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Review

Microgrids' Control Strategies and Real-Time Monitoring Systems: A Comprehensive Review

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Abstract

Microgrids (MGs) technologies, with their advanced control techniques and real-time monitoring systems, provide users with attractive benefits including enhanced power quality, stability, sustainability, and environmentally friendly energy. As a result of continuous technological development, Internet of Things (IoT) architectures and technologies are becoming more and more important to the future smart grid's creation, control, monitoring, and protection of microgrids. Since microgrids are made up of several components that can function in network distribution mode using AC, DC, and hybrid systems, an appropriate control strategy and monitoring system is necessary to ensure that the power from microgrids is delivered to sensitive loads and the main grid effectively. As a result, this article thoroughly assesses MGs' control systems and groups them based on their degree of protection, energy conversion, integration, advantages, and disadvantages. The functions of IoT and monitoring systems for MGs' data analytics, energy transactions, and security threats are also demonstrated in this article. This study also identifies several factors, challenges, and concerns about the long-term advancement of MGs' control technology. This work can serve as a guide for all upcoming energy management and microgrid monitoring systems.

Keywords: microgrids technologies; control strategies; real-time monitoring; Internet of Things; energy management

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1. Introduction

Microgrids (MGs) are becoming more and more crucial in improving the intelligence and efficiency of the utility grid since they can better utilize renewable energy sources (RESs) to lower carbon emissions and relieve grid supply pressure [1]. As a creative response to grid stability difficulties, energy security, and climate change, MGs are designed to satisfy the expanding demands and problems of contemporary power systems. Their original purpose was to increase the energy flexibility and dependability of vital institutions like hospitals and military installations. Furthermore, it has been expanded to include a variety of commercial, industrial, and residential uses. MGs can function in two different modes: islanded or independent mode and grid-connected or grid-tied mode [2,3]. It provides greater flexibility, resilience, and dependability than conventional centralized grid topologies. A major factor in the global expansion of microgrid deployments has been the integration of RESs. Lower greenhouse gas emissions, reactive power support for improved voltage profiles, decentralized energy supply, heat load integration for cogeneration, and fuel diversity are only a few advantages of microgrids. However, their sporadic nature and variable output make system stability and control challenging. To guarantee the reliable functioning of interconnected RESs and loads, current control techniques must be enhanced as microgrid topologies have become more complex and dynamic [4,5]. MGs' complexity, scalability, uncertainty variables, and intermittent sources necessitate a strong intelligent control strategy. The stochastic and unexpected output of the RESs complicates the efficient operation of the microgrids; an adequate control strategy is necessary to produce a constant and consistent power flow. Among Internet of Things (IoT) technologies, real-time monitoring, remote control, and predictive analytics contribute to MGs' efficiency [6,7]. The IoT facilitates easy communication between microgrid components, including DERs, storage systems, and consumers, improving energy allocation and load control. Since energy systems are quickly going digital, strict cybersecurity laws are needed to protect against hacker attacks, data breaches, and destructive control orders that could endanger infrastructure or energy distribution. IoT-enabled MGs are currently developing security techniques to safeguard their systems and data in the future [8,9].

Several reviews of MGs and their control strategies have been published. The authors of [10] provide a comprehensive review, focusing on the control strategies introduced for the various hierarchical control levels of microgrids. The authors of [11] review many MG-related problems and challenges. They also cover several MG-related topics, including their technical and financial challenges, the many controllers made to regulate power flow in MGs, their drawbacks and security concerns, as well as their possibilities for the future and market integration. In [12], the authors outline the primary benefits and difficulties of AC microgrids. The hierarchical control architecture is presented as a successful solution for AC microgrids, and its control levels are examined. The authors of Ref. [13] provide a brief explanation of the advantages and disadvantages of several modified droop controllers in microgrid systems in addition to traditional droop control techniques. The authors of [14] examine various primary control methods for inverter-based microgrids that are utilized to regulate their voltage and frequency. Additionally, the techniques are categorized, reviewed, and contrasted with one another based on their possible advantages and disadvantages. In [15], various control strategies used by MGs are thoroughly examined and categorized into four primary groups: decentralized, hierarchical, distributed, and centralized strategies. It examines their performances, operational tenets, and relevance. It also covers research gaps, future trends, technical issues for practical applications and potential fixes, and various integrated technologies for MGs that lead to the smart grid (SG). In [16], the study investigates islanded microgrids operating under hierarchical control and provides a comparative analysis of different control strategies used for active and reactive power sharing. It also covers the upcoming developments in islanded microgrid research. A thorough analysis of microgrid energy management and monitoring systems is provided in [17]. It discusses the advantages and disadvantages of various MG control systems and categorizes them based on their degree of protection, energy conversion, and integration. Furthermore, the relevance of the Internet of Things and monitoring systems for data analysis and energy management in the microgrid is emphasized in terms of many factors, challenges, and problems related to the long-term development of MG control technologies. In an attempt to standardize AC and DC microgrids, the authors of Ref. [18] offered a hierarchical control approach derived from ISA-95 and electrical dispatching standards to make MGs intelligent and adaptable.

This paper, which was inspired by literature reviews, offers a thorough and analytical examination of MGs' elements, distribution network modes (AC, DC, and hybrid MGs), and control schemes. Furthermore, this study addresses the management of MGs through the use of cutting-edge technologies such as blockchain technology, the impact of blockchain-based cybersecurity, cybersecurity standardization, cloud and fog computing-based data analytics, and smart meters monitoring systems. Additionally, this work is important because it takes a holistic approach to comprehending and improving MGs' control systems, integrating IoT technologies for reliable and efficient MG operation. This paper provides crucial information on operational and technological advancements that enable the global deployment of MGs, which can be of considerable use to professionals, engineers, and scholars. The contributions of this study are summarized as follows:

- An overview discussion of MGs' elements is one of the study's main outputs.
- MGs' distribution network modes—AC, DC, and hybrid—as well as their advantages and disadvantages, are thoroughly examined.
- A comprehensive analysis of MGs' advancements in control strategies and their impact on future microgrid developments is conducted.
- An in-depth examination is provided of how technology is transforming management operations at MGs through new developments in IoT real-time monitoring, including its difficulties and potential future paths.

This work is structured as follows: Section 2 provides an overview of the elements of MG systems. Section 3 provides the types of network modes in MG systems. Section 4 presents the control architectures of MG systems. A detailed analysis of MGs' control strategies and their implications is provided in Section 5. In Section 6, the significance of MG-based IoT monitoring systems, their uses, and how they complement other technological developments are discussed. Section 7 looks at the potential for MGs in the future. Lastly, Section 8 provides a brief overview of the work completed for this paper.

2. Elements of Microgrid Systems

Microgrids are localized electricity sources that can function directly with the centralized power grid or in an islanded mode, which allows them to continue generating electricity even in the event of unforeseen circumstances. Microgrid integration into the electrical industry is a comforting attempt to address the problems entailed in traditional grids, and offers numerous operational benefits over them, including (a) improved power network stability, (b) increased efficiency through lower transmission and distribution losses, (c) lowered pollutants that contribute to global warming through the use of low-carbon technologies, (d) permitted generation augmentation and assistance to local power networks, (e) plug-and-play ability to transition between grid-tied and autonomous modes of operation, (f) uninterrupted independent electric energy delivery to all MGs and loads during autonomous mode, and (g) ability to provide backup supply if the main grid's power fails [3]. The elements and functions of typical microgrid systems are summarized in the next subsection.

2.1. Distributed Energy Resources (DERs)

The main electrical energy sources in a microgrid are DERs. They include a variety of both renewable and non-renewable resources, including energy storage devices, fuel cells, wind turbines, solar panels, and micro-turbines. Depending on whether a utility grid connection is available, DERs can function in either grid-connected or islanded modes and contribute to power generation. DERs in microgrids are mainly used to improve the local energy system's efficiency, resilience, and dependability. During grid disruptions, they can supply electricity, lessen dependency on the main grid, and help create more sustainable energy alternatives. Through load shifting during periods of peak demand, DERs can also be used to optimize energy usage within the microgrid and help control changes in renewable energy supply [19]. The authors of [20] examine various state-of-the-art DER-based microgrid features that facilitate the installation and reliable functioning of renewable energy sources. Simulations are used to examine recent advances in the areas of energy management, power quality, control structures, and reliability. The impact of Energy Storage Systems (ESSs) and Electric Vehicles (EVs) on the microgrid's ability to operate reliably in workable topologies is investigated. According to the author of [21], the widespread usage of DERs has affected several power system issues, including the management and operation of these networks. Planning and managing energy in the new area that controls the distribution system in a way that enhances microgrid performance requires a great deal of research and analysis. Furthermore, by combining distributed resources, DERs can be utilized to build Virtual Power Plants (VPPs), which allow them to offer ancillary services to the grid [22].

2.2. Power Generation Units

Conventional generators, energy storage devices, combined heat and power (CHP) systems, and renewable energy sources (RESs) are examples of microgrid power generation units. Conventional generators, including those driven by natural gas or diesel, supply backup power during grid disruptions or periods of heavy demand, guaranteeing continuous service for vital loads. They increase the electricity system's overall dependability and lessen the strain on the main grid. Renewable energy sources, including wind, solar, and fuel cells, capture clean and sustainable energy. The goal is to provide reliable and efficient electricity, manage fluctuations in generation and demand, and potentially reduce reliance on the main utility grid. Energy storage devices, such as batteries, can be used to balance loads and stabilize the grid or store excess energy for later use. Furthermore, power generation units enhance MGs' efficiency and lower transmission losses by controlling local energy resources and loads and optimizing energy management. Additionally, they can facilitate demand response, which enables customers to modify their energy consumption in response to price signals [23,24].

2.3. Power Conversion and Conditioning Equipment

In microgrids, power conversion and conditioning devices are essential for balancing various power sources and loads, allowing for steady and effective operation. They transform AC electricity from solar panels or wind turbines into DC for storage or AC with the proper voltage and frequency for the AC bus of the microgrid. Additionally, this equipment controls the microgrid's power flow, maintains voltage and frequency stability, and can supply backup power in the event of a grid outage. To smooth out the power profile and increase grid stability, power conversion and conditioning equipment buffer power from sporadic sources. Transformers, converters, inverters, and power electronics devices make up the components. Inverters and converters facilitate the conversion of DC electricity from batteries or renewable sources into AC power for use or grid connection. The integration of power electronic converters into microgrid technology presents both opportunities and challenges [25]. In Ref. [26], the function of power electronic converters in microgrid technology is discussed. Power electronic converters in microgrid technology face several major issues, including power quality, voltage and frequency regulation, RES integration, creative management, and coordination. Grid-forming converters and other advanced control techniques are recommended to mitigate these challenges. The authors of [27] explain how power electronics are used in modern sustainable power systems, how power electronics and distributed generation are related, and how each static converter is classified and used to improve the performance of wind, photovoltaic, fuel cells, small hydro, and microturbines. Based on the characteristics of the power converters, it is established that using power electronics improves their performance.

2.4. Energy Management System (EMS)

Numerous researchers have published extensive definitions of energy management. Energy management oversees the microgrids' dependable and cost-effective functioning. A well-designed EMS ensures efficient regulation of energy generation, consumption, and storage; the most common EMS goal for MGs is to reduce fuel and maintenance expenses [28]. In practical applications, energy management in MGs is crucial for effective energy operation in the commercial, industrial, residential, and utility sectors. EMSs intend to limit greenhouse gas emissions, maximize distributed generation resource planning, and lower energy usage in day-to-day operations. By tracking the power production of generating resources, weather predictions, load demand, and current energy pricing, these systems seek to run the microgrid as efficiently as possible. The integration of EMSs with human-to-machine interface (HMI) and supervisory control and data acquisition (SCADA) systems makes data processing and monitoring easier. To regulate the power flow between sources, loads, ESSs, and the main power grid, an energy management approach is pertinent given the various properties of the microgrid [29]. EMS and microgrid optimization problems include managing the fluctuating operating conditions of distributed generation and guaranteeing flexible and economical operation with a variety of resources. The microgrid's EMS carries out several tasks, including tracking, evaluating, and predicting power generation based on load usage, energy market prices, distributed generating system characteristics, and meteorological circumstances. These characteristics enable microgrid optimization using EMSs [30]. Modern technologies like EVs, RESs, and ESSs are making EMSs more and more vital. The uncertainties surrounding these technologies have an impact on energy systems' adaptability. The three types of EMS-assisted MGs' problem solving are peak shaving (PS), optimal power flow (OPF), and optimal network configuration (ONC) [31]. Researchers have examined several strategies for effective EMSs in connection with MGs' operation, considering a variety of goal functions, limitations, mathematical programming, intelligent control, and optimization techniques [32]. The goals of EMS optimization solutions are system reliability, energy efficiency, and cost control. MGs that depend significantly on renewable energy sources can find these difficult to balance. MGs balance multiple objectives by using multi-objective optimization. To determine the best compromise, one must use complex algorithms to assess several goal trade-offs [33]. Stochastic programming is another tool used by EMSs to control input unpredictability, such as fluctuations in demand and the production of renewable energy. With this feature, EMSs can maximize system performance under a variety of circumstances. Depending on scalability, data availability, and computational complexity, some optimization strategies could be challenging [34]. Numerous optimization techniques require too much processing power for real-time applications. It can be challenging to comprehend system circumstances in rural or impoverished locations. Scaling optimization techniques become more challenging to use as MGs grow in size and complexity [35].

2.5. Distribution Networks and Loads

The physical infrastructure that links the power sources, loads, and control devices is MGs' distribution network. It includes communication infrastructure, transformers, switchgear, protection devices, and overhead or subterranean power lines. Within the microgrid, the distribution network makes it easier for electricity to move smoothly, guaranteeing that power is delivered to the associated load dependably and effectively [36]. Within the microgrid, loads are the electrical appliances and equipment that use power. These can include loads from homes, businesses, and industries, including HVAC (heating, ventilation, and air conditioning), lighting systems, and manufacturing machinery. Commercial, industrial, and residential users' electrical appliances, equipment, and machinery are among the several possible loads in a microgrid system. Industrial consumers are large-scale energy users with advanced measurement, control, and communication systems that provide several advantages, such as accurate and efficient scheduling. When DG is not available, industrial consumers' load patterns are modified by appropriate scheduling to reduce peak demand. In the production industry, the majority of loads are not interruptible. Industrial consumers are the largest users, followed by residential consumers. The three most prevalent types are uninterruptible, interruptible, and controlled. Appliances that are controllable, interruptible, and uninterruptible have been scheduled to minimize peak load, peak-to-average ratio (PAR), and electricity costs. MGs' generating and storage capacities must be coordinated with load management and operation to keep supply and demand in balance. These components must be coordinated and controlled for a microgrid to operate to provide a consistent and effective energy supply. The EMS forecasts loads, controls power flows, keeps an eye on the condition of generating units, and maximizes the performance of energy storage and DERs. Hence, a microgrid's operation entails sophisticated control, real-time monitoring, and optimization to guarantee a dependable and sustainable power supply for the loads that are linked [37,38].

3. Microgrid Operation/Distribution Network Modes

Consequently, there are two modes of operation for MGs, namely the islanded operation mode and the grid-connected mode. Each operating mode has its own set of operational needs. Grid-connected is the typical working mode in which the power quality of the main grid is unaffected. In this mode, the microgrid can import or export power to the main grid based on the total power generated by the local load, in addition to providing electricity to its entire local load. The microgrid also sustains bidirectional power flow in this mode. It appears that when the microgrid is in islanded mode (standalone), it cuts off from the main grid and runs on its own whenever there is a malfunction or problem with the main grid's power quality. In the event of power disruptions on the main grid, the microgrid will maintain superior power quality and may provide clients with a consistent supply. Additionally, the microgrid can be easily isolated from the main grid in the event of additional disruptions such as frequency drops, voltage sags, or any problem in the main grid. The microgrid must independently maintain the reactive power balance when operating in an islanded mode since it lacks an infinite bus. When MGs are in grid-connected mode, they are linked to the electrical grid by a static transfer switch. The microgrid voltage is determined by the host utility grid. Even if the power flow of the microgrid is two-way, in grid-connected mode, MGs can exchange power with the external grid to maintain the local microgrid's supply. When the microgrid is in islanded mode, its power supply must be able to meet the load's demands [39,40]. MGs are categorized as AC, DC, and hybrid systems in distribution network modes. Their advantages and disadvantages are shown in Table 1 of this study.

Table 1. Benefits and drawbacks of MGs' distribution network modes [41–44].

	AC Microgrid
Benefits	**Assessment**
Grid compatibility	• Integrating with the current AC utility grid is quite simple.
Use of standard equipment	• AC microgrids and commonly used AC equipment, including transformers, breakers, and protective systems, have lower complexity and cost.
Simple Interface Loads	• AC is intended for the majority of consumer and industrial loads.

Table 1. *Cont.*

		AC Microgrid
Drawbacks		**Assessment**
Problems with power quality	•	Variations in frequency, voltage, and harmonics can affect an AC microgrid.
Required synchronization	•	Careful management of voltage, frequency, and phase is required while islanding or connecting to the grid.
Limited efficiency	•	Inefficient AC microgrids are caused by unnecessary power conversion processes.
		DC Microgrid
Benefits		**Assessment**
Higher efficiency	•	Reduced conversion steps; PV and batteries do not require an inverter.
Simplified control	•	No frequency or phase synchronization required.
Improved reliability	•	Less reactive power, no frequency instability.
Drawbacks		**Assessment**
Minimal standardization	•	Insufficient interoperability and mature standards.
Complexity of protection	•	Protection is more complicated because there is no natural current zero-crossing.
High-priced equipment	•	Equipment for specialized DC can be costly.
		Hybrid (AC/DC) Microgrid
Benefits		**Assessment**
Versatility and adaptability	•	All kinds of loads and sources (AC and DC) can be supported by hybrid MGs without experiencing significant convergence.
Efficiency optimization	•	By matching the types of sources and loads, hybrid MGs minimize conversion losses. Direct service is provided by DC sources to DC loads and AC sources to AC loads.
Seamless grid integration	•	A hybrid able to effectively service internal DC loads while integrating with the AC grid.
Resiliency	•	Redundant power delivery pathways increase system dependability.
Drawbacks		**Assessment**
Higher complexity	•	More advanced power and control electronics are needed.
High-cost infrastructure	•	Protection systems, converters, and wiring for both AC and DC are required.
Complexity of maintenance	•	More challenging to control and diagnose than pure AC/DC systems.

3.1. AC Microgrid Systems

The primary elements that must be synchronized in an AC microgrid are active power, reactive power, unbalanced components, and harmonics. AC is used for both primary distribution and interconnection in a limited power system called an AC microgrid. The AC microgrid is the most popular kind of microgrid, particularly in places where an AC utility grid is already in place. It runs on 230 V/50 Hz or 120 V/60 Hz AC voltage and frequency standards. AC buses can be used to link large AC loads to AC resources in an AC microgrid. By using bidirectional converters, these buses can also be utilized with DC devices. Based on the distribution system, an AC microgrid can be divided into three categories: single-phase, three-phase without neutral-point lines, and three-phase with neutral-point lines. AC microgrid manages power flow, islanding, and synchronization through the supervisory controller. The point of common coupling (PCC) serves as the interface connection of the AC microgrid to the main grid. Figure 1 shows the connectivity architecture of the AC microgrid. Remote villages with existing AC appliances, campus microgrids, industrial parks with AC-dominated infrastructure, and grid-tied systems looking for simple backup or renewable integration are all places where AC microgrids are utilized [41,42].

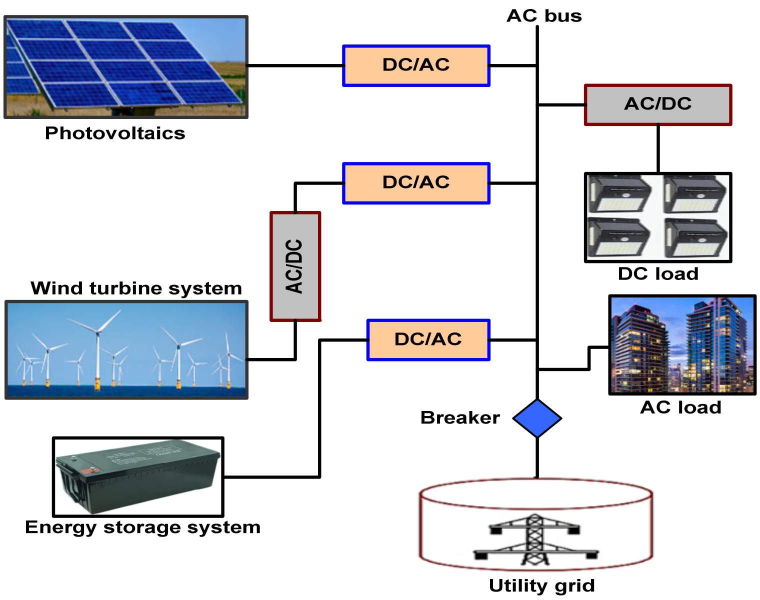

Figure 1. Architecture of AC microgrid [42].

3.2. DC Microgrid Systems

A DC microgrid is a distribution system with a DC output voltage that consists of DC loads, energy storage components, and DG resources, most of which are renewable. In a DC microgrid, direct current (DC) rather than alternating current (AC) is used to create, distribute, and consume electricity locally. DC power is the primary element in a DC microgrid that requires control. Therefore, compared to an AC microgrid system, a DC microgrid control system is simpler. The DC microgrid's converters are DC–AC converters. By connecting distributed renewable energy resources directly to DC buses, the network's overall efficiency is decreased since fewer converters are needed and less energy transformation is needed, but the network's power quality is also improved. There are three types of DC microgrid distribution networks: monopolar, bipolar, and homopolar. When connected to various DERs, DC microgrids offer greater benefits than AC microgrids in terms of increased dependability, efficiency, and convenience. Figure 2 illustrates the connectivity architecture. Due to the high DC demand, DC microgrids are anticipated in telecom networks and data centers. Electric car charging stations, distant off-grid systems (such as rural solar mini-grids), and industrial operations with consistent DC demand are all applications for DC microgrids [41,42].

3.3. Hybrid (AC/DC) Microgrid Systems

The distinct structures of an AC and DC microgrid are combined to form a hybrid microgrid. Figure 3 shows the layout of a hybrid microgrid, which is connected to the main grid via a static transfer switch (STS). To connect the AC and DC microgrids, bidirectional AC–DC converters are utilized. To connect DC power generators to DC microgrids, including fuel cell (FC) and photovoltaic (PV) panels, DC–DC boost converters are utilized [43]. Furthermore, AC loads are directly connected to the AC microgrid. When the

AC microgrid becomes overloaded, power will shift from the DC microgrid to the AC microgrid. With this approach, the primary converter will function as an inverter. In the event of microgrid overload, power will be transferred from the AC microgrid to the DC microgrid through a bidirectional converter called an interlinking converter. Stabilizing the microgrid's DC bus voltage, AC bus voltage, and frequency while managing the power flow between DC and AC microgrids is the main objective of a bidirectional AC–DC converter. A hybrid microgrid's construction seeks to save energy costs, improve reliability, control bidirectional power flow, limit conversion stages, reduce the number of interface devices, and promote overall network efficiency. Hybrid microgrids are used in commercial buildings and campuses with a variety of AC and DC loads, military installations that need essential facilities, industrial parks with both conventional AC machinery and DC automation systems, and smart cities that incorporate EVs, renewable energy sources, and digital infrastructure [44,45]. According to the authors of [46], the hybrid microgrid is a good strategy in contrast to AC and DC grids because it combines the benefits of both grid types, such as reliable power quality, environmental friendliness, constrained sizing, and the ability to provide special, tailored services for stabilizing a variety of loads.

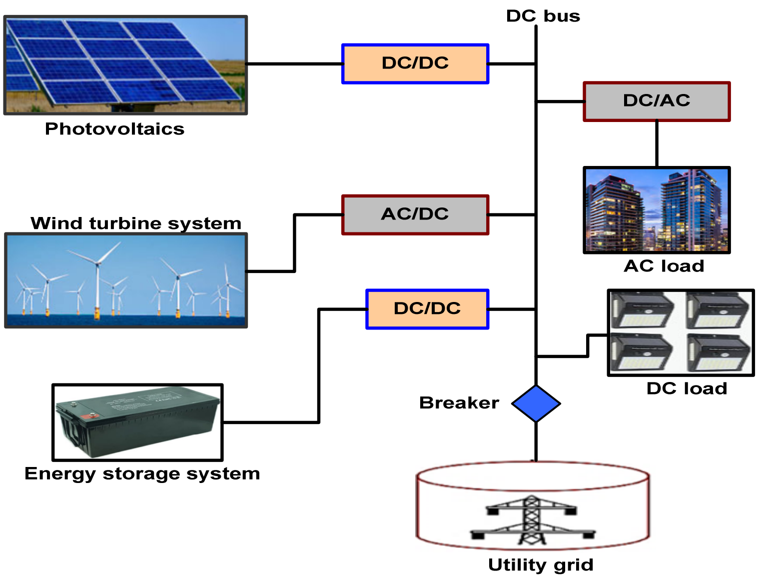

Figure 2. Architecture of DC microgrid [42].

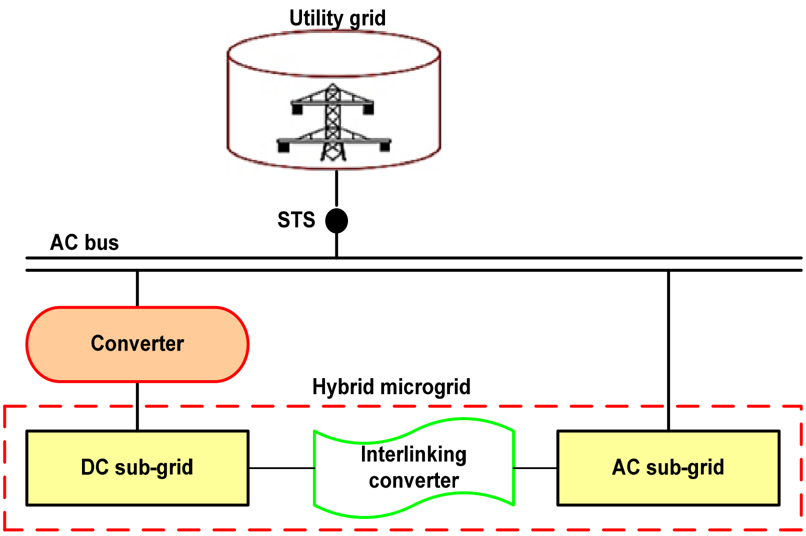

Figure 3. Architecture of a hybrid (AC/DC) microgrid [42].

4. Microgrid Control Architectures

A hierarchical control system, which displays main, secondary, and tertiary levels of control, strikes a balance between centralized and decentralized control systems. The term "primary control" describes the autonomous localized control of DERs, in which synchronous generators and micro-turbines are controlled to maintain nominal output voltages and a steady operating frequency. The secondary level of control involves coordinating several DERs to carry out cost-effective power balancing and electricity dispatch operations using clever electronic devices. Tertiary control handles diagnostics, fault protection, and interactions between the utility grid and the MGs using a centralized control architecture [47].

Three levels of control, including distributed, centralized, and decentralized control techniques, can be used to describe the MGs' control structures. The DGs can be operated independently, as seen in Figure 4a, or through a local controller (LC) in a decentralized control system, where each controller operates solely based on its measurements. The drawback of a decentralized control system is that, because DGs function independently, LCs lack sufficient information about their operational status. However, because it eliminates the requirement for communication linkages between various units, it is regarded as the most dependable control approach. This communication-free control approach may be the best option for large-scale microgrid systems. Decentralized control, which regulates each unit independently, helps improve energy management as electrical MG complexity rises. This control method allows the system to function even in the event that the DGs lose contact with one another. Decentralized control also works effectively with large-scale, complicated, and varied systems. It is computationally efficient, has plug-and-play capability, and can continue to work even in the event of numerous point failures. The absence of a coordinated communication structure, however, is a significant disadvantage that may make it more difficult for DGs to synchronize [38,48]. Under a centralized control technique, each DG in the microgrid is managed by an LC in the system. Every LC is connected to the central controller via a communication link. The central controller obtains all required data from the DGs and sends control commands to every local controller, as shown in Figure 4b. The LCs in this control method are unable to act independently and lack any means of communication with one another. One benefit of the centralized design is that it allows for the control of the entire system from a single location. However, the drawback of this feature is that it makes the microgrid more vulnerable to controller or communication failures, which might cause the entire system to collapse. Measurement inaccuracies and communication delays can cause the system to function poorly, which is another disadvantage. Master–slave control is the most often utilized technique that makes use of a centralized approach. Despite various disadvantages, centralized control may be a good option in particular circumstances where system stability and dependable communication are crucial [47,49].

In MG systems, the idea of distributed control offers an alternative to the centralized and decentralized control strategies. Distributed control, as shown in Figure 4c, does not have a central controller; instead, each DG has an LC that communicates with other LCs to keep the MG operating steadily. This tactic can be applied at both the secondary and tertiary control levels and is primarily employed in islanded mode. The durability of distributed control, which can withstand component failures and faults without resulting in catastrophic MG failures, is one of its primary benefits. Conversely, the central controller is a common point of failure for the centralized approach. Due to its great scalability, distributed control makes it possible to integrate new distributed generators (DGs), energy storage devices, and loads without interfering with the functionality of the microgrid's current components. It makes it possible for DGs to function plug-and-play, just like in the decentralized approach. However, there are drawbacks to distributed control; measurement errors and communication lags can negatively impact its precision and overall effectiveness [50]. Many strategies have been proposed to address these issues. The multi-agent technique and its variations are frequently used at the secondary control level. In the tertiary control level, the following techniques are used: distributed power injection, distributed economic dispatch, the predictive control technique, the consensus technique, and the decomposition technique. Although distributed control offers many advantages, such as flexibility, scalability, and robustness, it is a promising approach for MG control. However, to achieve optimal performance, it necessitates careful consideration of communication protocols, measurement accuracy, and control algorithm design [51].

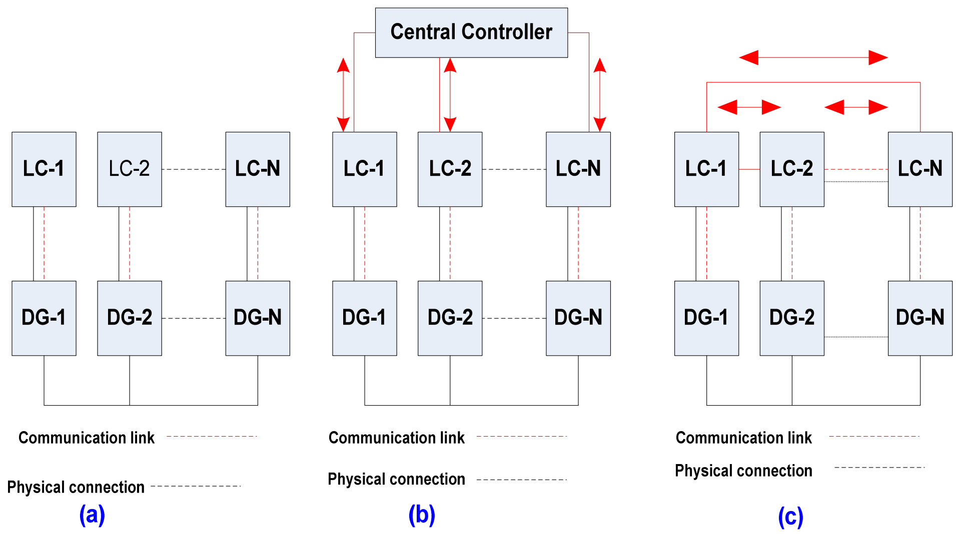

Figure 4. MG control architectures: (**a**) decentralized, (**b**) centralized, (**c**) distributed [47].

5. Advanced Control Techniques

Energy networks in the modern day are getting more complex, especially those where renewable energy is widely used. The rapid temporal reaction of microgrid operations allows them to begin with standard control tactics. In the event of an abrupt disconnect, automation and a smooth transition are made possible by advanced control mechanisms. This is necessary to accomplish the aforementioned objective about the flow of electricity between MGs and the power grid. These technologies increase the effectiveness and shock resistance of MGs by utilizing machine learning (ML) and artificial intelligence (AI) [52]. This section will present a comprehensive review of the literature, stressing both the benefits and drawbacks of sophisticated approaches in the context of modern MG construction, as indicated in Table 2.

Table 2. Benefits and drawbacks of different control strategies.

Ref.	Control Method	Types	Advantages	Disadvantages
[53,54]	Droop Control	Traditional	• Integrating with the current AC utility grid is quite simple. • Scalable and adaptable to varying microgrid sizes.	• Poor voltage-frequency regulation, particularly in systems with low voltage. • Slow dynamic reaction.
[55]	Proportional–integral–derivative	Traditional	• Frequently employed to maintain stability in the regulation of voltage and current. • Ideal for microgrid systems that are connected to the grid.	• Requires exact adjustment. • Unable to handle non-linear systems or variations in renewable energy.

Table 2. *Cont.*

Ref.	Control Method	Types	Advantages	Disadvantages
[56]	Multi-agent systems	Traditional	• Agents can function independently. • Effective for decentralized control, enhancing coordination and communication.	• Difficult to plan and execute. • Performance is highly dependent on the communication network.
[57,58]	Fuzzy logic control	Advanced	• Flexible and robust to different system conditions. • Manages nonlinearities effectively.	• Less rapid dynamic reaction. • For complicated systems, a lot of rule-setting is necessary.
[59,60]	Model predictive control	Advanced	• Minimizing forecast error and future states to achieve optimal control. • Appropriate for real-time control and nonlinear methods.	• High processing power is needed. • Implementing in large-scale systems can be challenging.
[61,62]	Artificial neural networks	Advanced	• Capable of gaining knowledge from data and gradually enhancing control. • Ideal for dynamic, very complex systems.	• Large datasets are necessary for training. • High computational costs and challenges in tuning.
[63,64]	Reinforcement learning	Advanced	• May interact with the environment to discover the best control tactics. • Ideal for complex and non-linear systems.	• Requires a significant amount of computing power and training time. • In extremely volatile environments, it might not function well.
[65,66]	Sliding mode control	Advanced	• Sturdy performance in the face of varying conditions and fluctuations. • Quick dynamic reaction.	• Potential for chattering problems as a result of frequency switching. • Sensitive to measurement noise and requires complex control laws.
[67]	Virtual impedance control	Advanced	• Enhances voltage management and power sharing, especially for nonlinear loads. • Offers appropriate transient response with no frequency fluctuations for active and reactive power sharing.	• Under certain circumstances, voltage regulation is not assured. • Complex implementation requiring prior system parameter knowledge.

5.1. Artificial Neural Networks (ANNs)

ANNs' basic design consists of an input/output layer, weights, an activation function, and a hidden layer. ANNs are more intelligent and self-learning controllers that enable more flexibility and easier implementation for a range of operating conditions. The robust behavior and quick decision-making capabilities of ANNs during operation further contribute to MGs' stability. ANNs are one of the best methods for identifying, regulating, and optimizing system parameters. ANN's primary benefits are parallel processing, data collection, processing, learning, robustness, generalization, and better decision-making. Additionally, ANNs can address challenges with non-linear data approaches in large-scale systems in microgrid systems. ANN applications include load sharing, parametric optimization and identification, prediction, self-learning, fault tolerance, stability systems, and self-learning [68]. When an ANN is used effectively, it can help with other controller structure functions. Similarly, the adoption of an ANN-based PI-controller with real-time coefficient adjustments guided by an integrated genetic algorithm (GA) for effective frequency control of the islanded microgrid is investigated by the authors of [69]. Figure 5 illustrates the implementation and application of ANN intelligent control to produce the voltage reference for a converter. It is challenging to incorporate ANNs into real-time systems with constrained processing power because of their high computational cost. Also, it is challenging to discover and adjust control measures when one does not understand an ANN's decision-making. Therefore, the availability of vast amounts of data required to train ANNs has significantly risen due to contemporary big data analytics and machine learning [61].

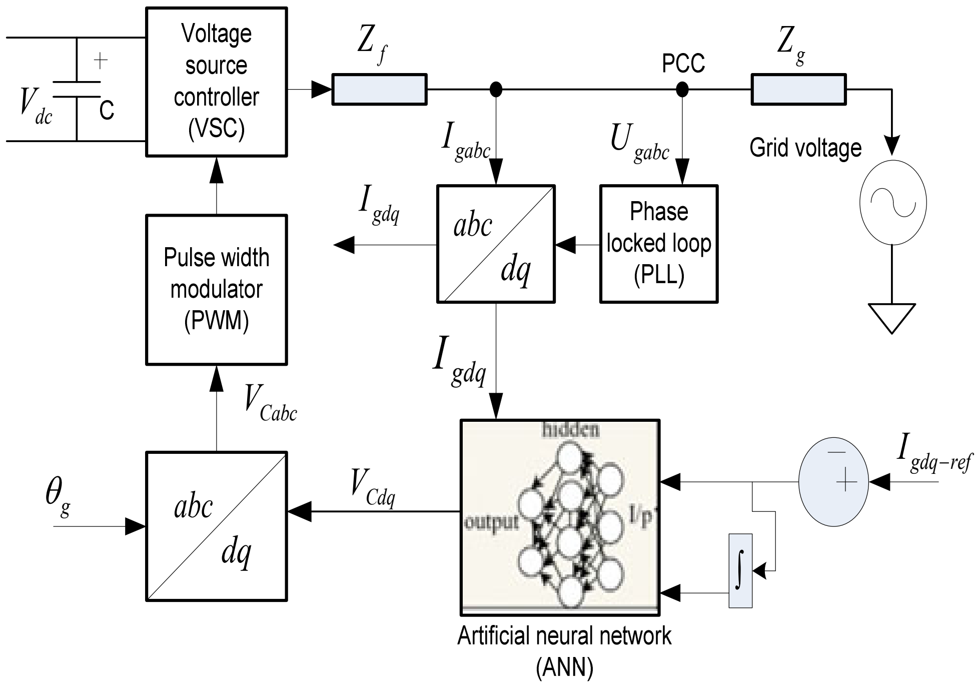

Figure 5. ANN intelligent control [65].

5.2. Fuzzy Logic Control (FLC)

Fuzzy optimization uses logical thinking to make decisions and addresses difficulties with uncertainty. FLC is an intriguing technique for microgrids. Numerous scholars have investigated the possibilities of fuzzy logic techniques for resolving microgrid system parameters. The authors of [70] suggest using the Tabu search algorithm scheme to automatically define a fuzzy rule for a fuzzy controller. Similarly, the authors of [71] describe a microgrid with a fuzzy-based power management system that determines the different power references based on load requirements and ESS state of charge (SoC). A non-linear barrier function-based first-order sliding mode control (NBF-SOSMC) regulates the currents of the connected sources once these references are input into the lower level of control. An intelligent control technique that combines FLC and particle swarm optimization (PSO) is shown in Figure 6. In this control method, the PI parameters for MGs' secondary frequency control are adjusted using fuzzy rules based on PSO's online measurements. The intelligent fuzzy system unit modifies the PI control variables, including proportional gain (Kp) and integral gain (Ki), depending on inputs like frequency variation (Δf) and load perturbation (ΔPL). To adjust the PI controller in a separate microgrid system, it maps input variables using fuzzy rules [69]. Additionally, FLC is a straightforward and adaptable tool that can handle imprecise sensors because it does not require exact inputs. Due to its low computational cost, the FLC technique is perfect for microgrids that rely on renewable energy sources while making decisions with inadequate or unclear inputs. MGs' stability and performance are enhanced by FLC's flexibility and ability to control vast amounts of uncertainty, including the penetration of renewable energy. Lastly, FLC scaling may be challenging in systems with varying demands or multiple interacting DERs. The dynamic responsiveness of FLC can be improved by researchers by combining it with machine learning techniques or predictive control systems [57].

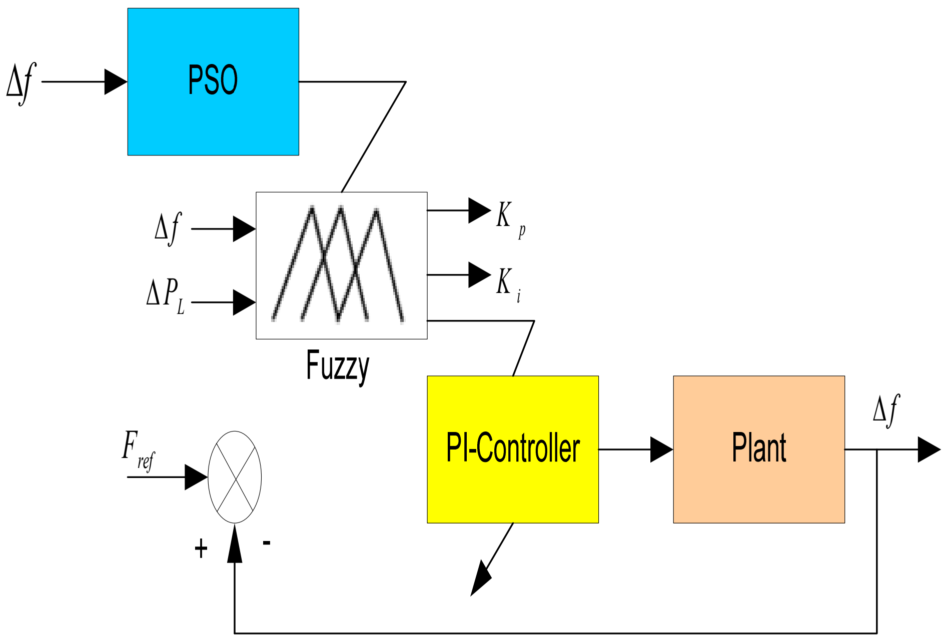

Figure 6. MG secondary frequency control using a PSO fuzzy-based PI-controller [57].

5.3. Model Predictive Control (MPC)

A process control technique called model predictive control (MPC) makes use of the model itself to forecast future model states across a period called the time horizon. It is also known as receding horizon control. Its concept has been widely used in many different areas of research, especially power systems optimization, due to its ability to handle problems with complex dynamic systems. Similar to this, Ref. [72] proposes control of a distribution network structured into microgrids, with the primary objective being to provide flexible services using the available hydrogen ESS and BESS. The authors of Ref. [73] suggested utilizing a data-predictive control framework for real-time optimization. Using cooperative distributed MPC optimization, a multi-microgrid system is dispatched. The authors of [74] employed MPC-based energy scheduling, which performed better than a fuzzy-based heuristic approach since it could account for future generation and load demand. As shown in Figure 7, the MPC optimization algorithm's structure determines the strategy's success. For the inputs, the MPC algorithm computes a set of M values, $\{u\ (k + i - 1), i = 1, 2, 3 \ldots M\}$. The collection consists of $u(k)$ present inputs and M-1 future inputs. Calculations are made until the P predicted output equals $\{y\ (k + i), i = 1, 2, 3 \ldots P\}$. At every sample instant, a set of M control motions is calculated, but only the initial move is utilized. The following sampling moment is used to calculate a new series. In the absence of more recent observations, it employs the original motion. Every sample instant uses the same methodology. An MPC strategy's effectiveness is dependent on the optimizer and process model. A controller that functions well can be produced by a model with excellent prediction capabilities. Through the use of real-time data to update models, MPC enhances the performance of real-time applications. It is necessary to understand mathematical approaches and system operations to apply MPC successfully in real-time systems. MPC provides flexible decision-making by considering potential future events, which increases MPC's significance and accuracy. Furthermore, MPC has been used to address several parameters in both isolated and grid-connected MG systems. On the other hand, MPC requires more computing power than the fuzzy approach [59].

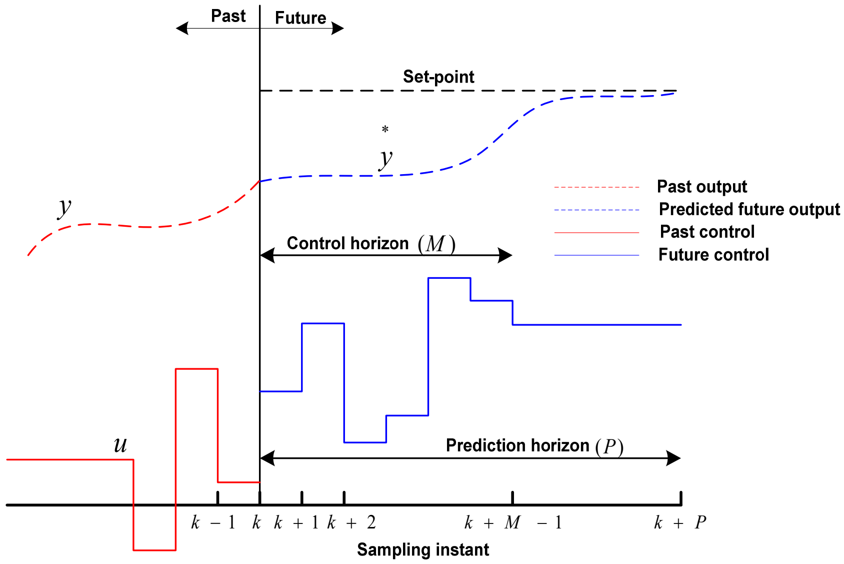

Figure 7. Control strategy of MPC [65].

5.4. Sliding Mode Control

The sliding mode control (SMC) methodology is a nonlinear control method that modifies the outputs of a system based on its current state in a dynamic process. In a dynamic system, SMC can reject the uncertainties that act on the same channel of the controllable variables and do not amplify the unmatched disturbances. Additionally, SMC is used to change the system's dynamics by using discontinuous control signals, which makes the system slide along a cross-section of its typical behavior. SMC is used in MGs' closed-loop system network to solve the robust stabilization problem for uncertain time-varying networked control systems subject to state delay. This problem avoids the challenges of solving linear matrix inequalities and determining quadratic Lyapunov functions by using auxiliary matrices. This SMC alters the system's dynamics by using discontinuous control signals, which makes the system slide along a cross-section of its typical behavior. Therefore, this control enhanced the system's resiliency [65]. SMC has been utilized in many physical systems during the past few decades, including power systems, robotic manipulators, and automotive engines. However, its usefulness has been compromised by sensitive sensors or communication networks. SMC's intricate control theories are challenging to implement, particularly in big systems, because they necessitate a deep comprehension of the system being controlled [66]. Furthermore, SMC is susceptible to outside disruptions and undesired chattering when the frequency signal is switched. Therefore, lowering measurement noise may be possible by combining SMC with Kalman filters or another noise-reduction technique. As seen in Figure 8, SMC is a variable structure control technique that sends signals to the Space Vector Modulator (SVM), which then sends pulses to the converter after active power and reactive power have been computed and compared to reference values. Ref. [75] uses an intelligent terminal SMC to control the frequency in an islanded MG made up of several renewable sources. In the study, an artificial bee colony (ABC) optimization algorithm is integrated to optimize the parameters of SMC by tuning the number of sliding mode parameters. The terminal SMC algorithm stabilizes the frequency with roughly zero steady-state error after comparing the simulation result with ABC-based PID control.

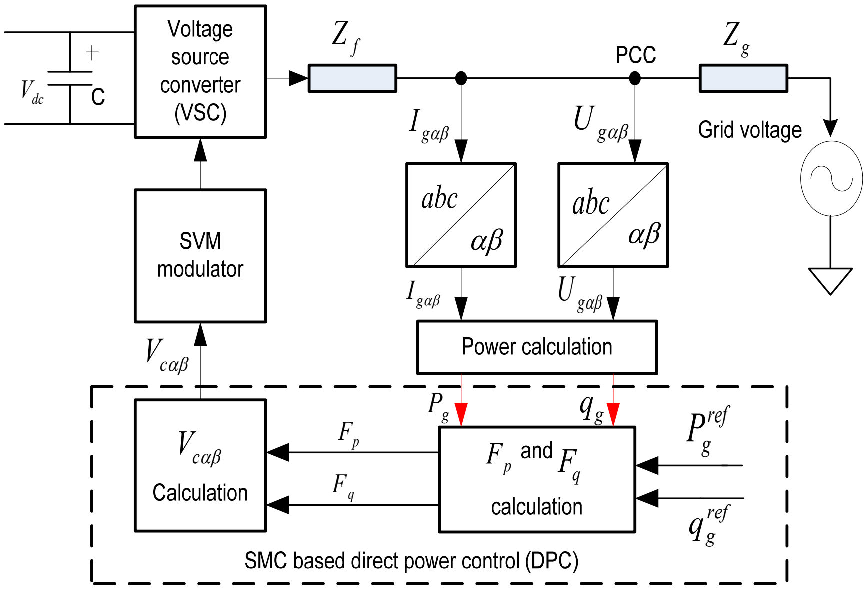

Figure 8. Sliding mode control technique [65].

5.5. Adaptive Control

Continuous updates are made to an adaptive control system to guarantee that plant changes are managed effectively and without the need for human intervention. It is simple to build adaptive control for the systems. Adaptive regulation adjusts the parameters to accomplish the control goals and guarantee that the system operates as planned. The adaptive control technique is shown by a block in Figure 9. Based on the feedback signal, adaptive control efficiently manages a constraint in a control system. Adaptive control addresses the biased terms and uncertainty in the state space representation [76]. Real-time parameter optimization is possible with adaptive control techniques, unlike traditional controllers. Its methods are crucial in lowering the frequency of switching caused by variations in the source and load [77]. However, because adaptive control adapts slowly, it is difficult to apply prior knowledge of system parameters and it cannot guarantee that the voltage will be regulated in all circumstances. Nonlinear or time-varying processes employ adaptive control, which is implemented by adjusting the system's control parameters using intelligent control techniques like fuzzy logic control (FLC) and artificial neural networks (ANN) [78].

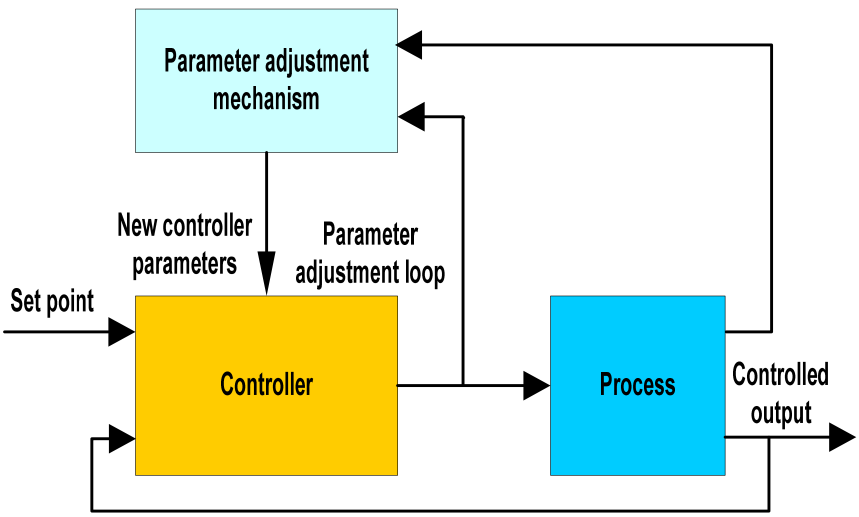

Figure 9. The method of adaptive control [65].

5.6. Deep Reinforcement Learning (DRL)

Reinforcement learning (RL), is a crucial technique in machine learning, allows agents working in a given environment to make decisions autonomously and sequentially without the need for labeled datasets or previous historical data. "Sequential decision-making is the focus of the machine learning field known as reinforcement learning." The goal of reinforcement learning is to determine the best course of action for agents to maximize cumulative rewards in a given environment. Furthermore, RL is a powerful learning algorithm that learns the best course of action by interacting with surroundings that are either model-based or model-free. It predicts the best solution for a given policy by using agents that interact with the environment to learn the value function. Following the value function, it will keep learning the best course of action until convergence is reached [63]. Figure 10 illustrates the basic representation of the fundamental reinforcement learning. It makes use of agents that interact with the environment to learn the value function for a particular policy in order to forecast an optimal solution. Then, it continuously evolves and learns the optimal policy until convergence is reached [79]. In addition, the authors of [80] offer an Easy Transfer Reinforcement Learning (ETRL) technique that combines DRL and Easy Transfer Learning (ETL) to modify a multi-objective controller for grid-following converters with different system characteristics. Effective knowledge transfer with little data and parameter adjusting is made possible by the five-stage ETRL method, which consists of system design, DRL training, transfer learning, fine-tuning, and implementation. It guarantees consistent converter performance under various circumstances, increases controller adaptability, and lowers training effort by 96.4%. Results from experiments verify its effectiveness and provide a scalable method for power electronics controller design.

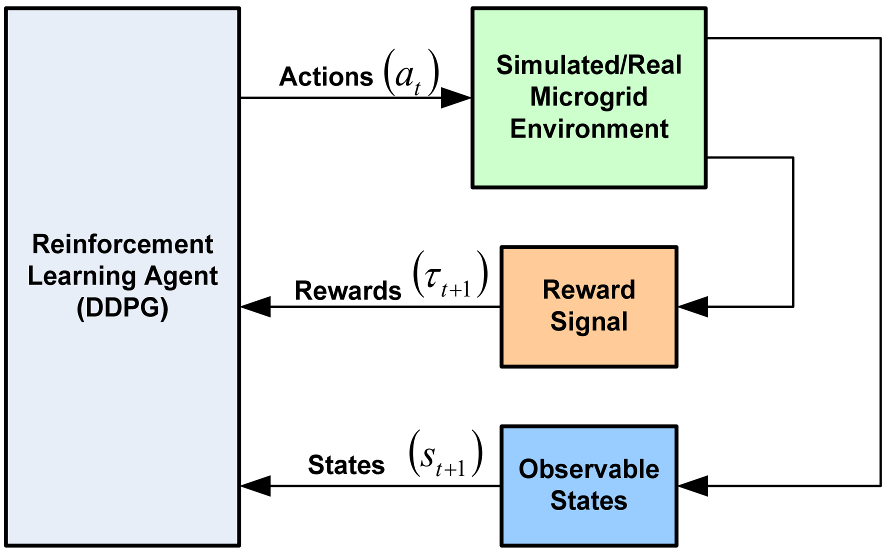

Figure 10. Basic representation of DRL setup [79].

5.7. Impact of Control Strategies on Future Microgrid Developments

This section explores in greater detail how management practices in MGs impact the development of new technologies and the resulting worldwide economic effects. MGs are smaller-scale systems that either connect RESs, such as solar PV, wind turbines, and battery storage, to the larger power grid or may operate independently (in islanded mode) in the case that the larger grid is unavailable. The ability to operate with different kinds of RESs and satisfy load demand in the event of outages are the two most crucial objectives of a microgrid. Since their output varies according to the weather, modern MGs suffer from the intermittent nature of RESs. Advanced control techniques are necessary for real-time supply and demand synchronization. These techniques also aid in preventing power imbalances, which can lead to system breakdowns or inefficiencies [81]. Future developments will be influenced by MGs' control techniques in several sectors, including economic growth, environmental sustainability, and energy resilience. The resilience of the energy system is determined by MGs' control solutions in regions vulnerable to natural disasters or grid instability. Even when isolated, these systems maintain a steady energy supply by utilizing real-time supply and demand balancing. In the event of a power outage, they guarantee that other critical medical equipment, like life-support systems, receives priority attention [82]. A notable example of the necessity of robust microgrid control mechanisms is the Brooklyn–Queens Demand Management (BQDM) initiative in New York City [83]. MGs' management systems support efforts to mitigate climate change and cut greenhouse gas emissions by maximizing RESs and reducing the usage of fossil fuels. Financial implications also result from these strategies; MGs' management systems optimize the use of intermittent RESs, such as solar and wind, while preserving grid stability, reducing peak demand, and increasing energy efficiency. During periods of high energy costs or peak demand, local electricity generation helps to lessen reliance on expensive main grid imports. Additionally, these methods contribute to the reduction of peak loads and grid congestion. Energy, capacity, and auxiliary services are just a few of the grid services they provide to help and improve the larger grid. MGs are an excellent tool for enhancing the sustainability and effectiveness of the broader energy ecosystem due to their adaptability, flexibility, and versatility. The global economy is greatly impacted by MGs as more countries choose decarbonized energy systems and cut back on their use of fossil fuels. By reducing electricity costs, increasing job opportunities in the design, installation, and maintenance industries, and bringing energy independence to otherwise underdeveloped or disadvantaged regions, MGs will contribute to the achievement of net-zero emissions targets [84,85]. The effective communication of MG management strategies is significantly impacted by monitoring infrastructure (IoT, smart meter, cloud computing, and SCADA system), control infrastructure (distributed control system, remote terminal units, and programmable logic controller), and protection infrastructure (protective relays, static transfer switch, and islanding detection mode). Traditional, centralized power networks deliver electricity to distant consumers from distant sources. Peer-to-peer energy trading and distributed energy markets are made possible by MGs' cutting-edge control technologies, which democratize energy control and lessen dependency on utilities. Also, since electric vehicles have grown in prevalence significantly, combining EVs and MGs can offer important insights for the development of power systems [86,87].

6. Microgrids'-Based IoT Monitoring Systems

This section explains how real-time monitoring, data analytics, and decision-making are transforming MG management operations with IoT technology. This section also covers recent advancements in cloud/fog computing applications, smart meters, and blockchain-based cybersecurity. The development of IoT technologies and their application in microgrids has led to their recent rise in popularity. The IoT is a key technology that makes it possible to collect data in real time, perform sophisticated analytics, and integrate various energy sources seamlessly, all of which increase the sustainability, dependability, and efficiency of microgrids. Through IoT, utilities can carry out operational tasks like reducing outage investigation times, improving load balancing, optimizing line voltage, identifying defects, lowering service costs, and speeding up service restoration. Furthermore, the flexibility and reliability of microgrid systems are increased by utilizing IoT technologies for variable loads, charging stations, EVs, smart homes, ESSs, and other devices [64]. The MG-based IoT monitoring systems are shown in Figure 11. The MGs have several sensors to gather data (temperature, power, voltage, and current). The data gathered from these sensors is examined in real-time to ascertain the best control plan depending on the existing circumstances (weather, occupancy, and energy production and consumption statistics). Predictive control approaches, in particular, require that this data be stored for future research. Through data collection, energy sharing, trading, and demand response (DR) management, IoT may increase energy efficiency. IoT can help MGs manage their DERs by collecting real-time data on system operation, output, and energy use [33]. IoT devices evaluate the MGs in a variety of scenarios to support energy distribution, waste minimization, decision-making, and energy consumption optimization. IoT monitoring utilizes predictive algorithms to keep the grid stable and boost energy efficiency. IoT devices offer automated load shedding, demand-side control, and energy-saving solutions with accurate consumption data. In the event of a breakdown, outage, or cyberattack, IoT-based sensors detect anomalies and trigger an alarm. Microgrid resilience is enhanced by IoT in remote or disaster-prone places. MGs can be integrated with IoT devices in buildings or residences to provide coordinated energy use in smart home and building integration. Grid signals provide the basis for the operation of smart appliances and HVAC systems [88,89].

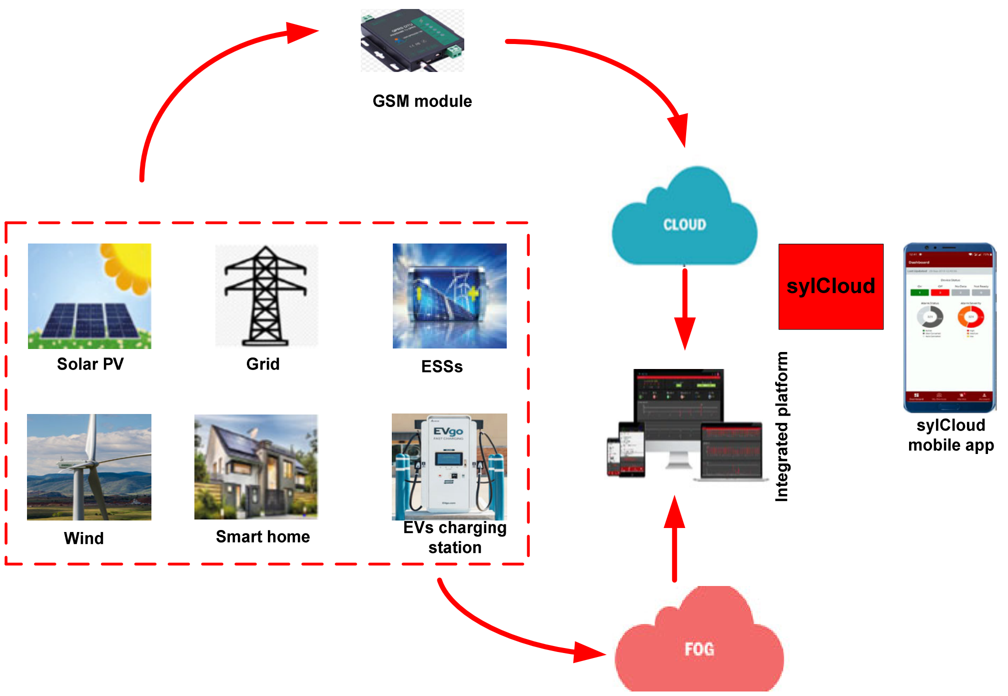

Figure 11. Microgrids'-based IoT monitoring systems [33].

Several researchers have employed IoT methods to monitor a microgrid's systems. The authors of [90] examine the real-time aspects of security measures for Internet of Things connectivity. Investigations are conducted on how IoT protocols affect the protection, control, and monitoring requirements of smart grid operations in real time. The authors of [91] have developed an IoT-based remote energy monitoring system for controlling, planning, optimizing, and conserving energy in smart grids and houses. The system effectively gathers data on the household's energy resources, minimizes energy waste, and offers data for examining trends in energy usage. The authors of [92] describe a web server-based real-time microgrid monitoring system. An Ethernet network module was utilized for data collection and wireless transmission, while the Arduino embedded system served as the control core. The development of IoT has addressed numerous practical problems, but it has also brought up significant ethical and legal concerns, according to literature reviews. Data usability, safety and trust, privacy protection, and data security are some of these issues.

The advancement of power electronics converter control techniques necessitates the creation of fresh approaches to periodic signal monitoring and regulation. Phase-locked loops (PLLs) and Second-Order Generalized Integrators (SOGIs) are sophisticated signal processing techniques used in microgrid monitoring and control. They are mainly employed for grid synchronization, voltage and current measurement, and power quality analysis. The micro source inverter's control strategy relies on PLLs for phase and frequency detection in addition to the standard microgrid active-power/frequency and reactive-power/voltage droops. PLLs are control systems that lock the output signal's phase to that of an input reference signal, usually a grid-supplied sinusoidal voltage. When connecting DERs, such as inverters, to the main grid, PLLs are necessary. The grid voltage and the inverter's output must be in sync. Additionally, PLLs monitor the input voltage signal's phase angle (θ), frequency (ω), and occasionally amplitude—all of which are critical for control and protection. Phase imbalances, frequency drifts, and oscillations can all be found with the aid of PLLs. For three-phase balanced systems, it is therefore utilized. The authors of Ref. [93] suggested a control technique based on the usage of PLLs to measure the microgrid frequency at the inverter terminals and to make it easier to regulate the inverter phase with the microgrid. With this control approach, MGs may switch between grid-connected and autonomous operation with ease, and vice versa. In a real microgrid with several sources, the controller has been put into use. The complete control technique is depicted in Figure 12. Phase voltages and currents are converted into a stationary reference frame quantity, which is used as the first stage in the control method. The voltage components are used by the PLL to estimate the frequency and establish the phase reference for the inverter. The phase regulator receives these values and uses them to calculate and control the desired voltage magnitude of the inverter. As a result, the pulse width modulation (PWM) generator generates the PWM output signals by taking the desired voltage magnitude and phase [94].

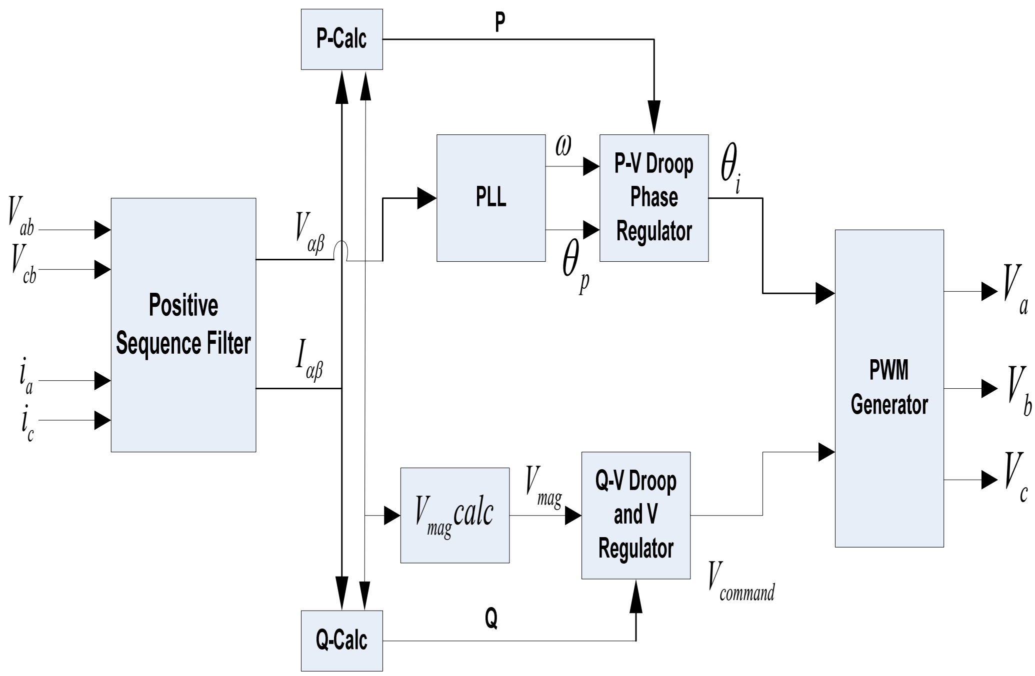

Figure 12. Control strategy based on PLL [94].

SOGIs are signal processing filters that are intended to extract the essential component of a sinusoidal signal, even when noise or distortion is present, in the context of extracting numerous harmonics for power quality analysis. Filtering tools known as SOGIs are used to remove clear sinusoidal components from distorted grid signals. Frequency-locked loops (FLLs) or other PLLs are commonly implemented using SOGIs. The application of the SOGI depends on its band-pass filtering capabilities and the creation of orthogonal waveforms. SOGIs clean signals for precise measurement before supplying them to control algorithms. When the voltage is distorted, SOGIs assess its phase, frequency, and amplitude. SOGIs are therefore utilized in both single- and three-phase systems. Frequency estimation in SOGI-FLLs enables tracking of the input signal's fundamental frequency while concurrently modifying the resonance frequency to the estimated value. Band-pass filtering and orthogonal signal creation in orthogonal signal generators (OSQ) and SOGI-OSQ allow for their application to phase-locked loop systems, specifically for tracking the power grid voltage waveform. A thorough implementation of the SOGI as a current controller for grid-connected converters was described in Ref. [95], which included active filters, stator current harmonic control for doubly fed induction generators, single-phase and three-phase grid-connected inverters, and more. Nonetheless, the discretization difficulty is explained. Three types of discretization technique are currently available for SOGI: integrator discretization, SOGI-transfer-function discretization, and complete transfer-function discretization. The author of Ref. [96] suggests a new discretization technique by altering the integrator discretization structure. Both theoretical analysis and experimental verification demonstrate that this approach improves performance in both the phase and the quadrature characteristic with a manageable computation overhead.

Additionally, the Kalman filter (KF) is important for microgrid estimates, control, and monitoring. MG control and system state estimation depend heavily on KF, commonly referred to as linear quadratic estimation. KF implementation consists of three steps: state estimation, state prediction, and parameter identification. Even when there is imbalanced voltage or harmonic distortion, KF can reliably estimate a fundamental frequency and phase angle. Additionally, KF makes power quality monitoring and active power filtering possible. Using voltage and current data, it calculates the state of charge (SoC) for batteries or supercapacitors. In poor grid and islanded settings, KF-based phase estimation is more reliable than PLLs. KF is hence advantageous in dynamic and nonlinear microgrid operations [97]. In Ref. [98], the author predicts the fundamental amplitude and frequency of grid voltage in a single-phase MG using a frequency Adaptive Linear Kalman filter (ALKF) that is implemented in real-time under defective situations. The MG voltage and frequency are controlled by an 18-bus test system and an Extended Kalman filter (EKF). The KF state estimator maintains its accuracy even when the frequency fluctuates.

6.1. Challenges of IoT Standardization

The need for a standardized architecture to manage common backend functionalities—like data processing, storage, and firmware updates—is becoming more and more urgent as the IoT sector develops. However, there are significant obstacles to overcome in the creation and adoption of this standard model, including those related to platform, connectivity, business model, and killer applications. The framework of the IoT standardization challenges is depicted in Figure 13. For large-scale, interoperable, and sustainable IoT deployments to be possible, each category represents a crucial obstacle that needs to be removed [99].

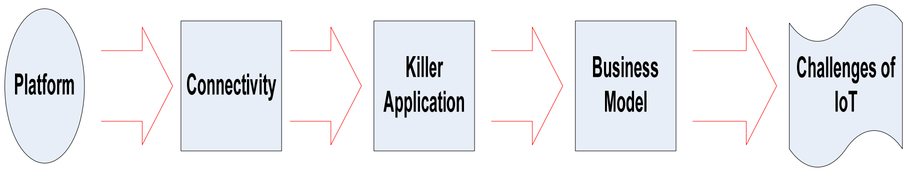

Figure 13. IoT standardization challenges [99].

- Platform: this component covers the product's form and design (UI/UX), analytics tools for handling the huge data streaming from all products in a secure manner, and scalability, which necessitates the widespread usage of protocols like IPv6 in all horizontal and vertical markets.
- Connectivity: this stage covers every aspect of the consumer's day and nightly routine, including the use of wearable technology, smart cars, smart houses, smart grids, and, ultimately, smart cities. From a business standpoint, M2M communications are the dominant field, and we have connectivity through the Industrial Internet of Things (IIoT).
- Business model: IoT ventures must have a solid business plan to be successful and long-lasting. Without it, the sector could degenerate into yet another unsustainable bubble. The approach needs to handle major legal and regulatory obstacles while serving all e-commerce types, including consumer, vertical, and horizontal markets.
- Killer applications: three functions are required in this category to have killer applications: "things" control, "data collection," and "data analysis". In order to drive the business model with a unified platform, IoT requires killer applications.

6.2. Emerging Technologies: Cloud, Fog Computing, and Smart Meter Systems

Another method of microgrid monitoring is based on cloud-based connectivity between the monitoring platform and power sources. Through the measurement device, the measured data is transmitted straight to the cloud. However, the present growth of cloud computing technology is unable to handle the massive amounts of data generated by huge microgrid systems. The current cloud computing infrastructure is unable to handle the volume, diversity, and velocity of created data. Therefore, it takes a lot of data transfer capacity to upload data directly to the cloud for processing, analysis, and storage. As a result, the advent of fog computing has solved several issues that cloud-based SCADA systems frequently face. At the network's edge, it provides temporary data storage and analysis. It offers a better option for applications that are sensitive to delays and lowers the amount of data that is transmitted and stored to the cloud. The main challenges in integrating the MGs' data with the cloud computing environment are the stringent security, low latency, and high service availability integration requirements [100]. The most important problem is that cloud platforms lack effective and robust security and user authentication methods, which results in limited control and screening of cloud data replication. As a result, data security methods and procedures are strictly required, as is the highest level of control over authorization and authentication. Fog computing is a local controller that manages microgrid energy distribution in real-time and is not constantly reliant on internet connectivity. In general, fog computing outperforms cloud computing for microgrid control operations, especially when it comes to continuous monitoring, control, data filtering, data analytics, system-wide communication, and decision-making. Among its real-time uses are autonomous systems, smart grids, and industrial control. Demand response, fault detection and isolation, real-time load balancing, and local energy source coordination are all applications that fog computing can handle. In contrast to cloud computing, it is helpful for strategic planning, predictive analytics, historical data mining, optimizing maintenance schedules, training machine learning models, and other applications [101,102].

Using a distant cloud server, the authors of [103] offer a real-time solution for effective grid power system monitoring and control that enhances universal control and response time while implementing a novel security measure for user identification. A cloud computing platform for microgrid power management is offered by the authors of [104]. To improve data processing and interaction and give MGs a quick and affordable way to satisfy their computational needs, the method connects the system's existing computer and storage capabilities with external computing devices. In distant MGs, fog computing enables localized data processing, minimizing reliance on costly long-distance communication links, while cloud computing reduces hardware demands through centralized resource optimization. The real-time analytics capabilities of artificial intelligence (AI)-enhanced fog computing facilitate the detection of anomalies such as harmonic distortions, hence enhancing system monitoring, communication, and control. Additionally, proactive stability management can be aided by the creation of anticipated insights into system behavior through the use of substantial data analysis on the cloud. In complex, distributed microgrid environments, fog and cloud computing work together to provide scalability, visibility, and operational reliability [105].

Moreover, numerous networks and devices must cooperate to form a reliable system for an intelligent distribution system to operate. Smart meters and the Internet of Things are key elements that will change the traditional consumer–operator relationship into a creative, interdependent system that can communicate more quickly and reliably. Utilizing smart meter technology benefits both energy corporations and individual end customers, including homes and businesses. Smart meters have a communication module known as a smart meter gateway. It comprises three major components: network management, advanced metering element, and data management unit [106]. Among the several energy-saving and energy-management techniques that are available, it is one of the most effective ways to control the growing electricity demand. Its ability to communicate in both directions between the MGs and the end-user facilitates dynamic pricing, demand-side management, and improved billing accuracy [107]. The requirement for enhanced flexible billing and management of billing information in the case of two-way power flow necessitates intelligent meter technology. In commercial and industrial settings, smart meter technology gives customers daily market values for their energy use and monitors consumption statistics on an hourly or minute-by-minute basis, peak demand periods, and power quality indications. This data, which is sent to the central EMS or SCADA system, helps manage loads, improve energy distribution, and guarantee effective distribution. Furthermore, smart meters make it possible for central control to act swiftly in the event of tampering. This helps to lower power theft and improve the security of the power system by providing an easily accessible, quick report as part of the data-gathering process. MGs can function more effectively and help users make better decisions regarding their energy consumption when smart meters give operators and consumers access to real-time data [108]. Table 3 illustrates the comparison of different IoT monitoring systems.

Table 3. Comparison of IoT monitoring systems [105,108].

System	Functionality	Local Processing	Latency	Scalability
SCADA systems	Supervisory control and data acquisition from field devices.	Centralized (control center)	Moderate	Limited
Smart Meters	Monitor energy usage, support billing, and load profiling.	Edge (device level)	Very low	Moderate
Cloud computing	Large-scale data storage, analytics, forecasting, and remote monitoring.	Remote/cloud data centers	High	High
Fog computing	Local data preprocessing, control coordination, and communication bridge.	Intermediate (between edge and cloud)	Low	High

6.3. Microgrid Systems: Cyberattacks and Cybersecurity Issues

IoT-enabled MGs offer numerous benefits, but they also present new challenges, particularly in the areas of cybersecurity and data management. Data breaches and cyberattacks are increasing in frequency as MGs become increasingly reliant on digital communication networks. MGs are particularly vulnerable to cyberattacks, including ransomware attacks, malware infections, denial-of-service attacks, and data breaches, because they depend on IoT devices and cloud computing. These attacks can pose a threat to physical safety, disrupt operations, and compromise sensitive data. These risks may cause monetary losses, power outages, and equipment damage for both users and operators. MGs' dependability is also determined by data integrity. Data from smart meters may reveal personal information about energy consumption, so privacy protection is essential [109,110]. Among several cyberattacks, one of the most difficult MG risks is a fake data injection (FDI) attack that targets data integrity. Intelligently designed attacks can infiltrate the system and go undetected by the standard attack detection technique. These strikes are also known as stealth attacks. In addition to steady-state and dynamic stability challenges, a successful FDI attack could cause serious economic problems. Due to the system's low inertia, which leaves it more vulnerable to disturbances in both transient and steady-state stability, cyberattacks can be especially harmful in microgrids with a large penetration of power electronic converters, especially when the system is in islanded mode. Additionally, with hybrid (AC/DC) microgrid systems, any cyberattack that targets one of the AC or DC subgrids would impact the other. Through the interconnection of power converters between AC/DC subgrids, any cyberattack that compromises the frequency stability of the AC subgrid would also impact the DC side's DC voltage stability. The increasing automation and connectivity of microgrid systems make them vulnerable to cyberattacks. The methods that these attackers use to target operational technology (OT) and information technology (IT) systems are constantly evolving. To guarantee the dependability and security of the power grid, all MG operators, engineers, and specialists must address cybersecurity issues [111,112].

DER systems are susceptible to many cyberthreats due to their interconnectedness. Although this interconnection is necessary for smooth operation, it also gives hackers several points of access. Remote control and monitoring are crucial components of microgrid systems. They enable operators to change settings and view real-time data. Remote access points may become entry sites for cyberattacks if appropriate security measures are not in place. MGs communicate commands and data using communication protocols. Devices can communicate with one another, with central control systems, and with outside parties like utility companies or grid operators thanks to these protocols. However, cybercriminals can take advantage of flaws in these systems. These flaws could be design flaws in the protocol, incorrect implementation, or out-of-date versions without security improvements. They might change commands, eavesdrop on data being sent, or insert malicious data, which could have a number of negative effects. Data communication is also essential for grid stability and effective energy management. The data produced by microgrid systems is often sensitive. The protection of this information is crucial. If it is not sufficiently secured, bad actors can take advantage of weaknesses to intercept private information while it is being transmitted, change or modify data to give misleading information, or violate the privacy of people or organizations by obtaining access to data. Microgrid components like DERs and IEDs that have outdated firmware or software may reveal serious flaws, making them prime targets for hackers. To address known vulnerabilities, improve efficiency, and protect against new attacks that could jeopardize system functionality and data integrity, regular security upgrades are crucial. Hardware and software components for DER systems can be purchased from a variety of manufacturers and sources. Components from various suppliers may have unique security features and weaknesses. In microgrid systems, maintaining a consistent security posture can be difficult due to these differences in security characteristics throughout the DER environment. In order to overcome these obstacles, MG networks must be equipped with strong cybersecurity measures, including encryption, access controls, frequent updates, intrusion detection, and monitoring. Risk assessments should also be carried out in order to determine and rank any threats and weaknesses [113–115].

6.4. Microgrid Systems: Cybersecurity Standardization Protocols

A cybersecurity framework is a vital resource for businesses, particularly those in charge of overseeing smart grid technology. Cybersecurity hazards can be identified, addressed, and mitigated in an organized manner with the help of such a framework. The system, which is based on five essential functions—identify, protect, detect, respond, and recover—offers a scalable and adaptable approach to managing cybersecurity threats. Cybersecurity needs a comprehensive approach to guard against the many cyberthreats and attacks that could compromise the safety and dependability of microgrid systems. Additionally, it comprises risk management, threat landscape analysis, the construction of secure communication infrastructure, control system security, endpoint security, data security and privacy, compliance with regulations, awareness and training, and incident response and recovery [116]. Furthermore, MG networks must adhere to cybersecurity requirements in order to be secure and resilient. The Advanced Metering Infrastructure System Security Requirements (AMI-SEC) are a few well-known and significant cybersecurity standards and protocols. Their purpose is to create strong security guidelines for a section of the microgrid. The AMI-SEC suggests a control system and communication protection, which includes voice-over-Internet protocol, cryptographic key establishment and management, security function isolation, and the transmission of security parameters. An analytical framework for creating successful cybersecurity plans for microgrid systems is provided by the National Institute of Standards and Technology Interagency Report (NISTIR) 7628. This strategy recognizes that the electric grid is evolving from a closed system to intricate, highly linked systems, leading to an increase in the variety and multiplicity of grid security threats [117]. For power system communication protocols of the TC 57 series, including IEC 60870-5 [118], IEC 60870-6, IEC 61850 [119], IEC 61970, and IEC 61968, security rules are provided by the International Electrotechnical Commission (IEC) 62351. These protocols cover important security goals, such as intrusion detection, shielding against eavesdropping, spoofing, and replay attacks, and data authentication through digital signatures [120]. A foundational standard for information security management, ISO/IEC 27001 covers a wide range of topics, such as system security testing, regular security policy compliance checks, and technical assessments to guarantee proper hardware and software control implementation. Regarding industrial control system security, the National Institute of Standards and Technology (NIST) 800-82 is a widely accepted standard. In addition to providing instructions on how to use vulnerability assessment and penetration testing tools, it guarantees that specific security rules are applied correctly and effectively [121].

6.5. Impact of Blockchain in Cybersecurity

Blockchain is one of the most promising technologies for data security because it allows data to be transported and stored in a decentralized network using intricate calculations. Blockchain establishes an unchangeable, secure record for each energy transaction, guaranteeing accountability and transparency. By utilizing blockchain technology, MGs enable energy buyers and sellers to engage in distributed energy markets, hence removing the necessity for centralized utilities. Blockchain technology could offer immutable energy transfer monitoring, ensuring that all data is secure and verifiable. Data encryption, robust authentication systems, frequent software updates, firewalls, intrusion detection systems, and blockchain integration are all components of a multi-layered security approach that operators should implement to lessen the effect of risks and improve data control. The implementation of cybersecurity protocols helps MG operators protect their systems from threats and ensure safe data processing, storage, and transmission. Furthermore, blockchain technology offers transparent, unchangeable methods for exchanging and storing data that are traceable but not centralized. Blockchain has benefits for MGs, but there are significant obstacles to its adoption. Energy-intensive consensus procedures, such as Proof of Work (PoW), are not suitable for environments with constrained energy supplies. With a rise in transactions, scalability problems may result in latency and network congestion. Additionally, compatibility with smart contracts, secure communication protocols, and current energy management systems is necessary for successful integration [122,123].

Ensuring strong data security in microgrid systems is still very difficult since data protection flaws can impair grid operation as a whole. In order to solve this problem, the authors of [124] presented the Service-Centric Blockchain Data Security Model (SBDSM), which uses unique blockchain signatures for various kinds of service data, allowing for safe and classified data transfer between linked grids. This blockchain-based communication is utilized to control the microgrid's operational mode and voltage flow in addition to exchanging data. Choosing the best voltage regulation plan is the responsibility of a centralized controller. It embeds control information in a blockchain to transmit decisions to the microgrid. Each microgrid can recognize the type of data by using its own blockchain signature and hash code. The controller specifies the voltage levels to be controlled while simultaneously continuously monitoring incoming voltage levels and identifying a subset of microgrids that require switching to discharge mode. This data is safely incorporated into the chain's blocks. Every microgrid that receives the blockchain decrypts it and extracts the pertinent instructions to determine the necessary voltage regulation for the current cycle. Furthermore, the controller sends a distinct blockchain with mode-specific data for every microgrid in order to perform switching actions. Through this method, the SBDSM model contributes to more stable and secure microgrid operations by ensuring improved voltage regulation performance and greater data security. Additionally, an evaluation of data security measures for microgrid systems is required. An Edge Blockchain-Based Data Aggregation (EBDA) methodology was introduced by the authors of [125]. Higher data security communication in MGs is supported by the model. Blockchain-based wallets are used to handle transactions on smart meters. These wallets leverage smart contracts to facilitate automatic electricity delivery and use blockchain as an authentication system. Similar to this, A Blockchain-Based Novel Paradigm (BBNP) is introduced in [126], which enhances data security by utilizing auxiliary information production and sharing technologies as well as pseudorandom functions. To assist the security enforcement, a blockchain-based peer-to-peer trading system that leverages integer linear programming is provided in Ref. [127]. Additionally, Ref. [128] presents a blockchain-based authentication strategy that enhances data security through the application of cryptographic algorithms.

In order to guarantee blockchain technology's security, confidentiality, and integrity, cryptography is essential. It is essential to many parts of blockchain systems, protecting the anonymity, immutability, and authenticity of information and transactions. Cryptographic techniques are used to encrypt transaction data when a user initiates a transaction on the blockchain. This guarantees that the only person who can decode and access the data is the intended recipient, who possesses the necessary private key. Confidential communication via the network is therefore ensured. The suggested approach takes advantage of a number of cryptographic primitives, such as the hash function, digital signature, and encryption algorithm. Asymmetric cryptography (private and public keys) is used to create digital signatures, which are essential for confirming the legitimacy and non-repudiation of transactions. These signatures allow transactions to be traced back to their source and verify the sender's authenticity. Additionally, cryptography supports consensus techniques like Proof of Stake (PoS) and Proof of Work (PoW). These systems use cryptographic methods and puzzles to protect the network, stop malicious activity, and make sure that every node agrees on the current state of the blockchain.

Similarly, distinct, fixed-length representations of block data are produced using cryptographic hash algorithms. Because of the cascade effect on succeeding hashes, these hashes serve as the linkages between blocks, guaranteeing that any effort to change a block's contents would be instantly detected. This characteristic is necessary to preserve the blockchain ledger's tamper-evident structure [129]. Blockchain technology and AI technology can be combined to further improve MG automation and control. When combined, these technologies provide a strong foundation for the integration and optimization of AI-powered microgrid systems in the future. Additionally, this will assist MG operators in safeguarding their systems from intrusions and guaranteeing secure data processing, storage, and transit. By implementing this improvement, system security will be ensured, and future data will be protected.

7. Challenges and Future Direction of Microgrids

Microgrids have a lot of potential, but to be widely adopted robustly and sustainably in the long run, several obstacles need to be removed. These are technical, economic, social, and policy challenges. One of the main challenges is integrating various DERs, storage systems, and cutting-edge control technologies into legacy energy networks. In addition, the cybersecurity implications for networked systems present severe vulnerabilities, especially for highly populated places, energy markets, and peer-to-peer energy trading, where cyberattacks would affect huge areas. Additionally, the installation of smart microgrids is quite expensive initially, which is a major obstacle, particularly for communities with limited funds and resources that must compete with other priorities. Although the cost of solar panels, batteries, and other parts has decreased, it is still very costly to integrate technologies that work well with these microgrids into larger energy systems. Furthermore, municipalities cannot participate in large-scale microgrid projects due to the lack of scalable financing options, such as innovative finance mechanisms or long-term public–private partnerships (PPPs). The fragmentation of regulations, public ignorance, and reluctance to change are the main obstacles to the implementation of smart microgrids. Current energy laws do not adequately support the decentralized, bidirectional operations of microgrids because they are typically designed for centralized grids. In view of this study, it is important to do in-depth research in these areas to enhance the design, functionality, and management of microgrids [130].

To fully achieve the potential of MGs in the global energy transition, further research should focus on the following areas:

- Future research should focus on creating strong, AI-driven optimization that can quickly detect and halt aggressive campaigns, create peer-to-peer energy markets, and use blockchain technology to encrypt transactions and protect private data.
- To accomplish dynamic changes in energy flow, fewer GHG emissions, and better control for microgrid systems, future research should focus on the application of AI-powered algorithms, based on the careful analysis of large data, rather than traditional and mathematical methods.
- To guarantee the security of energy transactions and DER operations in MGs, future research should employ blockchains and smart contracts.

- For MGs, next-generation ESSs are essential, particularly for those running unreliable RESs. Making storage solutions that are more cost-effective, long-lasting, and efficient without compromising quality should be the main goal of future research.
- Coordination and communication amongst MGs become more important as their numbers increase. The creation of standard interoperability, blockchain-enabled energy trade, and collaboration control mechanisms is an important research area.
- Research into AI-assisted security frameworks, regulatory standards, and methods for expanding the scalability of smart microgrids for wider use should be the main areas of future study.
- Future MGs may be able to detect problems and fix them on their own, which might speed up recovery and restore more loads to the network.
- Pilot projects that involve collaboration are an effective means of proving the viability and offering a plan for implementing creative design. Future studies should concentrate on how governments, academic institutions, businesses, and communities must work together to promote microgrid technologies.

8. Conclusions

This study examines new advancements in MG control strategies, an overview of MG configurations, elements, and advanced technologies monitoring systems based on the IoT, along with potential prospects. It gives a quick overview of the monitoring techniques utilized for the microgrid data analysis. An important result of this work is the thorough examination of the issues of stability, control, and power management of AC, DC, and hybrid AC/DC microgrids. According to the research, AC and DC microgrids are both very common. Still, hybrid AC/DC microgrids are gaining popularity due to their lower conversion losses, greater reliability, and increased efficiency. The two primary categories of control approaches include advanced techniques, such as adaptive control, ANNs, FLC, SMC, DRL, and MPC, and conventional methods, which include PID controllers, droop control, and multi-agent systems. The study offers a comprehensive analysis of their applications, benefits, and limitations. This study also highlights the significance of IoT-based monitoring systems that offer real-time information on energy production, consumption, and system performance. Furthermore, this article discusses significant topics, including data management, cyberattacks, cybersecurity, and smart contracts, and offers defenses against related risks. The results show that the emerging technologies, when combined with AI-powered algorithms, enhance MG automation, energy efficiency, and control.

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