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Review

A Review of Synchronous Fixed-Frequency Microgrid Droop Control Systems Based on Global Positioning System

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Abstract: Microgrids, as a new type of power supply network that connects distributed energy sources with power loads, can operate in both grid-connected and islanded states. It has the advantages of high reliability and flexible configuration. When the microgrid operates in islanding mode, ensuring voltage and frequency stability becomes a primary focus of research. This paper provides a brief overview of the master-slave control and peer-to-peer control strategies used in microgrids, analyzing the advantages and disadvantages of each approach. The application of droop control strategies to microgrid converters is emphasized. This research analyzes the implementation of droop control strategies in addressing microgrid frequency and power offsets. Given the advantages of the synchronized fixed-frequency droop control method, the authors provide a detailed overview of this strategy, which is based on the global satellite navigation system (GPS). On this basis, a comprehensive comparison of various synchronous frequency control methods is conducted, analyzing the advantages and disadvantages of each approach. Finally, the research findings in this area are summarized, and the future development trends of research in this field are discussed and anticipated.

Keywords: microgrids; droop control; constant-frequency synchronous; GPS

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1. Introduction

Microgrids represent a new type of power supply system that integrates generation, transmission, distribution, and consumption [1]. They primarily manage and regulate distributed energy sources such as wind, solar power, and energy storage, utilizing power electronic devices like AC/DC and DC/DC converters. This enables the generation, distribution, storage, and delivery of electricity within a localized area. Microgrids can operate in both grid-connected and off-grid modes, depending on the condition of the larger power grid [2]. In grid-connected mode, they can either draw power from or supply power to the medium- and low-voltage distribution network, depending on their energy production. In off-grid mode, microgrids can achieve self-sufficiency in their power supply by utilizing internal distributed energy resources through power electronic devices. They offer benefits such as operational flexibility, reliability, and cost-effectiveness. Since the concept was introduced by American scholar Professor Robert H. Lasseter in 2001, various countries, including China, the United States, Denmark, Germany, and Spain, have conducted research on microgrids. This research has focused on islanding operations, control methods, and inverter control strategies for islanding microgrids [3,4].

In general, microgrids comprise various complementary distributed energy supply units, including photovoltaic and wind power generation systems, as well as energy storage solutions. These components can significantly enhance the reliability and security of power delivery to electrical loads [5]. Inverters play a crucial role in microgrid systems, acting as the power conversion devices that connect the functional units to the AC bus. However, the unpredictable nature of renewable energy sources, such as solar and wind power, introduces uncertainty into microgrid control. Moreover, achieving synchronous and cooperative operation among multiple inverter units during off-grid conditions presents a significant challenge. Therefore, researching control strategies for microgrid operations and their associated inverter units can optimize the utilization of power generated by distributed energy sources, improve their efficiency, and facilitate rapid adjustments to maintain the system's power balance. Additionally, these strategies can ensure that each converter system operates synchronously and cooperatively during off-grid scenarios, thereby enhancing the overall reliability of the microgrid system.

Over the past two decades since the introduction of the concept of microgrids, research on this topic by scholars both domestically and internationally has remained highly active [6]. For example, a search for "islanded microgrids and droop control" in the Web of Science yielded over 840 results, with more than 440 of those published in the last three years. It is important to note that the control strategies and requirements for various converter systems in microgrids differ based on their specific application contexts. For instance, in photovoltaic power generation units within microgrid systems, the primary focus of converter control is on active power sharing. During the islanding operation of a microgrid, the equitable distribution of power among distributed generation units is a critical area of research. Furthermore, managing the grid's voltage and frequency during microgrid islanding is also receiving increased attention. L. Ahmethodžić et al. [7] offer a comprehensive overview of power allocation methods for AC microgrids. A study [8] offers a comprehensive review and analysis of AC microgrids and hybrid AC/DC microgrid control strategies. Another study [9] presents an overview of control methods for inverters in microgrids, examining the research challenges and future trends associated with these methods. To elaborate on the droop control method that utilizes GPS-based fixed-frequency control, this paper provides a detailed overview of synchronized fixed-frequency control methods for microgrids.

Based on the analysis presented above, what is the precise structure of an islanded microgrid? What is the configuration of the control system components? What sag control methods are currently employed in isolated, islanded microgrids? Additionally, what are the research directions for GPS-based synchronized frequency control methods, along with their advantages and disadvantages? This paper will be organized, synthesized, and analyzed.

The paper is structured in the following manner. Section 2 outlines the fundamental framework of a microgrid and discusses three operational control methods applicable during the microgrid's islanding state. Section 3 details three inverter control strategies within microgrids, with a comprehensive explanation of the droop control method. Section 4 centers on the GPS-based synchronized frequency control approach. Finally, Section 5 presents the paper's conclusions.

2. Basic Structure of Microgrids and Their Operating Systems

2.1. Microgrid Topologies

Currently, AC microgrid topologies primarily consist of two main configurations: radial microgrids and ring microgrids. The radial microgrid facilitates distributed energy pooling and load power supply through a single AC bus that radiates outward. Its specific

structure is illustrated in Figure 1. Typically, a radial microgrid consists of a public AC bus, distributed energy sources, electrical loads, inverters, and transmission lines [10]. As illustrated in the figure, the AC bus of the microgrid connects three feeders to the low-voltage (LV) distribution network. The connection between the AC bus and the LV distribution network is established through the point of common coupling (PCC). The distributed energy sources consist of photovoltaic cells, energy storage batteries, wind turbines, micro gas turbines, and others, which are connected to the three feeders through power electronic converters like inverters based on their specific distribution. A simplified structure of a radial microgrid is illustrated in Figure 2a. This configuration is vulnerable to internal disturbances and lacks interoperability with other power systems. To enhance the reliability of the power supply, a ring microgrid is a more dependable option. As illustrated in Figure 2b, the ring microgrid features several independent common AC buses that are interconnected via switches to facilitate power sharing among various microgrids. Furthermore, ring microgrids are typically linked to different LV distribution networks through multiple common coupling points. As a result, the ring microgrid experiences a shorter average sustained outage time and has a greater capacity to integrate conventional power from distributed generators (DGs).

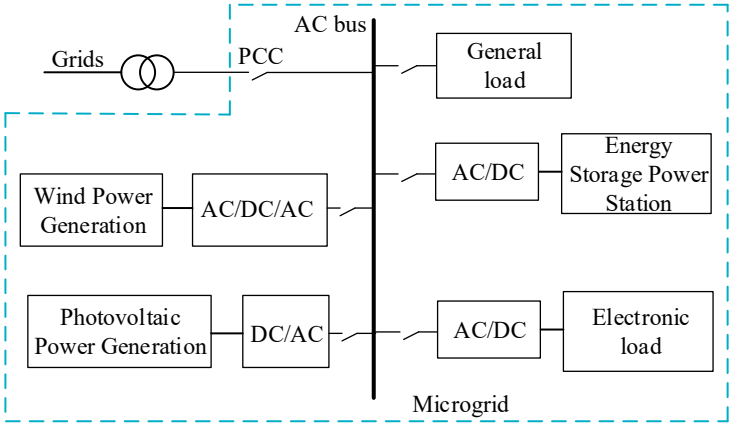
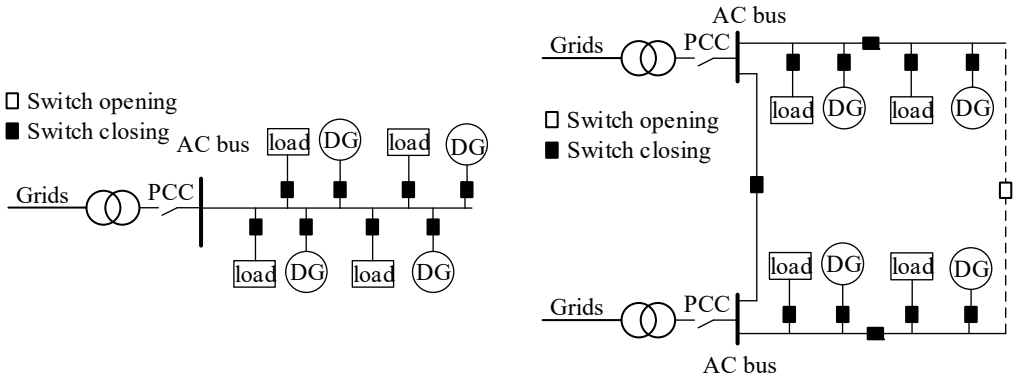


Figure 1. Structure of microgrids.



(**a**) radial microgrid (**b**) ring microgrid

Figure 2. Structure of radial and ring microgrids.

As shown in Figure 1, the microgrid can operate in both grid-connected and off-grid modes, depending on whether the PCC at the common connection point is open or closed [11]. When connected to the LV distribution network through the PCC, the microgrid operates in grid-connected mode. This configuration enables bidirectional power transmission and interaction with the LV distribution network, depending on its energy

supply status. Conversely, when the PCC is disconnected, the microgrid operates in off-grid mode. In this state, the converter system generates power from its distributed energy sources and supplies it to internal loads through the microgrid's power transmission lines, thereby achieving self-sufficiency in power supply.

2.2. Microgrid Control Structure

As illustrated in Figure 3, the dual-mode operation of the microgrid—both on-grid and off-grid—depends not only on the appropriate hardware configuration but also on the control system. The current composition of the control system in microgrids typically consists of three layers: the dispatch management layer, the regulation control layer, and the local control layer [12]. The dispatch management layer oversees power scheduling within the microgrid and regulates the power flow between the microgrid and the distribution grid, ensuring stable overall operation as the highest level of control. The regulation control layer focuses on the secondary adjustments of control parameters, such as voltage and frequency offsets for individual grid-connected inverters. Meanwhile, the local control layer is responsible for maintaining stable voltage and frequency within the microgrid by managing local distributed energy resources, including local converters. Effective coordination among these three control levels often requires a dedicated communication network, which can raise the investment costs of the microgrid system.

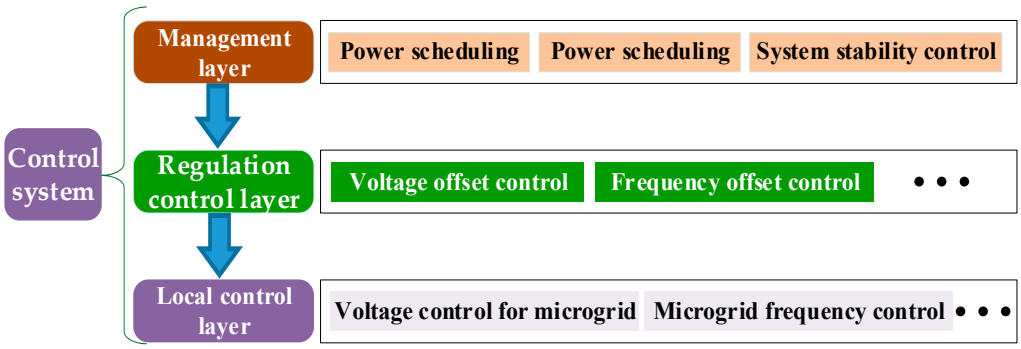


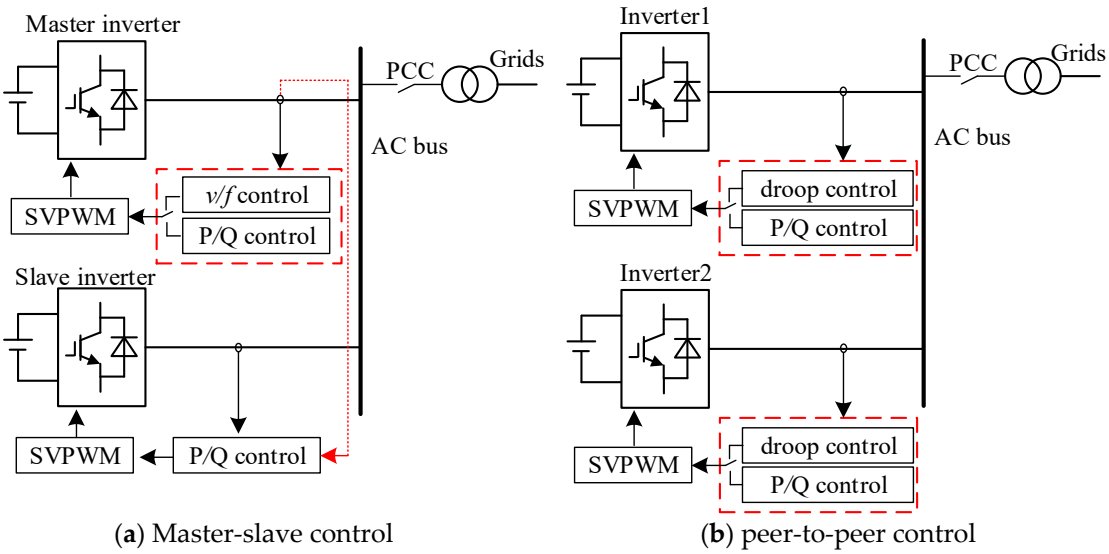
Figure 3. The control system in microgrids.

2.3. The Control Method of Microgrid Under Island Operation Mode

When a microgrid operates in islanded mode, it no longer receives voltage and frequency support from the distribution grid and relies entirely on its own distributed power sources for energy. In this scenario, the control strategy for the islanded microgrid is crucial for maintaining voltage and frequency stability. Distributed renewable energy sources typically require inverters for power conversion and grid connection. Consequently, ensuring the stable operation of islanded microgrids within the field of microgrid power electronics has become a significant area of research for scholars worldwide [13].

Currently, the two primary control methods for islanded microgrids are hierarchical control and master-slave control, both of which manage the operation of the microgrid through a communication network [14]. Hierarchical control emphasizes optimizing the output of distributed power systems while ensuring efficient and economical operation through comprehensive global power management [15]. However, this method requires frequent information exchange between master and slave controls, which can elevate communication costs and the expenses related to developing the communication infrastructure. The master-slave control structure divides the inverter into master and slave inverters, as illustrated in Figure 4a. When the microgrid operates in off-grid mode, the main controller employs a voltage/frequency (v/f) control strategy to stabilize the system's bus voltage. The output current from the master inverter is transmitted to the slave inverter, where

it serves as a reference for its operation. Therefore, the main inverter is typically configured with a high-capacity power supply to ensure the frequency-voltage stability of the microgrid system. The remaining slave inverters operate in P/Q control mode, following the master inverter. However, when the master inverter stops functioning or fails, the stability of the entire microgrid system faces significant challenges [16]. Additionally, this operational method relies on the existing communication network of the microgrid, which increases the overall construction costs of the system.



(**a**) Master-slave control (**b**) peer-to-peer control

Figure 4. Master-slave and peer-to-peer control block diagrams.

In order to address the limitations of the two aforementioned control methods, researchers have proposed a peer-to-peer control approach [17,18]. This method assigns a peer-to-peer status to each distributed power source. When the microgrid operates in off-grid mode, each inverter implements a droop control strategy, ensuring that the output power is distributed proportionally among the inverters. The peer-to-peer control strategy enables cooperative operation among various power sources by utilizing local voltage and frequency information. This approach eliminates the need for a complex communication network, significantly reducing reliance on high-frequency bandwidth communication for microgrid operations. Each power source can support and back up one another to maintain synchronized and stable performance. The peer-to-peer control method offers two primary benefits: it decentralizes decision-making among distributed power supplies, eliminating the need for a central controller, and it facilitates flexible configuration and plug-and-play capabilities of the distributed power supplies. However, challenges such as complex power coupling, frequency offsets, and voltage rectification may arise during peer-to-peer operations.

Currently, droop control is a significant area of research within peer-to-peer control methods. Droop control emulates the droop characteristics observed between the active and reactive power outputs of synchronous generators in conventional power systems, as well as the system frequency and output voltage. This enables timely and dynamic autonomous adjustments to the voltage or current output from inverters, based on real-time information from grid connection points. This capability facilitates effective power distribution among distributed energy sources and ensures the stable and continuous operation of the microgrid system. Consequently, implementing droop control in the inverter management of isolated microgrids significantly enhances the reliability and flexibility of the overall system [19–23].

Drawing from the synchronous generator output droop control technique, researchers have proposed a conventional droop control method for distributed power sources [24]. It is assumed that the output impedance of the distributed power supply is primarily inductive. The active and reactive power contributed to the microgrid by the distributed power supply is expressed in Equation (1).

$$\begin{cases} P_i = \frac{U_i U X_i}{X_i^2}\theta_i \Rightarrow P_i \infty \theta_i \\ Q_i = \frac{U}{X_i}(U_i - U) \Rightarrow Q_i \infty (U_i - U) \end{cases}, \quad (1)$$

As a result, the active output of the microgrid is directly linked to the frequency, while the reactive output is proportional to the port's output voltage. Consequently, the droop control, which depends on the power factor (PF) and voltage (QV), can be summarized in Equation (2).

$$\begin{cases} f_i = f_{\text{rated}} - m_p(P_i - P_{\text{rated},i}) \\ U_i = U_{\text{rated}} - n_p(Q_i - Q_{\text{rated},i}) \end{cases}, \quad (2)$$

In this context, f_i and U_i refer to the rated values of the microgrid system and voltage, respectively, while PQ denotes the average output power. The terms f_{rated} and U_{rated} indicate the rated values for the frequency and voltage of the microgrid system, respectively. The variables i_{P} and i_{Q} represent the average output power derived from instantaneous power using a low-pass filter, and $P_{\text{rated},i}$ and $Q_{\text{rated},i}$ signify the rated active and reactive output power of the distributed generation unit (DG_i).

From Equation (2), it is evident that droop control can regulate the frequency and voltage at the grid connection point based on the active and reactive power data from the distributed power supply's connection. This indicates that droop control can autonomously regulate operations using local information, thereby eliminating reliance on communication lines and significantly reducing the system's construction costs. Furthermore, the local control features of droop control enhance the plug-and-play capabilities of distributed power supplies in microgrids. This ensures that if one distributed power supply fails, the others can continue to operate normally and stably without disruption. Given these benefits, researchers both domestically and internationally have conducted extensive studies on microgrid droop control strategies, primarily focusing on power-frequency droop control.

3. Characterization of Droop Control Systems for Islanded Microgrids

Droop control is essential for the effective operation of islanded microgrid systems. Current research in this field primarily focuses on three key aspects: first, modeling microgrid systems utilizing droop control; second, achieving power balance and frequency regulation through droop control; and third, developing innovative droop control techniques for microgrids [25,26].

3.1. Microgrid Modelling Based on Droop Control

Analyzing the stability of microgrids during droop control is essential. The study referenced as [27] aims to determine the optimal ratio of virtual to external inductance using a small-signal model; however, this approach proves ineffective when the microgrid exhibits a high impedance ratio. To assess the stability of microgrids and assist in selecting droop coefficients, a study [23] presents a mathematical model for an islanded microgrid with linear loads and inverters. This model analyzes the microgrid's stability during inverter voltage-frequency droop control, offering valuable insights into the selection of controller droop coefficients. A study [21] addresses the optimal operation of isolated microgrids through droop control by establishing an optimal droop curve for distributed generation units. This is achieved using stochastic scenario modeling of renewable energy and a

fuzzy particle swarm algorithm. This approach effectively reduces operating costs and carbon emissions while achieving multi-objective optimization. To enhance the operational characteristics of microgrids, reference [28] presents a reduced-order oscillation model for inverter droop control, considering the low inertia of distributed power sources. This model simplifies the equivalent network and the small-signal model, facilitating controller design while preserving the same level of control effectiveness as the more detailed model.

In [29], the authors present an operational control method that employs droop-free control to improve the stable self-regulation capabilities of AC microgrids during communication link failures. This method enables active power sharing and frequency regulation, ensuring that the microgrids operate continuously and stably. Ref. [30] presents a model for the cascade control loop of distributed power supplies based on droop control and introduces a sequential algorithm for performing harmonic analysis in islanded microgrids. This approach emphasizes a thorough examination of harmonics and the interactions among different harmonics within the microgrid. Ref. [31] investigates the stability of microgrids using nonlinear droop control techniques and develops a comprehensive small-signal state-space linearization model for the microgrid system, analyzing its overall stability. Ref. [32] suggests a fractional-order derivative (FOD) droop controller designed to enhance the dynamic performance and stability margin of shunt inverters in microgrids. The authors utilized small-signal modeling and stability analysis to evaluate the system's stability. Their findings indicate that the droop control performance of the FOD controller surpasses that of IOD droops, conventional droops, VOC, and virtual synchronous generator controllers.

3.2. Power Equalization and Frequency Offset Control Based on Droop Control

To replicate the power-frequency regulation capabilities of a traditional synchronous machine, the study referenced as [33] introduces a droop control technique that modifies the inverter control parameters. This adjustment ensures that the inverter output impedance remains inductive, thereby mitigating the effects of the high impedance ratio (R/X) in microgrid lines. Similarly, the work cited as [34] regulates the equivalent output impedance of the power supply through a virtual impedance approach, which helps minimize the impact of line parameters on power distribution from the supply. The research in [35] builds upon [34] by proposing a method that corrects the Q-U droop characteristic curve, significantly enhancing the accuracy of power allocation from the supply. Additionally, the study in [36] introduces a droop control strategy that improves virtual impedance, utilizing the droop characteristics of virtual impedance to facilitate coordinated control among multiple power sources.

To enhance the dynamic features of droop control methods, reference [37] introduced an improved droop control technique. This approach adjusts the droop control coefficient to mitigate frequency offsets by detecting power fluctuations in the region. Reference [38] presents an adaptive droop control strategy that utilizes discrete consistency to evaluate the average voltage across the entire network. This approach establishes the target virtual resistance through communication among neighboring power sources, facilitating adaptive droop control with variable virtual resistance. Reference [39] addresses the challenges associated with the low X/R ratio in microgrids, which diminishes the power equalization capability of converters and establishes a strong coupling between active and reactive power. The authors propose a power control method that employs angular droop control, integrating angular velocity control with a power decoupling factor to enhance effective power distribution. Reference [40] introduces a hierarchical droop control method that utilizes first-order inertial units. This approach separates the control of multiple distributed generation units in an islanded AC microgrid into two distinct processes: automatic load sharing on a short time scale and compliance with scheduling management on a longer

time scale. Lastly, reference [41] proposes a cost-based droop control method designed to minimize the overall generation costs of microgrids.

3.3. Novel Droop Control Method Applied to Microgrids

To address the various challenges encountered in the operation of microgrid systems, researchers have developed innovative droop control techniques. In [42], a novel control method utilizing *V-I* characteristics was proposed to overcome the slow dynamic response associated with traditional power droop control methods, demonstrating enhanced dynamic performance. Ref. [43] examines an adaptive voltage droop control method that adjusts the inverter's voltage droop slope through a real-time communication link to ensure accurate reactive power distribution. For various types of distributed renewable energy sources within microgrid systems, a literature study [44] presents a droop control method for dynamic load sharing that is based on the generation capacity of different distributed generation sources. This method involves configuring droop controllers for various renewable energy sources, such as wind and solar, and adjusting droop parameters based on the available power generation capacity to enable effective load sharing. Additionally, Ref. [45] proposes a distributed pin-based droop control method designed for different communication networks in microgrid systems, emphasizing the sharing and distribution of active and reactive power among distributed power sources. This approach improves the autonomous operation of islanded microgrids while reducing communication requirements.

Additionally, in [46], a novel method for controlling harmonic droops in microgrids is introduced to enhance power quality and system efficiency. This method not only minimizes voltage distortion at the PCC but also promotes harmonic sharing among shunt inverters. Ref. [47] discusses a droop control approach that emphasizes power sharing and compensating for voltage imbalances in islanded microgrids, effectively addressing discrepancies in voltage and power distribution. Ref. [22] establishes a relationship between temperature and power droops through an electrical heat and temperature estimation model for inverters. Additionally, a droop controller designed to extend the lifespan of inverters has been developed to balance thermal stresses among parallel inverters, thereby enhancing the reliability of the microgrid.

To mitigate the effects of system frequency deviations caused by load changes in droop control, a secondary frequency control method that employs the injection of small AC signals (SACS-SFC) has been introduced in [48]. This approach not only corrects frequency deviations but also resolves power imbalance issues among parallel inverters. Additionally, the authors propose a method to regulate the output power of each distributed energy source by establishing a relationship between the injected SACS frequency and the corresponding rated real power compensation. In [49], a novel impedance-power droop control technique is introduced, which is based on virtual impedance control. This technique eliminates the inherent impedance of the inverter through a feed-forward mechanism, enabling effective power sharing without the need to know the microgrid parameters. A study [50] examines the effects of power flow on switching lines during changes in microgrid network topology, proposing a new method for seamless switching of low-inertia islanded microgrid lines. This method aims to minimize power flow in the switching line, optimize the switching sequence, and reduce total switching power by fine-tuning the droop control parameters of each distributed power source.

3.4. Analysis of Droop Control Method Applied to Microgrids

As shown in Table 1, the current sag control methods used in islanded microgrids primarily focus on ensuring stable operation, power equalization, and secondary regulation of frequency and voltage within the microgrid system. In the field of stability control for

isolated, islanded microgrids, many researchers have employed downscaling modeling and stability analysis of grid systems to conduct their studies. For instance, Ref. [21] addresses the optimal energy scheduling of the microgrid system based on the established grid model. Obviously, the primary research focus of the stability analysis of islanded microgrids is achieved through the modeling and analysis of microgrid systems. Furthermore, Ref. [23] presents a reduced-order model for isolated, islanded microgrids and examines the stability of these microgrids under various conditions. Additionally, the parameters of the sag controller are designed to ensure stability control of the microgrid based on the developed model. Secondary regulation of voltage and frequency for islanded microgrids is currently a prominent research topic. For instance, references [29,39] proposed a power equalization method utilizing droop control to achieve power equalization among inverters. Additionally, references [40,48] introduced secondary frequency regulation methods based on droop control.

Table 1. Comparison of droop control methods in islanded microgrids.

Ref.	Innovation Point	Control Target	Islanded Microgrid	To Be Improved
[21]	Optimal scheduling	Minimize the emission	Yes	Multi-objective optimization
[23]	Model order reductions	Stability of the microgrid	Yes	Parameter design guidance
[29]	Droop-free control	Power sharing	Yes	Improved communications immunity
[32]	Derivative droop	Improving the stability margin	Yes	Load harmonic sharing
[39]	Angle droop control	Load sharing	Yes	Harmonic distortion
[40]	Dispatchable droop control method	Frequency restoration	Yes	distributed control for voltage regulation
[46]	New harmonic droop control	Harmonic compensation	Yes	System stability
[48]	Decentralized secondary control	Frequency restoration	Yes	Power secondary regulation
[50]	Optimizing the droop control	Minimization of the power flow	Yes	Multi-line switching

It is evident that the current islanded microgrid system primarily achieves frequency stabilization and power control through the sag control of the converter. However, deviations in control and other factors can easily result in frequency and power fluctuations within the islanded microgrid system. Notably, the issue of frequency fluctuations in isolated, island microgrids has become a central concern in the stability control of microgrid systems. Therefore, further research is needed to enhance frequency stabilization and centralized control in microgrid systems.

4. Synchronized Fixed-Frequency Control Systems to Microgrids

4.1. Droop Control Methods Based on GPS Timing Signal

The aforementioned literature has prompted a related investigation into droop control strategies that take into account the resistive characteristics of microgrid transmission lines. A crucial factor in the effective distribution of power among various distributed energy sources is the operating frequency of the microgrid. However, the droop control techniques discussed do not adequately address the issue of frequency offset in microgrids resulting from droop control. In islanding mode, the microgrid experiences significant fluctuations in both distributed power sources and loads, which ultimately result in variations in grid fre-

quency. This, in turn, affects the power distribution among the distributed energy sources, leading to a decline in both power quality and the stability of the microgrid [36,51,52].

To address the challenges associated with droop control methods, some researchers have proposed the implementation of fixed-frequency control for microgrids. This approach aims to mitigate frequency fluctuations and improve dynamic performance [53]. By utilizing a communication system, a synchronized clock can be provided to smaller microgrids, allowing for stable operation at a synchronized fixed frequency among the distributed power sources. However, in larger microgrid areas, delays in the synchronization signal from the communication system may lead to instability in system operation [54–56]. With advancements in global positioning systems (GPS), a synchronous positioning control strategy based on GPS has garnered significant attention from researchers. They have proposed control methods that utilize satellite timing signals for synchronous frequency stabilization. This approach employs GPS-based phase measurement units or the GPS pulse per second (1 PPS) signal as a reference for measuring or controlling inverters, thereby synchronizing the microgrid's operating frequency to the industrial standard of 50 Hz. This ensures that all inverters operate within the same rotational coordinate system, effectively preventing frequency deviations and stabilization issues associated with traditional droop control methods that treat frequency as a variable.

Ref. [53] introduces a novel distributed droop control technique that leverages GPS timing technology. This method synchronizes each distributed power supply to a common rotating coordinate system with a standard frequency, utilizing the GPS-synchronized clock. To enhance the stability of the control system and mitigate the effects of potential GPS signal disruptions on the microgrid, this method incorporates an adaptive Q-f droop control strategy. This strategy facilitates balanced control of both active and reactive power within the synchronized reference coordinate system, and the structure of this method from Ref. [53] is illustrated in Figure 5.

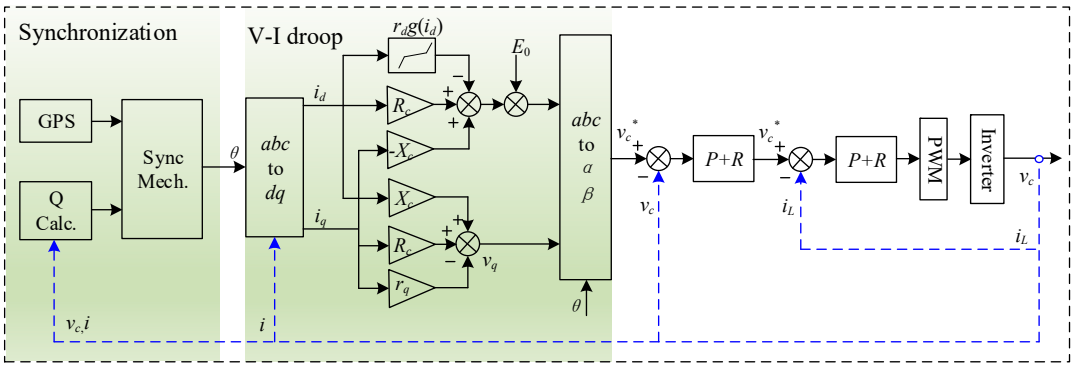


Figure 5. Distributed droop control that utilizes GPS timing technology.

Ref. [57] proposes a multi-objective optimization algorithm for microgrids, addressing the unwanted effects of frequency perturbations and deviations on system stability. To address this issue, Ref. [41] introduces a power loop control strategy that employs angular droop control to address the strong interdependence between active and reactive power in medium voltage lines with a low X/R ratio, which affects the distribution of rated power among converters. This approach significantly enhances the balance of reactive power. Similarly, Ref. [58] presents an angle droop control technique for managing power distribution among shunt inverters in an isolated microgrid. This method synchronizes the timing of microgrid inverters using GPS and regulates power distribution among them through angle droop control. It effectively dampens oscillations in the controller by utilizing robust internal inverter control and small-signal analysis. In [59], a hierarchical control approach

that utilizes GPS for frequency stabilization is proposed. This method integrates droop control, power sharing, and voltage regulation. The inverters in each distributed power source are synchronized for frequency-stabilized operation using GPS timing technology. The output voltage of each inverter is managed according to an adaptive voltage-current (*U*/*I*) droop characteristic, which facilitates proportional current equalization and power sharing among the distributed inverter units.

In response to the power angle and frequency stability challenges associated with the master-slave control method in islanded microgrid operations, the authors in [60] propose an *I*/*U* droop control technique that employs synchronized satellite timing signals. This method generates phase-aligned currents and maintains a stable industrial frequency through synchronization signals, facilitating the effective distribution of active and reactive power via *I*/*U* droop control. The core concept involves treating the inverter as a controllable current source by fixing the phase and frequency of its output current. The amplitude of the output current is adjusted through *I*/*U* droop control to manage the voltage at the grid connection point within an acceptable range. This approach effectively distributes the active and reactive power of the load according to the rated capacity of the power supply. Ref. [61] introduces a synchronized fixed-frequency droop control method that utilizes navigation satellite timing to resolve the issue of unsynchronized operation among distributed power supplies in no-pass scenarios. This control strategy regulates the output voltage of each distributed power inverter based on line impedance and the voltage at the grid-connected port, achieving independent fixed-frequency control without the need for communication. Additionally, the authors propose a secondary voltage regulation strategy for microgrids that utilizes real-time operational data to dynamically adjust droop curves in response to load variations, thereby facilitating the secondary regulation of distributed power sources.

Furthermore, Ref. [62] addresses the challenge of inconsistent line impedance in islanded microgrids, which hinders the dynamic distribution of output power among distributed power inverters based on their capacity. The authors propose a method for identifying microgrid line impedance, building on the satellite synchronous fixed-frequency down-control strategy. This approach facilitates power equalization among distributed power sources through line parameter identification and the design of power equalization controllers. Expanding on this, Ref. [63] introduces a control strategy that integrates satellite synchronous frequency fixing with line impedance identification and its control method diagram is shown in Figure 6. This approach mitigates the effects of voltage phase differences and variations in line impedance on power distribution by utilizing a second pulse signal from GPS to calculate the synchronized phase angle of the converter's rotating coordinate system. This enables each inverter to generate output voltages with a consistent phase and a frequency of 50 Hz. Furthermore, the authors implement a virtual resistance compensation mechanism within the *d*-axis control loop to address voltage dips caused by resistance, thereby ensuring balanced power distribution.

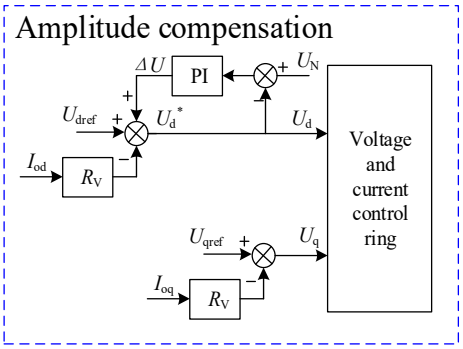


Figure 6. Amplitude compensation control block diagram.

Ref. [64] proposes a synchronous fixed-frequency current control method based on a virtual harmonic resistor. This method offers strong resistance to voltage perturbations and features a straightforward implementation process, which helps reduce the low-frequency output impedance of the inverter while suppressing voltage distortion and imbalance. Additionally, the authors developed an output impedance model for the inverter and mitigated resonance through active damping control, achieving effective harmonic current equalization among parallel inverters. Similarly, Ref. [65] addresses the issues of voltage deviation and power allocation imbalance in microgrids under traditional U/I droop control. It proposes a synchronous frequency-fixed control strategy based on synchronous phasor measurement units (PMUs) that does not require differential regulation of U/I droop. This method utilizes PMUs to provide a global synchronous reference signal for the inverters within the microgrid, enabling synchronous fixed-frequency operation. Additionally, the authors introduce a voltage deviation regulation link to achieve secondary voltage regulation through droop curve leveling, resulting in high-precision power allocation.

To enhance the stability of synchronous fixed-frequency microgrids during transitions between grid-connected and islanded states, Ref. [66] explores seamless switching technology for these microgrids without inter-device information interaction. The authors employ satellite timing signals to detect the islanding condition and utilize tracking differentiators to achieve phase overshoot-free tracking. This approach ensures a rapid and smooth transition of the microgrid from a grid-connected to an islanded state. Additionally, the authors propose a frequency offset-based method for detecting the grid-connected state, which facilitates synchronous and stable operation of the microgrid during the transition from islanding to grid-connected mode. In addressing the issues of frequency deviation and the inability to accurately allocate power due to the droop control used in microgrid islanding operations, a synchronized fixed-frequency control strategy based on PMUs is proposed in [67]. This method utilizes the second pulse generated by the PMU as the synchronization reference signal for each distributed power inverter, enabling the generation of a uniform real-time rotational phase angle. Using this phase angle, the schedulable distributed power inverters at each node are synchronized to output voltages with a fixed frequency and in phase. Furthermore, the output voltage of the inverters is adjusted quadratically to achieve precise power distribution, taking into account the rated capacity share of each distributed power source. Building on this foundation, a new U/I droop-based control method for full-inverter microgrids is proposed in Reference [68]. The method aims to eliminate errors associated with conventional phase angle measurements by utilizing a synchronized PMU that provides a globally synchronized reference signal. The U/I droop control allows each inverter to operate in voltage control mode, distributing the power of each distributed power inverter in equal proportions. The overall block diagram of the method in Ref. [68] is illustrated in Figure 7. However, none of the previously mentioned methods employed

the analytical and modeling techniques described in [69,70] to model the microgrid excess process and analyze the data.

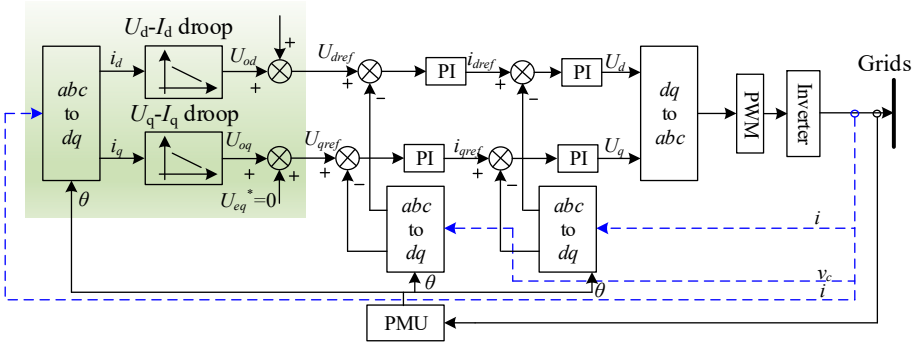


Figure 7. Control block diagram of overall system structure.

Aiming to address the issue of islanded microgrids that generate minor perturbations during state switching, which can lead to transient oscillations, a study [24] has been developed to enhance the dynamic characteristics of inverter-based microgrids and facilitate smooth transitions between different operational modes. The authors derive an accurate small-signal state-space model of the entire microgrid, incorporating the droop controller, network, and load. They also design the key control parameters of the inverter and determine their optimal ranges through eigenvalue analysis, which significantly influences the damping frequency of the oscillatory component in the transient response. Ref. [44] addresses the slow dynamic characteristics inherent in power droop control methods. The authors of this paper propose a novel control method based on U-I characteristics to enhance the flexibility and dynamic response of distributed inverters. This method implements segmented droop control of the current through the DC and quadrature axis voltage components, resulting in improved dynamic performance and better damping characteristics. The segmented droop control curve from Ref. [44] is illustrated in Figure 8b.

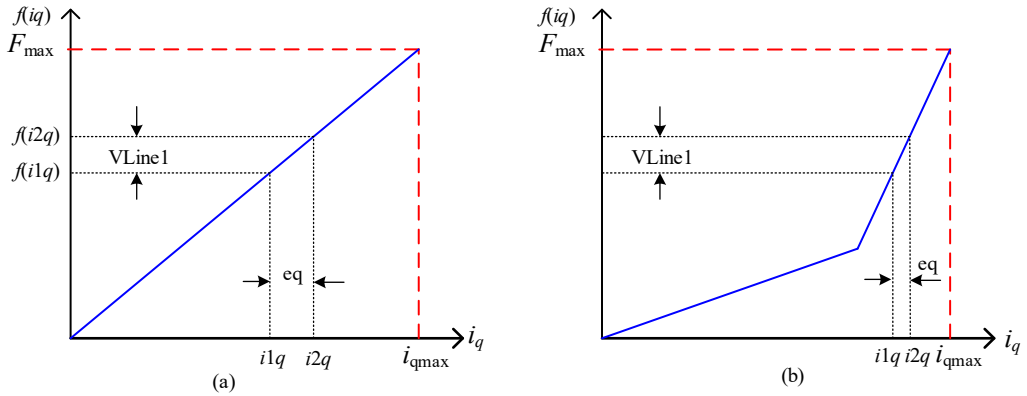


Figure 8. Droop function: (**a**) linear and (**b**) piecewise linear.

In addition, to address the synchronization and power balancing challenges among distributed power sources in cascaded microgrids, an f-P/Q droop control method has been proposed in [71], and its stability has been analyzed. This droop control method can automatically achieve power balancing under resistive-inductive and resistive-capacitive loads. A significant advantage over the inverse power factor droop control is its broader application range. Ref. [55] has thoroughly analyzed the requirement that inverters operating in parallel must have identical unit impedance to accurately share the load in proportion to their rated power when employing a conventional droop control scheme.

However, fulfilling both conditions is challenging in practice, often resulting in errors in the load-sharing ratio. Consequently, the authors of this paper propose an enhanced droop control method that enables precise proportional load sharing without the need to meet these two conditions, while also minimizing the load voltage drop caused by load effects and droop effects.

4.2. Comparative Analysis of Synchronous Fixed-Frequency Control Methods

Table 2 provides a detailed analysis of the application of existing synchronous fixed-frequency control methods in islanded microgrids. As shown in the table, these synchronized frequency control methods primarily rely on GPS or PMU timing signals to determine the inverter angle. Since this control approach establishes a fixed operating frequency for the microgrid, the main objectives of droop control are to manage power distribution within the system and voltage adjustment. Most synchronous fixed-frequency control methods primarily rely on V-I droop control or I-V droop control. Notably, the angular droop control proposed in references [41,58] primarily facilitates power distribution among the inverters.

Table 2. Comparison of synchronous fixed-frequency control methods in islanded microgrids.

Ref.	Clock Source	Control Target	Droop Control	Frequency *f*	To Be Improved
[41]	GPS	Power decoupling	Angle droop control	Constant	Further reduction of THD
[53]	GPS	Power quality	Q–f droop	Constant	Using GPS for harmonic current sharing
[58]	PMU	Power sharing	Angle droop control	Constant	Harmonic current sharing
[59]	GPS	Power quality	*V-I* droop	Constant	GPS in grid connected control applications
[61]	GPS	Secondary regulation of voltage	*I-V* droop	Constant	Voltage threshold design
[62]	GPS	Power sharing	*V-I* droop	Constant	Modeling of line impedance
[63]	GPS	Power sharing	*V-I* droop	Constant	Precise power distribution
[65]	PMU	Voltage regulation	*V-I* droop	Constant	Power secondary regulation
[66]	GPS	Seamless transfer	*I-V* droop	Constant	Tracking resolver designs
[67]	PMU	Power secondary adjustment	*V-I* droop	Constant	Circulation suppression
[68]	PMU	Power allocation	*V-I* droop	Constant	Plug-and-playperformance

This class of methods enables synchronous operation without the need for communication links between converters, utilizing synchronous frequency control. This capability significantly reduces the construction costs of islanded microgrid systems. Furthermore, synchronized frequency operation via satellite timing can facilitate synchronous operation among local microgrids, which holds considerable research significance for regional microgrid power mutual aid and interconnection. However, these methods heavily rely on a synchronized clock signal. If the GPS or PMU timing signal source fails, the entire microgrid system will operate without a synchronized signal. Therefore, it is essential to investigate strategies to enhance signal immunity and develop replaceable solutions for synchronous frequency-fixed microgrids. Additionally, research on circulating current suppression and precise power allocation in this context has not yet been conducted, making it crucial to pursue these studies to enrich the theoretical framework and control systems associated with these methods. In addition, distributed energy storage and photovoltaic systems are being increasingly utilized in microgrids and distribution systems. Consequently, new distribution system planning that focuses on droop control is becoming

increasingly important [72,73]. For instance, the reinforcement learning algorithm proposed in literature [74] has gained traction in microgrid systems. Therefore, conducting research on droop frequency control utilizing new energy storage and generation systems is of significant importance.

5. Conclusions

The microgrid droop control method, which is based on GPS-synchronized frequency stabilization, not only addresses the issue of synchronous operation among distributed power inverters but also effectively resolves the frequency challenges within the microgrid. In this paper, we review and analyze the droop control strategy and frequency stabilization methods for isolated microgrids. We provide a detailed introduction to the structure, operational modes, droop control strategies, and synchronous frequency stabilization techniques employed in isolated microgrids. Among them, the synchronized fixed-frequency control strategy of the microgrid is emphasized. Finally, the contents of this paper are summarized and future directions are outlined. The primary research contributions of this paper are summarized as follows:

(1) The structure and control methods of microgrids are briefly introduced, and the issues associated with microgrids, such as frequency offset and voltage deviation present in current control methods, are analyzed through modeling and summarization.
(2) The specific applications of the droop control method in microgrid inverters for secondary regulation of system frequency and voltage are presented in detail. As the primary control method within the microgrid's peer-to-peer control strategy, droop control offers distinct advantages in power equalization and frequency regulation of the inverter.
(3) A GPS-based synchronous frequency control method for microgrids is presented. This method enables synchronous frequency control of microgrids without the need for communication between inverters, significantly reducing the hardware construction costs of the microgrid system. Furthermore, since the frequency clocks of the inverters are derived from GPS, the operation of different inverters can be highly synchronized, which holds substantial research and application value.

Synchronized fixed-frequency control methods in future research directions and innovations are as follows:

(1) Through a detailed analysis of energy storage and distributed energy sources, such as photovoltaic and wind power, the ratio of energy storage to these sources plays a crucial role in the stabilization and control of microgrids. Consequently, the capacity allocation and modeling of energy storage units and distributed energy sources for synchronous frequency control in isolated microgrids will be a significant area of research in the future.
(2) The GPS-based synchronized frequency control method is highly dependent on satellite timing signals. When the satellite timing signal is unavailable, the converter operation in a microgrid loses its time reference. In such cases, identifying an alternative clock signal is of significant research value for ensuring the synchronized and stable operation of microgrids.
(3) With the advancement of topological diversification in isolated microgrids, synchronous frequency-fixing control technology for AC/DC hybrid microgrids remains an area requiring further research. The implementation of GPS-based synchronous frequency-fixing technology in hybrid microgrids holds significant promise, particularly in the realm of innovative frequency-fixing control strategies.
(4) Since the microgrid operates independently from the larger grid, any transient increase or decrease in load can easily result in fluctuations in voltage and frequency within

the microgrid. Therefore, researching dynamic real-time compensation methods for synchronous fixed-frequency control in the event of load disturbances holds significant importance.

(5) The black start process of a microgrid requires both frequency and voltage support. Therefore, studying the synchronized fixed frequency control method is particularly important for understanding the frequency and voltage support control mechanisms during the startup process.

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