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The Operation and Control Strategy of Microgrids: A Brief Review

Mohammad S. Alam[1], Salsabila Zaman[2]

[1]School of Electrical Engineering and Computer Science, University of North Dakota, Grand Forks, ND 58202, USA; Email: mohammad.alam.3@und.edu

[2]Institute of Information Technology, University of Dhaka, Shahbagh, Dhaka, 1000, Bangladesh; Email: bsse1443@iit.du.ac.bd

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ABSTRACT

A microgrid is an effective approach for integrating various distributed energy resources to meet local energy demand. It possesses the capability to operate independently or in conjunction with the main utility grid. Typically, a microgrid is a small-scale power system (usually several megawatts or less) comprising three primary components: the ability to function in both grid-connected and islanded modes, distributed power generation sources, and autonomous control centers. Microgrids enhance system resilience by ensuring uninterrupted operation during grid disturbances. Additionally, they are environmentally sustainable and contribute to improved power quality. As a crucial element of modern power systems, microgrids can effectively mitigate peak load demands on the utility grid. The incorporation of renewable energy sources within microgrid frameworks significantly reduces CO_2 emissions. However, achieving optimal performance requires precise control techniques to balance energy supply and demand. This review article provides a comprehensive analysis of microgrid operations and control strategies. The first section examines the fundamental principles of microgrid operation, while the second section evaluates advanced power control strategies, with a particular focus on multi-agent control methods for microgrids.

Keywords: microgrid, renewable energy, CO2 emissions, multi-agent.

I. Introduction

The concept of the microgrid was introduced by the Consortium of Electric Reliability Technology Solutions (CERTS) in the United States to enhance consumer confidence and improve power quality. A microgrid consists of electrical loads, power generation sources, energy storage systems, and control equipment. It can exchange electrical power with the main grid through a single point of coupling, enabling seamless integration of renewable energy sources. The successful implementation of microgrids offers several benefits, including the reduction of CO_2 emissions, improved energy stability, emergency energy storage, and mitigation of the adverse effects of sudden grid outages [1-3]. Furthermore, microgrids enhance energy quality and contribute to lowering overall energy production costs [4, 5].

Energy management policies for microgrids are designed based on commercial and operational objectives. Depending on system requirements, microgrid configurations and energy management techniques are classified into AC, DC, and hybrid modes [6-8]. AC microgrids provide several advantages, such as fault detection, load management, and reliable operation. In cases of grid uncertainty or transient disturbances, AC microgrids can smoothly isolate from the main grid, minimizing disturbances to connected loads. Additionally, AC microgrids help regulate peak load

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demands, ensuring improved power quality and reliability, particularly for applications with sensitive loads [9-11].

In contrast, DC microgrids eliminate the need for reactive power regulation and frequency synchronization, simplifying power management. The direct integration of DC loads reduces conversion losses associated with AC-DC or DC-AC transformations [12]. Hybrid microgrids combine the characteristics of both AC and DC microgrids, offering enhanced flexibility, improved power quality, cost efficiency, and reduced converter complexity. This hybrid configuration represents a promising approach for future power system applications [13].

Microgrids can operate in two primary modes: grid-connected and standalone (islanded) mode. The ability to transition between these modes is crucial; however, abrupt switching can lead to transient overcurrents or power oscillations, potentially compromising system stability and equipment safety [14].

With advancements in power electronics and energy storage technologies, microgrids are gaining increasing significance in modern power systems. Unlike conventional grids, microgrids are characterized by the inherent intermittency and variability of renewable energy sources. These challenges can be mitigated by implementing an effective energy management system (EMS). Due to the diversity of power sources within a microgrid, maintaining stable frequency and voltage coordination among multiple generators remains a critical challenge [15-17]. A key priority in microgrid operation is ensuring acceptable power quality, including independent active and reactive power control, voltage sag correction, and system imbalance mitigation.

This review aims to analyze microgrid operational procedures and control strategies. The paper is structured as follows: Section II presents the operating modes of microgrids, while Section III discusses different microgrid types. Section IV explores promising control strategies, and Section V provides concluding remarks [18].

II. The operating modes of microgrids

A microgrid is a small-scale power system capable of operating in both grid-connected and islanded modes. In grid-connected operation, the microgrid interfaces with the main power grid at the Point of Common Coupling (PCC). The choice between grid-connected and islanded configurations depends on the specific application requirements and operational objectives.

II.I) Islanded mode of operation:

In islanded mode, a microgrid operates independently, generating all the power required to supply its connected loads. Islanding occurs when a microgrid or a segment of the power grid, consisting of distributed generation sources, loads, and power converters, is disconnected from the main utility grid. In this operational mode, the microgrid must maintain stable voltage and frequency within the desired range. Additionally, since it is not connected to the main grid, a reliable power source is essential to meet load demand [19]. Electrostatic or electrochemical energy storage devices are commonly used as dependable power sources in islanded microgrid systems [20, 21].

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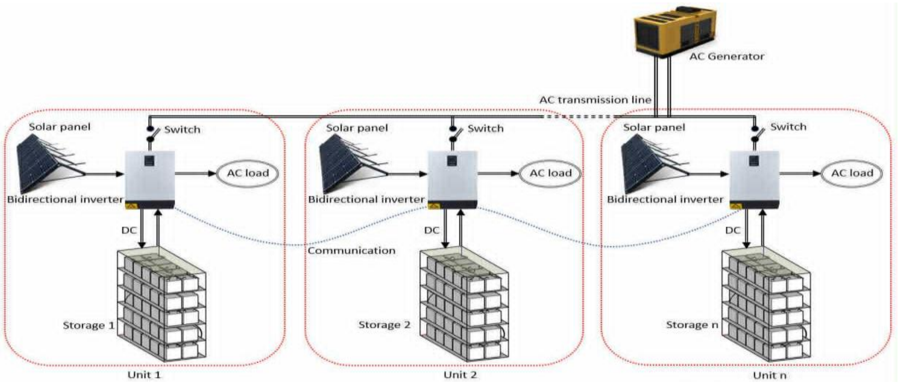

Figure 1. Schematic of a microgrid in islanded mode.

Figure 1 illustrates a schematic representation of a microgrid operating in islanded mode. The integration of distributed energy resources within a microgrid requires adherence to established standards to ensure optimal efficiency and reliable operation. IEEE Standard 1547 defines the criteria and requirements for interconnecting distributed energy resources with electrical power systems [22]. This standard provides essential guidelines concerning performance, operation, testing, safety considerations, and maintenance of interconnections. Distributed energy resources include fuel cells, photovoltaic (PV) generators, wind turbines, microturbines, other distributed generators, and energy storage systems [23].

Ibrahim et al. [24] investigated the adaptive role of islanded microgrid components in enhancing voltage and frequency transient responses. They introduced a novel coordinated voltage and frequency control strategy that utilizes inverter-based devices to ensure fast reactive power compensation and rapid frequency regulation under challenging operating conditions. This approach improves voltage and frequency stability, enhances transient response, and strengthens overall microgrid stability. Similarly, Kim et al. [25] examined voltage and frequency control strategies for standalone microgrids with high penetration of intermittent renewable energy sources. To address unpredictable power fluctuations from a frequency control perspective, they employed a battery energy storage system (BESS) instead of a conventional synchronous generator [26]. A reactive/active power droop controller was implemented to mitigate voltage fluctuations effectively.

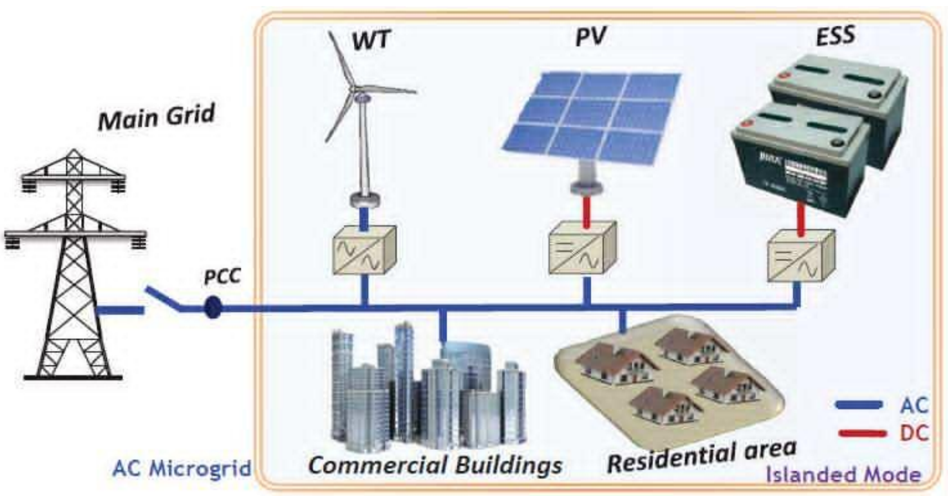

Figure 2. Schematic of a microgrid connected with the utility grid [27].

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II.II) Grid connected mode of operation:

Grid-connected microgrids are considered a key component in the development of a smarter and more resilient electric grid. In this configuration, the microgrid is connected to the main utility grid through a static transfer switch, with the point of interconnection referred to as the Point of Common Coupling (PCC) . The microgrid controller continuously monitors power generation and demand, ensuring that excess power is exported or additional power is imported through an inverter based on real-time load and source conditions. To successfully integrate with the utility grid, the microgrid must synchronize its voltage and frequency with the grid [28].

Kumar et al. [29] analyzed a customer-oriented energy demand management approach for grid-connected microgrids, developing an energy management system that encourages active consumer participation. Grid-connected microgrids offer significant advantages in mitigating common challenges faced by local distribution systems. Voltage sag and swell are among the primary power quality issues that adversely affect loads in distribution networks. To address these challenges, power quality compensation strategies must be incorporated to enhance system reliability [30].

To improve the stability of grid-connected inverters under varying grid impedance conditions, an impedance-phased compensation control strategy has been introduced into the current controller [31]. While the traditional virtual resistor (TVR) approach increases the system's output resistance, it struggles to adapt to a broad range of grid impedance variations, resulting in prolonged transient response times. To overcome this limitation, a stability enhancement method based on an adaptive virtual resistor has been proposed, offering improved performance in microgrid applications [32, 33].

III. Objective of microgrid control:

The energy management system (EMS) of a microgrid consists of power sources and energy storage devices. The main controller enables the microgrid to seamlessly transition between grid-connected and islanded modes. Additionally, load management strategies can be developed based on real-time power generation and demand. With advancements in power electronics and energy storage technologies, the microgrid concept has gained significant attention. Modern microgrid control devices operate with greater speed and efficiency, allowing for the design of an optimal Point of Common Coupling (PCC) on the bus that runs parallel to the utility grid. This facilitates real-time analysis of output power, frequency, and voltage [34].

While commercial power grids are generally stable, reliable, and resilient, microgrids exhibit inherent characteristics of randomness and intermittency. When integrating a microgrid into the utility grid, it must be managed through an EMS, as illustrated in **Figure 3**. The EMS regulates output power in both grid-connected and islanded modes. To ensure smooth operation, a combination of local and cascade control strategies has been proposed [35]. This system effectively compensates for power fluctuations caused by variable loads and renewable energy sources. If power consumption within the microgrid exceeds its generation capacity, the available power will only supply a designated portion of the total demand [17, 36].

Yang et al. [37] developed a model for microgrid interconnection control, outlining key parameters for successful integration. They emphasized that when a utility grid connects to a microgrid, the voltage difference on both sides of the switch must be minimized, the grid frequency should be slightly higher than the microgrid frequency, and the grid voltage should lead the microgrid voltage during synchronization. Tang et al. [38] proposed an active and synchronous control method based on the phase-locked loop (PLL) principle. Their approach effectively reduced voltage deviations between the utility grid and the microgrid, ensuring a smooth transition from islanded to grid-connected operation. Additionally, Guo et al. [39] designed a specialized inverter utilizing sine current pulse-width

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modulation (PWM) to reduce harmonic distortion within the power system, improving overall power quality.

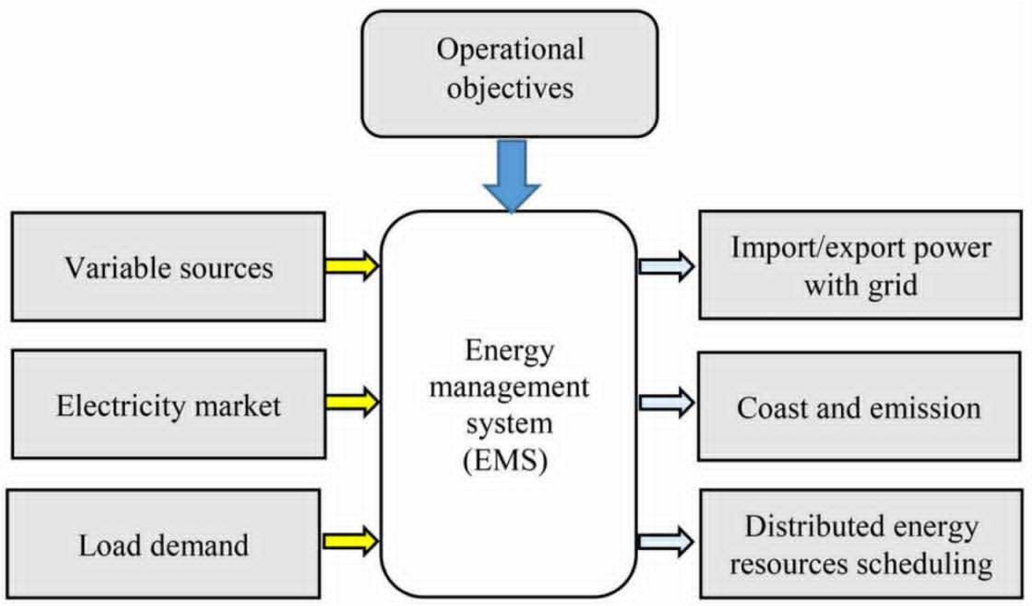

Figure 3. Energy management system structure of a microgrid [40].

III.I) Maintaining desired power quality:

System stability is a critical factor in microgrid operation. Key grid parameters, including voltage, frequency, and phase angle, are continuously monitored and uploaded through grid monitoring devices. When a microgrid connects to the distribution network, its voltage and frequency must be compared with those of the main grid to ensure synchronization. If deviations exceed permissible limits, the power output of energy storage devices and photovoltaic batteries must be adjusted accordingly [41-43].

The Energy Management System (EMS) plays a crucial role in maintaining system balance by calculating the necessary reactive power compensation and transmitting the required adjustment values to the energy storage device. The EMS ensures system stability by instructing the storage device to inject or absorb reactive power as needed. If a power failure or power quality disturbance is detected within the distribution network—potentially leading to voltage fluctuations—the monitoring system triggers the Point of Common Coupling (PCC) controller. This controller sends signals to circuit breakers, isolating the microgrid and transitioning it into islanded mode [44].

Once normal operation is restored in the distribution network, the monitoring equipment assesses voltage, frequency, and phase angle values for both the main grid and the microgrid. If these parameters are not synchronized, the EMS adjusts the microgrid's power output to achieve synchronization as quickly as possible, ensuring a seamless transition back to grid-connected operation [45].

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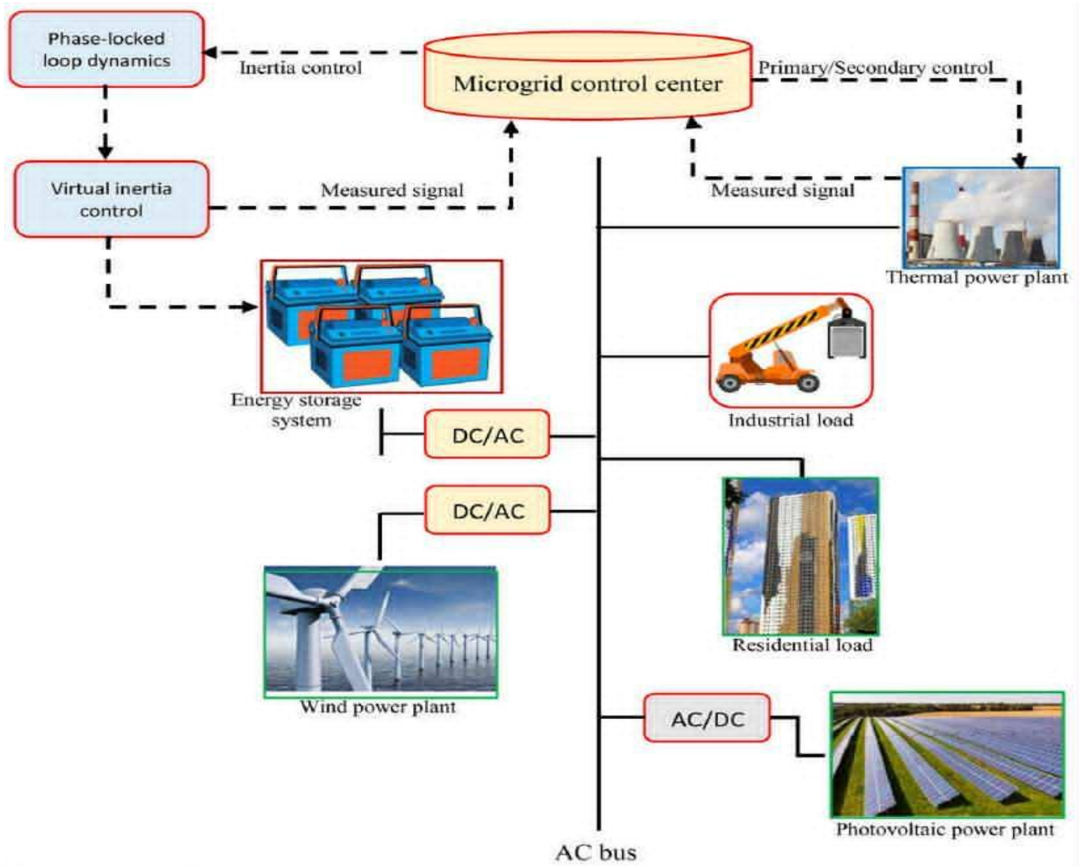

Figure 4. An AC microgrid connected with a centralized controller.

III.II) The load controller

Renewable energy sources play a significant role in modern power systems, particularly in the formation of distributed networks [46]. At the Point of Common Coupling (PCC), in addition to power quality monitoring devices, a controller based on load priority can be integrated. When the power generated by distributed energy sources exceeds the load consumption, the microgrid directly supplies power to the load [47, 48]. However, when the generation capacity is insufficient to meet the demand, the load controller issues commands to the load switches, disconnecting non-essential loads based on predefined priorities, thereby ensuring that only critical loads are supplied. Simultaneously, any surplus power generated by distributed energy sources is directed to the energy storage systems [49, 50].

Load frequency control is essential for ensuring high-quality electrical power in power system operations. A smooth transition between standalone and grid-connected modes is one of the fundamental requirements for the successful implementation of microgrids. Serban et al. [51] proposed a frequency control strategy utilizing an electronic load controller. To manage frequency stability, they employed a centralized controller that integrated battery storage systems with connected loads. In reference [52], an intelligent control strategy combining particle swarm optimization and fuzzy logic was developed to optimally tune the existing proportional-integral-based frequency controllers in microgrid systems.

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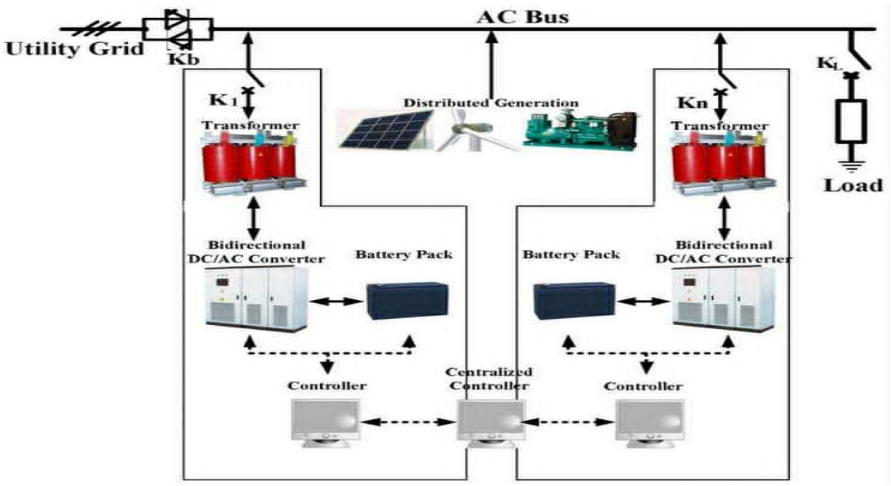

Figure 5. Schematic of a centralized control system [53]

IV. Microgrid control strategies

Ensuring the proper operation of multiple micro energy sources within a microgrid presents a significant technical challenge. Different power sources generate varying qualities of power, and effectively synchronizing them on a unified platform requires the deployment of robust control strategies. To date, three primary control structures have been commercially established: centralized, decentralized, and multi-agent [54-56]. The control process for an islanded microgrid is illustrated in **Figure 4**, where the power line facilitates the exchange of electrical power, while the communication line is responsible for the exchange of control and status information [57].

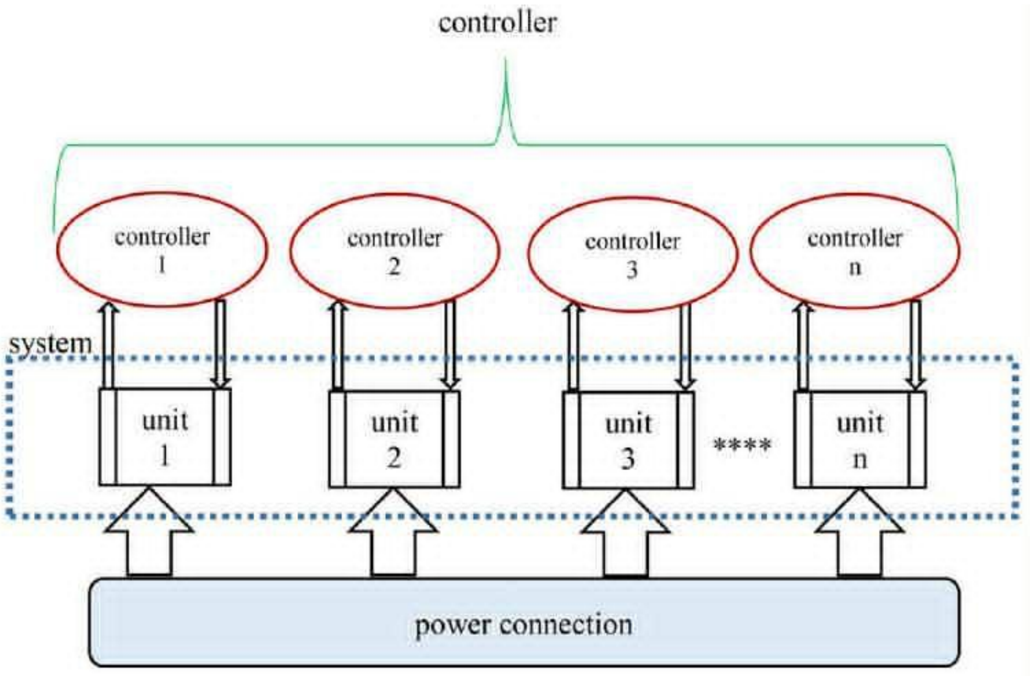

Figure 6. Schematic of a centralized control system [40]

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IV. I) Centralized control strategy:

The central controller of a microgrid is a critical component for ensuring the proper coordination of energy resources. In a microgrid, various energy sources are integrated, alongside energy storage systems and connected loads, to form an autonomous system. **Figure 5** illustrates a schematic of a centralized control system. Dragicevic et al. [58] proposed a double-layer hierarchical control strategy for coordinating multiple batteries within a standalone microgrid. The initial control layer at the unit level utilized an adaptive voltage droop technique. The system's objective was to regulate the common bus voltage and maintain the states of charge of the batteries close to one another during moderate replenishment.

Afrasiabi et al. [59] introduced an improved centralized control technique to compensate for voltage distortions in microgrids. They employed inverter-based distributed generators (IBDG) as distributed compensators to enhance power quality. The control strategy involved compensating for voltage disturbances at the control level, with secondary-level control managed by a centralized controller. Voltage imbalance and harmonic data from the microgrid's load bus were sent to the central controller, which then computed the compensation coefficients for the IBDG units. Reference commands were sent to the local controllers of the IBDG units, functioning as the primary level of control. The effectiveness of this approach was validated through simulation.

Tsikalkis et al. [60] proposed an optimized control strategy for the central controller of a microgrid, evaluating the controller's performance in interconnected mode. They concluded that the system effectively maximized the overall production capacity of local distributed generators. Wang et al. [61] developed a centralized control system for harmonic voltage suppression in islanded microgrids. Their approach successfully mitigated the 'whack-a-mole' effect using voltage detection-based active filter techniques, ensuring both nonlinear load sharing and harmonic load distribution among multiple distributed energy resources (DERs). Cai et al. [53] presented a centralized control structure for large-capacity, parallel-connected power conditioning systems, supporting operation in transfer mode, grid-connected mode, and islanded mode.

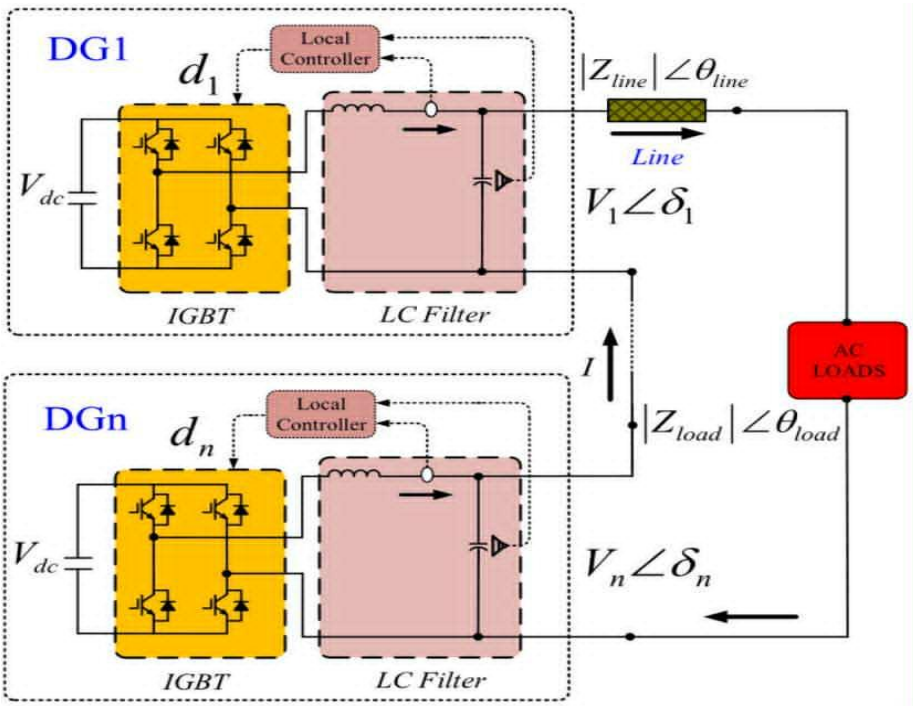

Figure 7. Distributed generator controller [62].

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IV. II) Decentralized control strategy:

This section aims to explore recent developments in decentralized control strategies for microgrids. Researchers are increasingly focused on integrating autonomous control systems into microgrids. To achieve this, various decentralized control strategies have been proposed. **Figure 6** illustrates a schematic of a decentralized control strategy for a microgrid. In [63, 64], an autonomous control strategy was introduced to decentralize the control scheme of a microgrid. The distributed generation units were connected to the point of common coupling (PCC), where a passive RLC load was also connected. The study demonstrated that the overall operation of the islanded mode microgrid could be managed using local controllers. The performance of the system was evaluated using the MATLAB/SimPowerSystemstoolbox.

A challenge with the existing reactive power polarity-dependent decentralized control for cascaded-type microgrids is the occurrence of multiple equilibrium points, which may lead to unexpected operating states. To address this, a decentralized power-sharing control structure was proposed [62], which improved the signal stability of the system. **Figure 7** presents a cascade-type microgrid. Nasir et al. [65] proposed an adaptive I-V droop technique for the decentralized control of a PV/Battery-based distributed architecture in an islanded DC microgrid, which was examined through simulation and small-scale laboratory experimentation. In [66], a decentralized control mechanism was introduced for frequency restoration in an islanded microgrid. Additionally, [67] proposed a decentralized control strategy based on V-I droop to enhance the dynamics of a hybrid AC/DC microgrid.

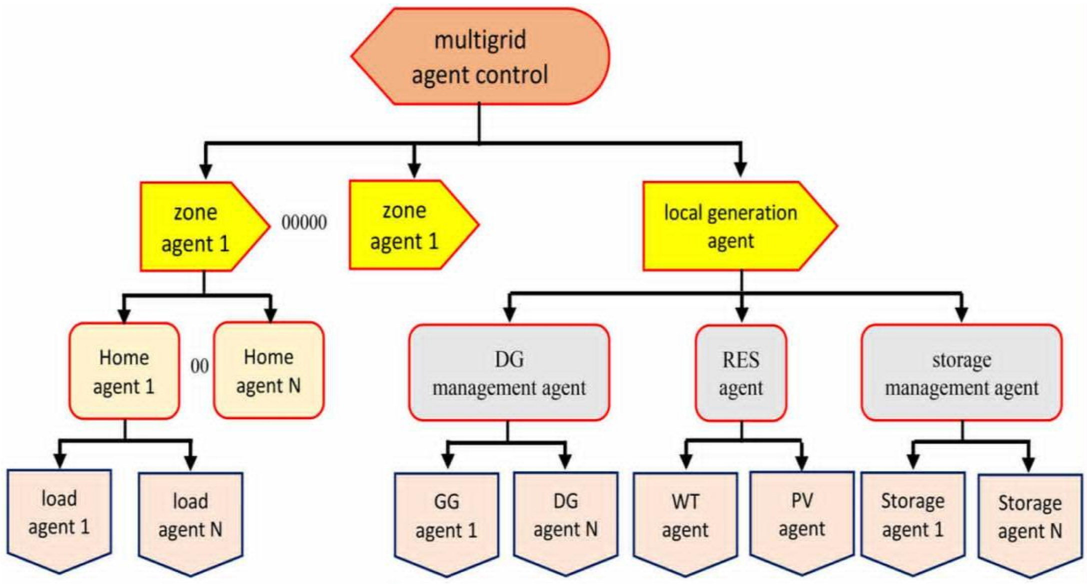

Figure 8. The hierarchical flowchart of multi-agent systems [40].

IV. III) Distributed multi-agent control:

Microgrids play a crucial role in addressing the objectives of smart grids and offer solutions for the expansion of existing power systems. They are particularly attractive when considered as autonomous, self-contained power system components. The power sources connected within the system can be controlled and coordinated in a decentralized manner. A multi-agent control system provides the utility network with a means to increase the contribution of distributed energy resources without overburdening the power management system [68]. **Figure 8** illustrates a hierarchical flowchart of a multi-agent system.

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To identify transmission faults and take rapid actions to minimize any adverse impacts, while ensuring prompt recovery and stabilization of the system's operating conditions, a self-healing process is incorporated into the microgrid [69, 70]. In [71], a multi-agent system-based hierarchical control framework for microgrids is proposed. This framework consists of primary, secondary, and tertiary control layers. Each agent is assigned a specific task for regulating the local output voltage and collaborates with neighboring agents to reduce power disturbances.

V.I) Emerging trends and enabling technologies:

The current microgrid implementations are more of an inverter than a synchronous inertia entity. This trend has revived grid-forming converter (like droop-based grid-forming control, virtual synchronous machine control, and virtual oscillator control) to serve as stable voltage/frequency references, black-start capability, and better transient performance in islanded operation [72, 73]. At the deployment level, interoperability is supported with the changing standards. The IEEE Std 2030.7-2017 outlines the functional requirements of the microgrid controller, and IEEE Std 2030.8-2018 outlines testing procedures used to check the functionality of the microgrid controller. Hit RF Requirements IEEE Std 1547-2018 [74, 75] takes care of the connection and interoperability requirements of distributed energy resources (DERs). Due to the fact that microgrids are based on communication networks that monitor, coordinate, and dispatch the system remotely, cybersecurity and cyber-physical system resilience have become a first-order design requirement. In NISTIR 7628 Rev. 1 [76], risk-driven security guidance to smart-grid infrastructures is provided. Figure 9 illustrates a summative view of a view hierarchy between physical assets (DERs, storage, loads, and protection), primary/secondary/tertiary control functions, and how communication and cybersecurity services are aligned with coordination in the hierarchy.

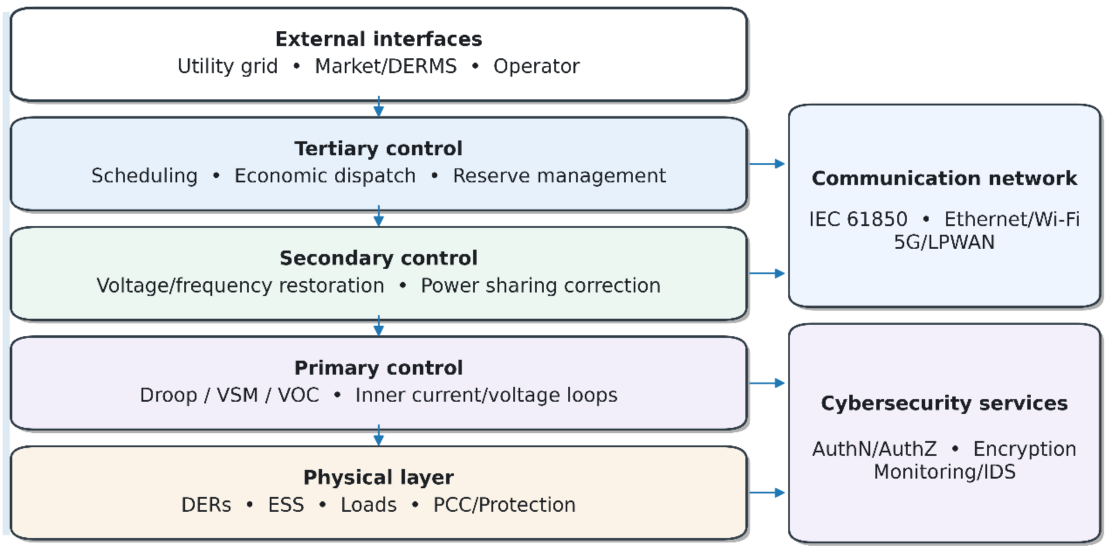

Figure 9. Cyber-physical architecture for microgrid operation and control.

Communication level required between DERs and the EMS, as well as the place of decision-making (local controllers or a supervisory controller), is often split into groups of microgrid control architecture. Table 1 condenses the key trade-offs between popular control structures in regard to the communication load, scaling, and fault tolerance.

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Table 1. Qualitative comparison of common microgrid control structures.

Control structure	Communication need	Scalability	Fault tolerance	Typical use case
Centralized	High	Medium	Lower (single point)	Campus/industrial microgrids with SCADA/EMS
Decentralized	Low	High	High	Plug-and-play DER sharing in islanded mode
Multi-agent / distributed	Medium–High	High	High	Distributed optimization, peer-to-peer coordination
Hierarchical hybrid	Medium	High	High	Utility-grade microgrids (primary/secondary/tertiary)

V.II) Open challenges and research opportunities:

1. Protection in inverter-based microgrids: Minuscule fault current and rapid converter controls make more conventional approaches of overcurrent protection more difficult, leading to adaptive protection as well as testing protection-in-the-loop.

2. Seamless transition and stability under weak grids: When isolating/redlinking, synchronization, emulating inertia, and interaction of impedances, oscillations can occur in the low-inertia system.

3. Forecast-aware and uncertainty-aware EMS: The advantage of integrating high-penetration renewables is based on forecasting, robust/stochastic optimization, and real-time model predictive control.

4. Cyber-resilient control and communications: Critical services require security architecture, intrusion detection, and graceful degradation modes in order to maintain such services during cyber incidents.

5. Validation and certification: It is possible to mitigate deployment risk and enhance interoperability by having hardware-in-the-loop and standardized tests (e.g., controller testing).

Figure 10 presents a rudimentary, qualitative decision guide towards the choice of a control architecture due to the trade-off between overheads in coordination/communication and system-level optimality that can be achieved. The directions emerging here imply that next-generation microgrids will be progressively integrated with grid-forming power-electronic interfaces, hierarchical/hybrid control, homogenized controller functions, and also secure communications in order to meet resilient, scalable operations.

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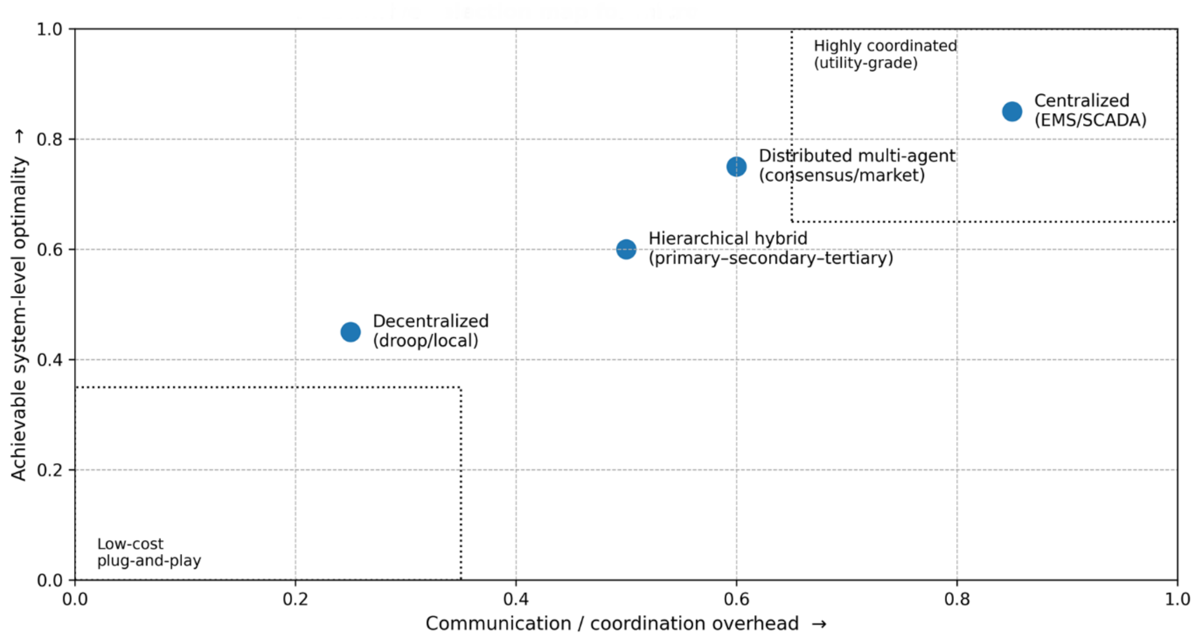

Figure 10. Illustrative selection map for microgrid control strategies.

VI. Conclusion

In this paper, a comprehensive review of the operation modes and control strategies for microgrids has been presented. Microgrids can operate in either islanded mode or grid-connected mode, with each mode requiring distinct control mechanisms to ensure smooth, reliable operation. The paper discusses various control strategies, including centralized, decentralized, and multi-agent systems, highlighting their strengths and weaknesses in different operational contexts. A comparative analysis of these strategies is provided to offer insight into their effectiveness in maintaining power quality, stability, and efficiency.

While centralized control frameworks are commonly used, their scalability and reliability limitations in complex microgrid systems have prompted the exploration of alternative control approaches. Decentralized and multi-agent control strategies, in particular, offer enhanced flexibility and adaptability, enabling better coordination among distributed energy resources. Additionally, integrating renewable energy sources and energy storage solutions within microgrids further enhances their resilience, sustainability, and ability to respond to dynamic grid conditions.

Overall, the review emphasizes the importance of selecting appropriate control strategies to optimize the performance of microgrids, addressing challenges such as load demand management, fault detection, and system stability. As the development of microgrid technologies continues to evolve, the integration of advanced control techniques will be essential in meeting the growing demand for clean, reliable, and resilient energy systems.

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