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Review

Review of Advances in Renewable Energy-Based Microgrid Systems: Control Strategies, Emerging Trends, and Future Possibilities

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Abstract

This paper gives a thorough overview of the technological advancements in microgrid systems, focusing on the Internet of Things (IoT), predictive analytics, real-time monitoring, architectures, control strategies, benefits, and drawbacks. It highlights their importance in boosting system security, guaranteeing real-time control, and increasing energy efficiency. Accordingly, researchers have embraced the involvement of many control capacities through voltage and frequency stability, optimal power sharing, and system optimization in response to the progressively complex and expanding power systems in recent years. Advanced control techniques have garnered significant interest among these management strategies because of their high accuracy and efficiency, flexibility and adaptability, scalability, and real-time predictive skills to manage non-linear systems. This study provides insight into various facets of microgrids (MGs), literature review, and research gaps, particularly concerning their control layers. Additionally, the study discusses new developments like Supervisory Control and Data Acquisition (SCADA), blockchain-based cybersecurity, smart monitoring systems, and AI-driven control for MGs optimization. The study concludes with recommendations for future research, emphasizing the necessity of stronger control systems, cutting-edge storage systems, and improved cybersecurity to guarantee that MGs continue to be essential to the shift to a decentralized, low-carbon energy future.

Keywords: microgrid systems; control techniques; internet of things; system security; real-time control; AI-driven control; future energies

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Academic Editor: Tek Tjing Lie

Received: 6 June 2025
Revised: 28 June 2025
Accepted: 9 July 2025
Published: 14 July 2025

Citation: Ojo, K.E.; Saha, A.K.; Srivastava, V.M. Review of Advances in Renewable Energy-Based Microgrid Systems: Control Strategies, Emerging Trends, and Future Possibilities. *Energies* **2025**, *18*, 3704. https://doi.org/10.3390/en18143704

1. Introduction

The rapidly shifting demands of consumers, the depletion of fossil fuels, greenhouse gas emissions, global warming, and environmental pollution are the main forces behind the modern energy sector's search for alternative power production methods. In view of this, microgrids powered by renewable energy sources (RESs) are an essential remedy for these issues [1]. According to the Green Energy (GE) Global Status Report (GSR), published annually by Renewable Energy Policy Network 21st Century (REN21), renewable energy sources contribute 26.2% of Brazil's electricity generation, with hydropower contributing 15.8%, wind 5.5%, solar photovoltaic 2.4%, and bioelectric 2.2% of electricity, while 0.4% comes from other energy sources [2]. Growing renewable energy technologies make it particularly difficult for governments to integrate distributed energy resources (DERs) into electricity networks as they try to meet global climate commitments [3]. The ability of MGs to handle this integration and provide distributed, renewable energy systems is growing [4]. The term "microgrid" refers to a collection of dispersed energy supplies and interconnected loads that function as a single, controllable entity within the grid, within well-defined electrical boundaries. MGs can function in both grid-connected and island mode by connecting and disconnecting from the grid [5]. In both modes, a microgrid may generate, distribute, and control its power. In the islanded mode, the microgrid functions independently, while in the grid-connected mode, it connects to the central grid. In regions that are vulnerable to natural disasters, outages, and grid instability, energy networks must change to increase resilience and reliability [6]. The concept of MGs is now reliable, strong, and cost-effective due to the extensive usage of RESs. It also provides several environmentally advantageous benefits over traditional utility systems [7]. Furthermore, MGs powered by RESs are a crucial technology for ensuring environmental sustainability and decarbonizing the electrical power grid [8]. The concentrated nature of microgrid systems reduces transmission losses and enables energy solutions in rural or impoverished areas that lack centralized networks. MG integration supports a dependable grid and balances the demand for grid electricity [9]. However, the controllability performance of MGs is hampered by several issues, including system complexity, scalability, uncertainty, and a lack of technical expertise. Because of the complicated framework created by the integration of many RESs, ESSs, and loads, standard controllers are challenging. The scalability and standardization of MG technologies provide yet another challenge. Due to the delayed feedback signals, typical controllers that employ linear control techniques have poor stability [10,11]. Standardizing protocols, control systems, and communication channels is necessary to ensure compatibility amongst microgrid systems in larger energy networks. Without established protocols, it is difficult to integrate DERs and create large microgrid systems [12]. To guarantee correct operation, power systems require suitable control strategies. Also, to provide steady and consistent power flow, an appropriate control approach is essential [13]. Advanced controllers such as Intelligent Control (IC), Model Predictive Control (MPC), Backstepping Control (BSC), and Sliding Mode Control (SMC) provide higher stability for MGs control than linear controllers because of their instantaneous time responsiveness. Among Internet of Things (IoT) technologies, real-time monitoring, remote control, and predictive analytics contribute to MG efficiency [14–18]. Simple communication across microgrid components—such as DERs, storage systems, and consumers—is made possible by the IoT, which enhances load management and energy allocation. Since energy systems are rapidly becoming digital, stringent cybersecurity regulations are required to guard against data breaches, hacker attacks, and destructive control orders that can jeopardize energy distribution or infrastructure [19,20].

The aim of this work is to examine, evaluate, and classify contemporary control systems that improve MG efficiency. This research attempts to fill the current knowledge gap by combining concepts on IoT-based monitoring systems with recent developments in MGs' architectures and control techniques. Here, the emphasis is on analyzing a variety of traditional and innovative control mechanisms, their applicability and constraints, and how they affect MG stability, sustainability, and scalability. The contributions of this study are summarized as follows:

- A comprehensive discussion on MG architecture control, benefits, and limitations is one of the study's main outputs.
- Examination of the variety of microgrid control strategies that require careful consideration, utilizing both conventional and sophisticated control approaches.
- Crucially, a study on how technology is changing MG management procedures includes IoT real-time monitoring technologies, SCADA, blockchain-based cybersecurity, and smart contracts.

- Emphasis on the critical role of grid codes (IEEE 1547-2018, IEC 61850, IEEE 2030-2018 [21–23]) in standardizing MG deployment and cybersecurity for scalable integration of innovative technologies.
- Analysis of the technological challenges facing the management techniques used by MGs today and offer of suggestions for overcoming them, especially by incorporating AI-driven control systems.
- Lastly, outline of the relevant research topic to enhance MG performance.
- This paper's continuation is organized as follows: Section 2 provides a thorough taxonomy and restrictions of MG control architecture. Section 3 provides a detailed analysis of MG control strategies and how they affect microgrid systems. Section 4 discusses the significance of IoT monitoring system-based MGs, their uses, and how they complement other technological developments (smart contracts, SCADA systems, and blockchain technology). In Section 5, prospects for MGs and important research areas that will impact future MG growth are reviewed. Finally, a succinct summary of the work performed for this article is given in Section 6.

2. Architectures' Control of Microgrids

This section analyzes the classification and constraints of MG control architectures, including its hierarchical, decentralized, and centralized control systems. In the context of MGs, the objectives of MGs control strategy should satisfy the following criteria: (a) independent management of active and reactive power, (b) correction of voltage sag and system imbalances, (c) smooth switching between MG operating modes, (d) improved energy efficiency, (e) monitoring of energy flow and important equipment, as well as grid fault management, and (f) satisfying grid load dynamics requirements [24–26]. Based on research in the literature, the research gaps and limitations with MG control architectures are presented in Table 1.

2.1. Centralized Control (CC)

In a centralized control (CC) of an MG, all DERs are managed by a single controller, encompassing their generation, storage, and load balancing. This type of technology is frequently employed in scenarios that call for coordination between many DERs or in a grid-connected microgrid. It improves energy flow by making control and coordinated operations simpler. However, the overall adaptability of the MGs is still constrained by the central controller's decision-making process and susceptibility to a single point of failure [27]. The CC connectivity of the MGs is shown in Figure 1a. In microgrid systems, it is inferred that CC oversees the functioning of several DG units. For direct communication with the CC, each DG unit has a local controller (LC). The centralization of control is quite simple to execute [28]. According to the authors of [29], CC has been discussed in price-based demand response (DR) schemes for scheduling residential appliances to lower electricity bills. While the authors of [30] showed how the control technique reduced the cost of electricity for consumers, including the cost of communication technologies, the authors of [31] suggested a control that saved prosumers more money than traditional end users. Additionally, a graphical user interface model was developed by the authors of [32] for two scenarios, including the islanded mode and the grid-connected mode. The flat load profile was obtained for both scenarios using the centralized control with Particle Swarm Optimization (PSO) technique, which made use of load agents, switch agents, central coordinator agents, and local controller agents. This control's primary drawback is its reliance on channels of communication with a single owner. The control method is not very flexible or expandable.

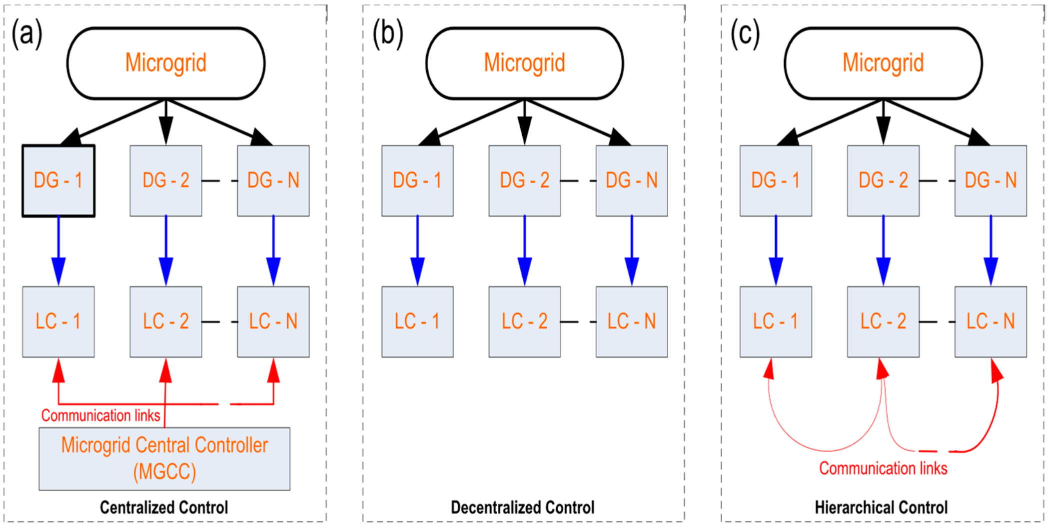

Figure 1. MG control architectures: (**a**) centralized, (**b**) decentralized, (**c**) hierarchical [28].

2.2. Decentralized Control (DCC)

Decentralized control (DCC) is a hybrid system that combines the finest aspects of centralized and distributed systems. The DCC approach determines action at the component level by using local measurements and pre-established algorithms that are integrated into it. The most effective way to apply the DCC method is via a multi-agent system (MAS). The two-stage design of this control method, which includes higher and lower-level controllers, is its key feature. When a high-rated microgrid has several components, DCC is typically used because the CC structure would be slow because of the massive amount of data being collected and processed in one place [33,34]. Additionally, DCC has been developed extensively to optimize the autonomy of micro sources and loads in microgrids. Reliability, stability, and economical operation are the core goals of this control strategy. The microgrid's DCC connectivity is shown in Figure 1b. Here, the DCC uses distinct LC jobs to maintain the MGs stable [35]. In a decentralized control approach, the dispersed energy can be managed using an interfaced power converter. Local measurements are used for DCC, and decisions are made at the component level using predefined algorithms that are incorporated in each node, but communication-free DCC has poor voltage regulation. Controlling each unit via LC-based local area communication is the main disadvantage of a completely decentralized system [36]. The authors of Ref. [37] asserted that depending on the particular operating circumstance within the MGs, the CC and DCC have varying advantages and disadvantages. The authors of Ref. [38] suggested a decentralized controller for a residential client with installed PV and wind installations. It has been suggested that the inclination block rate (IBR) pricing structure be used to achieve demand-side management (DSM). According to the author of [39], a residential consumer's performance metrics were used to critically compare the decentralized and centralized controllers. When compared to a centralized controller, the decentralized controller was found to be the best one for reducing the cost of electricity.

2.3. Hierarchical Control (HC)

In a hierarchical control (HC) system, each DER is under independent supervision, while individuals or groups of them handle their own generation, storage, and load balancing. This method improves flexibility and defect tolerance, enabling any DER to respond rapidly to changes in local load or generation [40]. In this variant of the DCC approach, each LC interacts with its neighbors to reap the advantages of a centralized design for the whole microgrid. Different control requirements have different time scales, which is the foundation of a hierarchical control framework. The International Society of Automation (ISA-95) is the source of this standard [41], which was created to facilitate interfaces or interoperability across various control and enterprise systems. Three control levels, such as primary, secondary, and tertiary control, make up the hierarchical control scheme, which was designed to address the shortcomings of the first two control techniques (CC and DCC). The hierarchical MGs approach enhances the distributed system's controllability, dependability, and security [42]. The active, reactive power, droop, inner voltage, and current control loops make up primary control. The primary control configures the reference set points for voltage and current. Primary control uses DG load sharing to stabilize the MG's voltage and frequency [43]. Secondary control comprises synchronization loops and voltage and frequency (V-F) restoration control loops. The V-F variations in the primary control are eliminated by the secondary control and cannot be integrated into large-scale microgrid systems. The slowest control level is tertiary control. It carries out the economic dispatch and optimizes the entire MG system [44]. Grid signals and the state of DERs units determine tertiary control over the grid and MG power flow. The economic management function and optimal DG scheduling are made possible by this control's control features. According to the authors of [45], hierarchical and distributed control strategies are complementary to one another. They both require the same type of control and communication infrastructure. In [46], the distributed control for the DSM on domestic consumers was covered. Peak demand, transmission losses, and grid dependence were decreased as a result of the devised control mechanism. The MG hierarchical control connectivity is shown in Figure 1c.

Table 1. Research gaps and limitations with MG control architectures [47].

	Centralized Control
Research Gap/Difficulties	**Evaluation**
Several interlinking converters	• It is necessary to provide a primary/secondary centralized architecture for P-Q exchange and V-F control to increase power quality, as well as fault current limiters in a multi-MG scenario.
Market participation	• By integrating market prices, supply and demand bids, and short-term load-generation projections into the EMS algorithms, together with the upstream Distributed System Operator (DSO) for ancillary services, operating costs could be reduced.
Strong decision-making	• Research and performance evaluation are needed to determine which intelligent control system is most appropriate for uncertain microgrid systems, as opposed to the current classical multiple control loops.
Optimal demand response	• The MGCC is designed to achieve appropriate Demand Side Management (DSM) under a variety of fluctuating quantities/variables, such as generation, grid price, MS, load status, LC parameters, etc.
MGCC's protection functions	• More research is needed to fully understand these capabilities, which include differential schemes, power rate restrictions, dual-mode operation, DER variability, and other adaptive relay functions.

Table 1. *Cont.*

	Decentralized Control
Cost-based nonlinear drooping	• It is necessary to create a cost-based goal function with a nonlinear droop coefficient update to achieve both optimal and quick transient response at the primary layer.
DC-bus signaling or power line	• By causing voltage level changes at control nodes by the LCs for each device, DBS communication can accomplish a certain degree of global coordination. This field requires an in-depth investigation.
System inertia	• Each controller made for the power electronic interface (PEI) of DERs should generate a specific amount of virtual inertia to maintain the normalcy of the MG frequency because inverter-based MGs lack the inertial characteristics of conventional power systems.
Model-free algorithms	• Control techniques that are resistant to changes in system parameters and independent of the detailed microgrid model must be designed to accommodate the uncertain MG's operating environment.
Overall systems stability	• More research is required to fully understand how this affects the convergence and stability of the entire MG system, even if it improves redundancy and reliability when compared to a centralized method.
	Hierarchical Control
Closed-loop designs	• Feedback signals from the upper to lower layer are necessary for the selection of set points in the majority of hierarchical structures, which are open-loop designs with a primary, secondary, and tertiary level.
Collaborative power quality assurance	• Due to the high charging current caused by EVs in microgrid systems, power quality deteriorates, and integrated management is required to improve voltage fluctuation and harmonic compensation.
Contemporary control methods	• The most widely used PI control is classical, but multi-layer optimum and MPC have not yet been investigated. There is room for a thorough investigation into how these are implemented on MG's hierarchical functions.
System for managing outages	• A proper operation management system (OMS) is necessary to maintain high reliability, particularly for important loads and coordination amongst the remaining loads.
Unified method of mode switching control	• A single circuit configuration with a unified design is required for smooth mode transition, or islanding and resynchronization of MG, to be able to instantly switch between the islanded and grid-connected operations.
Aspects of cybersecurity	• More focus is needed on creating strong control methods to stop cyberattacks on communication lines.

3. Microgrid Control Strategies

This section examines the scope of various MG control strategies. Effective control mechanisms are crucial for controlling system parameters due to the diverse features of microgrid components. Consequently, Figure 2 displays the framework of MG control approaches. Advanced (non-linear) controllers include adaptive control, sliding mode control (SMC), model predictive control (MPC), and intelligent control. Conventional (linear) controllers include droop control, proportional integral (PI), proportional integral derivative (PID), and multigrid agent control system (MACS). Furthermore, Table 2 indicates the efficacy of microgrid control systems based on performance parameters like robustness, interoperability, response time, scalability, and stability [48].

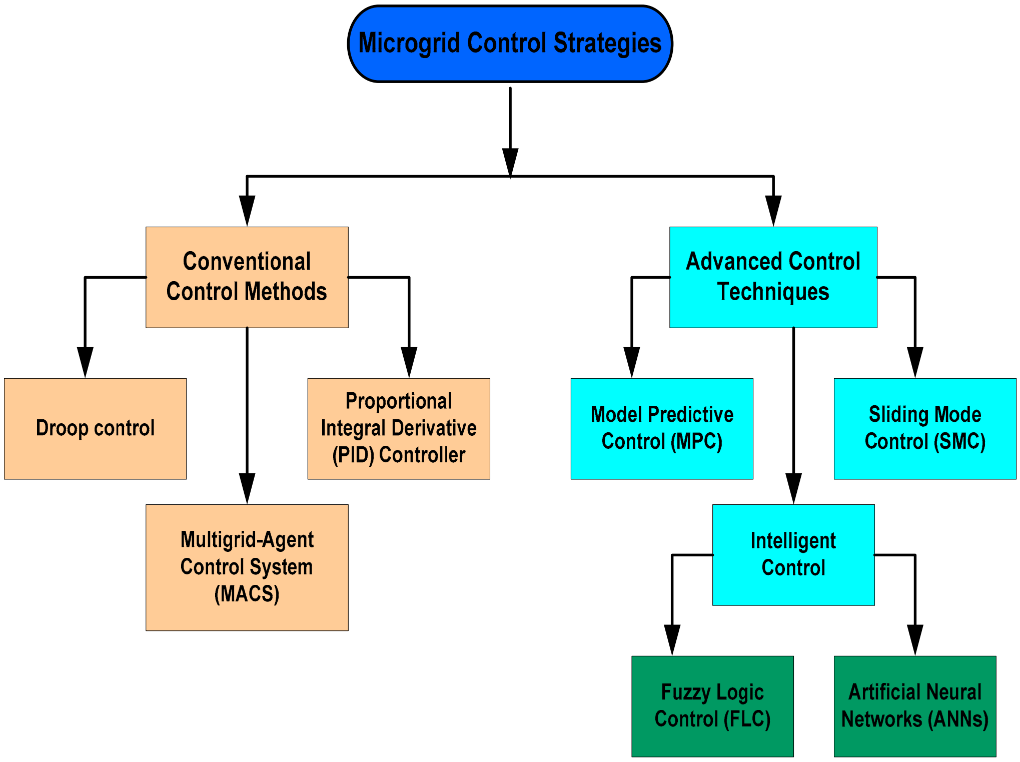

Figure 2. Framework of MG control strategies [48].

Table 2. The efficiency of MG's performance-based control methods [48].

Control Strategies	Stability	Scalability	Response Time	Robustness	Interoperability
Droop control	Moderate	High	Fast	Moderate	High
PI/PID	Moderate	High	Very fast	Moderate	High
MACS	Very high	Very high	Moderate	Very high	Very high
MPC	High	High	Moderate	High	Moderate
SMC	Very high	Low	Very fast	Very high	Low
Adaptive control	High	Moderate	Fast	High	Moderate
ANNs	High	Very high	Fast	High	High
FLC	Moderate	Moderate	Fast	Moderate	Moderate

3.1. Conventional Control Methods

Conventional control techniques are unable to manage the growing complexity of contemporary energy systems, despite being architecturally simpler and more often employed in previous microgrid installations. Due to the delay of feedback signals, classic controllers that employ linear control approaches have poor stability [49]. This section examines traditional approaches in the context of contemporary MGs construction by offering a comprehensive analysis in connection with the literature, highlighting their benefits, applications, and limitations.

3.1.1. Droop Control

The suggested method for MG load sharing is droop control. This is a classic example of distributed control. Droop management is best suited for systems with unreliable or impractical communication infrastructure since it eliminates the need for communication between DERs [50]. It is rather prevalent in both grid-connected and island MG voltage source inverters (VSIs). Droop control is a low-cost, straightforward method that requires minimal computing power for small to medium-sized microgrid systems. However, stability is difficult to maintain without significant changes or additional control levels. Inaccurate voltage and frequency management, sluggish system reactions to load or generating surges, and incompatibility with bigger systems are all possible outcomes of this [51,52]. Researchers have recently attempted to enhance the performance of droop control by adding more control layers or by enhancing its ability to regulate voltage and frequency through virtual impedance techniques [53]. The authors of [54] examined the stability requirements of droop-controlled inverter-based microgrids, and the authors of [55] used a droop controller to eliminate the circulating current in parallel operation of a single-phase inverter. The droop scheme removes both the AC and DC circulating current, allowing the inverters to share their load currents. Through MATLAB R2020b simulation, the viability of the suggested control approach is examined, and the outcomes are satisfactory. In [56], the inverter-based droop-controlled microgrid's controllable transient power sharing was investigated. The authors of [57] presented the real-time implementation of microgrid droop control based on self-adaptive swarm optimization, while the authors of [58] presented voltage imbalance correction for droop-controlled inverters in islanded microgrids. The authors of [59] suggested employing cascade forward neural networks to regulate droop in a bidirectional inverter-based microgrid under grid-connected/islanded operating modes. The suggested approach uses a bi-directional inverter operation method for a variety of battery energy storage systems or other distributed generation systems. The authors of [60] looked into how to improve reactive power sharing in an islanded microgrid using adaptive droop control and virtual impedance. The virtual impedance of each source in this study is calculated with the resource capacity and microgrid load. The suggested characteristic's slope is comparably altered according to variations in the microgrid's load. However, inequality in load sharing is a drawback of droop control.

3.1.2. Proportional Integral/Proportional Integral Derivative Controller

The PI/PID controller's simple architecture has led to decades of widespread use in industrial sectors and power systems. Three primary parameters are involved: proportional (P) to determine the desired set point and adjust the output controller; integral (I) to eliminate the control system's steady-state error and enhance the steady-state response; and derivative (D) to enhance the system's transient response. PI/PID is robust and reliable and provides nearly perfect control system performance when the gain is calibrated properly [61,62]. PID controllers are frequently used in MGs to control voltage, frequency, and current. PID controllers, which offer a simple and effective approach to linear system control, are widely used in both grid-connected and standalone microgrids. Because PID controllers have a basic control structure that enables constant voltage and current regulation, they are used in many industrial applications. Modern microgrid applications use PID controllers in conjunction with adaptive control methods, including fuzzy logic controllers, to better manage system dynamics and non-linearities. For MGs with a significant amount of RESs, these hybrid techniques are appropriate since they combine the flexibility of more sophisticated systems with the simplicity of PID control [63,64]. Non-linear systems that pose difficulties for RESs include solar photovoltaics and wind generation. To ensure stability and optimal performance, these systems require specific adjustments. Moreover, MGs with a large number of interacting DERs and dynamic loads—the latter of which they may find difficult to manage—may need more sophisticated control schemes. Even with these drawbacks, PID controllers are still a smart option for systems with predictable voltage and current generation and loads [65,66]. The authors of [67] look into how to improve power flow regulation in dispersed (distributed) networks by using proportional–integral (PI) controllers to control battery energy storage systems and a static synchronous series compensator (SSSC). Maintaining voltage and frequency stability under various operating conditions is the major goal of the study, which also shows how well PI management works to enhance dynamic performance and promote system reliability in distributed power systems. The authors of [68] suggest a fault-tolerant strategy for SSSC in P-Q control systems employing a PI controller with an appropriate compensation mechanism under faults and disturbances in the dispersed network units. Furthermore, the authors of [69] talk about PI's poor performance when there is a high voltage harmonic present. Because of its limited gain and simple structure, PI cannot adjust for harmonic frequencies due to disturbance. To correct for harmonics and disturbances in three-phase PWM converters, an intelligent control strategy is suggested.

3.1.3. Multigrid Agent Control System (MACS)

Recent developments in MG control have given rise to MACS, where several entities, such as DERs, collaborate to accomplish a shared objective of energy conservation or system stability. MACS is a digital system made up of several intelligent agents that interact with one another. It can resolve issues that are too complex or impossible for a monolithic system or a single agent to handle. For level distributed control systems, MACS has proven to be a practical approach. Using multi-agent technology in the microgrid application focuses on controlling frequency, voltage, current, and other variables. In addition to improving the system, MACS reduces the requirement for centralized control [70,71]. Since MACS depends on robust communication networks, problems may arise from erratic or slow connections. Ineffective agent coordination can lead to conflicts that jeopardize system objectives, resulting in instability or inefficiency. Notwithstanding these limitations, the MACS improves the performance of the microgrids. MGs need distributed MACS control, especially in renewable energy systems. MACS's capability has been enhanced by new AI and machine learning technologies, which also enable agents to learn from their mistakes and make better decisions. One of MACS's main obstacles to acceptability is its intricate design and implementation [72,73]. MACS was employed by the authors of [74] to address issues that are too complex or hard for a single agent to handle. Furthermore, the author of [75] presents the MACS solution for microgrid energy management, which is based on distributed hybrid renewable energy generation and distributed consumption. In this article, the multi-agent system technology is used to control the microgrid bus voltage. The proposed strategy is simulated in MATLAB R2016a, and finally, the result justifies how a multi-agent system can be a suitable solution to microgrid implementation requirements. The authors of [76] give a summary of multi-agent systems for managing and controlling microgrids. Design components and performance challenges are covered, and different performance metrics and optimization techniques are compiled and contrasted in terms of convergence time and effectiveness in accomplishing system goals.

3.2. Advanced Methods of Control

This section examines advanced techniques within the context of contemporary MGs construction by offering a comprehensive analysis of the literature, highlighting their benefits and limitations. Contemporary energy networks are becoming increasingly complicated, particularly those with significant penetration of renewable energy. In general, multi-frequency harmonic currents are impacted by grid distortion caused by non-linear loads. This calls for more sophisticated control strategies. The rapid temporal reaction of microgrid operations allows them to begin with standard control tactics. These cutting-edge procedures offer greater stability than conventional methods due to their feedback approach. Additionally, these technologies increase the shock resistance and efficiency of MGs through the application of AI and machine learning [77].

3.2.1. Model Predictive Control (MPC)

MPC, the complex control strategy, maximizes control actions by using future state forecasts from the system model. MPC optimizes high-variability systems, such as renewable energy generation, by reducing forecast errors and predicting future states. MPC improves the performance of real-time applications by updating models using real-time data. 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 [16,78]. The output of RESs in hybrid systems with thermal generators cannot be reliably predicted by a traditional unit commitment operation, which raises the effective operating cost. However, the development of MPC has contributed to improved control of prediction errors due to its superior feedback mechanisms. In both independent and hybrid systems, MPC promotes efficient interaction between several residential microgrids. Nonetheless, the design of the sample interval remains a major problem in MPC [79]. In Ref. [80], a model predictive control (MPC)-based voltage and frequency control strategy for inverter-based distributed generation is proposed. In this study, currents injected into an off-grid system at the point of common coupling (PCC) of the DG are considered as disturbances and used as feed-forward signals. The effectiveness of the scheme is demonstrated by extensive time-domain simulations using PSCAD/EMTDC v4.2.1 for various loads, fault conditions, and DG operation after switching in an islanded microgrid. The authors of [81] claim that MPC is essential to automating remote islanded microgrids. Among its advantages are its capacity to control current with the fewest harmonics, function at low switching frequencies, and provide reliable performance for nonlinear systems. In real-time systems, however, the computational cost of MPC has decreased due to cloud and edge computing. The accuracy and performance of MPC's prediction models may be enhanced with the addition of machine learning. In addition, the authors of [82] provide a large-signal model based on the dynamic equations for active and reactive power for grid-forming inverters linked to a microgrid. The method in this study is supported by a theoretical stability analysis, and experimental findings attest to its good performance in the presence of load imbalances, load step changes, and nonlinear loading situations.

3.2.2. Sliding Mode Control (SMC)

In a dynamic process, the SMC methodology is a nonlinear control technique that adjusts its outputs according to the system's current states. SMC modifies the dynamics of the system and causes it to slide over a cross-section of its normal behavior by employing discontinuous control signals. SMC is advantageous because of its resilience feature, which suppresses uncertainties that act on the same channel of the controllable variables and do not amplify the unmatched disturbances [17]. RESs and other fluctuating systems benefit greatly from SMC's dependable control technology. Because they need to react rapidly to changes in load or generation, MGs benefit greatly from rapid dynamic response. Sensitive sensors or communication networks, however, could make it less functional. The intricate control theories of SMC are challenging to implement, particularly in big systems, because they necessitate a deep comprehension of the system being controlled. SMC's data are more accurate, which improves performance, because of advancements in sensor technology and communication networks [83]. SMC was suggested by the authors of [84] as a way to stabilize the network control system in the presence of uncertainty and time delay. In order to accomplish voltage regulation and frequency restoration in a limited amount of time, the study uses a distributed observer in conjunction with a nonlinear controller that was created using a backstepping technique. Simulations on a modified IEEE 37-bus test system confirm the suggested approach, proving its efficacy, resilience to disruptions, and plug-and-play capacity. To control the frequency in an islanded microgrid. The authors of [85] suggested using full-order SMC (FOSMC). For every DG in the MG, a controller is utilized, and FOSMC is developed. In a finite amount of time (0.6 s), the sliding mode surface is separated from the sliding mode states to return the DG frequencies to a reference level. The test is conducted on a modified IEEE-37 bus system, and the outcomes show that the controller can withstand changes in load. To regulate the frequency in an islanded microgrid made up of several renewable sources, the authors of [86] devised an intelligent terminal SMC based on the method for optimizing artificial bee colonies (ABCs). Optimization of SMC parameters is achieved via the evolutionary algorithm. The ABC algorithm is used to tune these parameters. The frequency is stabilized by the ABC-based TSMC algorithm with a minimum settling time of 2.5 s, overshoot of 0.0254%, oscillation of 0.0127, and roughly zero steady-state error when compared to ABC-based PID control. SMC provides minimal harmonics and stable performance in the face of transients and voltage variations.

3.2.3. Adaptive Control

An adaptive control system is updated continuously to ensure that plant changes are handled efficiently and without requiring human involvement. Adaptive control for the systems is easy to implement. To achieve the control objectives and ensure that the system functions as intended, adaptive regulation adaptively modifies the parameters. Based on the feedback signal, adaptive control efficiently manages a constraint in a control system. The uncertainty and biased terms in the state space representation are addressed by adaptive control [87]. 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 variation in the source and loads. However, because adaptive control adapts slowly, it is difficult to apply prior knowledge of system parameters and 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 (ANNs) [88,89]. The authors in [90] employed self-adaptive secondary control to control the frequency regulation (FR) of MG's virtual synchronous generators (VSGs). Considering that MGs is made up of a wind turbine, solar array, and a cluster of electric vehicles, it is argued that the self-adaptive FR technique described here is more logical and effective since it fully utilizes FR resources while reducing the impact of reserve capacity constraints. An improved adaptive droop control technique for frequency regulation in asynchronous AC regions connected by Multi-Terminal DC grids (MTDC) is introduced by the authors of [91]. This work uses the features of Rate of Change of Frequency (ROCOF) and Frequency Deviation (FD) to alter the droop coefficients in order to share the active power among several asynchronous AC grids adaptively. The performance of the proposed technique in a modified multi-machine power system is tested using DIgSILENT PowerFactory vSP1. The effectiveness of the suggested strategy is validated by the simulation results. It is concluded that, in a variety of operating settings, the suggested adaptive control guarantees a strong and good frequency response.

3.2.4. Intelligent Control

Intelligent control ensures quick stability due to its quick convergence rate and computation speed. Stochastic decision-making problems are solved by intelligent control approaches, in which agents learn how to interact with their surroundings to maximize a reward signal. Intelligent control can effectively manage environmental uncertainty and guarantee a balance between exploration and exploitation during the training phase. In contrast, most intelligent control suffers from dimensionality issues as the complexity of the microgrid system rises, leading to information loss; consequently, fine-grained discretization is necessary. The majority of intelligent control also necessitates extensive training and calculations, making debugging and tracking challenging. To obtain a reasonable outcome, the reward function must also be well-designed. Numerous intricate algorithms, fuzzy logic control (FLC), and artificial neural networks (ANNs) are examples of intelligent control [18,92]. Complex, non-linear systems such as MGs rely on renewable energy and are excellent for ANNs. ANNs are machine learning techniques that use artificial intelligence (AI) to teach computers how to handle data. The primary benefits of ANNs are parallel processing, data collection, processing, learning, robustness, generalization, and better decision-making. When an ANN is used effectively, it can help with other controller structure functions. Small or newly built MGs may struggle to gather the massive data needed for these models. Due to their computational expense, ANNs are difficult to integrate into real-time systems with limited processing [93]. Understanding ANN decision-making makes it difficult to identify and modify control measures. Modern big data analytics and machine learning have substantially increased the availability of enormous quantities needed to train ANNs. Scientists also study hybrid models that combine MPC or SMC with ANNs to increase real-time system performance [94]. Similarly, the adoption of 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 [95].

Power systems frequently employ fuzzy logic control (FLC), an AI method for handling uncertain models. 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. MG stability and performance are enhanced by FLC flexibility and ability to control vast amounts of uncertainty, including the penetration of renewable energy. FLC reacts more slowly than other sophisticated control techniques. Human rule-making also makes it challenging to build large or complicated systems. In addition, FLC accuracy is harmed by the use of erroneous data, the requirement for subject matter experts to create the rules, and the requirement for frequent rule updates. 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. By fusing the precision and speed of contemporary methodologies with the flexibility of FLC, these hybrid approaches support microgrid systems of different sizes and complexity [96]. According to the authors of [97], FLC is proposed to control the performance and power quality improvement of a microgrid-connected photovoltaic system (PVS) with battery energy storage, against varying solar irradiance, temperature, and nonlinear and load conditions. In order to optimize solar power extraction and effectively manage battery storage, a fuzzy logic controller is employed. Moreover, it compensates for harmonic currents, manages active/reactive power, controls the DC link voltage, and guarantees high-quality power injection into nonlinear loads or the grid. The method is validated using MATLAB R2023a simulation, which provide better performance than PI controllers in terms of tracking accuracy, reactive power adjustment, harmonic distortion reduction, and robustness to load and irradiance fluctuations.

3.3. Limitations of Control Strategies

This section assesses the shortcomings of both sophisticated load-sharing strategies and traditional control approaches in microgrids. Droop control is typically used for low-voltage systems, but it loses precision and becomes unstable when subjected to high harmonic loads [50]. Despite being simple, PID controllers may not perform as well with RESs because of their high variance, as PID controllers have trouble with non-linear systems [61]. MACS are excellent for distributed systems, but they require robust communication lines [70]. MPC has a higher computational load. MPC is useless for load sharing and is unable to adapt to changes in the system's parameters. Its mathematical calculations are difficult to perform [98]. The adaptive control has a slow adaptation process [88]. Due to the complex system architecture and high switching frequency, SMC has chattering issues [99]. ANN complexity, which rises with the harmonic component, restricts the use of intelligent techniques. FLCs and ANNs offer flexibility and adaptability for control of MGs, despite their slower dynamic reflexes and higher processing resource requirements [92,96]. Cost-effectiveness, energy imbalance, scalability, integrating RESs and ESSs with MGs, and the kind and amount of demand-side response (DSR) are all crucial factors to consider when choosing control systems. Furthermore, Table 3 provides an overview of relevant literature on MG control strategies that were examined in the preceding sections. On the other hand, Table 4 lists the significant advantages and disadvantages of MG control methods.

Table 3. An overview of relevant research on MG control techniques.

Control Strategies	Control Goals (Case Studies)	Type of MGs	Mode of Operation	Simulation	Ref.
MACS	• To introduce the MACS solution for managing microgrid energy.	DC-MG	Nil	MATLAB/Simulink R2016a	[75]
Droop control	• Elimination of circulating current in the parallel operation of a single-phase inverter.	AC & DC MGs	Grid connected	MATLAB/Simulink R2020b	[55]
	• To eliminate harmonic and unbalanced voltages in microgrids that are AC-islanded.	AC-MG	Islanded	MATLAB/Simulink R2017b	[57]
PI/PID	• To enhance the control of power flow in scattered networks.	DC-MG	Islanded	MATLAB/Simulink R2022a	[67]
	• Control of a two-stage single-phase standalone photovoltaic system.	DC-MG	Islanded	MATLAB/Simulink v6.0	[68]
MPC	• Control of V-F for inverter-based DG.	AC-MG	Islanded	PSCAD/EMTDC v4.2.1	[80]
	• Managing an unbalanced load on a three-phase inverter's large-signal model.	AC-MG	Grid connected	PSCAD/EMTDC v4.5	[82]
FLC	• Control the performance and power quality improvement of a MG-based on DERs	AC & DC MGs	Grid connected	MATLAB/Simulink R2023a	[97]

Table 3. *Cont.*

Control Strategies	Control Goals (Case Studies)	Type of MGs	Mode of Operation	Simulation	Ref.
SMC	• To restore frequency and regulate voltage in a limited amount of time.	AC-MG	Islanded	MATLAB/Simulink R2019b	[84]
	• The regulation of microgrid load frequency.	AC-MG	Islanded	MATLAB/Simulink R2019b	[85]
Adaptive control	• The regulation of the frequency of virtual synchronous generators for AC microgrids.	AC-MG	Grid connected	MATLAB/Simulink R2018b	[90]
	• Improve frequency regulation of asynchronous grids.	AC & DC MGs	Grid connected	DigSILENT Power System vSP1	[91]
ANNs	• Concurrently regulates the microgrid's frequency and voltage.	Hybrid MGs	Islanded	MATLAB/Simulink R2020a	[95]

Table 4. Benefits and drawbacks of MG's control techniques [48].

	Conventional Control Methods
Benefits	**Assessment**
Simplicity	• Traditional techniques, such as droop control, are simple to apply and comprehend. • It uses less computing power than more sophisticated, contemporary techniques. • Its simple form and inexpensive cost make it a popular choice for industrial and power systems.
Decentralized functionality	• It enables independent operation of microgrid components (storage, generators) without requiring centralized coordination.
Consistent stability	• For many years, power system applications have been extensively tested and confirmed traditional control techniques. • Maintaining stability without major adjustments or more levels of control is challenging.
Low demands for communication	• Conventional methods are resistant to communication failures because they can operate without complicated communication networks.
Quick dynamic reaction	• When load or generation varies suddenly, the basic principles of control react quickly to guarantee local stability.
Drawbacks	**Assessment**
Restricted precision	• Voltage and frequency cannot be precisely controlled by conventional droop control in the presence of significant disturbances or fluctuating load circumstances.
Lack of scalability	• It gets more difficult to tune and maintain stable functioning as the number of DERs rises. • In low-voltage systems in particular, the traditional droop approach allows for poor voltage-frequency regulation.
Inadequate economic performance	• Conventional methods require further higher-layer (tertiary) optimization to optimize for cost, fuel consumption, or emissions.
Weak to intricate disruptions	• Microgrids with a high percentage of renewable energy, loads that change quickly, or unpredictable behavior (like EVs) pose challenges to conventional approaches.
Reliance on manual adjustment	• For dynamic or changing microgrid systems, traditional PI/PID controller parameters frequently need to be manually adjusted based on system variables.

Table 4. *Cont.*

	Advanced control methods
Benefits	**Assessment**
Great precision and effectiveness	• They can handle uncertainties and shocks with great resilience. • Power sharing, frequency, and voltage can all be precisely maintained by sophisticated controls, even in extremely dynamic situations.
Adaptability and Flexibility	• Controllers that are AI-based and learning can adjust to shifting system configurations and unpredictable environments. • Systems that are dynamic and extremely complex can benefit from advanced control techniques.
Improved integration of RESs	• Modern techniques successfully address the unpredictability and fluctuation brought about by RESs (wind, sun). • The control techniques enhance voltage regulation and power sharing, especially when nonlinear loads are present.
Scalability	• Large MGs and networked microgrid clusters are better suited for advanced algorithms. • The stability and performance of MG are enhanced by the advanced FLC technology, which controls vast amounts of uncertainty, including the penetration of renewable energy.
Predictive abilities in real time	• Methods such as MPC forecast future conditions and proactively modify control measures to avoid instability. • Real-time parameter optimization is possible with adaptive control techniques.
Drawbacks	**Assessment**
Complicated execution	• Complex design, programming, and tuning are necessary for advanced techniques, which lengthen development times and raise expenses. • In addition to being costly to compute, advanced approaches can be challenging to understand and adjust.
High demand for computation	• Strong processors are required for the real-time execution of learning and optimization algorithms, and these might be expensive.
Challenges with standardization	• Adoption of advanced control systems may be hampered by the absence of generally recognized standards for their implementation and validation.
Required data	• Methods such as predictive control and machine learning need a lot of real-time, high-quality data. • Large amounts of processing power and training time are needed for advanced approaches.
Reliance on communication infrastructure	• Strong, low-latency communication networks are necessary for many sophisticated control approaches, leaving the system open to malfunctions or cyberattacks.

4. Microgrid-Based IoT Monitoring System Applications

One area in which IoT technology has drastically altered energy system monitoring and management is MG operation and control. MGs utilize IoT-enabled technologies in combination with power grid equipment allowing local networks to offer extra services beyond the necessary electricity delivery to local networks that function either independently or in tandem with the regional grid [100]. This section discusses how IoT technology is changing MG management operations through real-time monitoring, data analytics, and decision-making. Additionally, this section presents new developments in blockchain technology, smart contracts, and SCADA applications.

The MG system benefits greatly from the enormous expansion of IoT devices, and its function is unavoidable. IoT monitoring systems use connected devices, sensors, and communication networks to provide real-time, comprehensive microgrid activity tracking. To maximize MG performance, energy efficiency, and system resilience, these systems process and evaluate data from load centers, inverters, batteries, wind turbines, and solar panels. Real-time data on power generation, load consumption, voltage, frequency, temperature, and other factors are typically collected and analyzed by MGs using IoT monitoring devices. IoT devices enable DERs for control, load balancing, and remote switching in automation and remote control. IoT devices analyze the MGs under various conditions to help with decision-making, waste reduction, energy distribution, and energy consumption optimization. IoT monitoring increases energy efficiency and uses predictive algorithms to maintain grid stability. With precise consumption data, IoT devices provide automated load shedding, demand-side management, and energy-saving solutions [101,102]. In the event of a cyberattack, outage, or failure, IoT-based sensors identify irregularities and sound an alarm. In isolated or disaster-prone areas, IoT improves microgrid resilience. 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 [103]. MGs mostly depend on DERs, such as solar panels, wind turbines, and energy storage devices, which the IoT might help connect. IoT can assist MGs in managing their DERs by gathering data on energy usage, output, and system performance in real time. MGs, especially those with a high renewable energy mix, need consistent and dependable IoT monitoring solutions. IoT technologies guarantee their operational efficiency by closely monitoring these resources in real time and providing feedback on the most effective way to distribute the energy. IoT-enabled sensors track each panel's power output in solar-powered MGs and indicate any efficiency drops brought on by dirt, shade, or malfunctioning machinery. Wind-powered MGs can optimize energy collection through IoT technologies that detect wind speed, turbine performance, and changing blade angle [104]. Many real-world issues have been resolved by the growth of IoT, but it has also raised serious moral and legal issues. Among these concerns are data security, privacy protection, safety and trust, and data usability [100].

4.1. Emerging Trends of SCADA Systems and Smart Contract Applications

The reliability, scalability, and effectiveness of microgrid monitoring systems that depend on the IoT are enhanced by numerous important technologies. These technologies include SCADA systems, blockchain technology, and smart contracts. SCADA systems monitor voltage, current, power, and frequency in real time from a variety of components, including loads, solar PVs, batteries, and diesel generators. In industrial applications, SCADA systems are essential for MGs to monitor and manage energy use, storage, and output in real time. Environmental conditions are tracked by SCADA systems for ambient temperature and sun radiation. SCADA systems track the health, usage trends, and State of Charge (SoC) of batteries in ESS management. SCADA facilitates smooth transitions between islanded and grid-connected modes. SCADA systems use predictions, tariffs, or generating capacity to assess load profiles and modify demand. In addition, they minimize peak demand and maximize energy consumption. For safety and dependability, SCADA separates the microgrid in remote locations when it detects problems. Real-time data collection from equipment is handled by SCADA systems based on preset parameters. Two ways that SCADA systems can automate MG control are by inverter setpoints to provide voltage stability and by automatically dispatching energy from storage as required [105], regarding alarm management, cybersecurity, and communication. SCADA systems use secure communication protocols, encryption, and access control. It makes data transfer easier and sends out alerts for errors, anomalies, or unauthorized access. In Figure 3, the SCADA system's graphical configuration is displayed. Sensors, actuators, and other Intelligent Electronic Devices (IDEs) comprise the MG control system. The sensors gather information from the equipment in real time, while the actuators support the central controller's chosen control mechanism. Sensor data are gathered by Remote Terminal Units (RTUs) and transmitted to the SCADA unit, which is the central controller. Information is sent over communication networks to the SCADA unit, which makes decisions about system monitoring and control. Decisions are gathered from the central controller by the Programmable Logic Controller (PLC) and transmitted to the actuators for control of the corresponding equipment. The SCADA system's software component, the Human

Machine Interface (HMI), helps monitor and control [30]. According to published research, insider threats and cyberattacks against SCADA pose a threat to its security. The hacker enters a system with harmful intent. Better microgrid management is possible with the development of IoT technology, as cooperating SCADA systems should provide operators with more precise control and real-time data viewing. Through integration, the power system's safe functioning is ensured by preventing and mitigating failures [106].

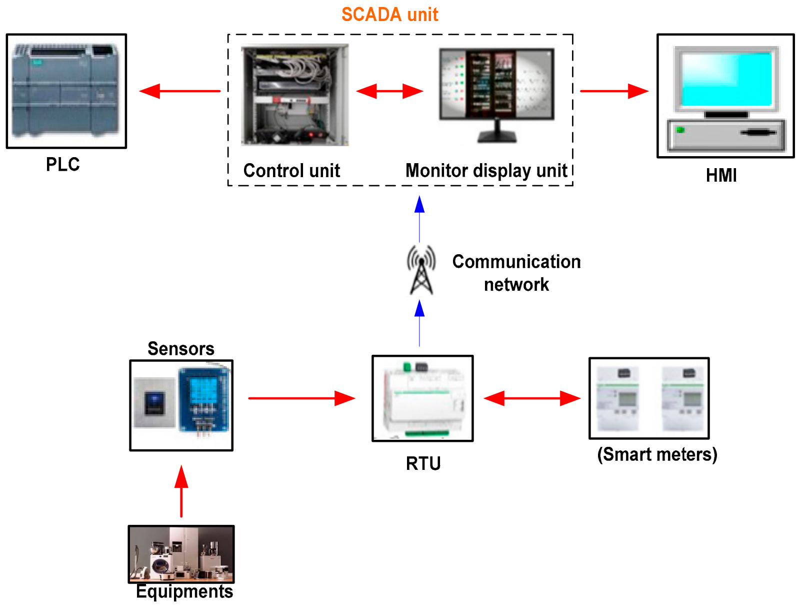

Figure 3. SCADA system configuration for MG control operations [30].

4.2. Microgrid Cyberattacks, Cybersecurity, and Standardization Protocols

Control systems for microgrids are frequently the subject of cyberattacks, depending on how they are used. Because of its interconnectedness, the incorporation of DER increases the potential cyberattack surface. Cyberattackers/hackers may use the different parts and systems as access points. Although remote monitoring and control have many advantages, they can also create weaknesses if they are not adequately secured. Cyberattacks may take advantage of the communication protocols employed in microgrid systems. They can intercept or alter device-to-device conversations, which could result in data breaches or control problems. Data transmission is sensitive, including data on energy production, consumption trends, load forecasting, and even information about system vulnerabilities or repair plans. These data must be kept secure. Malicious actors can use weaknesses to intercept private information while it is in transit, change or modify data to offer misleading information, and violate people's privacy if it is not sufficiently safeguarded. Insufficiently secured data transmission channels can be used for data tampering or eavesdropping, jeopardizing the integrity and confidentiality of data. Moreover, known vulnerabilities frequently affect software and firmware that is out of date. As security flaws are discovered, attackers can take advantage of them to obtain illegal access, alter processes, or jeopardize the integrity of data. Updating these elements is crucial to reducing cybersecurity threats. In cybersecurity, human behavior is crucial. Risky behavior, misconfigurations, inadequate training, bad password management, and unintentional data exposure can all make microgrid systems more vulnerable. To address these challenges, robust cybersecurity measures must be implemented across microgrid networks. These measures should include thorough threat landscape analysis, risk management, secure communication infrastructure, control system security, endpoint protection, data security and privacy, incident response and recovery planning, regulatory compliance, and continuous awareness and training programs [107,108].

Standardized technical requirements for MG control and communication are established by grid codes, which guarantee the safe, effective, and dependable integration of MGs into the main power grid or their operation in islanded mode. These codes, which were created by national grid operators, regulatory organizations like the Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), and others, specify protocols for communication, protection, synchronization, and power quality to enable smooth communication between MGs and the utility grid. Grid codes also require cybersecurity safeguards, such as authentication and encryption, to guard against online attacks that can interfere with MG's operations. The major goals are to reduce operating risks, maintain system stability, and guarantee interoperability, especially in a variety of scenarios. For example, DERs, including DGs inside MGs, must maintain voltage and frequency within allowable bounds, according to IEEE Standard 1547-2018 [21]. In electric power systems, IEC 61850 is a standardized communication framework that facilitates quick, dependable, and secure interoperability and cybersecurity. With models such as Generic Object-Oriented Substation Event (GOOSE) messaging for quick protection and control signals, IEC 61850 enables high-speed data transmission for monitoring and control. IEC 62786 defines critical control aspects such as voltage and frequency support, anti-islanding, power quality, and communication interoperability. Standardized testing methods are provided by IEEE Std 2030.8-2018 to verify the robustness, performance, and interoperability of microgrid controllers. It facilitates the creation of robust and dependable control systems by tackling important tasks, including fault response, islanding transition, V-F control, and DER coordination. Grid codes mandate that MGs independently maintain stability in the islanded mode, which calls for strong control hierarchies to manage load fluctuations and DG coordination in the absence of external grid support [22,23]. The variety of MG configurations and the incorporation of DERs with varying output make grid code compliance difficult. In remote MGs with inadequate infrastructure, for example, it can be difficult to ensure a low-latency connection for tertiary control. Furthermore, sophisticated algorithms and hardware are needed to modify control techniques to satisfy dynamic grid code requirements, such as ride-through capabilities during voltage sags. Another challenge is regulatory harmonization between areas, as worldwide MG deployment is complicated by disparate standards (e.g., North American IEEE 1547 vs. European EN 50549). However, following these guidelines guarantees that MGs serve decarbonization objectives, enhance grid dependability, and facilitate the scalable integration of dispersed energy resources [109].

4.3. Blockchain Technology

The basic idea behind blockchain technology is that it allows a group of individuals to enter transactional data in a shared ledger in a way that makes it impossible for anyone to alter it once it has been created and published. It also has to deal with several serious issues, including interoperability, scalability, energy consumption, and regulatory issues. A key component in guaranteeing the security and integrity of blockchain technology is cryptography. It is widely used in many different blockchain applications to ensure the immutability, confidentiality, and validity of data and transactions. When a user starts a transaction on the blockchain, the transaction data are encrypted using cryptography. This ensures secrecy and security because only the intended recipient with the corresponding private key can decrypt and read the data. In blockchain technology, the Merkle tree is an essential data structure that is used to effectively summarize and confirm the existence and integrity of block data. Its major purpose is to make it feasible to identify every transaction that is recorded in a block so that each block of the blockchain can be found.

One of the fundamental technologies in the field of blockchain is the consensus mechanism. It guarantees the synchronization and confirmation of transaction data and identifies the nodes in charge of keeping the ledger up to date. Additionally, the three types of blockchains—public, private, and consortium—are distinguished by their distinct criteria and intended applications. The public blockchain allows anybody to view and utilize it for transactions, and everyone can take part in the consensus-building process. It is completely transparent and trustworthy. Nevertheless, public blockchains must always have a lot of processing power, a fast internet connection, and a lot of storage capacity. In contrast to public blockchains, private blockchains operate within a closed network and are more permissive and restrictive. It is typically used in companies where access to the blockchain network is restricted to certain members. Although private blockchains are less secure than public blockchains, they nevertheless need to be highly scalable and have fast transaction processing speeds. Consortium blockchain is becoming more and more well-liked by businesses because of its special advantages. It is superior to public blockchains due to its scalability and high degree of security. Consortium blockchains are also far more secure and efficient than public blockchains, which makes them perfect for use cases requiring fast transaction speeds. Consortium blockchains have benefits including customization, security, and scalability. Nevertheless, compared to other blockchain variants, consortium blockchains might be less transparent. Furthermore, blockchain security includes tactics, procedures, and systems that guard against malevolent activity, illegal access, and data breaches. Integrity, confidentiality, and network availability are among the main priorities. Blockchain ensures that no single entity has complete control over the data by operating on a decentralized network of nodes. All things considered, the intrinsic qualities of blockchain guarantee safe and reliable information exchanges [110,111].

4.4. Impact of Blockchain Technology on Microgrids

The necessity of a constant internet connection has brought up several communications- and security-related concerns. Data breaches and cyberattacks are increasing in frequency as MGs become more and more reliant on digital communication networks. Because MGs rely on IoT devices and cloud computing, they are especially susceptible to cyberattacks, such as data manipulation, false data injection (FDI), energy theft through operating system modification or energy meter hacking, denial of service (DoS) assaults, and unauthorized access. These risks may result in monetary losses, power outages, interruptions to operations, and equipment damage for both operators and consumers [112]. 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 might improve monitoring accuracy, reduce administration expenses, safeguard the wholesale energy trading system, and boost energy production efficiency. Blockchain has the potential to reduce communication costs, promote the development of clean energy, provide fast payment and settlement systems for retail energy trading platforms, open up new avenues for investment and financing, and reduce the risks involved in energy financing and investment. In MGs, blockchain technology has the potential to improve the efficiency, security, and transparency of smart grids. It has been widely used for peer-to-peer (P2P) microgrid commerce because it enables users to manage their systems without needing a centralized infrastructure [113]. Blockchain establishes an unchangeable, secure record for each energy transaction, guaranteeing accountability and transparency. By using blockchain technology, MGs make it possible for purchasers and sellers of energy to participate in distributed energy markets, eliminating the need for centralized utilities. Furthermore, blockchain technology offers transparent, unchangeable methods for exchanging and storing data that are traceable but not centralized. Additionally, blockchain can enhance grid security by offering a transparent and impenetrable platform for energy transaction tracking and data integrity assurance. By doing this, the electrical grid's dependability can be guaranteed and cyberattacks can be avoided. Additionally, blockchain technology can be used to regulate the electricity market, allowing for waste reduction and more effective management of energy resources. Blockchain can assist in balancing the energy system and lessen the need for traditional energy suppliers by automating the process of matching supply and demand and delivering real-time data on energy production and consumption. Nevertheless, it is more complex, slower, and does not let users change the data they have added [114]. The authors of [115] propose a blockchain-based decentralized microgrid, which has been proven on a real-world system in China and has demonstrated a greater ability to stop any fraudulent activity. Each operator can only communicate boundary information with other operators through the use of optimization condition decomposition, and data transfer is secured through the use of State Machine Replication (SMR). To further enhance MG automation and control, blockchain technology can be integrated with AI technology. This can help MGs operators protect their systems from intrusions and ensure safe data processing, storage, and transportation. Following this enhancement will protect future data and guarantee system security [116].

5. Prospects for the Future of Microgrids

Improvements in energy management software, control systems, and IoT-based monitoring solutions over the next few decades will enable the growth of the mass microgrid industry. MGs are becoming increasingly reliable and efficient with the introduction of new control and management technologies, including blockchain, smart contracts, reinforcement learning, and deep learning algorithms. Blockchain ensures accountability and transparency by generating a safe, unchangeable record for every energy transaction. Smart contracts, based on blockchain technology, enable the use of MGs by automating energy trade by predetermined parameters. Smart contracts enable automatic energy contract negotiations between microgrid manufacturers and customers. These contracts are stored on the blockchain and begin to execute automatically upon the fulfillment of specific requirements. Three aspects of MG operations that can be enhanced by smart contracts include automation, trust, and transparency. Another potential advantage of smart contracts is cost reduction [114]. Blockchain technology has the potential to expedite the global shift to distributed energy systems and renewable energy, thereby mitigating the difficulties of integrating substantial amounts of renewable energy into traditional centralized networks. Controlling MGs is made easier using hybrid control systems that combine distributed and centralized control [115]. Deep learning algorithms are among the most significant applications of AI in MGs management because of their capacity to precisely predict future energy consumption. This capability decreases energy waste, enhances the distribution of energy resources, and lessens the demand for costly peaking power plants. AI ensures the most efficient and cost-effective battery charging and discharging by optimizing ESS performance [116]. Adhering to these innovations could change the global energy scene and make MGs more logical and scalable by enabling distributed energy trading and peer-to-peer energy marketplaces.

Important Research Topic to Enhance Microgrid Performance

This section highlights several crucial research fields that will influence future growth of microgrids. Future research should concentrate on the following areas to fully realize the potential of MGs in the global energy transition:

- Future research should focus on more sophisticated control systems that can sustain the stability of the voltage and frequency system in the face of demand fluctuations and the growing share of RESs.
- Future research has to concentrate more on creating standard interoperability, energy trading made possible by blockchain technology, cooperation control techniques, and AI-driven predictive maintenance.
- As the number of MGs continues to grow, future research should concentrate on improving communication and cooperative control of MGs to work together to maximize energy flows and increase system resilience.
- Falsified data could trick an operator in the event of a cyberattack. Future research should concentrate on examining the effectiveness of grid code-based communication in MG BESSs for hardware systems by integrating a real-time digital simulator (RTDS) with a microgrid controller.

6. Conclusions

The world's transition to more reliable and environmentally friendly energy sources will be substantially aided by MG technology. Because of the different disruptions that arise from their penetrations, the existence of RESs tends to make the MG environment's operation highly uncertain. This study examines current advancements in MG control methodologies and new technologies in real-time monitoring systems, as well as potential future directions in this area. An important outcome of this work is the comprehensive analysis of the two main categories of control approaches in MGs: conventional methods, which include PID controllers, droop control, and multi-agent systems, and advanced techniques, which include adaptive control, sliding mode control, intelligent control, and model predictive control. The paper provides a thorough examination of their uses, advantages, and drawbacks. The importance of IoT-based monitoring systems that provide real-time data on energy generation, consumption, and system performance is also highlighted in this study. Additionally, this paper covers important subjects including cybersecurity and data management, smart contracts, and protective measures against these threats. The findings demonstrate that the integration of blockchain technology and SCADA systems with AI-powered algorithms improves energy efficiency, integrates RESs, and enhances the resilience of key infrastructure. Therefore, this study will be highly valued by professionals, engineers, and academics as it establishes the foundation for future developments in the control, management, and technological integration of microgrids.

Author Contributions: Conceptualization, K.E.O., A.K.S. and V.M.S.; methodology, K.E.O., A.K.S. and V.M.S.; software, K.E.O.; validation, K.E.O., A.K.S. and V.M.S.; formal analysis, K.E.O.; investigation, K.E.O.; writing—original draft preparation, K.E.O.; writing—review and editing, A.K.S. and V.M.S.; visualization, A.K.S. and V.M.S.; supervision, A.K.S. and V.M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing does not apply to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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