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Review on recent control system strategies in Microgrid

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Abstract: Microgrids (MGs) are integral to the evolving global energy landscape, facilitating the integration of renewable energy sources such as solar and wind while enhancing grid stability and resilience. This review presents a comprehensive analysis of control strategies in MG systems, addressing both conventional and advanced methodologies. We explore traditional control methods, such as droop control and Proportional Integral Derivative (PID) controllers, for their simplicity and scalability, but acknowledge their limitations in handling non-linearities and real-time adaptation. Model Predictive Control (MPC), Adaptive Sliding Mode Control (ASMC), and Artificial Neural Networks (ANN) are some of the more advanced techniques that make systems more flexible, better at managing energy, and stable even when operations change quickly. The review further delves into the role of the Internet of Things (IoT), predictive analytics, and real-time monitoring technologies in MGs, emphasizing their importance in enhancing energy efficiency, ensuring real-time control, and improving system security. The review places emphasis on energy management systems (EMS), which optimize supply and demand balance, reduce uncertainty, and enable seamless integration of distributed energy resources (DERs). The paper also highlights emerging trends such as blockchain, AI-driven controls, and deep learning for MG optimization, security, and scalability. Concluding with future research directions, the paper underscores the need for more robust control frameworks, advanced storage technologies, and enhanced cybersecurity measures, ensuring that MGs continue to play a pivotal role in the transition to a decentralized, low-carbon energy future.
Keywords: *Advanced control, Conventional control, Distributed energy resources, Energy storage systems, Microgrids.*

1. Introduction

The global shift to renewable energy is critical due to fossil fuels' environmental and economic impacts. Growing renewable energy technologies render integrating distributed energy resources (DERs) into power networks especially challenging as governments attempt to reach worldwide climate targets [1], [2]. Microgrids (MGs) are becoming more capable of managing this integration and obtaining distributed, renewable energy systems [3]. A MG is a local power network that can operate either in tandem with the primary grid or on its own. It manufactures, stores, and supplies local users with both non-renewable and renewable DERs [4], [5]. In islanded mode, an MG operates autonomously; in grid-connected mode, it links to the central grid. Especially in places prone to grid instability, outages, and natural disasters, energy networks have to adapt to boost dependability and resilience [6]. Linked to the grid, MGs generate power, balance frequency and voltage, and include renewable energy sources. Should the central grid fail, the MG could rapidly switch to islanded mode, running large loads with its DERs. MGs are ideal for military locations, data centers, and hospitals because their dual operational mode ensures energy stability [7], [8]. Advanced control techniques, along with real-time energy supply and demand EMS, enable the integration of multiple energy sources into a consistent supply chain [9], [10], [11], [12].

MGs use renewable energy to reduce greenhouse gas emissions and decarbonize electricity. Their concentrated character lowers transmission losses and makes energy solutions possible in underdeveloped or rural areas without centralized systems. Predictive analytics, remote control, and

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real-time monitoring among Internet of Things (IoT) technologies help to increase MG efficiency [12], [13], [14]. The IoT ensures simple interaction among MG components, including DERs, storage systems, and consumers, resulting in improved load control and energy distribution. Renewable energy output is unpredictable and requires real-time supply-demand balance, making integration problematic [4]. To rectify these imbalances, the grid-connected microgrid absorbs excess energy or provides power during low generation. Islanded MGs must fully utilize their distributed energy sources, complicating energy management [5], [15]. The rapid digital transformation of energy systems necessitates strict cybersecurity rules to prevent data breaches, hacker attacks, and harmful control orders that could compromise infrastructure or energy distribution [12], [16], [17]. Currently under development are security techniques for IoT-enabled MGs to safeguard operations and data. There are many types of resilient control schemes that MGs need, such as droop control, proportional-integral-derivative (PID) control, hierarchical control with primary, secondary, and tertiary levels, neural networks, fuzzy logic, and model predictive control (MPC) [18], [19]. To maintain stability, these systems the real-time mentoring and control change operating settings and adapt to MG variations [20].

Effective MG energy management is vital; energy management in a multifarious grid is also vital. Using centralized control systems, conventional grids deliver electricity unidirectionally from big-scale sources to consumers [21], [22]. MGs, particularly those run on renewable energy—expensive and difficult to control—need energy storage systems (ESS). Careful monitoring of storage system size, placement, and operation helps to prevent inefficiencies or overinvestment in storage capacity [6], [23], [24]. MG technology presents yet another difficulty with regard to scalability and standardization. MG systems in larger energy networks must be compatible by standardizing protocols, control systems, and communication channels. It is challenging to integrate DERs and develop a sizable MG in the absence of set procedures [24], [25].

The need to look at, assess, and categorize modern control systems that increase MG efficiency drives this study. MGs are an essential part of the energy transition as renewable energy sources increasingly occupy world energy networks. Still, their effective application calls for tackling many important problems in data administration, real-time monitoring, and control systems. By grouping recent advancements in control methods and including ideas on IoT-based monitoring systems, this paper aims to close the present knowledge gap. The focus here is on examining many conventional and creative control strategies and their implications for MG stability, sustainability, and scalability. This paper is important because of its thorough strategy to grasp and improve MG control systems. Attaining a low-carbon future depends on MGs, which improve system resilience and enable distributed clean energy generation from all around. This study offers vital information to legislators, engineers, and researchers on the operational and technological advancements in MG control, enabling the worldwide large-scale MG deployment. The study emphasizes how IoT technologies are becoming more important in improving monitoring, communication, and control systems, generating opportunities for the development of next-generation smart grids. Future MGs might greatly increase their security and adaptability by including artificial intelligence (AI), cloud computing, and blockchain technologies.

This paper presents a thorough study of MG control systems, as well as their application in improving energy distribution, stability, and the integration of renewable energy sources. The paper includes the following contributions:

- Traditional methods include droop control and PID controllers, while more advanced methods such as MPC and neural networks require in-depth analysis.
- A close study of how IoT technology, via real-time monitoring, data analytics, and decision-making, is transforming MG energy management.
- Analysis of EMS that lower uncertainty, improve the use of DERs, and match energy supply with demand, thereby enabling optimal functioning.
- Future research should identify the technological obstacles in current MG management techniques and provide recommendations for their resolution, particularly through the integration of AI-driven control systems.

This comprehensive review article comprises six sections, each of which focuses on the most recent and important MG control strategies. In the section 2, we look at basic control methods like droop control, PID controllers, and multi-agent systems (MAS). In the section 3, we look at more advanced control methods like MPC, adaptive sliding mode controller, and methods based on AI. Section 4 examines IoT-based monitoring systems, SCADA systems, cloud computing, and smart meters for real-time energy management. Section 5 talks about current trends in MG control, such as the use of blockchain, smart contracts, and deep learning algorithms. It also talks about possible research areas for improving MG performance in both island and grid-connected settings. In section 6, the conclusion summarizes essential findings and offers recommendations for future research, emphasizing technological developments to enhance the efficiency, reliability, and scalability of MGs.

2. Microgrid Control Strategies

There are several control strategies in microgrid, the following section discussing different types of microgrid control strategies. Figure 1 shows the different control strategies.

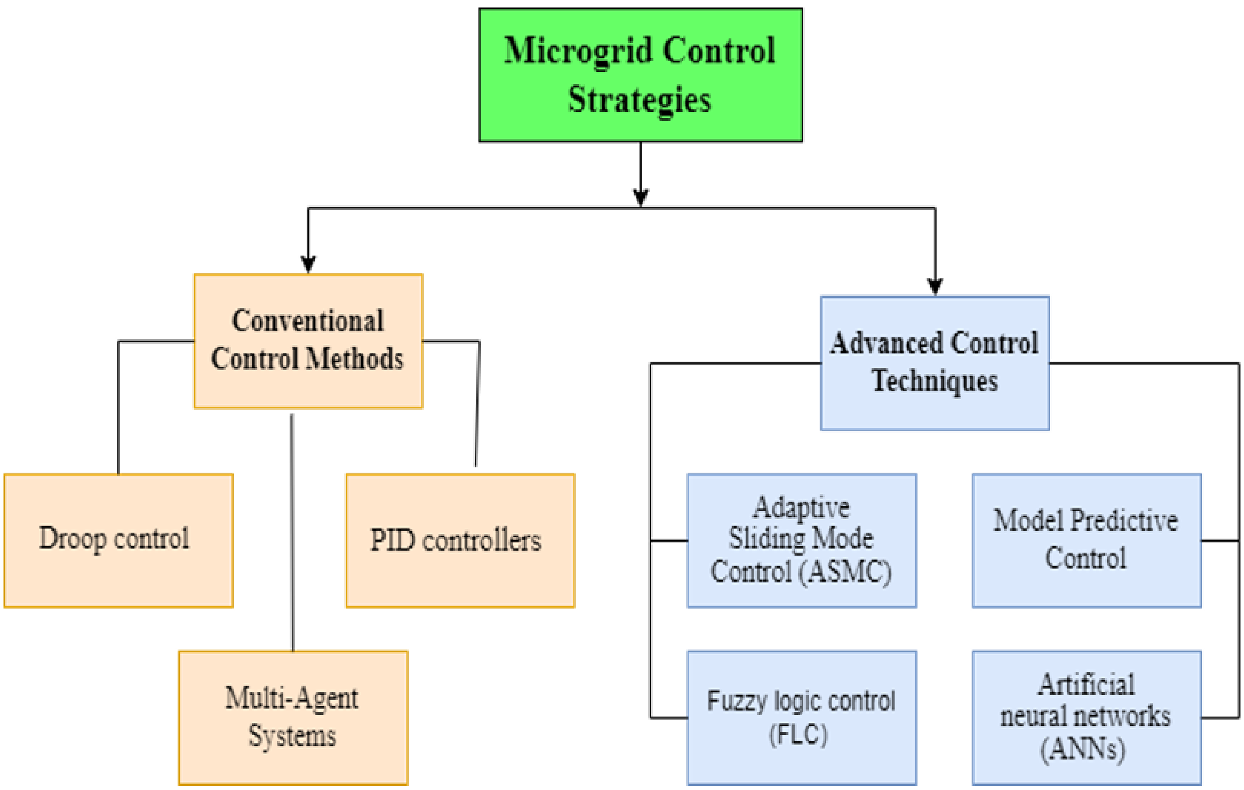

Figure 1.
Types of control methods in microgrid.

2.1. Conventional Control Methods

Although structurally simpler and more often used in past MG installations, traditional control methods cannot handle the increasing complexity of modern energy systems. This section will look at traditional methods, including droop control, PID controllers, and MAS, within the framework of modern MG construction, therefore providing a thorough study of their uses, advantages, and disadvantages [26], [27], [28].

2.1.1. Droop Control
Droop control is the recommended approach for MG load sharing. This is a classic instance of distributed control. Because it does not involve communication across DERs, droop management is ideal for systems with unstable or unrealistic communication infrastructure [29], [30], [31]. It is rather common in island MG voltage source inverters (VSIs) and grid-connected ones. For small to medium-sized MGs, droop control is a cheap and simple solution with few processing resources. Scalability allows for the addition of more DERs, while decentralization reduces the likelihood of a failure point [32], [33], [34]. Maintaining stability is challenging, though, without major modifications or extra control levels. This could lead to inaccurate control of voltage and frequency, slower system responses to load or generation surges, and incompatibility with larger systems [35], [36]. Using virtual impedance approaches to boost droop control's ability to manage voltage and frequency, or by adding more control layers, researchers have lately tried to improve its performance. Sadly, many times these developments lead to more complexity and less scalability [37].

2.1.2. Proportional-Integral-Derivative Controllers
MG systems widely use PID controllers to manage voltage, frequency, and current. Both grid-connected and stand-alone MGs frequently use PID controllers, which provide a straightforward and efficient method of linear system control [38], [39], [40]. Many industrial applications use PID controllers because of their basic control structure, which allows for constant voltage and current control. Solar and wind power are two examples of non-linear systems that present challenges for renewable energy sources [41], [42], [43], [44]. These systems need particular modifications to guarantee stability and best performance. MGs with many interacting DERs and dynamic loads—the latter of which they could find challenging to control—may also require more complex control strategies [45], [46]. Despite these disadvantages, PID controllers are still a wise choice for systems where the loads and generation are predictable in terms of voltage and current. Current MG applications are coupling PID controllers with adaptive control methods like fuzzy logic controllers to better manage non-linearities and dynamic changes in the system [42], [47]. These hybrid approaches combine the simplicity of PID management with the adaptability of more complex systems, making them fitting for MGs with a large volume of renewable energy [48], [49], [50].

2.1.3. Multi-Agent Systems
New advances in MG control have led to the development of MAS, in which different entities (like DERs) work together to achieve a common goal (like saving energy or keeping the system stable). Every agent can communicate with each other to coordinate their activities and form adjustment based on local data. Improved communication and coordination across DERs, scalability, and autonomous control are other advantages of MG management systems, such as MAS [51], [52], [53]. It enhances the system and helps to lessen the need for centralized control. For big or complex MGs, careful planning and implementation are necessary. MAS relies on strong communication networks; therefore, unstable or high-latency connections can pose issues. Poor agent coordination can cause conflicts that compromise system goals, causing instability or inefficiency [54], [55]. Despite these constraints, the MAS makes the MG work better. MGs, particularly in renewable energy systems, require distributed MAS control. New AI and machine learning technologies have improved MAS's capacity and allowed agents to learn from their failures, improving decision-making. Complex design and execution are MAS's major barriers to acceptance [52], [56].

2.2. Advanced Control Techniques
Modern energy networks, especially those with high renewable energy penetration, are becoming more complex. This requires more advanced control tactics. MG operations can start with typical control tactics. These solutions use AI and machine learning to make MGs more shock-resistant and efficient [57], [58].

2.2.1. Model Predictive Control

The complex control approach MPC maximizes control actions based on system model projections of future states. Non-linear systems, such as MGs, are ideal for MPC because they use renewable energy. Through future state prediction and forecast error reduction, MPC optimizes high-variability systems like renewable energy generation. Due to their non-linear system regulation, MGs can use several energy sources and loads [59], [60], [61]. By updating models with real-time data, MPC increases real-time application performance. MGs, or large-scale systems with low processing power, may struggle to run due to their high demand. A successful MPC application in real-time systems necessitates knowledge of mathematical methodologies and system operations [62], [63]. Cloud and edge computing have reduced the computational cost of MPC in real-time systems. Moving computational activities to the cloud allows MGs to benefit from MPC's optimal control without expensive on-site hardware. Adding machine learning to MPC's prediction models might improve their accuracy and performance [64], [65].

2.2.2. Adaptive Sliding Mode Control

Adaptive Sliding Mode Control (ASMC) works well for systems with many shocks or uncertainty. ASMC rapidly adapts the control approach as the system grows, providing excellent uncertainty and disturbance resistance. ASMC's reliable control technology works well with fluctuating systems, such as renewable energy [66], [67]. Rapid dynamic responsiveness is ideal for MGs, which must respond quickly to load or generation variations. However, sensitive sensors or communication networks may compromise its usefulness. ASMC's complex control theories require a thorough understanding of the system under control, making them difficult to apply, especially in large systems [68]. Combining ASMC with Kalman filters or another noise-reducing method may help reduce measurement noise. Thanks to advances in sensor technology and communication networks, ASMC's data is more accurate, enhancing performance [67], [69], [70].

2.2.3. Artificial Neural Networks

Artificial neural networks (ANNs) can learn and improve their control technique. Complex, non-linear systems, such as MGs, rely on renewable energy and are excellent for ANNs. ANN benefits include self-learning, adaptation to difficult nonlinear systems, and superior decision-making [34]. 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 [71], [72], [73]. 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 ASMC with ANNs to increase real-time system performance [73], [74], [75].

2.2.4. Fuzzy Logic Control

Fuzzy logic control (FLC) is appropriate for uncertain or volatile systems. The fuzzy logic approach for making decisions with inadequate or confusing inputs is ideal for renewable energy-dependent MGs [42], [76]. FLC is adaptable and regulates enormous amounts of uncertainty, including renewable energy penetration, which improves MG stability and performance. Systems can include mathematical models even when they are scarce, because they do not require perfect models. FLC is slower than other advanced control methods' dynamic reactions. Large or complex systems are also difficult to implement due to human rule-setting [77], [78]. Finally, FLC scaling can be difficult in systems with several interacting DERs or fluctuating demands. Combining FLC with predictive control systems or machine learning algorithms helps researchers enhance its dynamic responsiveness. These hybrid techniques help MG systems of all sizes and complexity by combining the adaptability of FLC with the accuracy and speed of modern methods [79], [80].

2.3. *Difference between Conventional Control Methods and Advanced Techniques*

This section discusses conventional control methods and advanced techniques for load-sharing in MGs. Traditionally employed for low-voltage systems, droop control suffers with precision and can be destabilised under strong harmonic loads. Though basic, PID controllers may not operate as best they could with renewable energy sources because of their great variance [30], [35], [45]. Although they demand strong communication links, MAS are great for distributed systems. Although MPC is known for its predictive accuracy but has real-time computational demands that restrict its scalability for big systems, advanced solutions include [42], [43], [47]. Though they need more processing resources and have slower dynamic reactions, fuzzy logic and neural networks provide flexibility and adaptability for MG control [34], [42]. Focussing on stability and scalability as more renewable energy sources are combined, Table 1 offers a whole perspective of control strategies for MG systems.

Table 1.
An overview on different control strategies.

S/N	Control method	Type	Advantages	Disadvantages	Ref .
1.	Droop control	Conventional	• Easy to implement without communication. • Modular and scalable for different MG sizes.	• Poor voltage-frequency regulation, especially in low voltage systems. • Slow dynamic response.	[29], [30], [31], [32], [34], [81], [82], [83]
2.	Proportional-integral-derivative	Conventional	• Commonly used for stability in voltage and current regulation. • Suitable for grid-connected MGs.	• Requires precise tuning. • Can struggle with non-linear systems or renewable energy fluctuations.	[19], [28], [38], [44]
3.	Multi-agent systems	Conventional	• Agents can operate autonomously. • Useful for decentralized control, improving communication and coordination.	• Complex to design and implement. • Performance relies heavily on communication network reliability.	[48], [83], [84]
4.	Proportional-resonant controllers	Conventional	• Effective in reducing steady-state error. • Suitable for AC systems.	• Requires careful tuning. • Can have poor harmonic performance.	[85], [86]
5.	Model predictive control	Advanced	• Optimal control by predicting future states and minimizing forecast error. • Suitable for nonlinear systems and real-time control.	• High computational power required. • Difficult to implement in large-scale systems.	[10], [11], [60], [61], [62], [63], [83], [87], [88]
6.	Fuzzy logic control	Advanced	• Flexible and robust under varying system conditions. • Handles nonlinearities well.	• Slower dynamic response. • Requires extensive rule-setting for complex systems.	[42], [76]

7.	Adaptive sliding mode control	Advanced	• High robustness in handling disturbances and uncertainties. • Fast dynamic response.	• Sensitive to measurement noise and requires complex control laws.	[66], [67], [82]
8.	Artificial neural networks	Advanced	• Capable of learning from data and improving control over time. • Suitable for highly complex and dynamic systems.	• Requires large datasets for training. • High computational cost and can be difficult to interpret and tune.	[34], [71], [72]
9.	Reinforcement learning	Advanced	• Can learn optimal control strategies through interaction with the environment. • Suitable for nonlinear and complex systems.	• Requires significant time for training and computational power. • May not perform well in highly volatile environments.	[56], [71], [89]
10.	Virtual impedance control	Advanced	• Improves power-sharing and voltage regulation, particularly under nonlinear loads.	• Not guaranteed to regulate voltage under all conditions. • Complex implementation with prior knowledge of system parameters.	[34]

2.4. Impact of Microgrid Control Strategies on Future Microgrid Developments and the Global Economy

MGs are playing an increasingly important role in the ever-changing energy landscape, especially in improving the stability, resilience, and transition to greener energy sources [89]. MGs are smaller-scale systems that connect renewable energy sources like solar PV, wind turbines, and battery storage to the larger power grid or can function autonomously (in islanded mode) in the event that the larger grid is down [87], [90], [91]. Among the areas that MG control systems will impact going forward are energy resilience, environmental sustainability, and economic growth [92]. This paper delves deeper into how control strategies in MGs influence the evolution of new technologies and their global economic consequences.

MG control solutions in areas prone to grid instability or natural disasters define the energy system's resilience [92]. Using real-time supply and demand balancing, these systems maintain a constant energy supply even in isolation. They guarantee that, during a power outage, other important medical equipment, including life-support systems, gets first attention [93]. The Brooklyn-Queens Demand Management project in New York City clearly highlights the need for strong MG control mechanisms [94], [95], [96]. By optimizing renewable energy sources and minimizing the use of fossil fuels, MG management systems contribute to efforts to combat climate change and subsequently reduce greenhouse gas emissions [81], [97]. These techniques also have an impact on finances; MG management systems increase energy efficiency, cut peak demand, and save money by best using intermittent renewable energy sources like wind and solar while maintaining grid stability. Local electricity generation during times of high energy costs or peak demand helps to reduce dependency on costly main grid imports [98], [99], [100].

MGs have a significant impact on global economies as more nations opt for decarbonized energy systems and reduce their consumption of fossil fuels. MGs will help to meet net-zero emissions targets by providing energy independence to otherwise underdeveloped or underprivileged communities, lowering electricity costs, and boosting employment prospects in the design, installation, and maintenance sectors [25], [94], [101]. Smart grids and distributed energy markets greatly influence MG management techniques. Conventional, centralized power networks transport electricity from far-off generators to far-off users. MGs' advanced control technologies enable distributed energy markets and peer-to-peer energy trading by democratizing control of energy and thereby reducing reliance on utilities [102], [103], [104]. This 2017 Puerto Rico case highlights the crucial role of MG control technologies in rebuilding power networks following Hurricane Maria. These MGs, including solar and wind sources in the island's electricity mix, enable Puerto Rico to grow more sustainably [105], [106].

3. Energy Management Systems

3.1. The Role of EMS in Balancing Power Supply and Demand

Since they enable to maximize the balance of power supply and demand, EMS are vital parts of MG operations. The increasing integration of RES into MGs—such as solar, wind, and ESS—is changing the function of EMS in controlling variability and guaranteeing consistent energy supply. Effective control of energy generation, consumption, and storage guarantees with a well-designed EMS decreased operating costs and increased energy efficiency [107], [108].

Modern MGs suffer from the intermittent character of renewable energy sources, namely solar and wind, since they provide different production depending on changing weather conditions. Real-time supply and demand synchronization relies on an EMS, which also helps to prevent power imbalances that can cause system inefficiencies or failures [109], [110]. A solar-powered MG might create extra electricity during periods of intense sunlight, which the EMS either exports to the main grid or stores in batteries. On the other hand, during periods of low generation, the EMS meets demand using stored energy [111], [112]. This dynamically alters MG energy flow to ensure a consistent power supply, regardless of changes in renewable output. Demand response systems enable MGs to regulate or decrease their power consumption during high demand periods, thereby averting grid overload and excessive energy consumption [113], [114]. By means of smart appliances, HVAC systems, and lighting control, the EMS can provide real-time load control. During peak times, this saves energy; during off-peak hours, it uses less expensive electricity [115].

3.2. Impacts of Energy Management Systems on the Global Economy

EMS are changing worldwide consumption, storage, and energy generation. Their significant influence on the global economy spans industrial production, urban development, integration of renewable energy sources, and rural electrification, among other sectors. More energy-efficient energy consumption made possible by EMS technologies lowers running costs, boosts productivity, and stimulates long-term economic development by means of their foundation [116], [117].

EMS enable cost savings and efficiency increases in companies where power consumption makes up a significant share of running expenses, driving the worldwide shift to energy-efficient technologies. By automating manufacturing schedules to match low electricity prices, EMS technologies lower running expenditures and energy waste. They also assist building managers in reducing energy consumption by controlling HVAC systems, lighting, and other appliances [118], [119], [120]. Smart city initiatives increasingly employ EMS to regulate public transport systems, street lights, and other city-wide infrastructure in large metropolitan areas. EMS can provide security and energy independence to locations that rely on imported energy or malfunctioning power systems [121], [122]. By incorporating EMS into off-grid MGs to provide power to remote sites disconnected from the central infrastructure, developing countries can reduce their dependency on imported fossil fuels and increase the resilience of their energy systems. Given that energy availability is exactly proportionate to economic stability and output, this development in energy security has major financial consequences [123], [124].

The increased need for EMS technologies in a wide spectrum of sectors, including engineering, maintenance, software development, and energy system integration, is stimulating job growth. As specialized labor to design, install, and maintain smart grids, intelligent transportation systems, and renewable energy projects expands, engineers, technicians, and data scientists are finding opportunities [125]. EMS has a significant economic impact on regions that are heavily involved in renewable energy infrastructure or are undergoing energy transitions. In nations including the United States, Germany, and China, green jobs sectors have grown dramatically. By encouraging a more energy-efficient economy, EMS helps companies flourish in once unstable areas of power, therefore eradicating energy shortages in developing nations [126], [127].

3.3. Comparative Analysis of Centralized, Decentralized, and Distributed EMS Schemes

Three types of energy management exist in MGs: centralized, distributed, and decentralized systems, each with benefits and drawbacks. Optimizing performance and guaranteeing system resilience depend on an awareness of the features of these systems, since they fit the MG's special requirements and design. Within an MG—that is, generation, storage, and load balancing—a centralized EMS is one in which one controller manages all DERs [128], [129], [130]. This kind of technology is commonly used in grid-connected MGs or situations requiring coordination among numerous DERs. It simplifies control and coordinated operation, resulting in better energy flow. However, the central controller's decision-making process and sensitivity to a single point of failure still limit the MG's general adaptability. Notwithstanding their shortcomings, sophisticated systems with varying DERs depend on a coherent decision-making platform centralized EMS provides [131], [132].

In a distributed EMS system, each DER is under independent supervision, while individuals or groups of them handle their own generation, storage, and load balancing. This approach increases defect tolerance and flexibility, allowing any DER to react quickly to local load or generation changes [133], [134], [135]. To guarantee that every DER runs in harmony, increasingly complex communication protocols and algorithms required. Moreover, the absence of a central controller could lead to coordination problems, therefore compromising system equilibrium and efficiency. In general, decentralized EMS offers both benefits and drawbacks [135], [136].

A decentralized EMS is a hybrid system leveraging the finest aspects of centralized and distributed systems. Under conjunction with a higher-level supervisory controller, local controllers in a EMS are in charge of managing particular DERs or groups of DERs. Thus, local controllers can make decisions while still optimizing the system overall [137], [138]. The main features of EMS systems are scalability and robustness, which let one easily include new DERs and provide redundancy. Their maximization of local and system energy flows comes from combining distributed management with central monitoring [138], [139], [140]. Robust networks are necessary to transmit data and coordinate actions between supervisory controllers and local ones, resulting in significant communication needs. Because of their hybrid character, EMS systems are more expensive and difficult to establish and operate than either centralized or scattered ones. Decentralized EMS systems have advantages and drawbacks, really depending on the situation [141], [142].

3.4. Challenges in Integrating Renewable Energy Resources and Maintaining System Stability

As the use of renewable energy sources increases in MGs, new challenges arise in ensuring system stability. Solar and wind power, among other renewable energy sources, can produce quite different outputs depending on the temperature and other external factors. Although renewable energy is crucial in reducing carbon emissions and promoting sustainability, MG voltage and frequency stability can be difficult to reach [143], [144]. Because renewable energy sources are weather-sensitive, there is a demand-supply mismatch covering wind and solar energies. EMS is critical in reducing the effects of these imbalances because it constantly monitors power generation and consumption. ESS allows EMS to store additional energy during high renewable output and release it during low output, preserving power availability even in low renewable generating conditions. MGs need voltage and frequency stability to work [145], [146], [147]. Demand-side management lowers system strain and avoids major voltage or frequency aberrations; automated generation control (AGC) allows real-time generator output changes; and voltage control maintains MG voltage levels. These methods optimize MGs, improving power transmission and protecting sensitive equipment [148], [149].

3.5. Balanced Optimization Techniques and Practical Challenges

EMS optimization solutions aim to balance cost control, energy efficiency, and system dependability. MGs that rely heavily on renewable energy may struggle to reach equilibrium. MGs use multi-objective optimization to balance many goals. One needs sophisticated algorithms to evaluate

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multiple goal trade-offs to find the optimum compromise [150], [151]. EMS also employs stochastic programming to manage input unpredictability like demand swings and renewable energy generation. EMS can optimize system performance in various conditions using this capability. Depending on computational complexity, data availability, and scalability, some optimization tactics may be tough [152], [153]. Many optimization methods are too computationally intensive for real-time applications. Understanding system conditions in rural or underdeveloped areas may be difficult. As MGs develop in scope and complexity, scaling optimization methodologies become harder to use [154], [155], [156].

4. Monitoring and IoT Technologies

Control is one area where IoT technology has rapidly changed energy system monitoring and management. The IoT can help MGs manage their DERs by collecting real-time energy output, consumption, and system performance data. MGs, especially those with a high renewable energy mix, need dependable and stable IoT monitoring solutions [157], [158], [159], [160]. Smart meters, cloud computing, SCADA, and IoT applications are covered in this section. The section also addresses emerging cybersecurity and MG data management challenges.

4.1. IoT-Based Monitoring Systems and Their Application in Microgrids

IoT monitoring systems allow real-time, detailed MG activity monitoring via linked devices, sensors, and communication networks. These systems process and analyze data from load centers, inverters, batteries, wind turbines, and solar panels to optimize MG performance, energy economy, and system resilience [154], [159], [160]. MGs generally use IoT monitoring systems to collect and analyze real-time data from system health, storage, consumption, and electricity production. To avoid downtime, operators can employ predictive maintenance to identify potential issues before they become system failures. IoT devices assist decision-making, energy consumption optimization, waste reduction, and energy distribution by analyzing the MG in different conditions [161], [162].

IoT monitoring improves energy efficiency and demand-side control in MGs. IoT devices employ demand-side management and energy-saving solutions with accurate consumption data. IoT thermostats can control heating and cooling depending on occupancy and outside temperature data, while smart lighting systems operating when a room is empty and automatically switch off or on the lights [163]. Systems for IoT-based lighting, HVAC, and equipment optimization consider operational demands, energy costs, and demand projections, thereby benefiting both industrial and commercial buildings. This optimization helps to stabilize the system and save energy expenditures by lowering demand peaks. MGs largely rely on DERs, which the IoT could assist to link: solar panels, wind turbines, and energy storage devices [164], [165]. By closely monitoring these resources in real time and providing comments on how best to distribute the energy to the EMS, IoT technologies ensure their running efficiency. Sensors connected to the IoT monitor the power production of every panel in solar-powered MGs and highlight any decrease in efficiency caused by dirt, shade, or malfunctioning equipment. IoT solutions allow wind-powered MGs to maximize energy acquisition by detecting wind speed, turbine performance, and changing blade angle [166], [167], [168].

4.2. SCADA Systems, Cloud Computing, and Smart Meters

Many key technologies improve the dependability, scalability, and efficiency of MG monitoring systems that rely on the IoT. Among such technologies are cloud computing, smart meters, and SCADA systems. SCADA systems are absolutely vital in industrial applications if MGs are to monitor and control energy output, storage, and consumption in real-time [169], [170], [171]. A MG control system is made up of sensors and transducers that read information from different parts of the system, RTUs that talk to the sensors, PLCs that use the readings to decide how to run the system, and HMIs that let operators see how the system is doing [172], [173], [174]. When IoT technology and SCADA systems cooperate to give operators finer-grained control and real-time data viewing, better MG management is feasible. SCADA systems can automate MG control in two ways: automatically dispatching energy from storage when needed, and inverter setpoints to ensure voltage stability [173], [175].

MG management is seeing increasing use of cloud computing, which lets one store, process, and analyze vast volumes of data generated by IoT-based monitoring systems. Through cloud platforms, MG operators may get advanced analytics, machine learning algorithms, and predictive models—all of which would be expensive or challenging to apply on-site [176], [177], [178]. MGs run on IoT monitoring systems, and smart meters are absolutely vital in these systems since they give real-time data on energy consumption in homes, companies, and buildings. Their two-way communication skills between the MG and the end-user enable demand-side management, dynamic pricing, and better billing accuracy [171], [179]. Smart meters track, among other things, power quality indicators, peak demand times, and hourly or minute-by-minute consumption statistics. The central EMS or SCADA system receives this data, which aids in load management, enhances energy distribution, and ensures efficient distribution. MGs are able to run more effectively, and users can make better judgments on their energy use thanks to smart meters that give operators and consumers real-time data [175], [180], [181], [182].

4.3. Cybersecurity Concerns and Data Management in IoT-Based Microgrid Systems

MGs running IoT technology have many advantages, but they also bring fresh problems, especially with relation to data management and cybersecurity. Cyberattacks and data breaches are becoming more common as MGs grow ever more dependent on digital communication networks [183], [184]. MGs are particularly vulnerable to cyberattacks, including data tampering, denial of service (DoS) attacks, and unlawful access, as they depend on IoT devices and cloud computing. For consumers and operators, these hazards could lead to financial losses, power interruptions, and damage to machinery [184], [185].

Moreover, MG systems are based on the IoT. Ensuring safe storage and quick access to the massive volumes of data produced by IoT devices—some of which may be private or proprietary—depends on finding effective storage solutions. Data integrity also determines the MG's dependability. Smart meter data could reveal personal information about energy consumption; consequently, privacy protection is rather important [186], [187]. MG operators are looking to distributed data management technologies—including blockchain—to solve these challenges. Blockchain technology could monitor energy transfers in an immutable way to ensure that all data is safe and verifiable [188], [189]. Data encryption, strong authentication systems, regular software upgrades, firewalls, intrusion detection systems, and blockchain integration constitute a multi-layered security strategy operators should follow that helps to reduce the effect of these hazards and better control their data [190]. Implementing cybersecurity policies assists MG operators in ensuring safe data storage, transportation, and processing, as well as defending their systems from intrusions. Adhering to these rules will safeguard future data and ensure the safety of their systems [191].

5. Future Directions

Innovations in control systems, energy management software, and IoT-based monitoring solutions are enabling mass MG industry growth in the next decades. MGs are becoming more resilient and efficient as new control and management trends, including blockchain technology, smart contracts, and deep learning algorithms, find application. Depending on developments in blockchain, AI, machine learning, and the IoT, MG research and development will likely evolve in the next few years [192], [193], [194]. Thanks in part to these technologies, MGs hold promise in fields such as autonomy, efficiency, resilience, and financial viability. These are among the most amazing recent developments in MG control, management, and technological integration. Among these developments are deep learning algorithms as a tool for efficiency improvement, smart contracts as a tool for MG automation, and blockchain's growing relevance in the energy sector [195], [196], [197]. These developments could enable distributed energy trading and peer-to-peer energy markets, thereby changing the global energy picture and making MGs more logical and scalable [198].

5.1. Emerging Trends in Microgrid Control

One area where blockchain technology is finding fresh uses is MGs, originally meant for safe financial transactions in digital currencies like Bitcoin. MGs means of direct links between energy producers and customers, MGs replaces the need for human interactions in utilities or centralized energy markets. Given its distributed character, blockchain presents a fantastic substitute for enabling this kind of energy exchange [194], [195], [199]. Blockchain ensures responsibility and transparency by creating a safe, unchangeable record for every energy transaction. Smart contracts, built on blockchain technology, automate energy trading based on predefined parameters, allowing the use of MGs. Smart contracts enable customers and MG creators to automatically negotiate energy contracts. The blockchain encodes these contracts, which initiate automatic execution upon meeting specific criteria [200], [201], [202]. Three areas smart contracts can enhance MG operations are automation, trust, and openness. Smart contracts also have the potential to reduce costs. Two peer-to-peer energy markets are experimenting with smart contracts based on blockchain technology: Power Ledger in Australia and Brooklyn MG in New York [203], [204].

AI and machine learning algorithms are transforming MG management by enabling predictive maintenance, automatic energy flow optimization, and real-time decision-making that process the data analysis of enormous quantities gathered by DERs, ESS, and IoT devices, AI-driven systems which can improve the general MG stability, dependability, and efficiency [160], [202], [203], [204]. Deep learning algorithms are among the most significant applications of AI in MG management because they can precisely estimate future energy demand, improving energy resource allocation, lowering the need for costly peaking power plants, and reducing energy waste. AI ensures the most economical and least expensive charging and discharging of batteries by optimizing the operation of energy storage systems [205], [206].

MGs enable distributed energy markets—where buyers and sellers of energy do not require centralized utilities—through blockchain technology. These markets let individuals, businesses, and other entities trade the additional power their distributed resources generate [207], [208]. Blockchain technology could alleviate issues with integrating large amounts of renewable energy into traditional centralized networks and hasten the global change to distributed energy systems and renewable energy. Hybrid control systems that combine distributed and centralized control enable MGs to be better controlled [209], [210].

5.2. Potential Research Areas for Optimizing Microgrid Performance

Their continuous improvement is offering several fresh directions of research on MG efficiency, resilience, and scalability. This section emphasizes many significant study domains that will influence MG evolution going forward. MGs have inherent volatility, which renders integrating large amounts of renewable energy challenging [211], [212]. Future research should aim to identify control systems that can withstand significant swings in energy generation while still maintaining system stability. In this sense, one can use adaptive control strategies, advanced energy storage integration, and predictive algorithms for energy generation and demand forecasting [213].

Next-generation energy storage systems are absolutely essential for MGs, particularly for those running renewable energy sources that are not always consistent. The current technology falls short in three areas: cost, lifetime, and scalability; these relate to lithium-ion batteries [213], [214]. Future research should concentrate on developing more affordable, longer-lasting, and more efficient storage solutions without compromising quality. Future research subjects include hydrogen storage, solid-state batteries, and flow batteries, which are all feasible. As the number of MGs rises, coordination and communication among them become increasingly important. Important research topics include cooperation control strategies, blockchain-enabled energy trading, and standard interoperability development. MGs' growing complexity and interconnectedness call for AI's usage in predictive maintenance and system optimization [215], [216], [217]. AI-powered algorithms can analyze data from sensors, IoT devices, and SCADA systems to optimize the MG and project operation when repairs are required. Predictive maintenance systems using machine learning look at sensor-generated data to ascertain when parts are most likely to break. Optimization algorithms track data in real-time and change the system's operation so as to maximize the efficiency of the MG's energy resource use. A self-healing network can keep running well once it finds and isolates a problem [169], [217], [218], [219].

6. Conclusion

MG technology will greatly assist the world in transitioning to more robust and environmentally sustainable energy sources. Along with future directions in this field, this paper reviews recent developments in MG control approaches, EMS, and monitoring technologies based on the IoT. As they grow, MGs will help greatly with the integration of renewable energy sources, energy efficiency improvement, and critical infrastructure resilience enhancement. MG control systems are emerging to make use of innovative ideas, including ASMC, model predictive control, and ANN, in response to the challenges presented by the widespread use of renewable energy sources. EMS allow MG stability, integration of distributed energy resources, and power supply-and-demand balancing. Although there are other EMS systems available with different advantages and drawbacks, distributed EMS is fast becoming the preferred approach because of its scalability and flexibility. Monitoring technologies based on the IoT provide real-time data on energy generation, consumption, and system performance, therefore creating new cybersecurity and data management challenges. Emerging technologies—distributed energy markets, automated system optimization, smart contracts, AI, and machine learning—are ready to change MG operations.

6.1. Recommendations for Future Research

As the energy scene changes, MGs will become more and more important in giving communities dependable, cheap, and ecological energy. If MGs overcome the challenges described in this article and continue to develop in key sectors, they will be very important for the future of the planet's energy system. To fully realize the potential of MGs in the global energy transition, future research should focus on the following areas:

- We are developing control systems that can uphold system stability by enduring fluctuations in demand and the increasing share of renewable energy sources.
- Improved energy storage technologies will help MG energy storage systems be more scalable, cost-effective, and efficient.
- We are enhancing cooperative control and communication among MGs so they may cooperate to maximize energy flows and raise system resilience.
- AI-driven algorithms for predictive maintenance and system optimization enable MGs to operate consistently with less downtime and improved energy economy.

6.2. Research Contributions

The efforts significantly advance the knowledge and practice of IoT technology, EMS integration, and MG control methodologies. The primary contributions of this study are summarized as follows:

- One of the key outputs of this work is the careful analysis of both conventional and innovative control techniques in MGs. Classifying the applications into two main categories—conventional methods and advanced techniques—the paper provides a thorough evaluation of their uses, advantages, and constraints. Conventional techniques consist of PID controllers, droop control, and multi-agent systems. Advanced methods include AI-driven systems, ASMC, and model predictive control. Particularly in places with significant penetration of renewable energy, researchers and engineers striving to improve MG control systems will find this to be a valuable resource.
- Crucially, research on MG management and control systems including blockchain, smart contracts, and deep learning algorithms must include blockchain, smart contracts, and deep learning algorithms. Through an analysis of how these technologies might open the path for P2P energy trading and distributed energy markets, this paper adds value to the sector by improving system security, transparency, and efficiency. As scientists look at hybrid control systems that

might combine scattered decision-making with centralized optimization, MGs are growing more scalable and durable.

- This paper emphasizes the importance of monitoring systems based on the IoT so that MGs can gather data in real time and maximize their performance. Results reveal that, together with IoT devices, cloud computing and supervisory control and data acquisition (SCADA) systems improve system stability and energy economy. We also address important issues like cybersecurity and data management, and provide strategies to prevent such threats.
- This paper identifies key areas for future research, such as advanced energy storage technologies, predictive maintenance driven by AI, and resilient control strategies, so laying out a plan for engineers and researchers to address the always shifting issues of MG optimization and integration in the dynamic energy market.
- Academics and business will greatly value this study because it lays the groundwork for future advancements in MG control, management, and technological integration.

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