Literature Review of Microgrid Control Functions and Services

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Abstract

This paper presents a comprehensive literature review of microgrid control functions and services that address complexities related to integrating renewable energy, transitions between grid-connected and islanded operational modes, and the need for reliable power supply. We adopt a structured review approach focusing on the key domains of microgrid control, including energy management, protection and control, resiliency, ancillary services, and data management. The review provides analysis of relevant articles, reports, and case studies to synthesize current practices, technologies, and theoretical frameworks. The main findings of this study suggest a significant advancement in energy management strategies for balancing generation and consumption, optimizing operations, and managing uncertainties associated with renewable resources. The analysis of resiliency strategies aligns perfectly with the effectiveness of load shedding, system reconfiguration, and contingency planning in maintaining stability under extreme conditions. Ancillary services, including demand response, power reserves, and black-start capabilities, are shown to be critical for sustaining microgrid reliability. The study also emphasizes the emerging role of data management in enhancing operational efficiency through advanced standards, security protocols, and real-time analytics. However, persistent gaps and challenges exist in current microgrid control practices, mainly in integrating adaptive, real-time control mechanisms. Future research directions include insights into developing integrated control systems that leverage artificial intelligence and machine learning to enhance reliability, efficiency, and resilience. The findings in this paper may guide evolutionary microgrid technologies that support global energy transition and sustainability objectives.

Keywords: Ancillary Services; Controllers; Energy Management; Microgrids; Literature Review; Protection; Resil

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1. Introduction

The global electric power industry is undergoing a major transformation towards renewable energy resources. The objective is to meet rising energy demands and address non-renewable power generation's environmental impacts. About 63% of global power generation, estimated at 27 Terawatt-hours, comes from fossil fuels that produce billions of tons of carbon dioxide emissions annually. These emissions largely contribute to climate change and global warming, which lead to extreme weather conditions and the expansion of wildfires. As a result, major grid outages occur, leaving millions without reliable access to electric power. The growing power outages, dioxide contamination, and the need to provide remote communities with reliable power resources have motivated the rise of microgrids as evolutionary small-scale renewable power grids. Different shapes and sizes of microgrids exist at sites that belong to urban and rural communities, military bases, university campuses, healthcare institutions, and commercial and industrial organizations. The growth of microgrids is unprecedented. For instance, the number of microgrids in the US alone has grown from 166 in 2018 to 660 in 2022, with an estimated market size of 6 billion US dollars. However, the market size of worldwide microgrids will grow to reach about 63.1 billion US dollars in 2027.

Integrating renewable energy into electric power grids and implementing microgrids requires careful consideration of policy frameworks, financial mechanisms, and technological advancements. Several studies from Energy Studies Review provide valuable insights into these areas and align with the core themes of energy management, policy effectiveness, and economic impacts in renewable energy transitions. For example, (Laitner et al., 2006), (Painuly et al., 2006), and (Kancs, 2006) explore uncertainties in the US energy technology landscape, financing mechanisms for renewable energy, and policy evaluation of their adoption while examining energy security and future growth of power generation, (Gedes et al., 2010). In addition, (Almozaini, 2020) investigates the macroeconomic impact of renewable energy adoption in China, demonstrating how sustainable energy transitions and investment in microgrid technologies can drive economic development and growth in developed and developing markets.

Much research addresses microgrids because of their importance and rapid growth. Microgrids include a mix of renewable resources, conventional generating units, and energy storage systems that interconnect and operate to supply power to end users. Renewables are intermittent, and microgrids operate in both islanded and grid-connected modes. As a result, they continuously undergo frequent and abrupt dynamic transitions, during which they must provide stable and reliable power to balance load at consistent voltage and frequency. Microgrid control is, therefore, complex. A sample review of centralized and decentralized control has been published by (Hirsch *et al*., 2018) and (Coelho *et al*., 2017). Recent studies have also explored reviews of specific applications and functions of microgrids. For example, (Khan et al., 2024) provide a comprehensive review of microgrid energy management strategies while considering electric vehicles, storage systems, and AI technologies. The review by (Ahmad et al., 2023) discusses how microgrids deliver dependable and cost-effective energy to specified locations, such as residences, communities, and industrial zones. (Albarakati et al., 2022) evaluates microgrid control strategies in detail, classifying them according to their level of protection, energy conversion, integration, benefits, and drawbacks. It also discusses the role of IoT and monitoring systems in energy management and data analysis.

While existing literature reviews have offered valuable insights to the microgrid research community, they tend to be broad and general, often needing more specifics to tackle the complexities of microgrid control. This paper contributes to a more focused and structured review to address, most and foremost, the essential functional requirements of microgrid control as defined by (Liu et al., 2016) and further expanded by (Liu et al., 2024). The critical domains of the functions are energy management, protection and control, resiliency, ancillary services, and data management. The novelty of this paper lies in its comprehensive analysis and evaluation of control functions and services in these domains. This review identifies the fundamental shortcomings, gaps, and challenges in microgrid control practices and technologies to guide future research to advance microgrid control technologies, ultimately supporting more reliable and resilient energy systems.

The remainder of this paper is organized as follows. Section 2 of this paper reviews the microgrid architecture and the critical requirements of microgrid control. Sections 3 to 7 provide a detailed literature review of the specific functions and services of energy management, protection and control, resiliency requirements to address reliability and stability during extreme conditions, ancillary services necessary, and data management, respectively. Section 8 presents the conclusions and outlines avenues for future research.

2. Microgrid

The authors (Dan et al., 2012) define a microgrid as a group of interconnected loads and distributed energy resources in a single controllable entity that can connect and disconnect from the main grid. A distributed energy resource is a small-scale generating unit that operates locally and produces power from wind, photovoltaic, geothermal, hydro, biomass, natural gas, and fuel cells. It also refers to a storage battery, an electric vehicle, and a controllable load. A microgrid operates either as a stand-alone islanded power system or in connection to the utility grid through a point of coupling.

The literature presents a variety of microgrids, introducing their concept (Lasseter, 2001) and (Lasseter, 2002) as a new paradigm for defining distributed generation, control and protection, and energy management in a single controllable system. The concept adapted to different topologies around the institutional, remote, military, industrial, community, and utility microgrids (De Jaeger, 2017) (Abhishek et al., 2018). Microgrids come in different sizes and operate as islanded or grid-connected AC, DC, or hybrid power systems (Guerrero and Kandari, 2022). AC microgrids are conventional and can easily integrate with the utility grid. DC microgrids can easily integrate with DC-based renewables, storage, and loads. The merits of AC and DC microgrids combined in a hybrid structure are becoming common in community microgrids.

A microgrid typically transits between grid-connected and islanded modes. In a grid-connected mode, the microgrid operates in sync with the utility grid, trading in and out power deficit and excess. In an islanded mode, the microgrid thrives on balancing generation and load in real-time and maintaining reliable power flow and stable voltage and frequency (Pomodakis et al., 2020) (Awal et al., 2020). In remote and fragile areas, the islanded microgrids are isolated, have no interconnection with the utility grid, and operate as stand-alone power systems.

Microgrids pose operational and economic uncertainties in renewable power generation, weather forecasts, and power demand profiles. Power flow at the point of common coupling with the utility grid is bidirectional and can reverse at the low-voltage distribution feeders. Stability issues arise during the transition between islanded and grid-connected modes and generation and load disturbances and can lead to severe voltage and frequency deviations (Li et al., 2023). Therefore, conventional utility grids' generic models of control technologies are invalid. A breadth and depth of technologies mitigate microgrid uncertainties to provide power, improve reliability, reduce carbon emissions, and lower operational costs using the renewable generation mix, energy storage, and responsive power demand (Tsikalakis et al., 2008).

Table 1. Key functions and services of microgrid control.

Category	Functions and Services
Energy Management	• Energy Balancing; Energy Market Participation; • Operation Optimization; Forecast; Energy Storage Control; • State Estimation; Backup Plan for Islanding Operation • Two-Way Communication; EV Charging and Discharging Management; • Load Balancing; Uncertainty Management of Renewables; Scalability
Protection and Control	• Relay Protection and Coordination • Frequency Control in Islanding Mode • Volt/ VAR and Reactive Power Control • Grid-Connected to Islanding Transition
Resiliency	• Severe Events • Load Shedding • Reconfiguration • Backup Plan
Ancillary Services	• Demand Response • Power Reserves and Congestion Management • Spinning Reserve and Power Balancing • Reactive Power and Power Factor Support; Black-Start Capacity
Data Management	• Standards and Database Design • User Authentication and Event Logging • Security Issue Reporting and Alarms

Much research has been devoted to identifying microgrid operation and control's essential requirements and technologies (Xiao et al., 2015), including the specific functions widely accepted in the microgrid industry (Liu et al., 2016, 2024). The functions are classified into five categories: energy management, protection and control, resiliency, ancillary services, and data management. Table 1 shows the specific functions and services in each domain. In (Alaqtash et al., 2023) and (Al-Agtash et al., 2023), we have explored implementing some functions using AI-driven predictive models and SPADE-based multi-agent frameworks. While these studies contribute to the implementation of intelligent control, this paper differs significantly by providing an extensive review of microgrid control functions and services rather than their specific implementation.

3. Energy Management

The primary goal of energy management is to balance generation and consumption in a steady state through strategies and tools that maximize efficiency and enhance competitive positions (Capehart et al., 2020). The process involves recording energy use at the building or facility sites and using the historical data to implement energy management successfully through curtailment and load shaving. Home automation systems may embed these tools and strategies to efficiently control home energy consumption and increase consumer participation using advanced analytics, actionable information, and control features while ensuring ease of use, availability, security, and privacy (Aman et al., 2013). The critical requirements for an energy management system include but are not limited to the following:

- Seamless integration with user activities and monitoring consumption.
- Real-time data acquisition and analysis of appliances' voltage and current to provide more accurate AI-driven curtailment and decisions at peak loads.
- Seamless access to power generation and consumption data through applications.
- Machine learning and decision-making through integrating data on temperature, humidity, light, occupancy, and other sensors.
- Control automation via secure data communication, authentication, and authorization.

These requirements define a set of functions and services in the energy management domain, including Energy balancing, Energy Market Participation, Operation Optimization, Forecast, Energy Storage Control, State Estimation, Backup Plan for Islanding, Two Way Communication, EV (Electric Vehicle) Charging and Discharging Management, Load Balancing, Uncertainty Management of Renewables, and Scalability. The following subsections give a literature review of each of these functions and services.

3.1 Energy Balancing

References (Jiang et al., 2013) and (Moutis et al., 2016) present details of energy balancing services in grid-connected and islanded microgrids and decision-tree planning tools. The standard mechanisms of energy balancing are unit commitment, economic dispatch, and optimal power flow. Unit commitment is presented in the context of hybrid intelligence (Dey and Bhattacharuua, 2019), optimization (Nemati et al., 2018), quantum distribution (Nikmehr et al., 2022), and stochastics (Alvarado-Barrios et al., 2020). Microgrid economic dispatch is presented as a non-linear convex cost model (Bhattacharjee & Khan, 2018) and in the pursuit of renewable energy resources (Antillan-Lemus et al., 2019). Finally, the details of the optimal power flow of microgrids are reviewed by (Abdi et al., 2017). (Alvarado-Barrios et al., 2020) adds energy storage elements, and (Levron et al., 2013) add a dynamic multiplier when solving the optimal power flow problem for microgrids. These papers present innovative approaches to energy balancing in microgrids but need more emphasis on real-time adaptability, computational complexity, and scalability for large-scale implementation.

3.2 Energy Market Participation

Microgrids are generally integrated with utility grids and actively participate in the energy market. The authors (Prinslo et al., 2018) present transactive energy management principles in rural village microgrids using multi-agent systems. The design of mechanisms of transactive microgrids (Akter et al., 2020) and bidding strategies (Haddadipour et al., 2022) represent the core of microgrid energy market participation. While these references offer innovative solutions to transactive microgrid mechanisms, the models lack technologies to handle market volatility and integration with diverse energy resources.

3.3 Operation Optimization

This functionality is core to energy management to optimize operation and energy usage. The primary services include peak shaving, valley filling, loss optimization, and conversation. Vehicle-to-grid technologies (Attou et al., 2021) and strategic bedding of load aggregators (Liu et al., 2021) are presented in detail as essential services for peak shaving. (Iqbal et al., 2021) and (Jiang et al., 2022) introduce novel approaches to loss minimization in community and parallel connected microgrids. Conservation voltage reduction scenarios and case studies have been discussed in detail as promising technologies for energy management and optimization (El-Shahat et al., 2020) and (Singh et al., 2020). Research needs more insights into real-world applications in a variety of grid configurations.

3.4 Forecast

Accurate load forecasts and wind and solar renewable power help in efficient planning and management of energy through optimal scheduling of generation-load balance at various timestamps. References (Semero et al., 2020) and (Tayab et al., 2020) present neural networks and wavelet packet transform for short-load forecasting. (Aslam et al., 2021) review details of deep learning approaches for load renewable energy forecasting. (Rodriguez et al., 2020) present the forecasts for wind power using artificial neural networks, and (Heydari et al., 2019) demonstrate a promise for wind and solar power, yet uncertainties in weather patterns persist. (Zhen et al., 2021) and (Mellit et al., 2021) present similar neural networks and deep learning methods for photovoltaic power forecasting.

3.5 Energy Storage Control

The mechanisms for islanding and battery storage operations and control in energy and ancillary markets are discussed by (Kazem et al., 2017). Stochastic modeling and energy storage-based intelligent frequency control and optimal energy storage are presented in (Mu et al., 2019) and (Malyz et al., 2014). (Arani et al., 2019) provide a thorough review of energy storage control methods, although challenges remain in optimizing real-time performance and integration with diverse grid conditions.

3.6 State Estimation

Optimization and control require higher state estimation accuracy of active microgrid distribution systems. (Manousakis & Korres, 2021) present state estimation for embedded microgrids, while its IoT-based implementation is discussed by (Rana et al., 2018). (Adi et al., 2020) and (Lin et al., 2019) introduce short-term memory networks and robust state estimation techniques, although challenges remain in handling real-time data and maintaining reliability under dynamic microgrid conditions.

3.7 Backup Plan for Islanding Operation

A robust back plan is crucial during contingencies to maintain microgrid operations. Islanding prevents failures and stabilizes frequency and voltage profiles, enhancing microgrid resilience. (Wu et al., 2019) provide a detailed analysis of contingency planning to identify backup storage resources. (El-Biadairi et al., 2020) discuss optimal sizing and frequency control of storage systems, while (Sati & Azzouz, 2021) offer viable strategies for coordinating islanded microgrids. Yet, real-time implementation and scalability remain a challenging research problem.

3.8 Two-Way Communication

Effective communication between the energy management system and the controllable resources and loads is crucial to providing timely control signals for various microgrid devices. (Mateska et al., 2018) present a communication scheme for controllable load based on a gossip algorithm, while (Pourbabak et al., 2017) explore communication protocol for control and energy management system. However, both approaches need scalable and real-time responsiveness in larger, more complex microgrid environments.

3.9 EV Charging and Discharging Management

Electric Vehicles are effective forms of energy storage when their charging and discharging are adequately managed within microgrids. (Li et al., 2021) present vehicle-to-grid management for multi-time scale grid power balancing, while (Yu et al., 2022) provide a comprehensive review of architectures and technologies for vehicle-to-grid operations. (Qin et al., 2020) introduce an adaptive bidirectional droop control for electric vehicle charging in microgrids. Yet, challenges remain in optimizing real-time control and grid integration.

3.10 Load Balancing

(Sagar and Debela, 2019) provide strategies and implementation schemes for optimal load balancing, which was further advanced by (Karthik & Kavithamani, 2021) using a fog computing-based deep learning model for optimizing load balancing between interconnected microgrids. (Mehta and Basak, 2021) review various control techniques, but achieving real-time optimization and scalability across diverse microgrid configurations remains an open research problem.

3.11 Uncertainty Management of Renewables

Renewables are intermittent, leading to uncertainties in renewable power production across different time scales. Proper management of these uncertainties and the analysis of their impact on microgrid resilience are critical aspects thoroughly discussed by (Hussain et al., 2019) and (Fouladi et al., 2020). However, challenges remain in developing robust strategies to mitigate the variability and ensure consistent microgrid performance under fluctuating renewable inputs.

3.12 Scalability

The scalability of microgrids is a critical factor in modern grid infrastructures, achieved by coordinating multiple or community-networked microgrids in clusters to enable renewable power exchange in transactive energy markets. (Janko & Jhonson, 2018) discuss scalable multi-agent negotiation and decentralized control, while (Yu et al., 2022) discuss the clustering architecture of microgrids. Despite these advances, ensuring efficient coordination and real-time responsiveness in more extensive networks remains challenging.

4. Protection and Control

The primary goal of protection is to ensure stable voltage and frequency control across the microgrid network. Essential functions include relay protection and coordination, frequency control in islanding mode, volt/ VAR and reactive power control, and seamless transitions between grid-connected and islanding modes. The following subsections present a detailed literature review of each of these functions.

4.1 Relay Protection and Coordination

While relay protection and coordination offer essential fault detection and system reliability for microgrids, several challenges remain. (Farkhani et al., 2019) discuss common directional overcurrent relay protection, but its efficiency may be compromised in complex, bidirectional power flow environments. In essence, we discuss the technical literature of Short-Circuit Protection, Ground Protection, Fault Location, Isolation and Service Restoration, Disturbance Logging, Time-Tagging, and Analysis as the primary service functions in the relay protection and coordination category.

(Almutairy & Lluhaidan, 2017) provide insights on short-circuit protection as an essential bi-directional switching device based on freewheeling or solid-state voltage interruption to maintain system reliability and continuity when a fault occurs. (Bhadra et al., 2021) introduce advanced protection schemes with AI for short-circuit faults, yet their implementation in dynamic, multi-source microgrids remains complex. They used a hierarchical generative model based on convolutional operation and feature extraction process. (Yu et al., 2016) present a DC short circuit fault analysis and protection of microgrids by detecting transmission lines' input and output currents and identifying the corresponding differential current as a tool to locate and isolate the fault lines

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Ground Protection, as described by (Nassif, 2020), is a practical scheme for the reliable protection of power systems. In microgrids, the design and size of ground sources must meet the needs of distributed energy sources, extensive solar facilities, storage systems, and wind turbines in islanded scenarios. (Guo et al., 2016) present an overview of fault location, isolation, and service restoration in a distribution management system context to support self-healing power distribution systems. Microgrids generate bidirectional power flow and require a more sophisticated protection scheme for fault location, isolation, and service restoration based on a communication-based fault location methodology and restorative system (Rivera et al., 2019).

Disturbance logging, time-tagging, and analysis are other essential relay protection and coordination services. (Feng et al., 2017) extract log patterns to detect anomalies and power quality disturbances using machine learning detective models. The models integrate collection among harmonic monitoring indicators and perturbation records. (Liu et al., 2014) detect anomalies in frequency disturbance and monitor records by examining various correlations in the record elements. While these schemes are promising, they still face challenges in handling real-time data and improving detection accuracy across varied microgrid setups.

4.2 Frequency Control in Islanding Mode

The dynamic responses associated with the frequency control in microgrid islanding transition have been a challenging research problem. (Norbu & Wangdee, 2019) offer valuable insights into sensitivity analysis and automatic control and load-shedding strategies. (Neves et al., 2015) provide optimum time analysis for switching the operation control mode of microgrids after unintentional islanding occurs using classical and fuzzy control strategies for voltage, frequency, and active and reactive powers. (Liu et al., 2014) introduce engine-based generation units for frequency regulation in the islanded mode of microgrids equipped with advanced controls. They proposed a unique adaptive dynamic programming approach to optimally reject uncertain disturbances in load and operating point variations and reduce the impacts of nonminimum phase dynamics caused by the engine delay.

Steady-state device Level Control based on Droop/V-f/PQ Control and Coordinated Control of Multiple Devices within short intervals are the main functions in the frequency control category. (Davari et al., 2021) present an active DC bus signaling method for managing multiple energy storage devices in a DC microgrid beyond the conventional way, such as droop control. It has the advantage of accurate, current sharing through the master controller, which shares with each slave battery bank. It actively alters the DC bus voltage levels to monitor the current change. (Li et al., 207) developed a benchmark distribution system to investigate the control and energy management of distributed generation at a residential level using three single-phase microgrids. It accommodates microgrids operating in both grid-connected and islanded modes.

Transient Device Level Control and frequency smoothing are other functions or service areas. (Mathew et al., 2019) proposes a multi-level control and optimization scheme for an islanded microgrid with a distributed compensation system and central supervisory controller. A battery-supercapacitor system manages system transients during load perturbations. (Liange & Sun, 2019) provide analysis on frequency smoothing during the transition from a grid-connected mode to an islanding mode. The study reveals a linkage between voltage and phase pre-synchronization when solving the problem of frequency jumps when connecting to the grid. (Wei and Mantooth, 2021) used resonant converters with a wide range of input voltage for frequency smoothing and control based on a morphing control topology. The results have shown progressive power to overcome frequency and transient voltage mismatches during the islanded and grid-connected transitions.

Low-Frequency Ride-Through and Emergency Load Shedding are other functions or service areas. In this area, (Babu & Padhy, 2022) and (Ni et al., 2023) provide a detailed investigation of grid synchronization during low-voltage and low-frequency rides. Controls were introduced based on phase-locked loop, impedance damping, phased shifting transformer, and three-phase rectifier to eliminate harmonics and smooth voltage and frequency variations. Furthermore, (Wang et al., 2021) and (Zhang et al., 2021) present emergency load shedding to prevent frequency drops and power outages. Data-driven and deep Q learning constitute the main features of such a mechanism to guarantee adaptability under different operating environments.

Yet the effectiveness of the above schemes in highly variable and decentralized microgrid environments requires further investigation to ensure real-time adaptability and robustness.

4.3 Volt/ VAR and Reactive Power Control

Voltage support and control are essential for the protection and control of microgrids to overcome the lack of reactive power sources. Inverter control (Kongjeen et al., 2020), index-voltage/var control capability (Chen et al., 2019), and mixed integer linear programming (Gupta et al., 2021) represent effective strategies for reactive power balance and voltage stability control. (Wu and Wang, 2019) investigated the steady-state device level droop/V-f/PQ control based on a model predictive control for a 4- 4-level T-type nested neutral point clamped converter. They introduced a finite control set optimization process and a simplified capacitor voltage balancing strategy.

(Cao et al., 2021) investigated the use of optimally coordinated load tap changers to coordinate the two voltage control devices. (Deilami et al., 2013) present a genetic algorithm-based optimal scheduling of the load tap changers and switched shunt capacitors is presented while considering random charging of plug-in electric vehicles. Voltage control based on distributed energy resources and capacitor banks use an iterative distributed algorithm (Wang et al., 2015) or a wide range of capacitor banks, as discussed by (Hasibuan et al., 2019) and (AlAhmad & AlDahmi, 2021). Meanwhile, (Caramanis et al., 2016) provide a unique approach based on co-optimizing real and reactive Power. Its parallel architecture enables tractable marginal pricing dependent on optimal generation, loads, and scheduling of energy resources.

Voltage fluctuation is a challenge in microgrids because of the intermittence of renewable resources. Research has addressed the management of voltage fluctuations. (Sadek et al., 2021), for instance, used a stochastic energy management system to demonstrate day-ahead non-linear optimization that considers a variety of renewable resources, energy storage, and diesel generators. (Jeong et al., 2022) established high-voltage direct-current systems and voltage source converters to suppress voltage fluctuations based on optimal secondary voltage control. (Jintaka et al., 2019) investigated the impact of voltage regulation at low voltage levels generated at renewable photovoltaic resources. The authors concluded that installing renewables close to power transformers can achieve better voltage fluctuations. (Pilehvar & Mirafzal, 2020) present a somewhat modified control of battery storage systems to mitigate voltage fluctuations of islanded microgrids during transients. In similar settings, (Kim et al., 2016) offer a battery storage system that generates a nominal frequency and a Q/P droop control to reduce the voltage-damping effect.

4.4 Grid-Connected to Islanding Transition

Microgrids generally operate islanded and grid-connected and require smoothing control strategies to overcome voltage, current, and frequency fluctuations during the transition. (Ganjian-Aboukheili et al., 2020) present a linear voltage control with capacitor feedback and a modified drop control for a smooth islanded transition. (Li et al., 2017) introduce a predictive control model to enable ancillary services through power electronics and compensators and support seamless transition through synchronization and phase adjustment algorithms. An intelligent inverter solution has been demonstrated by (Zapata et al., 2020) for regulating the power and phase during the transition. (Krishnan and Gaonkar, 2013) present a control scheme based on detection, synchronization, and encloser algorithms for passive islanding. (Krishnan and Goankar, 2013) demonstrate a derived controller that manages internal production to zero the tie-line active and reactive power flows and suppresses perturbations. Intentional islanding transition control (An et al., 2018) achieved flexible islanded transition using a coordinated control of various renewable resources and loads.

On the other hand, unintentional islanding transition control requires better resource optimization and coordination. (Wang et al., 2021) introduced artificial machine learning control to enhance voltage and frequency stability. (Vyas et al., 2016) present a predictive (rather than a reactive) machine learning approach for preemptive islanding detection to trigger alters to grid-connected inverters for actions such as tripping one or more circuit breakers. (Wang et al., 2021) provide coordinated control between soft open, active distribution points, renewable resources, and energy storage to suppress power fluctuations during the transition. (Khan et al., 2022) present a hybrid control with machine learning to support intentional and unintentional islanding and effectively monitor grid conditions and control to make it less vulnerable to faults and abnormalities.

5. Resiliency

Resiliency is essential to microgrid control to ensure continuous operation and survival under disturbances or severe weather conditions. The following subsections present the technical literature on resilience in extreme events, load shedding, reconfiguration, and backup plans.

5.1 Severe Events

(Eskandarpour et al., 2016) propose a unit commitment scheme with resilience constraints using mixed integer linear programming. The objective is to guarantee a resilient power supply under disturbances and outages. (Song et al., 2022) investigate the resilience of intelligent power grids under extreme weather, natural disasters, human-made malicious attacks, and social crises. Enhancement strategies are proposed based on active distribution networks, integrated energy systems, and flexible energy resources. (Yan et al., 2022) propose a decentralized control to operate renewable microgrids in extreme conditions through load prioritization, sectionalization, and coordination of renewable resources.

5.2 Load Shedding

Load shedding is the primary function of resiliency. (Bayhan, 2018) studied how to protect microgrids when a fault occurs in the main grid while continuously supplying the critical loads using intelligent control and predictive load shedding algorithm. (Wang et al., 2021) propose a coordinated load-shedding control based on double-Q learning and Markov's decision to achieve balance in power supply and demand and stability of frequency and voltage during unintentional islanding. (Silva et al., 2015) apply an agent-based model to forecast generation and load, optimize demand via load prioritization, and implement proper means of shedding and rescheduling.

5.3 Reconfiguration

Coordinating energy resources with reconfiguration is another function of microgrid resilience. (Majee et al., 2018) introduces the Internet of Things in reconfiguring microgrids when faults occur, energy use patterns change and an energy resource is added or removed. (Dong et al., 2022) provide a mechanism to integrate transactive energy and self-healing control in distribution networks connecting renewable resources for better voltage regulation and service restoration. (Home-Ortiz et al., 2022) present a restoration scheme to improve the resilience of distribution networks through dynamic reconfiguration, islanding dispatchable renewable resources, and prepositioning emergency power generating units.

5.4 Backup Plan

A backup plan for resilience is another function in this service area of microgrids. (Lian et al., 2021) investigate a backup plan in the event of cyber and denial-of-service attacks on distributed control systems. The plan uses a distributed resilient control scheme for bus voltage restoration and optimal current sharing. (Shaker et al., 2021) address inadequate reactive power generation in extreme conditions using stochastic modeling of two-stage decision-making based on here-and-now and wait-and-see processes. (Nakiganda and Aristidou, 2022) provide a resilient operational plan incorporating frequency and voltage constraints for the sensitivity of active and reactive power injections during catastrophic events. (Raoufi et al., 2020) review resilience metrics with references presenting rich technical literature on microgrid resilience addressing resilience related to networked microgrids, self-healing, formation, proactive management, and design.

6. Ancillary Services

Like large-scale power grids, microgrids offer ancillary services to maintain reliable and secure power balance, voltage, and frequency. They include day-ahead and real-time demand response, power reserves, congestion management, frequency regulation, spinning reserves, phase balancing, active and reactive power, power factor support, and black-start capacity. The following subsections review the technical literature on these services.

6.1 Demand Response

(Chen et al., 2021) present demand response scheduling a day ahead for different residential customers based on customers' comfort and power demand requests. (Arun et al., 2022) introduce a demand response based on priority-based load shifting to reduce peak load and the need to operate high-cost and emission generators. (Kopsidas et al., 2017) introduced probabilistic scheduling of day-ahead demand response that considers a ranking of load reduction based on values and expected power outages. The optimization criteria consider customers' position in the Monte Carlo simulation of both energy and reserve markets. (Duan, 2016) demonstrate a price-based demand scheduling model a day ahead to enable an elastic power demand highly responsive to the market clearing price. (Equabal et al., 2021) investigated demand response in a day-ahead energy market setting that involves photovoltaic virtual power plants. The authors use a load-shifting mechanism between excessive and no excessive time zones to reduce energy costs. (Vidyamani & Swarup, 2018) introduced the concepts of active and transactive control of residential responsive load in real-time as an effective dynamic demand response strategy. (Behboodi et al., 2016) investigated the integration of electric vehicles based on transactive energy control while considering real-time energy prices to reduce the cost of charging. Further research is required to address real-time energy pricing in the grid-connected mode.

6.2 Power Reserves and Congestion Management

Active power reserves are essential for supporting dynamic frequency response in microgrids. (Cao et al., 2020) proposed a fast frequency response that is event-driven. They used a recovery scheme that monitored the deficit of active power, costs of controls, and reserves of energy. (Wu et al., 2020) provide a review of dynamic distribution networks for managing transmission congestion, coordinated scheduling, and dynamic reconfiguration and islanding. (Del-Rosario-Calaf et al., 2014) investigated the impact of electric vehicles on transmission congestion and introduced clever charging mechanisms while considering various constraints and maintaining reliability and quality of services. (Dai et al., 2019)] present analytical aggregated frequency response for wind turbines using small signal analysis. (Sun et al., 2022) used the sharing of reserves for frequency regulation control during emergency events. The reserves are divided into procured commercial contracts and purchased regular market-based reserves. Similarly, integrating these strategies into diverse grid environments while ensuring real-time responsiveness remains challenging.

6.3 Spinning Reserve

(Narimani and Goldani, 2015) investigated spinning reserve support with the active participation of renewable resources in multiple ancillary service markets. They used an adaptive neuro-fuzzy inference system to predict uncertainties and make decisions. (Li and Li, 2012) studied spinning reserve capacity in wind turbines and used Lagrangian relaxation for power scheduling while considering reliability constraints. (Liu et al., 2021) introduce a reserve scheme for islanded microgrids using a value-at-risk conditional model to forecast deviations in load and supply with extensive random sampling scenarios and risk-based. (Tong and Wang, 2015) demonstrated the use of Monte Carlo simulation to ramp wind turbines in the power dispatch while considering the expectation of a loss of power and curtailment of wind power. Real-time adaptation remains a key area for fully implementing these strategies.

6.4 Dynamic Power Balancing

(Heo et al., 2016) propose a power conditioning system for a single-phase microgrid that uses a dual photovoltaic array, energy storage, grid-connected inverter, and battery charger. (Raza and Jiang, 2022) introduce analytical analysis for the dynamic balancing of single-phase microgrids that involve rooftop photovoltaic systems, battery storage, and plug-in loads. Both studies contribute to improving energy efficiency and stability in single-phase microgrids, though challenges remain in scaling these solutions for larger and more complex systems.

6.5 Reactive Power and Power Factor Support

(Olowu et al., 2021) demonstrate the use of smart inverters for voltage control in microgrids. Active and reactive voltage settings are computed using rule-based sensitivity optimization and integrated into the optimal power flow algorithms. (Howlader et al., 2021) present optimal reactive power flow for the proper settings of photovoltaic inverters. The objective is to provide curtailment controls to support real-time voltage and frequency adjustments. Power factor correction is introduced in (Pachanapan, 2019) to meet grid-prescribed values and to avoid high-cost reactive energy bills in grid-connected microgrids. The correction is provided through reactive power compensation by photovoltaic converters. (Liou et al., 2011) use a converter-based power factor correction with load conditioning and fixed frequency switching, offering an additional method for enhancing grid stability. The practical challenges remain in fully integrating these solutions in real-world microgrid scenarios.

6.6 Black-Start Capacity

(Yi et al., 2022) presents a black start power supply that accounts for uncertainties, energy storage, and recovery time constraints while enhancing restoration efficiency. (Liu et al., 2018) uses a set of diesel generators as a lack of start for a fast and reliable recovery of power supply after the blackout. Both approaches improve resilience, though further refinement is needed to optimize performance across different grid configurations and outage scenarios.

7. Data Management

The functions in data management address interoperability and data management and include standards and database design for the interoperability of intelligent electronic devices, user authentication and event logging, and security issue reporting and alarms. The specific data management research in microgrids does not exist but can be easily adapted.

7.1 Standards and database design

(Falk, 2019) presents the international standard IEC 61850 for the interoperability of intelligent electronic devices. (Balan et al., 2019) demonstrates the application of IEC 61850 in substation automation and intelligent electronic devices. The authors discuss the interoperability of third-party vendors in realizing the advanced communication capabilities between diversified components in power grids. (Hadbah et al., 2014) illustrate the use of IEC 61850 in adapting, configuring, and deploying several intelligent electronic devices from different vendors. (Padiya et al., 2015) examine how to handle essential sensor data interactively through various storage mechanisms such as property and partitioned table, triple store, column store, and data ware hybrid storage systems. A challenge remains to ensure seamless integration and efficient data handling in complex multi-vendor environments.

7.2 User Authentication and Event Logging

(Kim, 2016) presents a user-centric authentication scheme to provide a consistent user experience, streamlined messaging, and secure authentication. (Sim et al., 2019) introduce a likelihood-based imputation scheme for event logs with missing data. The scheme repairs imperfections in event logs to obtain high-quality analytical results. Yet, research highlights the need for further refinement to handle scalability and complexity in real-world microgrid applications.

7.3 Security Issue Reporting and Alarms

Software vulnerability analysis is a crucial aspect of ensuring security in microgrids, though there is no specific microgrid domain for this service area. In general, (Goseva-Popstojanova & Tyo, 2017) identify security-related software bugs and classify them into key vulnerability classes such as exception management, memory access, risky values, and new entities. These classifications provide valuable insights but highlight the need for tailored security solutions specific to the unique operational challenges of microgrids.

8. Conclusions

This paper presented an extensive review of microgrid control functions, with a specific focus on energy management, protection, resiliency, ancillary services, and data management. The complexity of these control functions arises from the diverse generation sources, renewable intermittency, integration of energy storage, and the operational challenges of abrupt transitions between islanded or grid-connected modes. The literature reviews given in this paper highlight significant advancements in microgrid control technologies, including sophisticated strategies for energy balancing, fault protection, system resilience, and data-driven operational efficiencies. Despite these advancements, persistent gaps remain, particularly in the areas of real-time adaptability, seamless integration of decentralized energy resources, and robust data management frameworks. We offer valuable insights into the broader landscape of the framework technologies, guiding future research on the critical gaps, key challenges, and opportunities for advancing microgrid control strategies. Future research is also necessary to address data management and adaptation for the enhancement of microgrid performance, reliability, and scalability. Implementing integrated control architectures in microgrids is another promising area of research exploring emerging technologies such as artificial intelligence, machine learning, and Internet of Things frameworks. Enhancing interoperability standards and fostering cross-disciplinary collaborations will also be crucial for advancing microgrid capabilities. Ultimately, the insights in this review can guide an evolutionary approach toward developing a more sustainable, reliable, and resilient energy system.

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