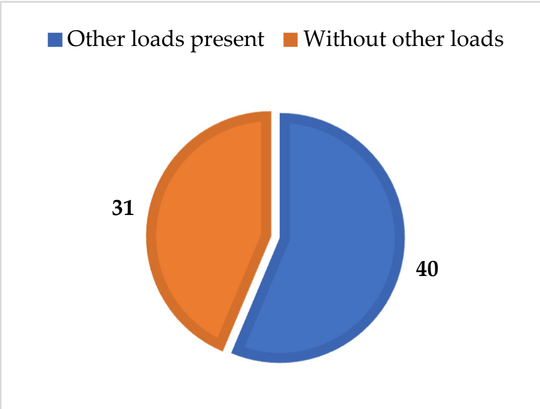


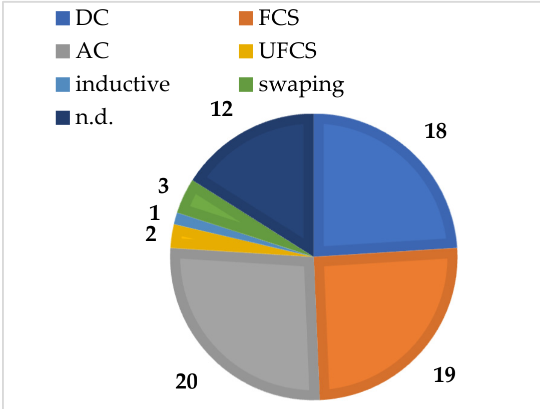
Figure 6. Distribution of different energy storage systems.

2.4. Loads and Charging Stations in Microgrids

There has been a significant increase in the adoption of electric vehicles in recent years as a result of international efforts to reduce greenhouse gas emissions and promoting sustainable transportation solutions. An increase in the numbers of electric vehicles consequently leads to an increase in the numbers of charging stations [16]. To prevent problems in electrical networks caused by the irregular nature of charging station consumption (electric vehicles charging) or to exploit advantages of energy transfer between electric vehicles and charging stations (vehicle to grid (V2G) concept), installations of electric vehicle charging stations within microgrids are being used and researched. In reviewed papers, different charging stations were mentioned and used in the control structure of microgrids. The distribution of different types of charging stations is shown in Figure 7b. The most used charging station type in reviewed papers was the AC charging station (CS), followed by the fast charging station (FCS), and the third most used type was slow DC charging. In 12 reviewed papers, the type of charging station was not clearly defined, and therefore to represent these cases we again use the abbreviation "n.d.". Additionally, charging stations with other loads (Figure 7a) were also implemented into the microgrids in a total of 40 papers from the final set. These loads represent residential loads in the form of houses or apartment buildings, workplace loads, or industrial loads that were connected to the discussed microgrids.



(a)



(b)

Figure 7. Distribution of loads (**a**) and different charging station types (**b**) in microgrids.

2.5. Control Strategies in Microgrids

The utilization of a microgrid system allows for implementing various control strategies that can improve microgrid operation, increase the utilization RESs, and maximize the economic benefit or other aspects associated with a microgrid system utilization. During the literature review, we have identified three major control objectives most frequently occurring in the literature. These objectives are power control, voltage control, and economic operation control in addition to other less frequently occurring control objectives (frequency control, current control, etc.). Figure 8 shows the distribution of different control objectives amongst the final set of papers discussed in this review. It is important to note that in some papers multiple control objectives were discussed and implemented to increase operational control or to compare multiple control strategies. A closer discussion of each major control objective is presented in the following sections.

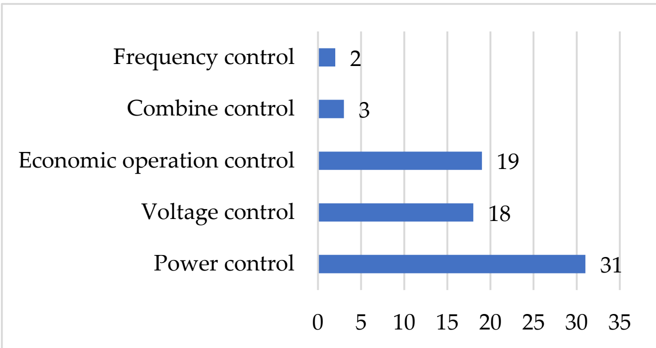


Figure 8. Distribution of control strategies in microgrids.

3. Power Control Strategies of Microgrids

Implementation of power control brings a number of possibilities which can improve microgrid operation. Power control in microgrid operation can improve the utilization of energy sources within the microgrid, minimize the dependence on the utility grid, or even manage the power flow. Control objectives used in combination with power control are discussed in the following subsections.

3.1. Power Flow Control of Microgrids

Power flow control strategy represents a method used for the optimal distribution of power between energy sources connected to the microgrid, utility grid, ESS, loads, and EVs connected to the microgrid through CS. Optimal distribution of power can improve the power balance, power quality, or stability of a microgrid, and in a microgrid with electric vehicle charging stations (EVCS) it can ensure that the EVs connected to the CS are charged to an optimal level. To achieve this, researchers are using different control methods or control algorithms, as well as different configurations of microgrid systems.

Most of the reviews studies with power flow control are focused on DC microgrids. In Sayed's work [17], the authors focused on energy management for a DC microgrid system in islanded mode to control power distribution from different RESs to EVs connected to the CS within a microgrid. Charging of connected EVs is regulated based on the amount of power produced from RES and energy stored in battery storage. Power flow management with a fuzzy logic controller in [18] is used for voltage stabilization in a DC microgrid for EVCS. The proposed controller is used to coordinate power flow between the PV power plant, BSS, and the utility grid based on variations in EVCS demand and intermittent power generation. The fuzzy logic controller was also used in [19] for a supervisory control system to achieve power balance between the energy supply and EVCS within a DC microgrid. In García-Triviño's work [20], a fuzzy logic controller is used for a decentralized energy management system to control power flow, bus voltage, and battery storage state of charge. The DC microgrid proposed in this paper consisted of FCS, PV system, and battery energy storage with connection to the utility grid. The control proposed in [20] was used to control the power flow of a PV system, BSS, and utility grid to supply the desired amount of power for the charging of EVs connected to FCS. Whit proposed how control of the FCS was able to work in a stand-alone mode for extended time periods. In Abraham's works [21,22], a strategy for the power management of reliable power supply was introduced. The proposed power management is based on fuzzy logic control, which directs bidirectional power flow between EVs, BSS, and utility grid. Vehicle-to-vehicle (V2V) concept was used in these papers to provide share power between EVs when necessary. In Naik's work [23], a smart energy management strategy is proposed to tackle issues of intermittent nature of PV power generation and EV load as well as ensure sustainable power flow control for EV charging stations connected to DC microgrids. Presented energy management used the control of BSS and small hydro generators to meet the peak EV load demand as well as to reduced dependency on the utility grid. Energy management system in [24] is presented for a hybrid system of DC microgrid with multi-battery storage system, a grid-tie inverter with a PV installation, and FCS. The energy management system in this paper is responsible for energy exchange control with the utility grid as well as for allocating the battery strings to different components of the hybrid system. String allocation control must ensure that the battery connected to this string can successfully meet the EV charging demand. Paper [25] presents an energy management strategy for the supply infrastructure of EVCS placed in a DC microgrid. The control system aims to control energy exchange between microgrid and utility grid and ensure reliable service to the users from cost-effective energy supply to EVs. The control system also controls charging/discharging of EVs to reduce power purchases from the utility grid or to take advantage of selling prices to the utility grid. The energy management system proposed in [26] represents decentralized control techniques used for the bipolar DC microgrid. The proposed system controls power sharing between individual parts of the microgrid and utility grid according to the load demand. In addition to power control, paper [26] proposed voltage control which will be discussed in Section 4. In paper [27], power management with voltage control was introduced. Power management was implemented to distribute available power to a fleet of EVs used as taxis. The proposed power management is capable of modifying the amount of energy sent to EVs depending on the microgrid situation. Paper [28] introduces intelligent hybrid energy management control to provide a reliable power balance for microgrid operation. The proposed control aims to effectively address fluctuations in a microgrid and enable reliable EV charging.

Only two of the reviewed papers with power flow control define their proposed control algorithms for AC microgrids. Authors in [29] study power quality improvement or precisely the active and reactive power control. They have proposed an approach to optimally control the active and reactive power of ultra-fast charging stations (UFCS) and RESs. Control strategy aims to coordinate the demands of EVs and other loads with power provided by RESs and to minimize the charging time of connected EVs. Reactive power regulation was achieved by control of UFCS and PV converters. Paper [30] presents a P/V droop voltage controller for voltage regulation by controlling active power flow between EVs and microgrids. The proposed controller ensures utilization of EVs as a distributed energy storage system. Through the utilization of this controller, EVs were used to provide peak shaving and valley filling, thus contributing to the stable operation of the islanded microgrid.

More studies proposed their algorithms for hybrid microgrids. A power management strategy is introduced in [31] for a hybrid microgrid with a hybrid energy storage system to enhance power sharing among subgrids of hybrid microgrids and improve steady state and transient response, as well as to enhance the voltage stability of both subgrids. To test the effectiveness of the proposed control strategy, authors performed simulations for varying loads, PV power outputs, DG outages, and EV charging. Similarly, in [32] the power flow control scheme was introduced to improve power stability, power quality, system reliability, and optimal power distribution in hybrid microgrids. The proposed control provided continuous and reliable power to all loads connected to the microgrid as well as to the CS. The control scheme in [32] was based on an adaptive neural network Q-learning full recurrent adaptive neuro-fuzzy control. Paper [33] presents a new configuration for a unified power quality controller (UPQC) in combination with EVCS to improve power quality while ensuring the demand of EVCS. UPQC control is modified to address the charging of EVs by using power from the utility grid directly while compensating for power quality issues. During power outages or power interruptions, EVs were used through UPQC control as emergency power sources. Energy management for optimal power flow from the PV system and the utility grid to EVCS, BSS, and loads is described in [34]. The proposed control is used to optimize the EVCS load for Aligarh Muslim University while reducing operational costs of the EVCS microgrid.

There are also a few papers that do not define the information about the proposed microgrid architecture, such as in [35–38]. In Parmar's work [35], a fuzzy logic-based control is proposed to control the charging and discharging of plug-in-hybrid EVs as well as to manage other loads connected to the microgrid. Fuzzy logic control implements the V2G concept to allow the utilization of EVs with different charging profiles to provide support to the microgrid for optimum management of the daily load demand. Paper [36] presents a demand management approach to reduce peak demand by utilizing power from RES and EVCS. The proposed system consists of residential loads, critical commercial loads, RESs, and EVCS. The EVCS is represented by BSS and EVs, which are used as charging/discharging loads. The proposed method is capable of reducing peak demand, increasing the reliability of the microgrid, and increasing the profits of EVCS. Paper [37] presents a Hunger Games Search optimization algorithm to optimally allocate distributed generators into the microgrid with the aim to reduce power losses in the presence of an EVCS. In Olama's work [38], a Lyapunov-based hybrid model predictive control is proposed for energy management of renewable energy sources, different ESS, and EV's batteries to achieve safe and reliable operation of the microgrid. The proposed control uses EV's batteries to avoid fluctuations in energy demand to achieve optimal operation. The proposed energy management strategy is capable of dealing with energy management problems as well as ensuring the close-loop stability of the microgrid.

Information about the microgrid systems of the papers mentioned in this section is presented in Table 1.

Table 1. Information about the microgrid systems with power flow control.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[17]	DC	Islanded	PV WT	n.p.	Battery storage	✓	DC FSC
[18]	DC	Grid connected	PV	n.p.	Battery storage	✓	n.d.
[19]	DC	Grid connected	PV WT FC	n.p.	Battery storage Hydrogen storage	✘	FCS
[20]	DC	Grid connected	PV	n.p.	Battery storage	✘	FCS
[21]	DC	Grid connected	PV	n.p.	Battery storage	✘	DC
[22]	DC	Grid connected	PV	n.p.	Battery storage	✘	DC
[23]	DC	Grid connected	PV SHG	n.p.	Battery storage	✘	DC
[24]	DC	Grid connected	PV	n.p.	Battery storage	✘	FCS
[25]	DC	Grid connected	PV	n.p.	Battery storage	✘	DC
[26]	DC	Islanded	PV	n.p.	Battery storage	✓	DC
[27]	DC	Grid connected	PV WT	n.p.	Battery storage	✘	FCS DC
[27]	DC	Islanded	PV WT FC	n.p.	Battery storage	✓	n.d.
[28]	AC	Grid connected	PV	n.p.	n.p.	✓	UFCS
[30]	AC	Islanded	PV WT	DG	n.p.	✘	AC
[31]	Hybrid	Grid connected	PV	DG	Battery storage Supercapacitor FCES	✘	n.d.
[32]	Hybrid	Grid connected	PV WT FC	MT	Battery storage Supercapacitor Hydrogen storage	✓	AC
[33]	Hybrid	Grid connected	n.p.	n.p.	n.p.	✓	DC
[34]	Hybrid	Grid connected	PV	n.p.	Battery storage	✓	AC
[35]	n.d.	Islanded	PV WT	DG	n.p.	✓	n.d.
[36]	n.d.	Grid connected	PV	n.p.	Battery storage	✓	n.d.
[37]	n.d.	Grid connected	n.d.	n.p.	n.p.	✓	AC
[38]	n.d.	Grid connected	PV WT FC	DG	Battery storage Supercapacitor Hydrogen storage	✓	AC

3.2. Controlling the Self-Consumption of Microgrids

Paper [39] presents a novel DC microgrid power architecture for efficient charging of EVs. The proposed microgrid is based on PV generation, BSS, and grid connection, with EVs having direct access to their DC charger input. Unlike conventional power architecture designs, the PV system is directly coupled to the DC link without a static converter, which increases energy efficiency and reduces control complexity. The power management proposed in [39] controls power output from a PV system, which thereby enables self-consumption of the energy produced within microgrid and the utility grid is used only as a backup power source. The authors in [40] proposed an energy management system based on hysteresis V2G control. The designed system is capable of minimizing the impact of continuous charging current modulation on the life of EV batteries and of maximizing microgrid self-consumption. The authors simulated the proposed system with data measured in an actual microgrid with intermittent RESs production. Papers [41–43] present the implementation and evaluation of self-consumption operational strategies based on data from a microgrid at the EUREF-Campus in Berlin, Germany. The focus of the operational strategy in [41,42] is on supplying energy for EVCSs by controlling the energy generation of local sources and energy supply from the utility grid. The presented operational strategy is capable of achieving the sustainable application of EVs in an urban microgrid and with the deployment of a BSS can achieve CO_2 emissions reduction. In Feizi's work [43], an optimalization algorithm for demand side management is used to reduce load peaks by using the EVs and BSS as flexible loads. The presented algorithm was able to achieve 100% self-sufficiency.

Information about the microgrid systems of the papers mentioned in this section is presented in Table 2.

Table 2. Information about the microgrid systems with self-consumption control.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[39]	DC	Grid connected	PV	n.p.	Battery storage	✘	DC FSC
[40]	AC	Grid connected	PV	n.p.	n.p.	✓	AC
[41]	AC	Grid connected	PV	CHP	Battery storage	✘	AC
[42]	AC	Grid connected	PV	CHP	Battery storage	✘	AC
[43]	AC	Grid connected	PV	n.p.	Battery storage	✘	AC

3.3. Controlling Maximum Utilization of RES and Power Quality in Microgrids

The maximum use of RESs within a microgrid provides the possibility to decrease the microgrid dependency on the utility grid. The paper in [44] discusses the technical issues related to the uncoordinated charging of EVs and how this can lead to ineffective utilization of RESs connected to the CS and the microgrid, and how this can cause overloading of the utility grid. For this reason, the authors of [44] proposed an energy management strategy with aims to minimize the usage of utility grid power and to maximize the use of PV power as well as to store PV power when the CS is not used. The proposed energy management also controls the charging of EVs and BSS and based on the state of charge of the EVs and BSS determines the operational mode of microgrid operation. In Locment's work [45], a control strategy for maximizing power extraction from the PV sources and power flow management is designed to consider the state of charge of the EVs and power demand of the load connected to the DC microgrid. The maximum use of RESs can also be used to improve the social welfare of EVCS users as is demonstrated in [46]. The authors of the paper used power from a PV system to charge EVs which led to the maximalization of social welfare. This charging control was introduced to optimally distribute available power from a PV system to connected EVs. Paper [47] proposes a control strategy for microgrids with EVs. The proposed control strategy is employing a multi-objective technique that aims to achieve power factor regulation as well as economic battery charging. The control strategy uses the EVCS control to support power factor issues, allowing for full PV generation.

Information about the microgrid systems of the papers mentioned in this section is presented in Table 3.

Table 3. Information about the microgrid systems with maximum utilization of RES and power quality control.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[44]	Hybrid	Grid connected	PV	n.p.	Battery storage	✓	DC
[45]	DC	Grid connected	PV WT	n.p.	Battery storage	✘	FCS
[46]	AC	Grid connected	PV	n.p.	n.p.	✘	AC
[47]	AC	Grid connected	PV	n.p.	n.p.	✓	AC

4. Voltage Control Strategies of Microgrids

Another strategy commonly used in research papers for microgrid control is voltage control. Voltage control provides the possibility for reliable control of individual components of microgrids, or for control of microgrid stability, or to design power converters and controllers with specific control structures. The papers with voltage control objectives are discussed in this section.

4.1. Microgrid Voltage Sag Mitigation Control

Papers [48,49] present a decentralized control system for microgrids with EV fast charging stations. The aim of this control is to reduce utility grid reliance and improve power quality. To improve power quality, the authors are using a distribution static compensator (D-STATCOM) with the objective of mitigating the voltage sag within a microgrid. The authors in both papers proposed the utilization of an EV battery as a DC source of a D-STATCOM through the V2G technology. One of the differences between these two papers is the utilization of different control methods. In Mohammed's work [48], the authors used a sliding mode control together with a fuzzy logic control, while in [49] the authors used a decentralized control system based on Proportional Integral (PI) controllers.

Paper [50] presents a coordinated control strategy of dynamic voltage restorer (DVR) and EVCS in a microgrid. In this paper, two categories of voltage sag (interior, exterior) are addressed with different compensating methods. For interior voltage sag, only the DVR is used, while on the other hand for exterior sag, DVR with cooperation from EVCS is used.

In Table 4, information about the microgrid systems of the papers mentioned in this section is presented.

Table 4. Information about the microgrid systems with voltage sag mitigation control.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[48]	DC	Grid connected	PV	n.p.	n.p.	✓	FCS
[49]	DC	Grid connected	PV	DG	n.p.	✘	FCS
[50]	AC	Grid connected	n.p.	n.p.	n.p.	✘	n.d.

4.2. Controlling the Bus Voltage of Microgrids

Most of the studies with bus voltage control have focused on grid-connected microgrid architectures. In paper [51], a bus voltage control strategy for a hybrid microgrid with EVCS is proposed. The proposed bus voltage control is maintained by a novel uninterruptible inverter which is used to provide uninterrupted power to the EVCS as well as ensure stable operation of the microgrid. Paper [52] presents a control strategy based on the virtual battery model. The primary aim of this control strategy is to control the bus voltage, dispatch power among the individual elements of the microgrid, and reduce the negative impact of EV fast charging on the electrical grid. In García-Triviño's work [20], the authors proposed a decentralized control method with fuzzy logic controllers to coordinate power flow as was mentioned in Section 3.1 with bus voltage and battery energy storage state of charge (BSS SOC). The bus voltage control was used to ensure power balance among the components within a microgrid (EV FCS, PV system, BSS, utility grid) and to control the BSS SOC. Similarly, as with [20] a decentralized control was proposed in paper [53], but in this paper a PI controller was used for the bus voltage control. DC bus voltage in [53] was controlled by the power sources within the microgrid to ensure stable charging of EVs. Paper [54] proposes smart charging of PEV with a small scale wind energy system as a source. The control strategy proposed in [54] is the coordination control based on DC link voltage to support the operation of EVCS in stand-alone as well as in grid-connected mode. To provide an efficient power management of a DC microgrid, a power reference-based drop controller is designed to regulate bus voltage through energy storage. The intelligent control method for DC FCS is proposed in [55]. The authors are using the comprehensive AC/DC converter control to inject reactive power into a network to control the voltage and thus keep DC bus voltage at a constant value.

On the other hand, there are just a few studies that have dealt with the islanded operation of the microgrids. The authors in [56] proposed an enhanced control method for UFCS in islanded DC microgrids to reduce the transients of the DC bus voltage. To achieve this, the authors proposed an enhanced control strategy for the local controller of the EV converter. The hierarchical control strategy for a PV-based microgrid with EV wireless charging station is presented in [57]. The control structure is composed of central and local controllers where the central controller is used to assess the operation mode of the system and to select the local controllers and the local controller is used for battery storage control, high frequency (HF) inverter DC bus voltage control, and EV charging control. The control structure proposed in [57] can through HF inverter DC voltage controller regulate DC bus voltage and thus change the wireless charging power. In Bhargavi's work [58], a control strategy for EV is proposed to increase the maximum rate of charging capacity only if generation exceeds the load demand.

Table 5 presents information about the microgrid systems with bus voltage control discussed in this section.

Table 5. Information about the microgrid systems with bus voltage control.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[51]	Hybrid	Grid connected	PV	n.p.	Battery storage	✓	AC
[52]	DC	Grid connected	PV	n.p.	Battery storage	✘	FCS
[53]	DC	Grid connected	PV	n.p.	Battery storage	✘	FCS
[54]	DC	Grid connected	PV WT	n.p.	Battery storage	✘	DC
[55]	DC	Grid connected	n.p.	n.p.	n.p.	✘	FCS
[56]	DC	Islanded	PV	n.p.	Battery storage	✘	UFCS
[57]	DC	Islanded	PV	n.p.	Battery storage	✓	Inductive
[58]	DC	Islanded	PV WT	n.p.	Battery storage	✓	DC

4.3. Voltage Regulation and Stability Control

In paper [59], a controller for an EVCS DC microgrid is designed to keep voltage stability and suppress the power system dynamics. To design the DC microgrid controller, the authors proposed a firefly algorithm combined with particle swarm optimalization. Paper [60] describes a new approach for the integration of EVs into the electrical grid, with the aim to reduce their impact on the grid and to provide ancillary services to the AC utility grid. The proposed control can stabilize the voltage of a DC microgrid while providing ancillary services. Additionally, the authors demonstrated that use of V2G mode in microgrids with EVCS can help to support the stability of the electrical system. The adaptive bidirectional droop control for an EV parking lot with V2G service is proposed in [61]. This control strategy is coupled with solid state transformer for the voltage regulation within the microgrid. To validate the effectiveness of the proposed control strategy, the authors conducted experimental testing using a physical prototype.

A close-loop control structure based on feedback signals from EVCS, distributed generators, and load demand in the microgrid is presented in [62] to increase the reliability and stability of the system. In paper [27], DC voltage control was implemented through a PI controller in the battery storage to manage the microgrid voltage. Additionally, power management was introduced in this paper as was discussed in Section 3.1. In Benamar's work [63], a nonlinear control was presented to ensure the voltage stability of a DC microgrid by considering the fluctuations of the PV production as well as the EV demand.

Information about the microgrid systems with voltage regulation and stability control discussed in this section is presented in Table 6.

Table 6. Information about the microgrid systems with voltage regulation and stability control.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[59]	DC	n.d.	PV WT FC	n.p.	Battery storage Hydrogen storage	✘	n.d.
[60]	DC	Grid connected	PV	n.p.	n.p.	✘	DC
[61]	AC	Grid connected	PV	n.p.	Battery storage	✘	DC
[62]	Hybrid	Grid connected	PV WT	n.p.	Battery storage	✓	DC
[63]	DC	Islanded	PV	n.p.	Battery storage Supercapacitor	✘	DC

5. Economic Operation Control of Microgrids

Economic operation control of microgrids presents the different aspects of microgrid control used to achieve desired outcomes. Desired outcomes can be beneficial for microgrid operators, users of microgrids, or both based on the control objectives. The most commonly occurring objectives used in economic operation control are discussed in this section.

5.1. Maximizing the Profits of Microgrids and Energy Trading

Paper [64] presents a control solution for a smart microgrid with an EVCS to maximize the profits of microgrid owners by selling energy to EVs. To achieve this, the authors proposed the energy management system which controls the power profile of the microgrid. The coordinated dispatch method for PV power generation microgrids with EVs is proposed in [65]. The proposed method is using the power forecasting model based on real data to maximize the profits of microgrids and thus maximize the PV power consumption.

The paper in [66] introduces a predictive control algorithm for economic optimization in a microgrid that is connected to the utility grid and EVCS. The system is modeled using the Energy Hubs methodology, and the proposed algorithm is responsible for managing electricity purchase and sale to the grid. In Mendes's work [67], a control strategy for optimal operation of microgrids as well as energy sale and purchase into microgrids is introduced. The proposed strategy can manage properly the purchase and sale of energy to the external network, ensure the charging of EVs, and manage load demand. Multi-period optimal energy scheduling and trading for multi-microgrids is discussed in [68]. In this paper, comprehensive models of multi-microgrids integrated with an urban transportation network through fast charging stations is formulated. Trading schemes are used to maximize profits for each microgrid through buy-low-sell-high fashion and at the same time minimize travel expenses in response to the FCS charging prices defined by the individual microgrids.

Table 7 presents information about the microgrid systems with profit maximization and energy trading discussed in this section.

Table 7. Information about the microgrid systems with profit maximization and energy trading.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[64]	AC	Grid connected	PV WT	n.p.	Battery storage	✓	AC
[65]	n.d.	Grid connected	PV	n.p.	n.p.	✘	n.d.
[66]	n.d.	Grid connected	PV WT	n.p.	Battery storage Hydrogen storage	✓	n.d.
[67]	n.d.	Grid connected	PV	n.p.	Battery storage Hydrogen storage	✘	FCS DC
[68]	n.d.	Grid connected	PV WT	DG	n.p.	✓	FCS

5.2. Minimizing the Operational Costs of Microgrids and Electricity Costs

Paper [69] proposes a two-stage optimal framework to handle the online dispatch problem of grid connected microgrids. The first stage in the proposed framework is to minimize the total operating cost and the second stage determines the power allocation for CS. The proposed framework can effectively realize the optimal dispatch and reduce the operating cost. An optimal management system to minimize operational costs of hybrid microgrids is proposed in [70]. The proposed approach manages power sources connected to the microgrid together with EVs charging/discharging to reduce operational costs of microgrids. In Han's work [71], an optimal control method for microgrid systems with residential loads based on EV virtual energy storage is proposed. For optimal control, multi-objective optimization is used with minimal electricity cost, EV battery state of health, and carbon emissions as objective functions. Paper [72] presents economical scheduling of EVs connected to the microgrid to reduce electricity cost. To minimize the electricity cost, the authors used charging/discharging control of EVs connected to microgrids. An optimal scheduling strategy is presented in [73] to minimize operational costs of EV charging-swapping-storage integrated stations and microgrids. The proposed coordination of the charging process is capable to transfer charging demand from the peak demand time to valley demand time, thus reducing the peak-to-valley difference and reducing operational costs of microgrids. In Xu's work [74], similarly to previous papers, optimal scheduling is proposed. The aim in [74] is to reduce charging costs of EVs as well as to reduce power loss of microgrids to improve overall efficiency of microgrids. Paper [75] presents a real-time power management strategy for intelligent infrastructure for recharging electric vehicles based on a microgrid system. The strategy proposed in the paper aims to minimize the energy cost of microgrids and maximize the use of PV power. An energy management strategy and an optimal operation strategy of EVs and battery swapping stations are discussed in [14]. The objectives of the operational strategy are the minimization of operational costs and the maximization of benefits of microgrids in islanded operation mode. To minimize operational costs, authors adopted price mechanisms to flatten the demand curves which reduces the difference between the peak and valley demand. The optimal operation of a community based microgrid is presented in [76] to minimize operational costs of microgrids and thus maximizing economic benefits for the prosumers. The goal of the paper is achieved by optimal scheduling of charging and discharging of EVs based on dynamic day ahead prices. Paper [77] presents an energy management system based on a dynamic optimalization model to minimize operational costs of microgrids as well as to minimize CO_2 emissions. The proposed approach is tested and applied to the case study of the Sanova University Campus. A day ahead demand schedule strategy is proposed in [15] to improve the cost-effectiveness of the microgrid. The proposed strategy is based on optimal load shifting of demand with incentive and penalty pricing as a decision support for uses. An energy management model for a smart community microgrid including battery swapping stations and residential loads is formulated in [78]. The optimization algorithm is formulated to minimize the average long-term energy cost of consumption and operational cost while securing the quality of service for battery swapping stations and residential loads. In Liao's work [79], an energy management system for a smart home and an EV charging parking lot is presented. Energy management aims to minimize electricity payment for smart home while ensuring users' comfort and minimizing costs of EV charging within the EV charging parking lot. The control strategy for smart homes involves control and scheduling of home appliances and scheduling is also used in the case of the EV parking lot. In the case of the EV parking lot, the EVs also join in an ancillary service market of emergency reserve capacity. Paper [80] presents real-time management and scheduling of EVs in a commercial microgrid with PV generation, partially curtailable load, and battery storage unit for backup. The proposed control structure is capable to allocate and distribute power based on the energy price thus minimizing the cost of power to the microgrid.

Information about the microgrid systems of the papers mentioned in this section is presented in Table 8.

Table 8. Information about the microgrid systems with objectives to minimize operational costs of microgrids and electricity costs.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[69]	DC	Grid connected	PV WT	n.p.	Battery storage	✓	DC
[70]	Hybrid	Grid connected Islanded	PV FC	DG MT	n.p.	✓	n.d.
[71]	AC	Grid connected	PV	n.p.	Battery storage	✓	AC
[72]	DC	Grid connected	PV FC	MT	Battery storage	✓	DC
[73]	n.d.	Grid connected	PV WT	MT	Battery storage	✓	FCS Swapping
[74]	AC	Grid connected	PV	n.p.	Battery storage	✓	AC
[75]	DC	Grid connected	PV	n.p.	Battery storage	✘	FCS
[14]	AC	Grid connected Islanded	PV WT	n.p.	n.p.	✓	AC Swapping
[76]	AC	Grid connected	PV	n.p.	Battery storage	✓	AC
[77]	n.d.	Grid connected	PV WT	MT	Battery storage	✓	n.d.
[15]	AC	Grid connected Islanded	PV WT FC	DG MT	Battery storage	✓	AC
[78]	n.d.	Grid connected	PV WT	n.p.	n.p.	✓	Swapping
[79]	AC	Grid connected	PV	n.p.	n.p.	✓	AC
[80]	AC	Grid connected	PV	n.p.	Battery storage	✓	AC

6. Other Control Strategies

The control strategies discussed in the previous section represented the most commonly used control strategies for microgrid control. This section contains control strategies that were presented only in a few papers from our final set. The following subsections discuss combined control strategies for microgrid control in which the authors used multiple distinctive objectives to achieve desired outcomes and frequency controls.

6.1. Combine Control Strategy for Microgrid Control

Multi-microgrid network energy management is proposed in [81] to maximize the energy exchange between microgrids to reduce the load fluctuation, minimize the amount of energy purchased from the distribution network, and encourage self-healing capability to maintain the system operation during fault events. To help deal with disturbances and maintain system stability, the V2G concept is used during fault events. Paper [82] presents a control problem of microgrids integrating renewable generation, hybrid storage technologies, and interaction with V2G systems. The objectives of microgrid control were to maximize the use of renewable energy sources, coordinate the use of battery bank and hydrogen storage to minimize the oscillation between production and demand, perform the charging of EVs, and make the purchase and sale management of electricity to the external network. In paper [83], the authors suggest an optimal planning technique for identifying the locations and sizes of EVCS and hybrid RESs inside a microgrid. The main objectives of the proposed technique are minimization of voltage deviation, power loss, the cost of building renewable resources, and the cost of charging EVs. To solve the proposed problem, the authors used a novel jellyfish search optimizer.

Information about the microgrid systems of the papers mentioned in this section is presented in Table 9.

Table 9. Information about the microgrid systems with combined control strategies for microgrid control.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[81]	DC	Grid connected	PV WT	n.p.	Battery storage	✓	FCS DC
[82]	DC	Grid connected	PV WT FC	n.p.	Battery storage Hydrogen storage	✓	FCS DC
[83]	n.d.	Grid connected	PV WT	n.p.	n.p.	✘	n.d.

6.2. Frequency Control of Microgrids

Paper [84] proposes a V2G strategy for primary frequency control inside an industrial microgrid. The primary frequency control is achieved by the charging and discharging of EVs based on the signals from the industrial grid operator. Paper [85] presents the droop-controlled charging/discharging strategy of EVs to ensure frequency stability in an islanded microgrid through primary frequency control. The proposed control strategy considers EV state of charge to maintain battery lifetime and ensures the availability of the EV as needed.

Table 10 presents information about the microgrid systems with frequency control discussed in this section.

Table 10. Information about the microgrid systems with frequency control of microgrids.

Ref.	Microgrid		Energy Generation		Energy Storage	Other Loads	Char. Stations
	Type	Architecture	RES	CES			
[84]	n.d.	Grid connected	PV WT	n.p.	n.p.	✘	AC
[84]	AC	Islanded	PV	DG	n.p.	✓	AC

7. Discussion

Integration of renewable energy resources and electric vehicle charging stations into the microgrid system has emerged as a significant research subject due to the potential it presents for the efficient use of these resources. This integration offers the possibilities to increase the reliability and self-sufficiency of microgrids while enabling them to provide ancillary services to the utility grid. To achieve the desired operational objectives, researchers have designed and tested various control mechanisms, as highlighted in the reviewed literature. The most commonly implemented control mechanisms discussed in the literature are power control, voltage control, and economic operation control of microgrid systems, as indicated in Figure 8. Each of these control mechanisms has been discussed in detail in previous sections, with corresponding literature cited for further reference and understanding. These control strategies play a key role in optimizing the performance and overall efficiency of microgrid systems, thereby preparing the way for sustainable and resilient energy management designs.

7.1. Operational and Control Strategies

The main aim of this review article is to provide a comprehensive overview of the different operational strategies employed in microgrids that incorporate electric vehicle charging stations. As mentioned above, the classification of various operational strategies or objectives has been discussed in previous sections. In the literature review, the use of charging stations has been observed in two different forms: active participation through controlled charging/discharging and passive participation as uncontrolled charging where the charging stations are considered only as loads. Figure 9 illustrates the distribution of charging station utilization in microgrid operational control. Notably, of the total number of papers reviewed (70), 46 papers actively employed charging stations for controlled charging or discharging to achieve specific goals based on the microgrid control strategy adopted. This active use of charging stations highlights their importance in improving the operational efficiency and overall performance of microgrids while facilitating a range of control options to optimize energy management and grid stability.

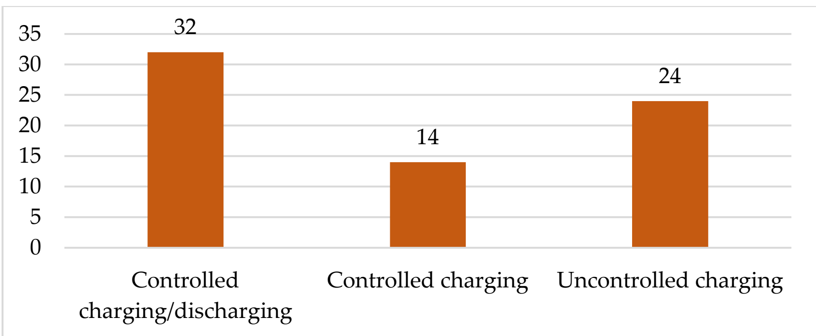


Figure 9. Charging station operation distribution.

For successful implementation of control strategies in real-world applications, it is important to validate these strategies using models that combine real-world data from the RESs and charging stations operation, EV user behavior, load demand, and other components of the microgrid. However, in the reviewed literature, the most common approach among the authors was to test their proposed control strategies in microgrid simulations with simplified models of EV charging habits without using actual real-world data. This lack of inclusion of real-world data in the testing may introduce uncertainties and limit the accuracy of the results. In papers [34,43,71], the authors used real EV charging data for simplified estimation of charging station behavior, and in [77,78] the authors used information from travel surveys. The authors of these papers used real-world data for charging stations representation and charging stations are actively participating in proposed control strategies. Data about real charging station power consumption were also used in [52,74] to test the proposed control strategies, despite the fact that the charging station participated only passively in the proposed control strategies. To represent more realistic behavior of charging stations during the testing of a proposed control strategy, it is important to use real EVs charging data that can represent EVs charging behavior in a specific microgrid system more accurately. Through implementation of different methods of data generation, it is possible to generate new simulation input data for charging station behavior, and thereby simulate different sets of scenarios with the same historical data. The most used method in the reviewed literature is the utilization of probability distribution functions, which are based on real EV charging data and can generate new simulation input data based on the shape of the distribution function [15,24,25,62,73,80]. Other methods used in the reviewed literature to generate data based on real data include the Monte Carlo method ([24,65]) and the Markov method [76]. These methods are used to simulate and generate data that mimic real-world properties. The Monte Carlo method was also used in [14,72] to generate SOC parameters for EVs. In papers [24,65], the authors used real data for charging station representation despite the fact that charging stations acted only passively in their control strategies. To implement the proposed strategies, it is imperative to test them by using real-world data.

7.2. Interaction of Proposed Control Strategies with Real-World Applications

Simulated operation time is another important aspect connected to the assessment of results for the proposed control strategy and in assessing if the proposed control strategy can be implemented in real-world application. In the reviewed literature, thirty-three papers simulated their control strategies on 24 h simulation operation and only four papers ([24,69,78,80]) used a simulation time longer than 24 h. Longer simulation time can provide the possibility to test the proposed system with more complex behavior and represent more precisely the real-world application.

In papers [19,21,22,31,44,57], the authors compared simulations of their control strategies on experimental models to see how real components could react with the proposed control. Compering simulation results with results from an experimental model provides a more comprehensive understanding of how the proposed control strategy will function in real-world implementation.

7.3. Research Shortcomings and Research Gaps

The literature review presented in this paper highlights several research shortcomings that require further attention to ensure the successful implementation of the proposed control strategies in real microgrid systems. Further research is necessary to effectively address these shortcomings. Specifically, future research efforts should prioritize the use of real data to test and validate control strategies, especially in charging station modeling. By incorporating real data, the reliability and applicability of the proposed methodologies can be improved in real microgrid conditions. Another shortcoming that often appears in the reviewed literature is that the presented control strategies are simulated on short time periods, which allows for better presentation of the results but does not allow us to see the more complex behavior of the simulated system. On the other hand, longer simulation times allow us to evaluate the long-term performance and see the more complex behavior of the proposed control algorithms on simulated systems. This literature review also revealed some research gaps, notably the aspect of validation of the proposed controls strategies through comprehensive comparison between simulated results and results obtained from experimental testing or real-world implementation on a microgrid system. Such a comparison provides indisputable evidence of the functionality and effectiveness of the proposed control approach, but the length of the operation window and different operation states used for comparison are also of utmost importance. Another research gap is the absence of a control strategy that would address the preservation of reserved capacity in the microgrid. This could provide a new approach for the power exchange between microgrid and main grid as well as increase the economic benefits of microgrid operation.

8. Conclusions and Research Prospects

8.1. Conclusions

With the global shift towards sustainability and the rapid deployment of renewable energy resources, electric vehicles, and charging stations, it becomes crucial to explore strategies that can provide grid support while addressing the inherent intermittent nature of renewables and EVs. In this context, microgrids offer an ideal solution as they can operate independently or in coordination with the main grid, facilitating the generation, distribution, and management of power flow among interconnected resources.

The growing number of EVs can significantly impact the operation of power systems, requiring more sophisticated control strategies to match EV charging patterns with grid conditions. This close interplay between electrical power systems and the transportation sector underscores the importance for advanced control measures to ensure the seamless integration of EVs into microgrids, thereby safeguarding a stable and resilient power supply for consumers of EV charging stations as well as stable and efficient operation of microgrids. In response to these challenges, researchers have been developing and testing various control strategies for microgrids with EV charging stations in recent years.

8.2. Research Prospects

This review paper aims to offer a comprehensive overview of the different control strategies proposed in the literature to control microgrids with electric vehicle charging stations. Additionally, this paper sought to identify common shortcomings and research gaps in the current literature. Among the most common shortcomings identified in the existing literature are the limited number of publications utilizing real EV charging data, the simplistic approach in determining EV charging station consumption, and the relatively short simulation time periods for the proposed control strategies. Addressing these shortcomings in future control strategies is crucial to increase the effectiveness and robustness of the proposed approaches and to increase their real-world applicability. In addition, this review highlighted gaps in current research, including the limited number of control strategies that have been tested on experimental microgrid models or directly in real microgrid settings. Notably, a significant research gap in the current literature is the absence of control strategies specifically adapted to address the preservation of reserved capacity in microgrids using EV charging stations.

To address these gaps and to advance microgrid control strategies, future research should focus on incorporating real EV charging data, adopting more sophisticated models to represent realistic EV charging station behavior, and conducting tests with longer simulation times to evaluate the long-term performance of control strategies. The experimental validation of the proposed control strategies within microgrid configurations, along with the development of novel control strategies addressing the preservation of reserved capacity of microgrids will further contribute to significantly improve the overall efficiency and practical implementations of microgrid systems with EV charging stations.

Furthermore, to facilitate a comprehensive comparison and evaluation of different control strategies in both current and future research works, it is essential to establish a universal benchmark network. This benchmark network will serve as a standardized platform for testing and evaluating the effectiveness of the proposed control strategies, thereby providing a deeper understanding of their application in different microgrid scenarios.

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Nomenclature

AC	Alternating Current
BSS	Battery Storage System
CES	Conventional Energy Sources
CS	Charging Station
DC	Direct Current
DG	Diesel Generator
D-STATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
ESS	Energy Storage System
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
FC	Fuel Cells
FCES	Fuel Cell Energy Storage
FCS	Fast Charging Station
HF	High Frequency
HSS	Hydrogen Storage Systems
CHP	Combined Heat and Power
MT	Microturbine
n.d.	not defined
n.p.	not present
PI	Proportional Integral
PV	Photovoltaic
RES	Renewable Energy Source
SC	Supercapacitor
SHG	Small Hydro Generators
SOC	State of Charge
UFCS	Ultra-Fast Charging Station
UPQC	Unified Power Quality Controller
V2G	Vehicle-to-Grid
V2V	Vehicle-to-Vehicle
WT	Wind Turbine

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