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Microgrid Control Techniques: A Review

Abdulmalik Ibrahim Dabo[1*], Sabo Aliyu[2], Olutosin Ogunleye[3], Noor Izri Abdulwahab[4], Hossein Shahinzadeh[5], Abdulmajid Muhammad Na'inna[6]
[1,2,3] Department of Electrical Engineering, Faculty of Engineering and Engineering Technology, Nigerian Defense Academy, Kaduna, Nigeria
[4] Department of Electrical and Electronic Engineering, Faculty of Engineering, University Putra Malaysia
[5] Department of Power Engineering, Faculty of Electrical Engineering, Islamic Azad University of Najafabad, Islamic Republic of Iran
[6] Pakistan Air Force (PAF) Air War College Institute, Karachi, Pakistan

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ABSTRACT

Microgrids (MGs) are localized energy systems that integrate distributed energy resources (DERs), including renewable energy sources, energy storage systems (ESS), and conventional power generation sources. A critical challenge in operating microgrids is maintaining frequency stability, particularly during transient disturbances or load imbalances. This review provides a comprehensive analysis of various frequency control strategies employed in microgrids to ensure stable and reliable operation. The paper categorizes existing approaches into primary, secondary, and tertiary frequency control methods, evaluating their mechanisms, advantages, and limitations. Primary control focuses on immediate frequency regulation through local droop control, while secondary control ensures the restoration of frequency to its nominal value through centralized or decentralized coordination. Tertiary control manages economic dispatch and energy optimization for long-term stability. The paper further highlighted emerging technologies in the field of microgrid control. Additionally, the review examines the impact of DER characteristics, including variability and intermittency, on frequency regulation. It discusses advanced techniques, including model predictive control, fuzzy logic control, and Neural network control. The paper concludes with a discussion on future trends in microgrid frequency control, emphasizing the need for robust encryption and intrusion detection systems that protect microgrid control networks from cyber threats, ensuring reliable frequency regulation even in the event of a cyber-attack.

1. INTRODUCTION

Due to the significant displacement of traditional rotating mass synchronous generators (SGs), a microgrid becomes a low inertia system [1][2]. The transition from centralized to distributed generation (DG) has presented major technical challenges for power system planners and operators, largely due to the unique features of systems interfaced with converters that alter the dynamic behavior of power systems. This shift has drawn attention to microgrids, which facilitate the integration of DGs into increasingly prevalent electricity systems. Microgrids, however, significantly reduce system inertia, leading to an excessive frequency nadir and a rapid rate of change of frequency (ROCOF) when disturbances occur [3]-[5]. Adding energy storage

*Abdulmalik Ibrahim Dabo
Email: abdulmalikdaboi@gmail.com

components like supercapacitors to the PV system and utilizing the stored energy in the rotating components of wind production can increase the microgrid's inertia [6]. More research is needed to integrate low or nonexistent inertia renewable energy supplies because of the significant impact that microgrid inertia has on microgrid frequency response and stability [7]. Microgrids typically operate in one of two modes: islanding mode or grid-connected mode [8][9]. The composition of diverse demands and micro sources is what defines a microgrid [10] Direct current (DC) and alternating current (AC) are the two forms of microgrids [11].

As a result of their scalability and environmentally friendly energy production, micro-sources ~~like~~ such as fuel cells, wind, water, and photovoltaics have recently entered the electrical market as viable alternatives [12]. Maintaining a stable supply-demand balance is the primary obstacle to the successful deployment of a microgrid's [13]. The connectivity of renewables in a microgrid causes this demand-supply imbalance because their operation is intermittent [14]. Each microgrid has the flexibility to operate in both island and grid-connected modes. The power system's high inertia helps maintain network stability during small disturbances when it connects to the grid. However, in island mode, the microgrid frequency fluctuates in response to even minor disturbances or changes in load [15]. In response to growing environmental concerns, there has been considerable interest in the concept of a microgrid that operates entirely on renewable energy sources (RES) with energy storage rather than traditional fossil fuel power plants. This could help address issues such as pollution and the depletion of fossil fuels, as well as improve the efficiency of the utility grid [16]. Table 1 summarizes the advantages and disadvantages that microgrids offer [17].

Table 1. Advantages and Disadvantages offered by microgrid

Advantages	Disadvantages
• The microgrid will disconnect from the utility in the event of a power failure or poor utility power quality, thereby protecting the loads connected to it. • Microgrids can handle peak loads by load shedding or by installing additional distributed generation (DG) systems, thereby increasing generation capacity. • Microgrids can help the environment by reducing carbon dioxide emissions through the use of pollution-free distributed generators. • Due to its ease of planning and quick installation, microgrids offer a rapid solution to the power requirements in areas frequently affected by natural disasters. • The total installation cost is lower than that of a conventional power system.	• A microgrid's power and energy balance depends on its ability to regulate voltage, frequency, and power quality parameters to acceptable levels. • Battery banks are needed to store electrical energy, which subsequently increases the space and maintenance requirements. • The process of resynchronizing a microgrid with the utility grid is a complex undertaking. • Microgrid protection is one of the most significant challenges encountered during the implementation of microgrids. • Microgrids must address issues related to net metering and standby charges.

This paper aims to review existing control techniques in Microgrids, offering researchers insight into frequency control strategies. The control strategies, their contributions, and drawbacks, as compiled by previous studies, are presented in Table 1. This paper is structured into consists of eight sections. The first section provides an introduction to microgrids, the second section highlights the various architectures of microgrids, and the third section discusses the different operating modes of microgrids. It also presents the advantages and disadvantages of microgrid operating modes and architectures.

Furthermore, the fourth section provides the control strategies of MGs. while In contrast, the fifth section outlines the classifications of different control techniques and emerging technologies with a review of different control strategies by different authors, the sixth section provides the control/damping of frequency oscillation in power systems, the seventh section outlines the future research areas in MGs and the eighth section provides the conclusion.

1.1. Microgrid Architecture

Researchers categorize microgrids into ACMG [18][19], DCMG [20][21], and HMG [22][23] based on their operating frequency. The three architectures are illustrated in Figures 1, Figure 2, and figure 3, respectively.

1.2. AC Microgrid

The advantages of AC microgrids, such as their transformability to different voltage levels and efficient long-distance transmission capacity, have led to their routing use for many decades. Depending on the frequency ratings, operators can use this AC network with or without a converter to connect distributed energy resources, energy storage devices, and different types of loads. Direct connection to the AC network is possible without converters for conventional AC sources. In ACMGs, DC sources require DC to AC converters. On the load side of ACMGs, DC loads require rectifiers, and AC loads can be directly connected to the grid [24]. Figure 1 shows the architecture of the AC microgrid.

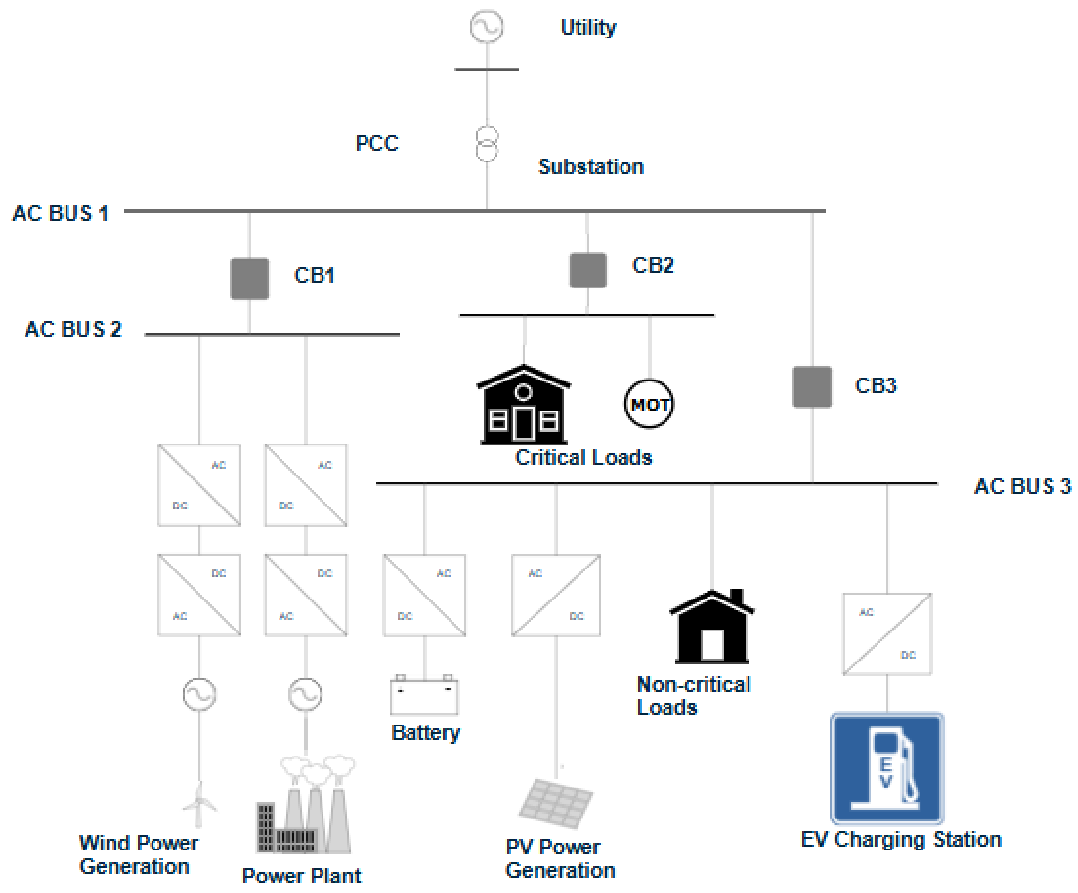

Figure 1. AC Microgrid Architecture

1.3. DC Microgrid

Figure 2 shows the architecture of DCMG. The DCMG requires an interlinking converter (IC) connected to the main grid at PCC and also for the voltage regulation at DC buses [25] . The aforementioned AC microgrid drawbacks, like complicated control and utility grid synchronization, are less of an issue in DCMGs. The benefits of direct current (DC) microgrids include reduced fuel costs, the elimination of inverters, and ease of installation. When it comes to DC microgrids, power quality problems are also rare. With the increasing prevalence of DC-powered equipment, DC microgrids are becoming increasingly important [24].

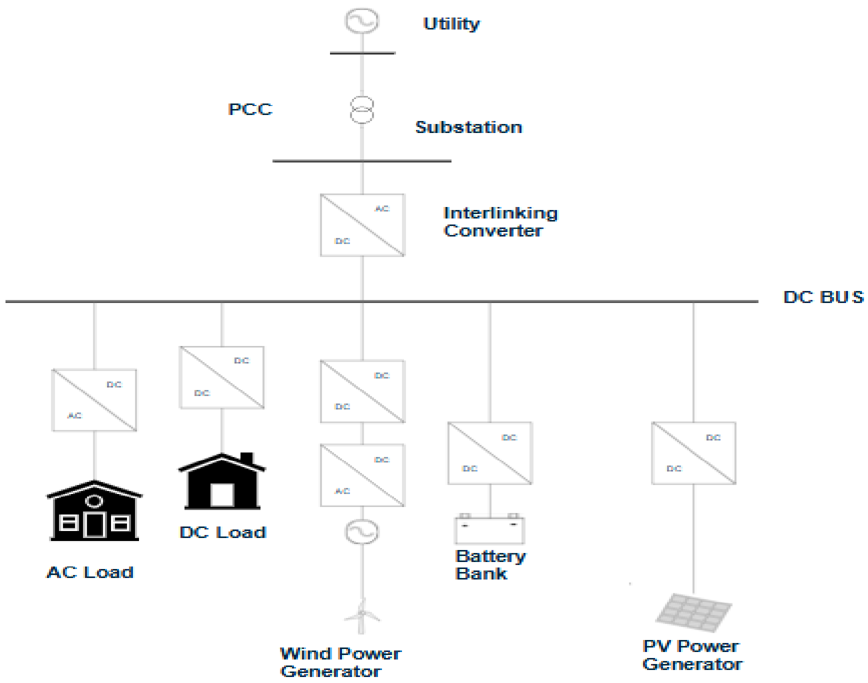

Figure 2. DC Microgrid

1.4. Hybrid AC-DC Microgrid (HMG)

HMG combines the best features of the ACMG and DCMG designs, which has led to its growth in popularity and outperformed its competitors. The connection of AC and DC-based DGERs and loads is possible without power electronics converters in an HMG architecture [26]. Here, bidirectional converters enable the system to exchange power between DC and AC subsystems, linking them to their respective DC and AC sources and loads. Connecting ESS to the DC subsystem is recommended [24]. Figure 3 shows the architecture of an HMG.

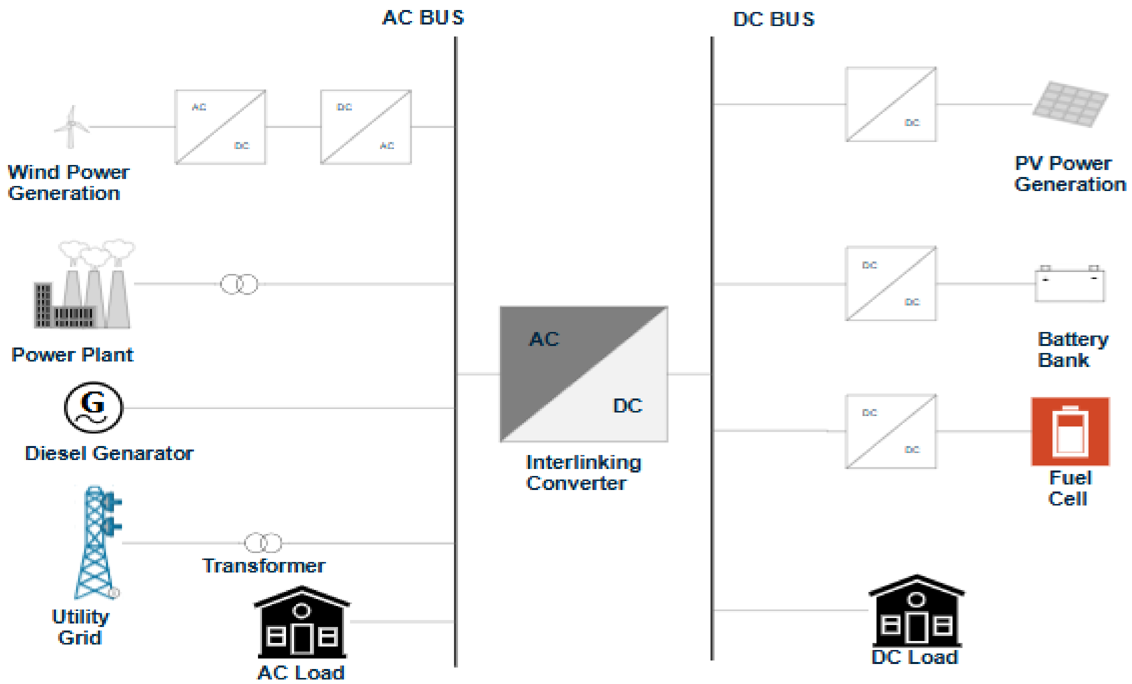

Figure 3. Hybrid AC-DC Microgrid

2. METHOD

Grid-Connected and Islanded Modes are the two distinct operational modes of microgrid, each with different requirements. Microgrids can be categorized based on their architecture and mode of operation, each with its own advantages and challenges. Details can be seen in Table 2.

2.1. Grid Connected Mode (GCM)

In GCM, the microgrid connects to the main grid via the PCC, ensuring that power quality issues do not affect the main grid. Operating critical loads in this mode necessitates a dependable energy supply that adheres to the established power quality standards [27].

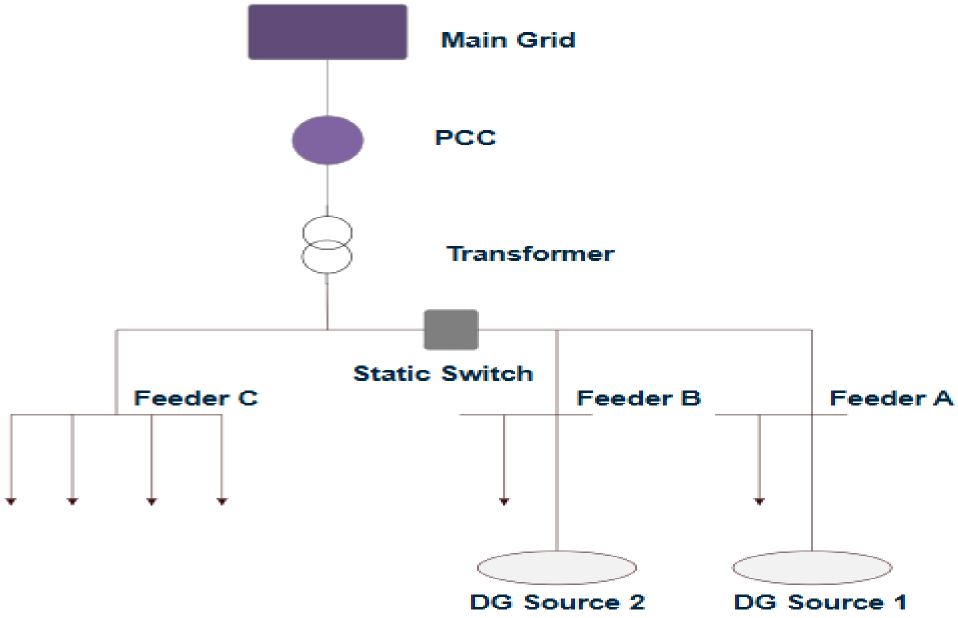

Figure 4. Grid-Connected Mode (GCM).

2.2. Islanded Mode (IM)

In IM of operation, microgrids run independently of the main grid. When grid power is unavailable, local DGs continuously supply electricity to microgrid loads by connecting a breaker at the PCC [28].

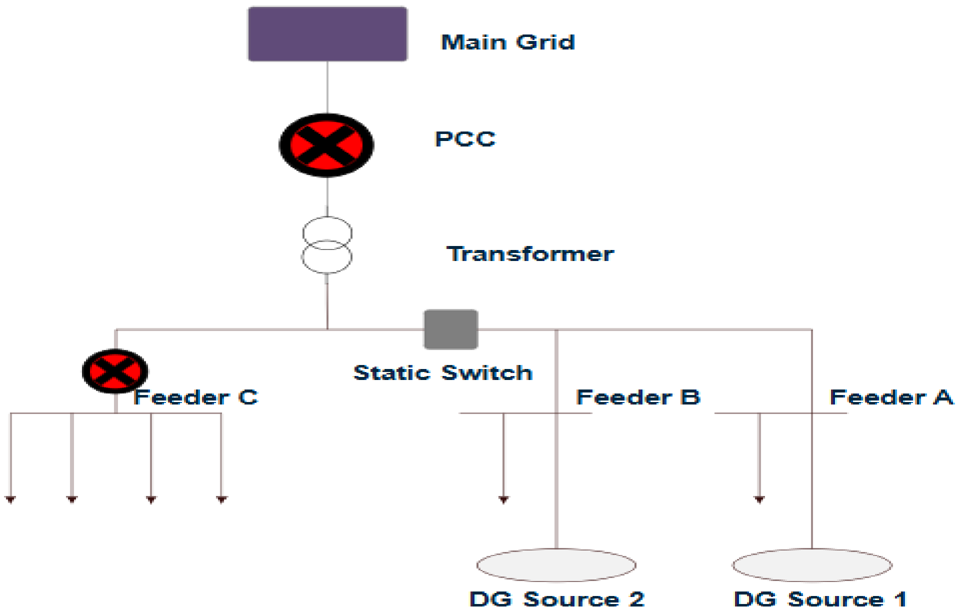

Figure 5. Islanded Mode (IM).

Table 2. Microgrid architecture and operating modes

Categories	Types/Modes	Advantages	Disadvantages
Microgrid Architecture	AC Microgrid [29]	• Seamless Integration with the Main Grid • Bidirectional Energy Flow • Less Complexity in Power Conversion	• Extra Conversion Losses • Harmonics and Voltage Flicker
	DC Microgrid [30]	• Reduced Power Conversion Losses • Efficient Integration with Energy Storage • Electric Vehicle (EV) Charging	• Challenges in Grid Connection • Limited Reactive Power Control
	Hybrid Microgrid [31]	• Enhanced Grid Stability in Islanded Mode • EV Charging Compatibility	• Integration of AC and DC Systems • Coordination of Multiple Power Sources
Microgrid operating modes	Grid-Connected mode [32]	• Backup Power in Case of Grid Outage • Grid Support and Frequency Regulation	• Grid Failures Impact • Grid Interaction Complexity
	Islanded Mode [33]	• Resilience to Grid Failures • Integration of Renewable Energy	• Capacity Constraints • Difficulty in maintaining Stability

3. RESULT AND DISCUSSION

3.1. Microgrid Control Strategies

Microgrids differ from conventional distributed generation (DG) systems in several important respects, one of which is the use of controllability techniques [34]. Microgrid control is crucial for maintaining system stability. Control schemes commonly used in microgrids include peer-to-peer and master-slave control [35]. In microgrids, primary control ensures that voltage and frequency remain constant by focusing on frequency, voltage, current, and power sharing, both active and reactive, as well as the main control unit, which employs master-slave control [36]-[38]. A V/f control manages the main control unit of a microgrid, while PQ control manages the distributed generators. These control strategies supply the system with the needed active and reactive power. There are two tiers of control in a master-slave system, with the higher tier serving as the master and the lower tiers as the slaves. Implemented through peer-to-peer control, the microgrid's plug-and-play capability is one of its most notable features. In this setup, other DGs in the network will not be affected when control equipment is added or deleted. There are three methods for controlling DGs: Droop control, V/f control, and PQ control.

3.2. PQ Control

Hybrid AC-DC systems connected to the grid ~~use~~ utilize the PQ control strategy [39]. PQ control becomes possible through regulating the active and reactive power output of DGs [40]. AC sources with interfaced inverters are well-suited for PQ control, and the resource type plays a crucial role in determining the required control method. PQ inverter control is possible by controlling DERs, which ensures a constant output of active and reactive power. The inverter supplies active power, while the microgrid central controller determines the amount of reactive power to inject into the system. The coordinated operation of the inverter and DER creates a voltage source that is controlled by current [24].

3.3. Droop Control

One typical method of control in peer-to-peer systems is droop control. Droop control mitigates the impact of rapidly fluctuating loads on system stability. Droop control determines the optimal operating frequency by utilizing the actual power output from a generator [41]. In contrast to V/f control, which focuses on the voltage-to-frequency ratio, droop control manages the frequency or voltage droop. Both the frequency and voltage droop methods are employed when multiple micro-sources collaborate to achieve power balance [42]. Using these techniques, we can adjust the DGs' operating points to maintain the power imbalance resulting from main grid isolation at a constant level. The goal of this control level is to maintain the active power and output voltage at a regulated level [43]-[46].

3.4. V/f Control

Due to the loss of voltage and frequency references in PQ mode, this control method is suitable for islanded mode operation of DERs. The result is a shift from PQ control to V/f control [42]. All storage devices need sufficient reserve capacity to achieve the same imbalance as the main grid. Since market demand and supply should determine the set points of other DERs, this change will have little impact.

3.5. Classifications of Different Control Techniques

There are three levels to the general idea of various controlled techniques: primary, [47] secondary, [48] and tertiary, [49] further categorized into centralized, [50] decentralized, [51] distributed, and hierarchical [52].

3.5.1. Primary Control

The output voltage, frequency, and tracked values from the inner-loop control are the main variable components of the primary control level, sometimes referred to as field control or the first layer in hierarchical control [66][67]. Improving voltage regulation, stability, and dependability, as well as ensuring appropriate power sharing to increase system performance, are the primary goals at the primary control level [48][49]. As a result, engineers employ both centralized and decentralized control strategies to manage inner-loop control of the converter's output voltage, current, and power-sharing [70].

In traditional microgrid systems, primary control often relies on centralized or hierarchical control. A central controller may manage multiple generators, batteries, or renewable sources to balance supply and demand in real-time. For instance, in a hierarchical structure, a microgrid operator at the top would oversee the actions of local controllers (e.g., inverter controllers or generator controllers), which directly manage the output from power sources.

In some advanced microgrids, primary control can be decentralized or distributed, where each component (like each generator or energy storage device) can autonomously respond to local grid conditions. For instance, a renewable energy source or a battery might adjust its output based on local voltage or frequency fluctuations without requiring central command.

3.5.2. Inner Control Loop

Researchers refer to inner control loops as zero control levels because they encompass the fundamental hardware controls. As an interface between MG and MS, power electronic interfaces are necessary. Converters, typically CSIs or VSIs, comprise the final stage of these interfaces. In both islanded and grid-connected modes, they feature current and voltage control loops that maintain synchronization with the power grid. For CSIs to function optimally, algorithms such as MPPT are typically necessary. In most cases, these loops can include either VSIs linked in parallel to MG or CSIs in addition to VSIs. This level control primarily serves to set a working point for the DERs' voltage and current loops. Here, PQ/voltage control is the method of control [39].

3.5.3. Inverter Control Level

The distribution generation system's output is regulated by controlling the voltage source inverter (VSI) using these control approaches. The two most common methods for controlling MGs are inverter output control and correct power-sharing control [70].

3.6. Secondary Control

Secondary control focuses on optimizing the microgrid's performance by adjusting its operational set points, such as adjusting the reference power set points, optimizing energy storage, and enhancing power sharing between distributed generation units. When working with DERs in MG, the secondary control is the energy management level. It might work with both centralized and decentralized control systems [71][72] . Important features of this control level include improvement of power quality and frequency deviations, minimization of average voltage, and increase in output voltage due to primary control in MGs. Furthermore, the secondary control mechanism regulates reactive power and output voltage in MGs.

In a centralized control structure, a central controller might oversee secondary control by adjusting power flow based on the state of energy storage or forecasted demand, ensuring optimal microgrid performance for efficiency, cost, or operational goals.

In a decentralized or distributed structure, secondary control may occur at the local level, where individual microgrid components (like energy storage or local power generation units) cooperate to optimize overall system performance. Here, secondary control could involve algorithms that allow distributed units to adjust their operations based on shared local information, thus enhancing overall system stability and efficiency without requiring a central authority to manage every adjustment.

3.7. Tertiary Control

Through the regulation of power transfer between the microgrid and the utility grid, this mode ensures the microgrid's optimal operation by adjusting the amplitude and frequency of DER voltages. Tertiary control helps enhance power quality at the PCC. When voltage instability occurs, the system isolates the MG and tertiary control loops from the main grid using islanding detection [24]. Additionally, tertiary control is responsible for transmitting information from the main grid and coordinating the functioning of interconnected microgrids. The tertiary control attempts to draw active power from the grid ~~in~~ during an unplanned islanding event, resulting in a decrease in frequency. To ensure safety, the system severs the microgrid from the grid and turns off all tertiary control loops when it deviates from the predicted values [29].

In traditional microgrid systems, tertiary control may be more centralized or hierarchical. The microgrid operator, which could be a utility or central authority, might make high-level decisions on how the microgrid interacts with the main grid, how it integrates renewable energy, and when to disconnect or reconnect based on grid conditions. This structure aligns tertiary control with grid-wide goals and regulatory standards.

In a decentralized or distributed structure, tertiary control might be more flexible. Each unit in the microgrid can participate in making high-level decisions based on real-time system conditions, such as when to export or import energy from the main grid, taking into account local demand, price signals, or operational status. For instance, energy storage systems or renewable generation could independently decide when to store or release energy based on market conditions rather than waiting for instructions from a central authority.

Overall, it is essential to distinguish between control levels (primary, secondary, and tertiary) and microgrid structures (centralized, decentralized, distributed, and hierarchical). In microgrids, primary, secondary, and tertiary control levels interact with centralized, decentralized, distributed, and hierarchical structures to manage grid stability, performance, and coordination with the main grid. As the control level transitions from primary to tertiary, decisions become more strategic and long-term. Centralized systems favor hierarchical control, while decentralized and distributed systems offer greater flexibility and autonomy at each level of control. This dynamic relationship enables microgrids to respond to real-time conditions, optimize their performance, and align with broader grid goals.

3.8. Centralized Control

Using data from a communication network, linked loads, and DERs, the centralized control method allows for an appropriate determination of dispatchable units in MG through a single controller or control center. Grid supervisory control extensively utilizes this control technology [53]. This controller is ideal for providing a set point to a local controller (LC) and offers several desirable qualities, including simplicity, reliability, flexibility, and stability. This method enables greater performance with simplified computation, cost savings, and is commonly employed in small microgrids [54]. As a result of primary-level operations in MG, the current control level has essential qualities, including restored frequency, enhanced power quality, and increased output voltage. The main control level and energy storage devices at the head of a complicated system are two potential sources of frequency deviation [55].

3.9. Decentralized Control

At the component level, decentralized control guides decision-making. This kind of control often employs upper- and lower-level controllers in a two-stage arrangement [56] . For increasingly complex microgrids with numerous components, decentralized control is often the most effective option. Centralized control systems are slow because they must gather and process large amounts of data simultaneously at a single location, often referred to as the point of common coupling (PCC). This method is preferred. Real and reactive power sharing in DG units can be enhanced using decentralized control techniques, even in the absence of a communication network [57]. Maintaining the MG networks' output voltage regulation and frequency variation is the primary goal of the secondary control level. With this kind of control, the system operates the MG reliably, improves power quality, restores frequency, manages energy more effectively, and increases output voltage [58][59]. When the main engine is off, the secondary control is at a higher level of the control hierarchy. It has additional capabilities, including regeneration of the main generator in grid-tied mode and black-start management. By supplying an appropriate algorithm for loads and DER units, it aims to resolve the microgrid's EMS issues. The decentralized control method relies on the measurement of local signals by each DER, allowing them to function autonomously [60][61]. In a decentralized control strategy, interfaced power converters manage the dispersed energy. Having to manage each unit through LC-based local area communication is the main downside of a completely decentralized system. The controller ignores various system parameters and the actions of other controllers.

3.10. Distributed Control

To take advantage of the many benefits of the centralized design often used for the entire microgrid [11], local controllers in a distributed control system [62] architecture [63] connect with neighboring units (over a reduced bandwidth channel), making it an improved version of the decentralized approach. It appears that the control of each device has been done by observing its immediate surroundings and responding accordingly.

3.11. Hierarchical Control

Hierarchical control builds on the differences in timeframes commonly seen with different control requirements [64][11]. There are three levels to the categorization: primary, secondary, and tertiary. Primary control, employed for inner DG units, assumes the bulk of the responsibility for directly controlling the device type state variable of microgrids, as is the case with V-f control and other aspects of microgrid control [65]. They are essentially methods of droop control; secondary control checks that the frequency and amplitude deviations inside the MG are within limits; tertiary control, sometimes called the auxiliary layer, regulates the power flow between the MG and the utility at PCC; and primary control slows down the response to steady-state type deviations [24]. Comparison between control structures can be seen in Table 3

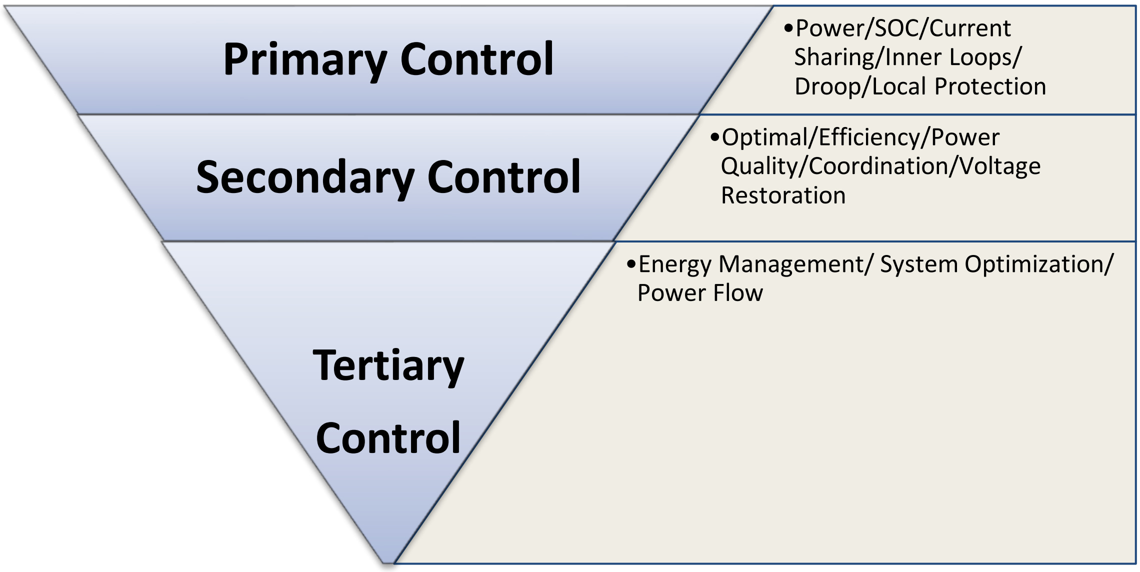

Figure 6. The hierarchical control structure for microgrids

Table 3. Comparison table between control structures

Characteristic	Centralized Control	Decentralized Control	Distributed Control	Hierarchical Control
Control Decision	Single central controller	Local control at each unit	Local with coordination	Multi-level, top-down/bottom-up
Scalability	Limited scalability	High scalability	Moderate scalability	High scalability
Communication	High (central to all units)	Low (peer-to-peer)	Moderate (unit coordination)	Vertical and horizontal
Resilience	Low (single point of failure)	High (units operate independently)	High (failure of some units is tolerable)	High (failures isolated to layers)
Complexity	Low to moderate	Low	Moderate	High
Global Optimization	High	Low	Moderate	High
Fault Tolerance	Low	High	High	High

3.12. Emerging technologies in Microgrid control

Emerging technologies in AI-based optimization methods, blockchain-enabled decentralized systems, and IoT's role in real-time microgrid control are shaping the future of microgrids. These technologies aim to enhance the efficiency, security, and resilience of energy systems, particularly in decentralized environments like microgrids.

3.12.1. AI-Based optimization methods

Researchers increasingly utilizing AI technologies to optimize microgrids operation, enhance energy management, improve fault detection, and boost system performance. Some emerging AI-based methods include:

a) Reinforcement Learning (RL): RL algorithms learn to make decisions by interacting with the environment and receiving feedback from their actions. In microgrids, RL can optimize energy dispatch, battery charging and discharging, demand response, and power flow by learning from real-time conditions.

Emerging Trends

- Autonomous decision-making in energy trading, resource allocation, and fault management.
- Adaptive algorithms that adjust based on changing loads, energy prices, or weather conditions.
- Multi-agent RL where different devices (e.g., generators, storage) cooperate for global optimization.

3.12.2. Blockchain-Enabled Decentralized Systems

Researchers are exploring blockchain technology for decentralized energy systems because it provides secure, transparent, and efficient transaction management.

a) Peer-to-peer (P2P) energy trading: Blockchain enables users in a decentralized microgrid to trade excess energy directly with one another, thereby creating peer-to-peer (P2P) energy markets.

Emerging Trends

i. Automating transactions and ensuring secure, efficient, and transparent energy exchanges.
ii. Energy producers and consumers trade digital tokens that represent energy units, creating incentives for participation.

b) Blockchain for grid security and Transparency: Blockchain can enhance the security and transparency of microgrid operations by providing immutable records of energy transactions, equipment statuses, and system performance.

Emerging Trends

i. Using blockchain to store operational data securely, ensuring authenticity and preventing tampering.
ii. Blockchain ensures transparency in renewable energy supply chains, making renewable energy credits traceable and verifiable.

3.12.3. IoT's Role in Real-Time Microgrid Control

The Internet of Things (IoT) plays a pivotal role in enabling real-time monitoring and control of microgrids, facilitating the integration of various energy resources, and improving grid efficiency.

a) Real-Time Data Collection and Monitoring: IoT devices (sensors, smart meters, weather stations) are embedded in microgrid components to collect real-time data on energy.

Emerging Trends

- Advanced Metering Infrastructure (AMI): Smart meters enable real-time monitoring of consumption patterns, grid health, and load distribution.
- Environmental Sensors: IoT-based weather monitoring systems for forecasting renewable generation (e.g., solar irradiance, wind speed).

b) Interoperability of IoT Devices in Smart Grids: The interoperability of IoT devices is crucial for efficient real-time microgrid control. Standardized communication protocols, such as MQTT and CoAP, ensure seamless integration between devices and control systems.

Emerging Trends

- Interoperable Platforms: Platforms that allow different IoT devices (e.g., smart meters, renewable generators, inverters) to communicate efficiently, enabling holistic microgrid management.
- Edge-to-Cloud Communication: IoT devices communicate with both local edge controllers and cloud platforms for global optimization and decision-making.

Table 4 summarizes the latest technologies in microgrids: AI-Based Optimization is used for load forecasting, disruption detection, and demand management through machine learning and intelligent optimization. Blockchain supports peer-to-peer energy trading, smart contracts, tokenization, and network security. Meanwhile, IoT enables real-time control through data collection from sensors and smart meters, automated energy management, and early disruption detection with the support of edge computing and device interoperability.

Table 4. Summary of emerging technologies

Technology	Emerging Trends
AI-Based Optimization	Reinforcement learning, deep learning, multi-objective optimization, AI for demand response, predictive analytics for load forecasting and fault detection.
Blockchain for Decentralization	Peer-to-peer energy trading, smart contracts, tokenization of energy, decentralized autonomous organizations (DAOs), and blockchain for grid security.
IoT in Real-Time Control	Real-time data collection (smart meters, sensors), automated energy management, edge computing, fault detection, and interoperability of IoT devices.

Table 5. Frequency control methods and their merits and demerits.

Author(s)/Reference Number	**Work done**	**Frequency Control Method**	**Contribution**	**Drawback**
Mariem Y. Yousef et al. 2024 [6]	Decentralized utilization of distributed energy storage resources for simultaneous frequency regulation in a microgrid	Frequency and inertia enhancement through the combined operation of PV and wind generation systems as a support.	Using PV only, wind only, or simultaneously using both increased the frequency deviation by 44.4%, 29.5%, and 53.3%, respectively. In addition, using PV and wind energy simultaneously reduces the required energy by 29.5% and 13.7%, respectively, and enhances the ROCOF by 61.9%.	The proposed control scheme relies heavily on the availability of sunlight and wind. Variability in these renewable resources can ~~lead~~ cause inconsistent performance, particularly during periods of low generation, which proposed strategy may not ~~be~~ adequately address.
Masoud dashtdar et al. 2022 [12]	Improving the Power Quality of Island Microgrid with Voltage and Frequency Control Based on a Hybrid Genetic Algorithm and PSO	The authors present a novel frequency control method for islanded microgrids, which incorporates an Artificial Neural Network (ANN) and Genetic Algorithm (GA) to optimize the Proportional-Integral (PI) controller.	The combination of Artificial Neural Networks (ANN) with Genetic Algorithms (GA) enables online training of the ANN, thereby enhancing the controller's adaptability and performance. The results indicate that this hybrid approach significantly reduces the maximum overshoot and settling time of the microgrid frequency, especially under uncertain conditions.	The integration of ANN and GA introduces computational complexity that may not be manageable with standard processing units. The authors acknowledge that high-resolution processors are necessary to handle the extensive calculations involved, which can increase the overall cost and complexity of the control system.
Juelin liu et al 2020 [73]	Coordinated control parameter setting of DFIG wind farms with virtual inertia control	Utilizing virtual inertia from wind farms to enhance the frequency stability of power systems.	The proposed method adjusts the active power output based on system frequency feedback, which is significant as it mimics the behavior of synchronous generators, providing necessary inertia support in systems with low natural inertia.	While the paper presents a comprehensive approach, it could benefit from a more detailed comparison with existing methods to provide a clearer context for proposed approach's advantages.
Amin Karimi et al 2019 [74]	Inertia Response Improvement in AC Microgrids: A Fuzzy-Based Virtual Synchronous Generator Control	The proposed method employs a fuzzy controller that adaptively adjusts the output power of the governor to improve the system's inertia during transient conditions.	The authors provided a comparative analysis between the proposed fuzzy control technique and traditional inertia response improvement methods. It demonstrates that the fuzzy approach offers superior performance in terms of responsiveness and efficiency.	The proposed fuzzy control system, while innovative, may introduce complexity in implementation. The design and tuning of fuzzy controllers require expertise and can be challenging in real-world applications.
Tong Chen et al 2020 [75]	Virtual Inertia from Smart Loads	The authors presented a frequency control method that utilizes electric spring (ES) technology to provide virtual inertia and primary frequency response through smart loads (SL).	The ES technology allows voltage-dependent loads to operate as smart loads, which can modulate their power consumption within a specified voltage range (±5% of nominal voltage). The control design allowed the system to provide up to 2.5 seconds of virtual inertia under specific conditions. The system frequency nadir improved from 48.95 Hz to 49.3 Hz when the smart load was active.	The discussion does not thoroughly address practical implementation challenges, such as integrating electric spring (ES) technology into existing infrastructure and assessing the economic feasibility of widespread adoption.

Author(s)/Reference Number	Work done	Frequency Control Method	Contribution	Drawback
Mohammad Ebrahimi et al 2019 [76]	An Improved Damping Method for Virtual Synchronous Machines	The Virtual Synchronous Machines (VSM) approach emulates the dynamics of a synchronous machine (SM) within the inverter's controller to allow for frequency control.	The proposed method introduces a novel damping strategy that does not require explicit frequency measurement. It utilizes internal information from the VSM to generate an auxiliary signal that interacts with the grid voltage, similar to phase detection in phase-locked loops (PLLs).	While the authors present mathematical analysis and simulations to support the proposed method, the absence of extensive experimental validation in real-world scenarios may raise questions about the practical effectiveness of the damping strategy.
Mahdi Saadatman et al 2021 [77]	Damping of Low-Frequency Oscillations in Power Systems by Large-Scale PV Farms: A Comprehensive Review of Control Methods	The frequency control methods in this work primarily revolve around the use of Power oscillation damping controller PODCs, particularly Linear–quadratic–Gaussian LQG controllers, to manage low frequency oscillations LFOs in power systems.	Literature review and simulations conducted by the authors demonstrate that the proposed Power oscillation damping controller PODCs for Large-scale PV farms LPFs show proper performance in damping low frequency oscillations LFOs.	The major drawback is the low capacity of BESSs, which limits their effectiveness in enhancing the reliability of large-scale PV farms for LFO damping.
Andrea Bonfiglio et al 2018 [78]	Design and Implementation of a Variable Synthetic Inertia Controller for Wind Turbine Generators	The authors present an innovative frequency control method through the design and implementation of a Variable Hidden Inertia Emulator (VHIE) for Wind Turbine Generators (WTGs) equipped with Permanent Magnet Synchronous Generators (PMSGs).	The initial tests were conducted on a simplified configuration, followed by a more realistic simulation. The simulations demonstrated that the VHIE controller effectively reduced the Rate of Change of Frequency (RoCoF) by approximately 40%. The frequency nadir, which is the lowest point of frequency during a transient, showed a 35% improvement.	Although the VHIE aims to provide effective frequency support, its performance during rapid frequency transients may still be limited. The synthetic inertia coefficient's dependence on rotor speed means that during critical moments of frequency deviation, the controller's effectiveness could diminish, potentially leading to inadequate support when it is most needed.
Thongchart Kerdphol et al 2018 [79]	Virtual Inertia Control Application to Enhance Frequency Stability of Interconnected Power Systems with High Renewable Energy Penetration	The frequency control method proposed by the authors revolves around the innovative use of virtual inertia control combined with a derivative control technique.	This work highlights the effectiveness of virtual inertia control in improving frequency stability, enhancing dynamic performance, and providing robustness against disturbances in interconnected power systems with high renewable energy penetration.	The study relies heavily on simulations conducted in MATLAB and Simulink. While this is a robust tool for modeling, the results may not fully capture real-world complexities and uncertainties present in actual power systems.
Thongchart Kerdphol et al 2019 [80]	Enhanced Virtual Inertia Control Based on Derivative Technique to Emulate Simultaneous Inertia and Damping Properties for Microgrid Frequency Regulation	The frequency control method proposed by the authors emphasizes the integration of virtual inertia and damping through a derivative technique.	The proposed virtual inertia control method effectively enhances microgrid frequency stability by balancing the roles of virtual inertia and damping while also demonstrating robustness in challenging operational scenarios.	The researchers did not adequately address the potential complexities introduced by integrating the proposed control method into existing microgrid systems.

Author(s)/Reference Number	Work done	Frequency Control Method	Contribution	Drawback
Ahmadreza Abazari et al 2020 [81]	High penetrated renewable energy sources-based AOMPC for microgrid's frequency regulation during weather changes, time varying parameters, and generation unit collapse	The authors proposed an innovative frequency control method known as Adaptive Optimal Model Predictive Control (AOMPC).	The researchers compared the AOMPC method with various existing controllers, including optimal proportional-integral (OPI), optimal fractional order PID (OFOPID), optimal fuzzy PID (OFPID), and adaptive MPC (AMPC). The results indicated that AOMPC provided the best performance in terms of frequency regulation during multiple load disturbances and changes in weather patterns.	The implementation of AOMPC may involve complex computations and require advanced algorithms, such as the CPSO algorithm for parameter tuning. This complexity could pose challenges in real-time applications, especially in systems with limited computational resources.
Mohammad-Hassan Khooban 2020 [82]	An Optimal Non-Integer Model Predictive Virtual Inertia Control in Inverter-Based Modern AC Power Grids-based V2G Technology	The authors presented a virtual inertia control-based vehicle-to-grid (V2G) concept for the secondary load frequency control of AC islanded microgrids (MGs).	The proposed control approach outperforms conventional MPC (CMPC) and model-free Sliding Mode Control (MFSMC) in terms of frequency regulation. The researchers effectively utilized the stored energy in electric vehicles to enhance both steady-state and transient performance, showcasing the benefits of integrating V2G technology into frequency control strategies.	The study assumes that operators can effectively control electric vehicles as mobile energy storage devices. However, this assumption may not hold ~~true~~ in all cases, as user behavior, charging patterns, and vehicle availability can vary significantly. These factors could impact the reliability of the V2G system and its ability to provide the necessary virtual inertia.
Rajasi Mandal et al 2021 [83]	Virtual inertia emulation and RoCoF control of a microgrid with high renewable power penetration	The frequency control method proposed by the authors combines virtual inertia and damping, optimized through genetic algorithms.	The proposed VI control system not only enhances the dynamic response and frequency regulation of the microgrid but also demonstrates robustness against various operational challenges.	The study relies heavily on the Genetic Algorithm (GA) for optimizing the parameters of the VI control system. While GA is known for its fast convergence, the paper does not explore alternative optimization methods or provide a comparative analysis of their effectiveness.
Siqi Fu et al 2022 [84]	Power oscillation suppression in multi-VSG grid with adaptive virtual inertia	The frequency control method proposed by the authors is an adaptive virtual inertia control method.	The adaptive virtual inertia control resulted in a significant improvement in frequency response, minimizing frequency deviations and enhancing overall system stability. The proposed method maintained its effectiveness even with communication delays of up to 100ms, ensuring continued performance in large networks.	While the proposed control method shows promise, the control strategy relies heavily on distributed communication among VSG units. Disrupted communication can introduce vulnerabilities due to this dependency.
Nicolas Sockeel et al 2020 [85]	Virtual Inertia Emulator-based Model Predictive Control for Grid Frequency Regulation Considering High Penetration of Inverter-based	The frequency control method proposed by the authors is a virtual inertia emulator (VIE) based Model predictive control MPC.	The MPC approach can reduce the minimum Energy Storage System (ESS) capacity required for frequency regulation by 55% compared to a P controller and by 2% compared to a PI controller. The researchers found that using MPC reduced the	While the proposed control method shows promise, it fails to explore real-time simulations and experimental validation to verify the efficacy of the proposed method.

Author(s)/Reference Number	Work done	Frequency Control Method	Contribution	Drawback
	Energy Storage System		energy throughput of the ESS by 86% compared to a P controller and by 36% compared to a PI controller. The study highlights that MPC effectively minimizes frequency deviation during disturbances, demonstrating its superior performance compared to traditional control methods.	
Amr Saleh et al 2022 [86]	Manta Ray Foraging Optimization for the Virtual Inertia Control of Islanded Microgrids Including Renewable Energy Sources	The frequency control method proposed by the authors is a virtual inertia control based on proportional-integral (PI) controller optimally designed by the Manta Ray Foraging Optimization (MRFO).	The MRFO-based PI controller demonstrated superior performance in frequency disturbance alleviation and reference frequency tracking compared to other optimization techniques, such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA). Specifically, the researchers found that it tracked the microgrid frequency reference point during disturbances four times better than the PSO-based controller and twice as good as the GA-based controller.	Although the MRFO-based PI controller exhibits superior performance compared to other optimization techniques, such as GA and PSO, the complexity of the MRFO algorithm may pose challenges in its practical implementation.

Various frequency control methods for microgrids have been developed, such as the use of virtual inertia from renewable generation, AI-based intelligent control, and MPC optimization. These methods are effective in improving frequency stability, reducing RoCoF, and improving nadir frequency, especially in systems with high renewable energy penetration. However, most still have limitations in terms of dependence on weather conditions, computational complexity, the need for sophisticated hardware, and the lack of experimental validation or challenges in field implementation. This can be seen in Table 5.

3.13. Control/Damping of Frequency Oscillation in Power Systems

Controlling and damping frequency oscillations in power systems is crucial for maintaining stability and reliability. In controlling/damping frequency oscillation, integer order, and non-integer order controllers can be used. Additionally, researchers can use damping controllers, energy storage systems, and advanced control techniques.

3.14. Integer Order Control

An integer order controller is a class of control systems characterized by their use of integer order transfer functions, where the exponents of the S variable (in the Laplace domain) are integers. Researchers commonly use them because of their simplicity and effectiveness. The most common types are proportional (P), Integral (I), and Derivative (D) controllers.

3.14.1. Proportional-Integral (PI) Controllers

PI controllers are commonly employed to improve the transient and dynamic performance of MGs through the implementation of that transfer function [87, 88] as follows:

$$C_{Pi}(S) = K_p + \frac{K_i}{S} \tag{1}$$

Where K_p and K_i proportional and integral constants of controllers

3.14.2. Proportional-Integral-Derivative (PID) Controllers

A PID controller is a widely used feedback control mechanism that aims to improve the stability and performance of various systems. Researchers can adjust PID parameters to optimize performance and minimize overshoot. Recent studies have explored adaptive PID controllers that modify their parameters in real-time based on system behavior, allowing for greater resilience in dynamic environments. The transfer function of the PID controller is:

$$C_{Pid}(S) = K_p + \frac{K_i}{S} + K_d S \tag{2}$$

Where K_d is the derivative constant of controllers

3.14.3. Tilt-Integral-Derivative (TID) Controllers

TID controllers are advanced control strategies that combine the principles of Proportional, Integral, and Derivative control, focusing on the "tilt" action that helps adjust the system's response to error over time. The tilt action allows for dynamic tuning of K_i and K_d gains to adjust how aggressively the integral and derivative terms respond to the current and past error. The transfer function of the TID controller is:

$$C_{Tid}(S) = K_T \left(\frac{1}{S}\right)^n + \frac{K_i}{S} + K_d S \tag{3}$$

Where K_T is the "Tilt" constant of controllers

3.15. Non-Integer Order Controllers

These are advanced control strategies ~~to~~ for integer-order controllers that utilize principles from fractional calculus. Unlike traditional integer order controllers, which use integer derivatives and integrals, non-integer controllers incorporate fractional derivatives, allowing for greater flexibility in system response and behavior.

3.15.1. Fractional Order (FO) Controllers

Fractional order controllers have garnered significant attention in control systems due to their ability to provide improved performance compared to traditional integer-order controllers. Unlike conventional controllers, FO controllers utilize fractional calculus, which enables greater flexibility in system modeling and control design. FO controllers can capture the dynamics of systems that exhibit non-integer behavior, making them suitable for a wide range of applications. The additional parameters in FO derivatives and integrals provide more tuning options, enabling better response characteristics such as overshoot, settling time, and robustness.

3.16. Damping Controllers

Damping controllers are specialized control devices or strategies used to reduce or eliminate oscillations in power systems. Damping controllers in power systems are primarily designed to damp out **low-frequency oscillations**, typically in the range of 0.1 Hz to 3 Hz [89].

3.16.1. Power System Stabilizers (PSS)

In synchronous generators, these offer an additional control signal dependent on generator speed or rotor angle to dampen low-frequency oscillations. Researchers typically design stabilizers for power systems to work in tandem with synchronous generators. In systems without traditional SGs, they omit power system stabilizers (PSS) as ~~a~~ low-frequency oscillations dampers [90].

3.16.2. Flexible AC Transmission Systems (FACTS)

FACTS are static power electronic devices installed to enhance power transfer quality, ensuring system stability and controllability in AC transmission networks [91][92]. FACTS devices, such as STATCOMs or SVCs, can provide dynamic reactive power support, which helps in damping oscillations.

3.16.3. Virtual Damping Stabilizers (VDS)

Damping stabilizers are used primarily in power systems to enhance stability. They work by adding a damping effect to oscillatory modes, which helps to reduce overshoot and settling time. The goal is to ensure that the system responds smoothly to disturbances without excessive oscillation.

Virtual damping stabilizers are a more advanced concept used in control systems, particularly in applications like power systems and robotics. They simulate damping effects without the need for physical components, providing flexibility and adaptability in managing system dynamics. With the high penetration of renewable energy sources, Virtual Damping Stabilizers (VDS) have proven useful due to their application in damping low frequency oscillations.

3.16.4. Interaction of VDS with Integer-Order Controllers

1. Complementary Roles: Virtual damping stabilizers can complement integer order controllers (such as PID controllers) by providing additional damping where needed, particularly in systems prone to oscillations or instability.
2. Tuning and Coordination: The effectiveness of this combination relies on proper tuning and coordination. The researchers must calibrate the virtual damping stabilizer to enhance the performance of the integer order controller, ensuring that both elements work synergistically without introducing excessive delay or instability.
3. Dynamic Response Improvement: In scenarios involving significant variations in system parameters or external disturbances, virtual damping stabilizers can adapt in real time, maintaining optimal damping effects while the integer order controller focuses on overall control objectives.

3.17. Energy Storage Systems

Battery Energy Storage Systems (BESS): Power injection or absorption using battery energy storage systems (BESS) enables a rapid response to frequency fluctuations, thereby stabilizing the frequency. One possible option for low inertia systems is to utilize an energy storage system (ESS) or the inertia of converter-connected generation, as proposed in [93].

3.18. Advanced Control Techniques

Advanced control techniques encompass a variety of methods designed to improve system performance, stability, and robustness in control engineering. Among these control approaches are model predictive control (MPC), fuzzy logic control, and neural network control [94].

3.19. Model Predictive Control (MPC)

To achieve precise current tracking, MPC primarily aims to enhance performance by reducing the expected error control. With MPC, it is possible to easily handle the nonlinearities and general restrictions of a system with multiple inputs and outputs. Following the controller's optimal switching state requirement for the cost function [95] [96]. Precise tuning and parameter sensitivity are the basis of the mathematical model of model predictive control (MPC).

3.20. Fuzzy Logic Control

Fuzzy controllers use rules based on human expertise to manage systems that are difficult to model mathematically. They handle imprecise inputs and provide a more intuitive control approach. In fuzzy logic control, a fuzzy logic controller consists of four steps: input fuzzification, rule base establishment, fuzzy inference, and output defuzzification [97].

3.21. Neural Network Control

By leveraging machine learning, neural networks can approximate complex nonlinear functions. Researchers often use this technique for adaptive control and system identification. In a neural network, simple nonlinear units known as nodes or neurons are connected, with the strength of these connections represented by parameters called weights. These weights are modified based on the task to enhance performance. They can set the parameters in two ways: either by applying a predefined offline algorithm that remains fixed during operation or by updating them through a learning process. The ability to learn is one of the main advantages that make neural networks so attractive [98].

3.22. Future Research Areas in MGs

Microgrids are becoming an increasingly important component of modern power systems, offering the flexibility to integrate renewable energy sources, improve energy reliability, and enhance grid resilience. One of the key challenges in operating a microgrid is maintaining frequency stability, particularly as microgrids incorporate an increasing number of intermittent renewable energy sources, such as solar and wind. Frequency control in microgrids involves maintaining the balance between generation and load, which can be difficult due to the dynamic and often unpredictable nature of renewable energy generation [108]. As microgrids become more connected and rely on digital communication and control systems, ensuring the cyber security of frequency control algorithms is critical. Future research could focus on robust encryption and intrusion detection systems that protect microgrid control networks from cyber threats, ensuring reliable frequency regulation even in the event of a cyber-attack. When microgrids operate in islanded mode (disconnected from the main grid), maintaining frequency stability becomes even more challenging due to the lack of support from the larger grid. Research can focus on developing advanced algorithms that enable a smooth transition of Microgrids (MGs) [109][110] from a state of being connected to the main power grid to operating autonomously. Energy storage systems, particularly batteries, play a critical role in mitigating frequency fluctuations. Research can focus on optimal sizing, operational strategies, and charging/discharging algorithms that enable ESS to respond effectively to frequency deviations. Various control methods are used in microgrid systems. Details can be seen in Table 6.

Table 6. Advantages and Drawbacks of different controllers

Categories	Control method	Advantages	Disadvantages
Integer-Order controllers	PI Controllers [99]	• Simple Implementation • Applicable to both single and three phase systems	• Unable to track the sinusoidal reference under non-linear load
	PID Controllers [100]	• Adaptable for Both Open and Closed Loop Systems • Simple Design and Implementation	• Limited Effectiveness in Nonlinear Systems • Sensitive to Noise
	TID Controllers [101]	• Time-Delay Compensation • Used in both linear and nonlinear systems	• Not suited for systems with high nonlinearity • Limited Applicability in Non-Delayed Systems
Non-Integer-Order controllers	FO controllers [102]	• Fast dynamic response • Robust and flexible control	• Sensitivity to changing control parameters is less
Damping Controllers	VDS [1]	• VDS are implemented through control strategies rather than through physical devices that consume energy • Cost-Effective	• Limited Impact on Very Low-Frequency Oscillations • Sensitivity to Communication Delays
	FACTS [103]	• Allow better integration of renewable energy sources by providing voltage and reactive power control • FACTS devices can enhance the damping of frequency oscillations.	• Limited Impact on High-Frequency Oscillations • Result in additional power losses due to the reactive power compensation.
Energy storage	BESS [104]	• BESS can be controlled with high precision • Integration with Renewable Energy	• Limited Energy Capacity for Large Disturbances • Complexity in Sizing and Optimization
Advanced control techniques	MPC [105]	• Precise current control with ~~less~~ fewer harmonics • Less switching frequencies. • Deals with non-linearity.	• Sensitive to parameter changes • More computation burden
	Fuzzy Logic Control [106]	• Handling System Nonlinearity and Uncertainty • Flexibility and Adaptability	• Difficulty in Handling Large-Scale Systems • Design Complexity
	Neural Network Control [107]	• Self-Learning and Optimization • Handling Complex Control Tasks	• Training Time and Data Requirements • Need for Continuous Training.

4. CONCLUSIONS AND LIMITATION

This paper presents a thorough examination of microgrid architectures and control techniques, highlighting their significance in modern power systems. The study categorizes microgrid architectures into three main types: AC-MG, DC-MG, and hybrid-MG. Each architecture presents unique advantages and challenges, particularly in terms of integration with distributed energy resources (DERs) and operational efficiency. The researchers classify microgrids control strategies into three hierarchical layers: primary, secondary, and tertiary. Each layer plays a crucial role in ensuring stable and reliable operation, with primary control focusing on immediate voltage and frequency regulation, secondary control on restoring nominal values, and tertiary control on long-term economic dispatch and energy optimization. The review highlights several control techniques, including Proportional-Integral (PI) controllers, Tilt-Integral-Derivative (TID) controllers, and Damping Controllers. Each of these controllers serves specific functions in managing the dynamics of microgrid systems.

For instance, PI controllers are essential for maintaining system stability by adjusting the output based on the error between desired and actual performance. TID controllers introduce a "Tilt" constant to enhance performance, while Damping Controllers, including Power System Stabilizers (PSS) and Virtual Damping Stabilizers (VDS), are crucial for mitigating frequency oscillations in systems with high renewable energy penetration. The review also highlights the significance of non-integer order controllers, which utilize principles from fractional calculus. These controllers offer greater flexibility in system response and behavior compared to traditional integer order controllers. By incorporating fractional derivatives, non-integer order controllers can better capture the dynamics of systems exhibiting non-integer behavior, making them suitable for a wide range of applications in microgrid control. BESS plays a crucial role in microgrid operations by providing energy storage solutions that enhance reliability and stability. They help manage fluctuations in energy supply and demand, ensuring ~~that~~ the microgrid can respond effectively to changes in load or generation.

The integration of BESS with advanced control strategies can significantly enhance the overall performance of microgrids, enabling improved frequency regulation and energy management. The paper discusses various advanced control techniques, such as model predictive control, fuzzy logic control, and neural network control. The researchers design these methods to enhance system performance, stability, and robustness. They offer more adaptable solutions to the challenges posed by integrating renewable energy sources and the inherent variability in microgrid operations. By leveraging these advanced techniques, microgrids can achieve improved dynamic response and operational efficiency. Looking ahead, the paper identifies several future trends in microgrid control strategies. As the integration of renewable energy sources continues to grow, there will be an increasing need for advanced control techniques that can handle the variability and intermittency of these resources. Researchers expect techniques such as model predictive control, fuzzy logic control, and neural network control to gain prominence, as they offer more adaptive and intelligent solutions for frequency regulation and energy management. Additionally, the review emphasizes the importance of cyber security in microgrid control networks. As these systems become more interconnected, robust encryption and intrusion detection systems will be essential to protect against potential cyber threats, ensuring reliable operation even in adverse conditions. The findings of this paper underscore the significance of effective control strategies in microgrids and highlight the need for ongoing research and development to address emerging challenges. The evolution of control techniques will play a pivotal role in shaping the future of energy systems, promoting sustainability and resilience in the face of growing energy demands.

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BIOGRAPHIES OF AUTHORS

Engr. Abdulmalik Ibrahim Dabo is a second-year master's student at the Nigerian Defense Academy Post Graduate School undergoing a research program in Power and Machine, Electrical Engineering. He received a bachelor's degree in Electrical Engineering from Bayero University Kano. He is a certified Electrical Engineer by the Council for the Regulation of Engineering in Nigeria (COREN). He is interested in microgrids, power systems optimization, Artificial intelligence, and Renewable Energy. He can be contacted at email: abdulmalikdaboi@gmail.com

Engr. Dr. Sabo Aliyu (Ph.D) MIEEE. PES. (Member, IEEE) Engr. Dr. Sabo Aliyu completed his Bachelor's degree in Electrical Engineering from the Prestigious Ahmadu Bello University, Zaria, Kaduna State, Nigeria in 2011. Engr. Dr. Sabo Aliyu completed his M.Sc and Ph.D Degrees in Electrical Power Systems Engineering from Universiti Putra Malaysia. His main research areas include the application of Neuro Fuzzy Controller to power system, Computational Intelligence techniques, Power System Oscillation Damping Controller Designs, Power Systems Optimizations, Power Flow and Optimal Power Flow, Power Quality, and Robust controllers with several online publications. Engr. Dr. Sabo Aliyu is currently a Senior Lecturer at Nigerian Defence Academy, Kaduna State, Nigeria. He is a registered Engineer under the Council for the Regulation of Engineering in Nigeria (COREN).

Olutosin Ogunleye is a Senior Research Fellow at the Centre for Innovation and Creativity, Nigerian Defence Academy. He obtained B.Eng in Electrical/Electronic Engineering and M.Eng Electronic/Communications Engineering from the Nigerian Defence Academy in 1998 and 2012 respectively. He also bagged a doctorate in Energy Studies from the Faculty of Multidisciplinary Studies, University of Ibadan, Nigeria in 2021. He has attended energy conferences within and outside Nigeria and his research interests include solar thermal systems and energy security. He is a corporate member of the Nigerian Society of Engineers, Nigeria Institute of Management and a chartered engineer of the Council for the Regulation of Engineering in Nigeria. He is also a fellow of the Army War College (fwc) Nigeria and fellow of the National Defence College (fdc) Nigeria.

Noor Izzri Abdul Wahab graduated from the University Of Manchester Institute Of Science and Technology (UMIST), UK, in Electrical and Electronic Engineering in 1998, received his MSc in Electrical Power Engineering from the Universiti Putra Malaysia (UPM) in 2002 and his PhD in Electrical, Electronic and System Engineering from Universiti Kebangsaan Malaysia (UKM) in 2010. He is an Associate Professor at the Department of Electrical and Electronic Engineering, Faculty of Engineering, UPM. He is a Researcher and the founding member of the Centre for Advanced Power and Energy Research (CAPER), UPM and an associate member of the Centre of Electromagnetic and Lightning Protection Research (CELP), UPM. He is a registered Chartered Engineer under the Engineering Council UK and the Institution of Engineering and Technology (IET) UK, a professional engineer (Ir.) awarded by the Board of Engineers Malaysia (BEM), a member of The Institution of Engineers Malaysia (IEM), an IEEE senior member, a member of the IEEE Power and Energy Society (IEEE-PES), a member of the IEEE Computational Intelligence Society (IEEE-CIS), a member of the Institution of Engineering and Technology (IET) UK, a member of the International Rough Set Society (IRSS). His areas of interest include power system stability studies (Dynamic and Control), application of artificial intelligence in power systems and power system quality.

Hossein Shahinzadeh (Member, IEEE) was born in Isfahan, Iran, in 1987. He graduated from the Iranian Center of Excellence in Power Systems, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran, with a scientific education in electrical engineering. Since September 2015, he has been an Academic Member of the Islamic Azad University of Najafabad's (IAUN) Department of Power Engineering, Faculty of Electrical Engineering. In Tehran, he works as an Associate Researcher at the Iran Grid Secure Operation Research Institute, AUT, and the Niroo Research Institute (NRI). He is also a Senior Scientist at SMRC, IAUN, Isfahan, where he works in the subject of smart city research. The Internet of Things (IoT), artificial intelligence, metaheuristic optimization methods, big data analytics, blockchain, V2G integration, 5G technology in smart grids, renewable energy deployment, energy storage facilities, power markets, microgrids, and long-term energy planning are some of his research interests in smart grids.

Abdulmajid Muhammad Na'inna is an inquisitive and hardworking academic always willing to take up new challenges, network with experts in relevant fields and find solutions to problems for the betterment of humanity. His current areas of research and teaching interests are: * Fire, explosion and safety engineering. * Explosives and nuclear engineering. * Electrical electronics engineering. * Defence and international politics.