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Emerging Advances in Hybrid Renewable Energy Systems and Integration
Muhammad Zakarya, Santosh Tirunagari, Jinguang Han and Peiying Zhang (Guest Editors)

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Study on frequency stability control strategies for microgrid based on hybrid renewable energy

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Abstract. The dynamic nature of renewable energy sources, such as wind and photovoltaic power generation, significantly impacts the frequency stability of microgrid systems due to their pronounced intermittency, inherent randomness, and limited output support. Despite ongoing research, a comprehensive understanding of control measures to enhance microgrid frequency stability remains lacking. This paper addresses this gap by summarizing domestic and global advancements in control strategies for microgrid frequency stability. Specifically, it examines the operating states of microgrids and associated frequency stability issues and expounds various methods for maintaining frequency stability. The paper proposes innovative control measures to enhance frequency stability, including improvements in master-slave control, droop control, phase-locked loop, and virtual synchronous generator (VSG) techniques, particularly during transitions between islanded and grid-connected modes. The findings demonstrate the effectiveness of these enhanced control strategies in maintaining frequency stability, and the paper concludes by suggesting future research directions in this field.

Keywords: Microgrid, Frequency stability, Islanding operation, Grid-connected operation, Transient state.

1 Introduction

Electric energy is a pillar of innovation for national and social development. As the seamless incorporation of emerging energy sources continues to evolve and the commissioning of large-capacity transborder direct current projects has occurred, frequency issues have also emerged in the source power grid and the destination power grid [1].

Currently, the frequency stability problem is a growing concern in modern large-scale power grids with weak inertial support, uncertain output, poor frequency modulation and damping characteristics [2, 3]. Most new energy sources are connected to the grid through power electronic converters and are decoupled from the system frequency. This decoupling results in their inability to actively provide inertial support to the grid in response to active power disturbances [4]. Apart from the changes in the power supply structure, the changes in the transmission/distribution side and load side also exert a certain impact on the system's inertia level. Furthermore, the rotational inertia level of the connected AC power grid will be weakened to a further extent after the flexible multi-terminal DC power grid is interconnected with the AC power grid [5]. With high-capacity DC and high-proportion new energy access, all types of fault scenarios such as DC block/consequential commutation failure, converter failure, and new energy cluster off-grid may impose enormous active impacts, resulting in an elevated frequency variation rate and frequency deviation within the system, and easily trigger the actions of safety automatic devices within the tertiary defence layer such as during frequency-based load shedding and high-frequency tripping, and there is a risk of large-scale load shedding/tripping [6, 7]. The frequency instability of the power grid has severely impacted industries, agriculture as well as other fields, and people's daily electricity consumption can not be guaranteed, and the country's scientific and technological level and market economy will be influenced as well. In recent years, there have been some frequent safety accidents incurred by frequency instability both in domestic and international power systems.

On August 9, 2019, the British power grid was struck by lightning, which resulted in a single-phase short-circuit grounding. After some offshore wind power, distributed power supply and gas turbines were disconnected from the grid in succession, the system frequency dropped significantly, triggering the activation of under-frequency load shedding. Ultimately, the whole UK lost about 5% of the load [8]. On September 28, 2016, the southern power grid of Australia was blacked out for 10 hours as a result of a typhoon. Before the accident, the asynchronously generated

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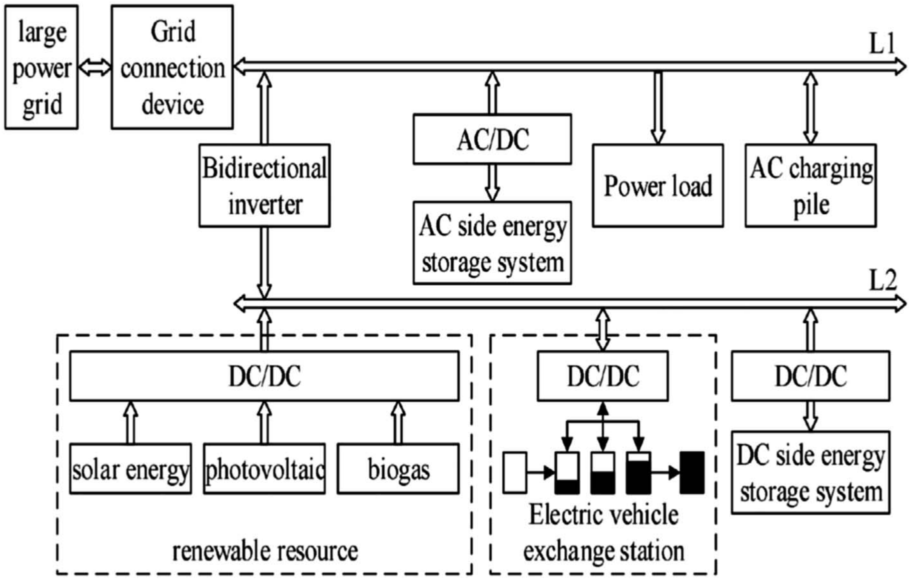


Fig. 1. Components of the microgrid.

power was close to 80%, and the rapid drop in power system frequency induced system disconnection at a rather low level of inertia [9]. On September 19, 2015, the Jinsute HVDC bipolar block caused a power vacancy of 4.9 GW in the East China Power Grid 12 s after the accident, the system frequency reached its nadir at 49.56 Hz, which was the first time that the frequency fell below 49.8 Hz [10] in recent 10 years.

Currently, as the large power grid is interconnected if a serious unforeseen event occurs in the power grid, it will result in a power outage and paralysis in a large area of the power system. Furthermore, the service and development of power in islands, deep mountains and borders, etc. are still lacking to some extent and cannot be integrated into the large power grid in a prompt and effective manner. In the event of a large power grid failure, a microgrid operating in islanding mode presents a viable solution. A microgrid is a small-scale power generation and distribution system primarily comprised of distributed generation, often utilizing renewable energy sources, as well as energy storage devices, energy conversion devices (inverters), associated loads, and monitoring and protection systems [11, 12]. The components of a microgrid are illustrated in Figure 1. Under normal conditions, the microgrid is interconnected with the main power grid through a Point of Common Coupling (PCC) and operates in grid-connected mode. However, when disconnected from the main grid, the microgrid seamlessly transitions into islanding mode, ensuring continuous power supply to its loads through various control strategies [13]. The specific configuration of a microgrid is depicted in Figure 2.

Depending on the various conditions of the main grid, a microgrid can be categorized into three states: grid-connected operation mode, islanding operation mode, and the transient state during the switch between these two modes [14]. In grid-connected mode, the microgrid can draw power from the main grid during shortages and provide auxiliary services to the main grid when it generates excess power. The microgrid in grid-connected mode is equipped with a PCC or Point of Interface (POI) to facilitate a seamless transition to islanding operation mode [15]. Islanding mode occurs when the microgrid operates in isolation after being disconnected from the main grid, with no PCC at this point. In this scenario, active and reactive power generation within the microgrid, including temporary power storage units, must balance with the local load demands. The capability to operate in both grid-connected and islanding modes is crucial for the microgrid to realize its advantages [16]. Smoothly transitioning between these modes is considered a primary challenge in microgrid operation [17].

Among the microgrid components, distributed generation predominantly utilizes solar energy, wind energy, water energy, and other renewable sources. Similar to the traditional large power grid, the dynamic characteristics of renewable energy, such as wind and photovoltaic generation, significantly impact the microgrid's frequency stability due to its intermittent, random, and variable output [18, 19].

On one hand, the microgrid faces more severe stability challenges in islanding mode compared to the traditional large power grid due to its smaller size [18, 19], higher renewable energy integration [20], increased uncertainty [21], reduced system inertia [22], higher R/X ratio of feeders, limited short-circuit capacity, and unbalanced three-phase loads [23]. On the other hand, during the transition from grid-connected to islanding mode, the microgrid's sudden shift can cause an imbalance between power generation and load demand, resulting in system frequency instability. Similarly, when reconnecting from islanding mode to the main grid, ensuring synchronous operation is a critical factor affecting frequency stability. Thus, it is necessary to bring forward higher requirements for frequency stability control of the microgrid. Many related researches have been

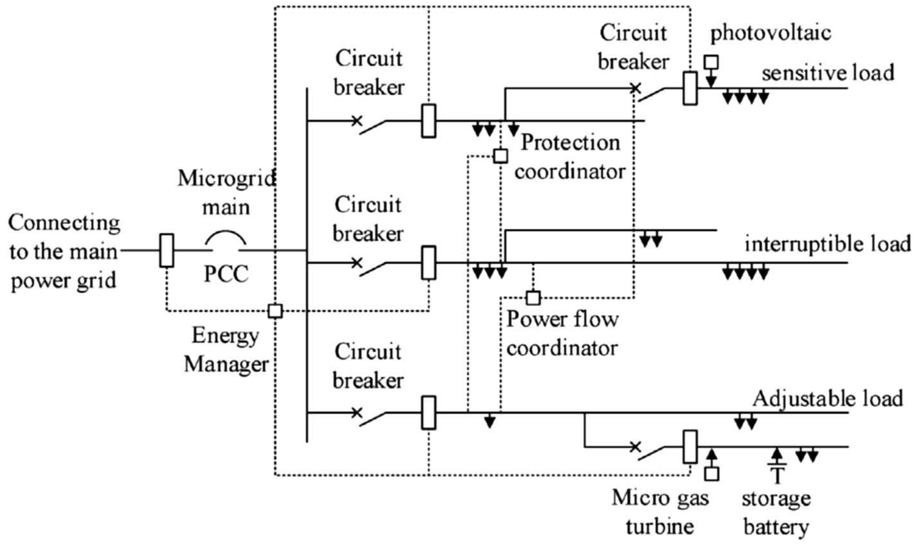


Fig. 2. Structure of the microgrid.

launched at home and abroad on the frequency stability of microgrids. However, the understanding of this issue is still not comprehensive enough, and in particular, no in-depth and comprehensive analysis and discussion have been carried out on the control measures to improve the frequency stability of microgrids. To better understand the threat of frequency stability of microgrids in the operation scenarios of islanding mode and switching state and work out countermeasures in response, this paper summarizes and looks forward to the domestic and international research progress in relation to the frequency stability of microgrids in the field of control strategy.

The structure of this paper is specifically as below: Section 2 gives an Introduction to the operation state of the microgrid as well as the corresponding frequency stability issues, and sets forth many methods of frequency stability and control; Section 3 brings forward the improved control measures to improve frequency stability from four aspects: master-slave control, peer-to-peer control, hierarchical control and droop control based on islanding mode; Section 4 brings forward the improved control measures to improve frequency stability from three aspects: phase-locked loop (PLL), virtual synchronous generator (VSG) and droop control based on the switching state of islanding mode and grid-connected mode; Section 5 prospects the research direction to be further explored in the future; Section 6 makes a summary of this paper.

2 Frequency stability of the microgrid

In the grid-connected mode, the microgrid system is connected to the large power grid as a whole, and the source-load mismatch incurred by the fluctuation in the output of renewable energy or load changes, etc. in the microgrid will be absorbed by the large power grid, and the system frequency is guaranteed by the large power grid, which is relatively stable. Thus, the frequency stability issue faced by the microgrid chiefly appears in the islanding operation mode and switching transient.

2.1 Frequency stability of islanding mode

When the microgrid is in the islanding operation state, it is tremendously influenced by the environment and is not stably supported by the large power grid. Thus, in case of any change in the external environment, the frequency of the system and the local load will fluctuate to a large extent, which will eventually influence the stable output of the system power of the microgrid [24, 25]. Hence, when it is in islanding operation mode, the microgrid must be able to maintain its own frequency stability. The frequency stability of the microgrid in the islanding mode is restricted by the following three factors: operation control mode, inverter control mode and converter type.

2.1.1 Operation control mode

Depending on the different roles played by distributed generation during islanding operation mode in a microgrid, the microgrid's operational control modes can be categorized into master-slave control, peer-to-peer control, and hierarchical control.

Master-slave control involves the division of control tasks in distributed generation (DG) systems into master control and slave control. During islanding mode, the system's frequency and voltage are regulated by the DG operating under master control, while power is supplied to the grid by the DG functioning under slave control. In this configuration, the master controller utilizes Voltage/Frequency (V/F) control to adjust output voltage and frequency, thereby maintaining system stability and proper operation. In contrast, the slave controller employs constant power control to deliver a fixed amount of power according to system demands. As illustrated in Figure 3a [26], this control architecture is notable for its rapid response and capacity to execute complex control algorithms.

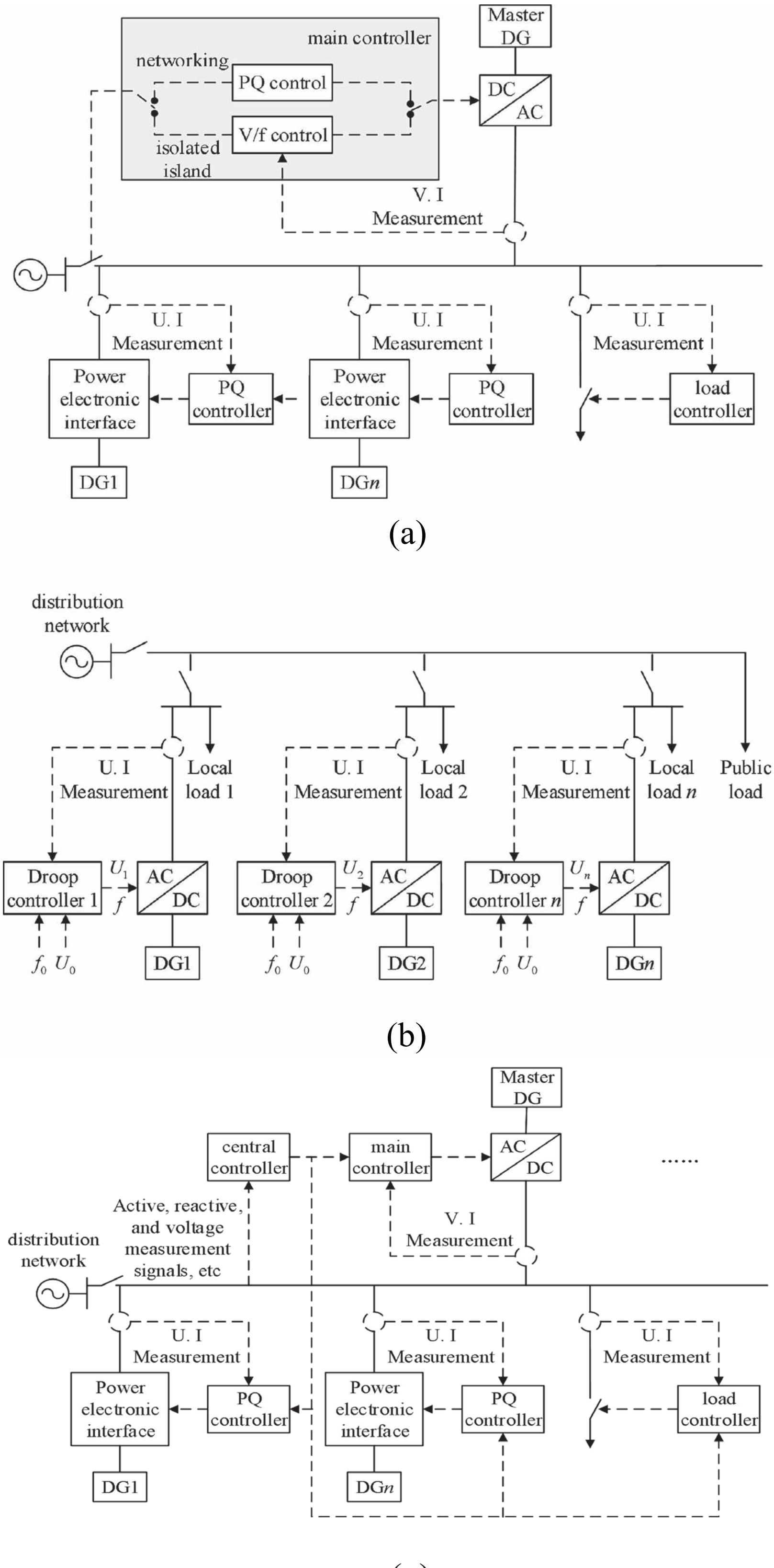
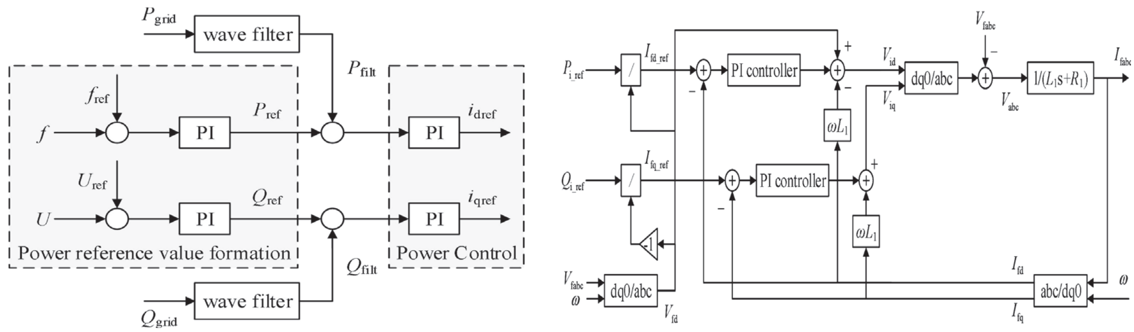


Fig. 3. Structure diagram of the operation control mode of the microgrid. (a) Master-slave control, (b) Peer-to-peer control, (c) Hierarchical control.



(a) (b)

Fig. 4. Structure diagram of control mode of the microgrid inverter. (a) V/F control, (b) Droop control.

Nonetheless, it is significantly dependent on the primary control unit; should the main control unit fail during the islanding mode, the subordinate units will lack frequency and voltage support, potentially leading to system instability.

Peer-to-peer control corresponds to master-slave control, which means that all controllers are on an equal footing and there is no master-slave relationship at all. Unlike traditional master-slave control, peer-to-peer control does not rely on a single central controller. Instead, each controller operates independently and communicates directly with other controllers, allowing for more flexibility and redundancy. This control mode reduces the switching between master-slave control modes, thus saving control time and cost. Its control structure is demonstrated in Figure 3b. For example, the withdrawal of any node will not influence the control, and it is feasible whether communication is absent or not. However, it should be noted that the power quality of the system cannot be guaranteed when the microgrid is severely damaged.

The hierarchical control structure is based on the time scale difference of a variety of control requirements. Originating from ANSI/ISA-95 (International Society of Automation), it is used by the upper management system to convey control information to the lower distributed generation control system. It is in a three-level structure: Level 1, Level 2 and Level 3. As demonstrated in Figure 3c, it is the block diagram of the hierarchical control structure of the microgrid.

2.1.2 Inverter control mode

Distributed generation in the microgrid has different characteristics, so its control strategy should be chosen and designed in view of different characteristics. There are two common control modes of distributed generation grid-connected inverter, respectively V/F control and droop control.

Constant voltage and constant frequency control are primarily employed to uphold system voltage and frequency stability. The frequency and voltage regulator maintain the system's voltage and frequency at predefined reference values by adjusting the active power and reactive power output of distributed generation. This control mode is typically applied in the islanding operation mode, serving a similar function to the balancing node in traditional power systems. Its control block diagram is illustrated in Figure 4a. However, this control mode exhibits drawbacks in terms of limited damping and weak interference resilience [27], making the system frequency susceptible to instability.

Droop control emulates the power-frequency characteristic curve of a synchronous generator, regulating system frequency and voltage by adjusting the output power of distributed generation (DG). This method allows for load distribution without the need for communication, mitigating transient oscillations associated with mode switching and facilitating the "plug and play" functionality of DG sets. It operates by mimicking the behaviour of synchronous generators, adjusting active power output in response to frequency deviations and reactive power output in response to voltage changes. However, droop control has limitations, including its limited applicability in systems with significant line impedance variations or large load changes. The system frequency under droop control is influenced by various factors such as load changes and line impedance, potentially leading to deviations from the nominal frequency that require additional control mechanisms to correct. Moreover, droop control can introduce steady-state errors that need to be managed. Its control block diagram is depicted in Figure 4b [28], illustrating the relationships between power output, system frequency, and system voltage.

2.1.3 Types of converters

Currently, most of the new energy grid-connected inverters in the AC microgrid system are grid-following converters, specifically as displayed in Figure 5a. The external characteristic of such converters is the current source. By directly controlling the output current, it can achieve the highly efficient utilization of distributed generation, but it lacks the capability of frequency and voltage support [29]. To address the issue of lack of inertia and weak damping in microgrid systems, domestic and foreign scholars have proposed a variety of control strategies for grid-forming converters [30, 31], specifically as displayed in Figure 5b, which enables the inverters to simulate the inertia and damping characteristics of synchronous generators and offer stable frequency support for the system.

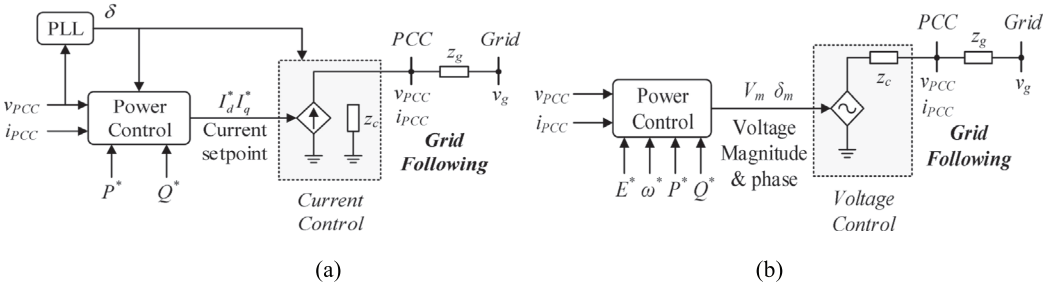


Fig. 5. Structure diagram of microgrid converter. (a) Grid-following converter, (b) Grid-forming converter.

At present, deficiencies exist in all of the above three factors, which will influence the stability of system frequency. Primarily, with regard to operation control, master-slave control is easily influenced by the failure of the main controller and affects the frequency stability of the system as a result; peer-to-peer control is disadvantageous in high communication overhead and unstable control; hierarchical control increases the complexity of calculation and communication, and there are also some problems in their control strategy selection, parameter regulation and interdependence. Besides, with respect to inverter control, V/F control is relatively simple but not suitable for dynamic load and power fluctuation, and droop control is influenced by load information and the response speed of generators. Finally, from the converter's point of view, the grid-following converter may be faced with the problems of slow response speed, insufficient control accuracy and limited regulation capability; there may be feed-forward control problems, distributed control difficulties and difficulties of system interruption recovery in grid-forming converters. Therefore, the frequency stability of the microgrid in islanding mode awaits for further research.

2.2 Frequency stability during switching between microgrid states

When a microgrid abruptly transitions from grid-connected mode to islanding mode, the mismatch between the electric energy generated by the microgrid and the load demand can lead to system frequency instability. Similarly, when the microgrid is reconnected from the islanding mode to the main power grid, the system frequency may differ from the two modes. Hence, it is crucial to employ appropriate control modes. Typically, the smooth transition between inverter operation modes is the primary consideration for frequency control during microgrid switching states. Inverter control modes within the microgrid typically encompass PLL control [32], VSG control [33], and droop control, among others.

To align the output current of the grid-connected inverter with the frequency and phase of the microgrid voltage, PLL technology is commonly utilized to capture frequency and phase information from the microgrid voltage. PLL can effectively track the positive-order component of the microgrid voltage's fundamental wave and is applied for frequency, phase, and amplitude testing during microgrid switching [34]. However, frequency detuning can occur in this control mode.

This paper [35–37] introduces the concept of VSG control. Essentially, it simulates traditional synchronous generators to configure virtual inertia and damping components. This allows power electronic grid-connected inverters to exhibit external characteristics akin to synchronous generators. This approach enhances the frequency stability of the microgrid system, improves power quality, and facilitates the application of traditional power grid operation control strategies to microgrids [38]. Figure 6 illustrates a virtual synchronous control system. However, in the VSG control mode, the VSG inverter can only mimic synchronous generator characteristics in control, and its main circuit still comprises power electronic components, resulting in comparatively limited overcurrent capability. If the VSG inverter is connected to the power grid using traditional synchronous generator introduction and synchronization methods, grid-connected surge currents may severely damage inverter switching devices and magnetic components, potentially causing frequency instability [39].

In the transient state of switching between the microgrid islanding mode and grid-connected mode, there are still some drawbacks in terms of the above methods and frequency stability still cannot be maintained well. Primarily, the response speed of PLL control to sudden load change is relatively slow, which may result in frequency fluctuation, and besides, there are inherent errors and drift with regard to frequency stability. During the transition, the PLL may not be able to regulate the output frequency promptly, resulting in frequency instability. Besides, the VSG may be sensitive to changes in system parameters and measurement errors, which may influence the frequency stability as a result, and apart from that, it may be difficult for the VSG to achieve good performance in large-scale and complex microgrid systems. Finally, the speed of the droop control to respond to sudden load changes is relatively slow, which may result in frequency fluctuations, and the parameter regulation of the droop controller is comparatively complicated as well.

In summary, there are currently numerous control strategies available to tackle the issue of frequency stability in islanding mode and state-switching mode. However, these methods often exhibit certain limitations and deficiencies,

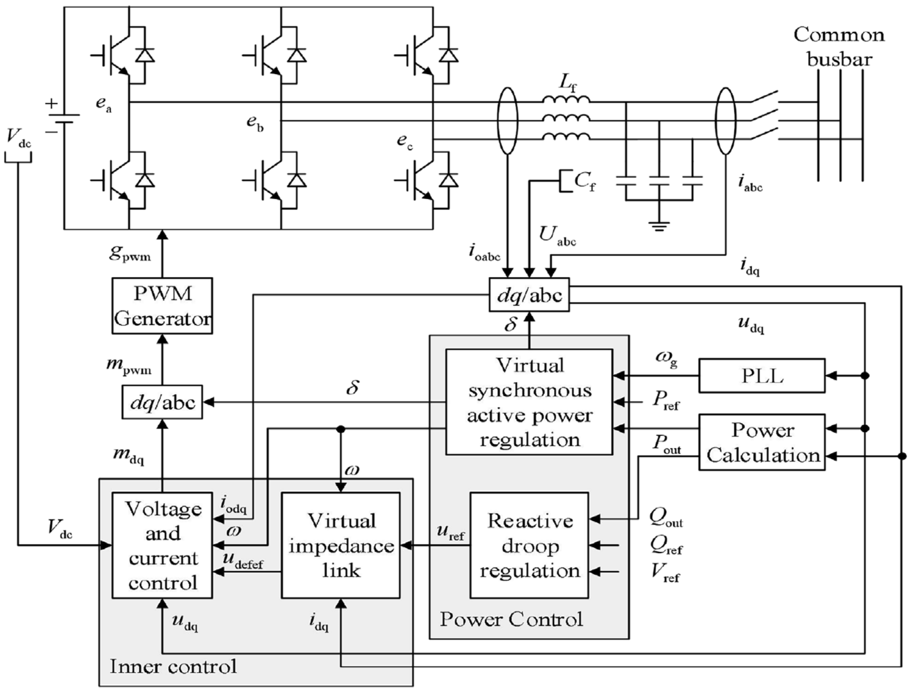


Fig. 6. Virtual synchronization control system.

particularly in three key aspects related to addressing frequency stability in islanding mode and implementing state-switching methods. In some cases, these strategies may not effectively resolve the challenges associated with frequency stability in today's microgrid, indicating the need for further refinement and enhancement.

3 Solution of transient frequency stability of the microgrid in islanding mode

In islanding mode, the transient frequency stability of the microgrid can be addressed by enhancing both the operation control mode and the droop control mode. The upgraded control modes enable more precise and adaptable frequency modulation, thus improving the overall frequency stability of the microgrid. Meanwhile, upgrading the droop control involves increasing the sensitivity of the frequency feedback loop and refining the regulatory mechanisms. This upgrade enhances the speed of response and the precision of power control, thereby ensuring a higher degree of frequency stability. By adopting these improved control strategies, a microgrid in islanding mode can effectively manage transient frequency fluctuations and maintain system stability.

3.1 Enhancement of operation control mode

Microgrid can respond to frequency changes in a more quick and flexible manner, and achieve frequency stability in the islanding mode by enhancing the principal operation control modes of the microgrid (master-slave control, peer-to-peer control and hierarchical control).

3.1.1 Master-slave control

Master-slave control enjoys numerous advantages in islanding mode of the microgrid. Primarily, it is characterized by coordination, enabling it to establish cooperation between devices and components and guarantee the frequency stability of the system. Next, master-slave control is capable of fast response, enabling it to quickly detect the frequency changes and respond in real-time through the regulation of the slave controller, thus enhancing the stability of frequency. Moreover, master-slave control is characterized by scalability, enabling it to be flexibly expanded based on the scale and demand of the microgrid to reach different operating conditions and requirements. Finally, master-slave control is characterized by robustness, enabling it to cope with all sorts of external disturbances and uncertainties and maintain the stability of system frequency.

This paper [40] introduces a novel control mode for inverter power supplies that combines the traditional droop control and V/F control. Additionally, it proposes a multiple master-slave control strategy for the microgrid based on this new control mode of inverter power supply, addressing the limitations of peer-to-peer control and single V/F-based master-slave control. In this approach, the battery, known for its rapid response, employs V/F control to follow power grid dispatching instructions in islanding mode, while a V/F-droop control mode is employed in both microgrid modes for other inverter power supplies with dynamic power regulation capabilities. The concrete implementation principle is illustrated in Figure 7, where DG1 utilizes V/F control, and DG2 utilizes V/F-droop control.

This paper [41] introduces an innovative master-slave control strategy for microgrids. This strategy combines elements of traditional master-slave control and peer-to-peer

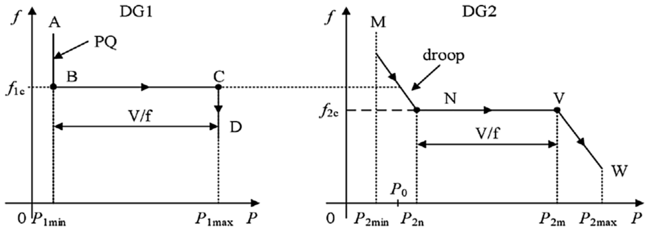


Fig. 7. Schematic diagram of multiple master-slave control.

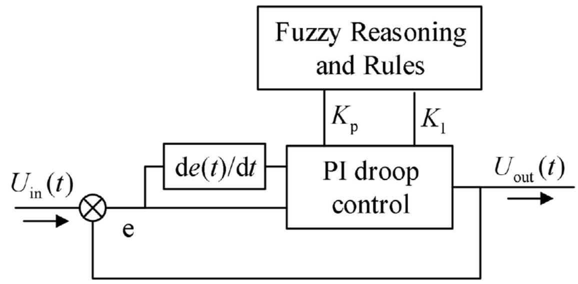


Fig. 8. Principle structure of fuzzy droop control.

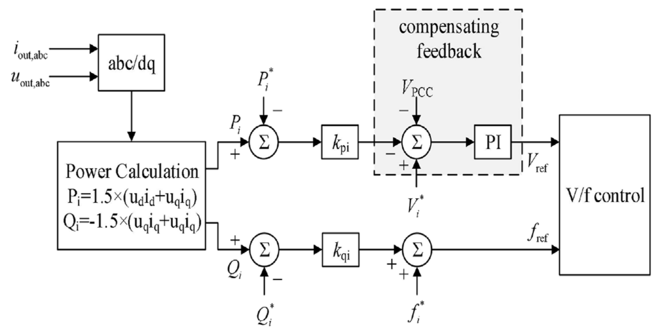


Fig. 9. Block diagram of anti-droop control with compensation feedback added.

control [42] and employs an enhanced droop control approach across multiple primary control units. This enables these units to efficiently allocate their outputs according to the system's operational requirements while maintaining microgrid frequency and voltage stability. During state transitions between grid-connected and off-grid operation modes in the new master-slave control microgrid, the primary control unit can maintain its control strategy without alteration. Furthermore, in the event of changes in system load, the micro-power supplies of multiple primary control units can rapidly coordinate and manage power distribution.

This paper [43] brings forward a new master-slave control strategy and introduces a fuzzy proportional-integral (PI) controller algorithm to set the droop coefficient in real time depending upon voltage fluctuation in view of the slow response speed and weak capability to resist load fluctuation in the traditional master-slave control strategy of independent microgrid. In comparison to the traditional master-slave control strategy, the control strategy of the new method can be employed to optimize the droop coefficient in real-time, thus raising the response speed of the system and enhancing the capability to resist load fluctuation of the system. Its structure is demonstrated in Figure 8.

This paper [44] brings forward an upgraded master-slave control strategy in combination with droop control to address the problem of light-storage-load coordination control in an islanding mode in view of a light-storage AC microgrid. Its multiple energy storage engages in AC bus voltage and frequency modulation through upgraded peer-to-peer control based on the state of charge (SOC), thus eliminating the risk of microgrid collapse due to the failure of a single energy storage support bus, achieving the rational distribution of output power of each energy storage. As a result, any energy storage can be switched on and off in real-time, and the SOC value of all energy storage will strike a balance in a steady state.

This paper [45] presents a power distribution strategy for the primary micro-power supply that ensures microgrid power balance. This strategy treats the output power of the primary micro-power supply as the load demand and allocates it to the secondary micro-power supply units in proportion to their capacities. By controlling the output power of the secondary micro-power supply units, this strategy indirectly modulates the output power of the primary micro-power supply, thereby reducing the system's reliance on the primary micro-power supply. The enhanced master-slave control strategy achieves system equilibrium and maintains voltage and frequency stability even in scenarios where the intermittent micro-power supply exhibits significant output power and load fluctuations.

3.1.2 Peer-to-peer control

Peer-to-peer control in the islanding mode of microgrid enjoys the advantages of decentralized control, instant responsiveness, adaptability and expandability. Peer-to-peer control regards the generator sets in a microgrid as equal control nodes, which can make instant regulation depending upon their own observations and the information of neighbouring nodes, quickly balance the relationship between supply and demand, and stabilize the frequency simultaneously. Each generator set is adaptive and can regulate its output power independently, adapt to the internal changes of the microgrid and enhance the frequency stability in light of the real-time measurement results. Furthermore, peer-to-peer control is easy to expand. Following the expansion of the microgrid scale, it is only required to add more generator sets to form a larger control network and secure the stable operation of the system.

This paper [46] takes anti-droop control suitable for distribution lines as the control mode of the peer-to-peer control strategy. The reference voltage of the inverter is modified by introducing compensation feedback of impedance voltage drop of lines on the basis of anti-droop control, thus eliminating the influence brought by the imbalance of line impedance. The anti-droop control structure is demonstrated in Figure 9. This control mode takes an anti-droop control mode which introduces compensation feedback of impedance voltage drop of lines. The peer-to-peer

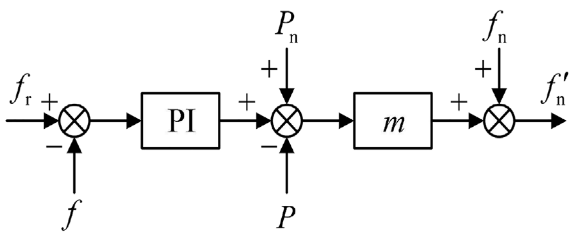


Fig. 10. Frequency compensation control chart.

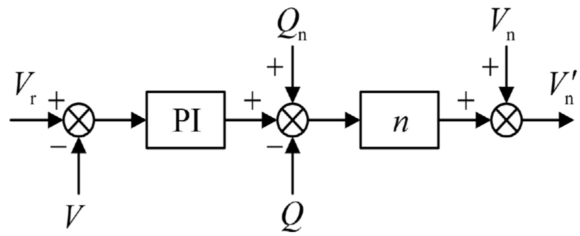


Fig. 11. Voltage compensation control chart.

control strategy can operate normally in a multi-micro power distribution line system. In islanding mode, it can distribute output power by capacity along with load changes, and guarantee stable control of voltage and frequency simultaneously.

To enable 'plug and play' functionality for distributed generation and loads, this strategy utilizes the microgrid model to regulate the inverter's output voltage and frequency based on the specified power values of distributed generation. This regulation is accomplished using enhanced P-F and Q-U droop curves across various microgrid operation modes, aiming to minimize deviations between frequency and bus voltage. This control strategy effectively mitigates deviations between system frequency and AC bus voltage. To address the issue of traditional droop control modes causing deviations between system frequency and AC bus voltage, this method introduces frequency compensation and voltage compensation mechanisms into the traditional droop control algorithm, as illustrated in Figures 10 and 11.

This paper [47] introduces an enhanced power loop-based peer-to-peer control strategy for the microgrid.

This paper [48] brings forward a hybrid control strategy combining peer-to-peer control based on a multi-main control power supply and centralized control of the microgrid central control centre (MGCC). This method, by means of peer-to-peer control mode, carries out the parallel operation of multiple diesel generator sets simultaneously as the same main control power supplies in an independent microgrid. It improves the economy and flexibility of parallel operation of multiple diesel generator sets based on peer-to-peer control by introducing the control module of economic output power limit (EOPL) into the droop control of diesel generator sets, thereby guaranteeing the stability of voltage and frequency in system operation.

3.1.3 Hierarchical control

Hierarchical control employed for the microgrid in islanding mode enjoys the advantages of fast response, high flexibility, strong reliability and low energy consumption. Hierarchical control can help achieve faster frequency response and avoid further expansion of frequency deviation by classifying the control task into multiple levels. In the meanwhile, the hierarchical control structure makes the control system more flexible and reliable, and besides, it can still be controlled at other levels even if the control strategy at some level fails. Moreover, hierarchical control can optimize energy consumption, minimize energy consumption and conform to the requirements of frequency stability by regulating energy distribution at different levels.

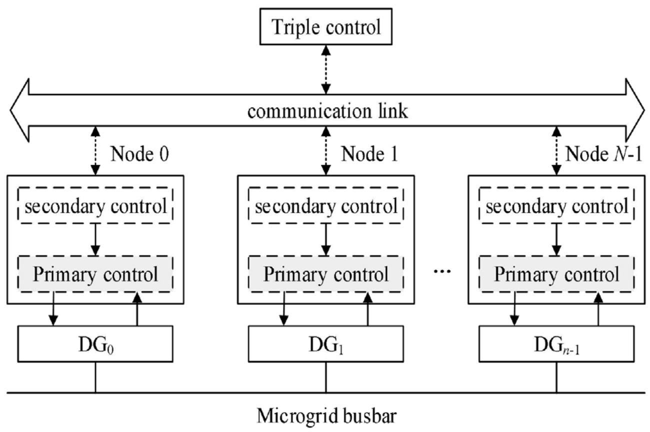


Fig. 12. Architecture of networked hierarchical control.

This paper [49] brings forward a networked hierarchical control strategy in combination with networked control technology on the basis of hierarchical control theory. Taking the characteristics of voltage and frequency control into full account, it designs control levels based on different time scales and makes a rational division of the control functions achieved by each level. As a result, a networked hierarchical coordinated control architecture suitable for low-voltage microgrids is proposed, specifically as displayed in Figure 12. In this architecture, the hierarchical control of the microgrid is classified into primary control, secondary control and tertiary control by functions.

This paper [50] brings forward a new hierarchical control system for multi-parallel DG coordinated networking in an islanding microgrid, which is classified into two layers: Primary control can achieve good control of PCC voltage and accurate distribution of active load simultaneously, which well resolves the inherent contradiction between voltage regulation performance and load distribution accuracy brought by droop mechanism at the bottom level of traditional hierarchical control. In the meanwhile, the weight coefficient is introduced into the primary control to determine the proportion of load power undertaken by DG in parallel networking. This coefficient can be generated by the secondary control in a distributed manner, which gets rid of the dependence on the centralized controller and improves the reliability of the system as a result.

This paper [51] introduces an enhanced hierarchical control strategy based on droop control. The aim is to maintain a constant voltage amplitude and frequency

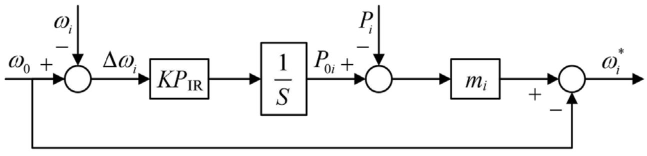


Fig. 13. Improved active frequency droop control during off-grid operation.

in the microgrid system while ensuring precise power distribution among converters through droop control.

This paper [52] presents a hierarchical control strategy for islanding microgrids based on the quality grades of voltage and frequency. The upper and lower layers collaborate to control the charging and discharging of a hybrid energy storage system, optimizing its performance. This hybrid energy storage system is composed of supercapacitors and lithium iron phosphate battery packs [53–55].

3.2 Enhancement of droop control

Droop control is an effective control measure for frequency stability in the islanding mode of the microgrid, which enjoys the advantages of fast response, independent control and flexibility, etc. Firstly, droop control can enable the quick regulation of the output power of generators, rapid response and restoration of frequency stability. Moreover, droop control can realize independent control for each generator. All generators respond to each other independently, thereby enhancing the stability and reliability of the system. Meanwhile, droop control can become flexible and adaptable by setting appropriate droop coefficients and the coefficients can be regulated in line with different working conditions and load requirements, in a bid to guarantee that the frequency is in a stable state under various conditions.

This paper [56] presents an enhanced control strategy for microgrid off-grid operation, focusing on improving the steady-state performance of traditional droop control. The upgraded control strategy enables the microgrid to achieve zero frequency deviation during off-grid operation. To address the issue of steady-state frequency deviation from the rated value in the microgrid system during off-grid operation, this paper enhances the active frequency characteristics of droop control specifically for off-grid operation, as illustrated in Figure 13.

This paper [57] brings forward a coordinated control mode of static var generator (SVG) and energy storage in view of the islanding microgrid with energy storage and SVG system. The voltage of the load node of the microgrid is changed through this control, and the system frequency is quickly regulated by the sensitivity of load to voltage. When the system frequency fluctuates owing to insufficient active power, the frequency of the microgrid is raised by lowering the system voltage to prevent the system from collapsing, thus improving the stability of the system. The control mode is demonstrated in Figures 14 and 15.

As the existing SOC equalization scheme of distributed energy storage units (DESU) in low-voltage islanding AC microgrid only gives consideration to the SOC equalization

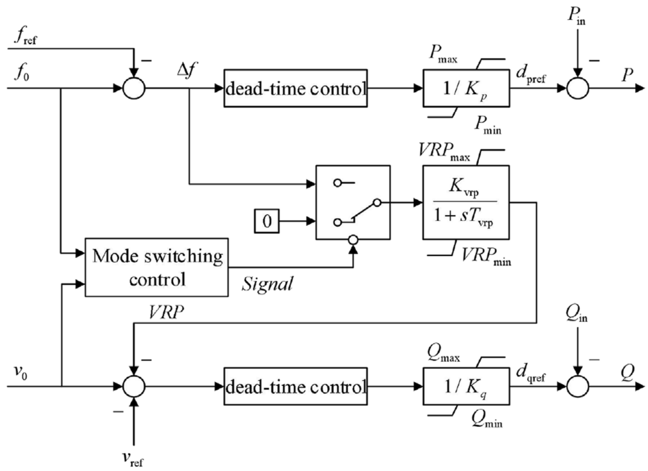


Fig. 14. Block diagram of energy storage droop control strategy.

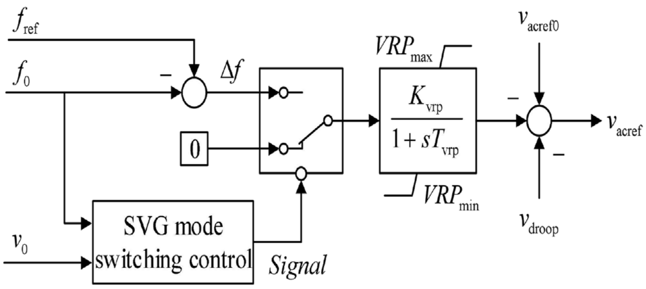


Fig. 15. Block diagram of SVG droop control strategy.

of DESU with the same capacity and a central controller and a pulse generator are in need, this paper [58], proposes a SOC equalization strategy suitable for DESU with different capacities in low-voltage islanding AC microgrid. The proposed strategy introduces multi-agent technology into droop control, which can achieve SOC equalization of DESU with different capacities at no cost of voltage quality, and can recover the voltage drop incurred by increased load. Meanwhile, the problem of frequency modulation is also taken into account.

This paper [59] takes the single neuron adaptive PI control algorithm as the secondary control algorithm of frequency of the microgrid, and the fuzzy logic is employed to regulate the proportional coefficient of the neuron. During online operation, the parameters of the PI controller can be actively regulated in consideration of the current state of the microgrid, the frequency is under control without deviation, and the online control parameters are adaptively optimized to achieve better control effect as well.

This paper [60] brings forward a control mode with a dynamic droop control factor as the goal of controlling the system frequency fluctuation in the islanding microgrid system of hybrid energy storage, which makes effective use of the high power density of superconducting magnetic energy storage (SMES) and quickly regulates the power balance under short-term power fluctuation. Moreover, the high energy density of batteries is utilized, under the long-term power fluctuation, to raise the rapidity of the system in controlling the frequency fluctuation and avoid the frequent charging and discharging of batteries and prolonging their service life as well.

4 Safe transition method of microgrid frequency during smooth switching between islanding mode and grid-connected mode

The safe transition of microgrid frequency is of particular importance during smooth switching between islanding mode and grid-connected mode. To achieve smooth switching and maintain frequency stability, traditional methods such as PLL, VSG and droop control await further upgrades. The upgrade of the PLL can be conducive to raising synchronization speed and accuracy and guarantee rapid and stable frequency matching. The upgrade of the VSG can make it more efficient to simulate the behaviour of the external power grid, send reliable reference signals and facilitate smooth frequency transition. The upgrade of droop control can be helpful in regulating generator power more quickly, meeting the load demand of the microgrid and maintaining frequency stability. These comprehensive improvement measures play a collaborative function in improving the frequency stability of the microgrid during switching.

4.1 Enhancement of phase-locked loop

Phase-locked loop is a key control strategy to secure the frequency stability of the microgrid during switching between islanding mode and grid-connected mode, and it enjoys the advantages of fast response, high accuracy, strong stability and adjustability, etc. Firstly, the PLL can make quick responses and regulate the output frequency to achieve fast stability. Besides, the PLL can achieve high-precision frequency tracking on the strength of the feedback control mechanism, hence achieving consistency between the output frequency and the reference frequency. Simultaneously, the PLL is characterized by strong stability, enabling it to resist external disturbances, keep the frequency stable and avoid frequency fluctuation effectively. Apart from that, the parameters and characteristics of the PLL can be regulated and optimized, to adapt to different operating conditions and load fluctuations and enhance the robustness and adaptability of the system.

In cases where the three-phase load's asymmetry causes an imbalance in the power grid's three-phase voltage, the traditional PLL becomes ineffective. This paper [61] addresses this issue by utilizing a two-coordinate positive-negative sequence decoupling PLL to synchronize with unbalanced voltage and extract positive and negative sequence components from it. In this approach, PIR control is employed, which involves adding a resonant controller to the conventional PI control to regulate the negative sequence components in voltage and current.

This paper [62] focuses on the two-stage photovoltaic system's islanding operation within the microgrid. It introduces an enhanced Double Second-Order Generalized Integrator Phase-Locked Loop (DSOGI-PLL) to address asymmetric faults in the power grid. Additionally, it proposes a two-stage photovoltaic low voltage penetration control mode, employing double current loop control of positive and negative sequences to improve the low voltage penetration performance of the photovoltaic power generation system. The overall structure of the upgraded DSOGI-PLL system is illustrated in Figure 16.

This paper [63] brings forward a new Software Phase-Locked Loop (SPLL) control mode suitable for master-slave control of the microgrid. When the microgrid detects the fault of the power grid and switches from grid-connected operation to islanding operation, the control mode will be switched from PQ control to V/F control. Owing to the existence of an integral link in the controller, the state of the V/F controller does not match the state of the PQ controller before switching in the course of switching, which will cause the output of the controller to jump, resulting in a comparatively large transient oscillation. To address this problem, the switching mode of the controller is improved in this paper, specifically as displayed in Figure 17.

This paper [64] presents a relatively simple PLL structure that facilitates smooth mode transitions in microgrid systems. The primary focus is on ensuring seamless transitions in microgrid systems based on a master-slave control structure during mode switching. The paper introduces the control strategy of the master inverter in the microgrid and provides a detailed analysis of the working principles of a novel software PLL suitable for microgrid systems. This novel software PLL consists of the following components: grid instantaneous phase detection, islanding phase locking technology, and phase pre-synchronization frequency compensation algorithm.

4.2 Upgrade of virtual synchronizer

As a key control method for frequency stability during switching between the islanding mode and grid-connected mode of the microgrid, a VSG is advantageous in the following aspects. In the first place, a VSG is characterized by accurate frequency response capability, enabling it to monitor the frequency changes of the microgrid in real-time and respond quickly to guarantee frequency stability. Besides, a VSG is characterized by high reliability, enabling it to respond quickly to frequency abnormality and achieve frequency stability by regulating output power. Moreover, a VSG is characterized by flexibility and adjustability, enabling it to make regulations based on the system requirements and load changes. Finally, the VSG can achieve balanced load sharing and prevent violent fluctuation of frequency, thus improving the frequency stability of the microgrid.

With reference to the literatures [66, 67], this paper [65] brings forward a VSG control technology of adaptive parameters for AC-DC bus interface converter, which endows the converter with inertia and damping, and improves the too long recovery time of transient state of frequency. A new control strategy is worked out by adding adaptive control of moment of inertia and damping coefficient on the basis of the basic VSG control strategy of AC-DC hybrid microgrid converter, which effectively

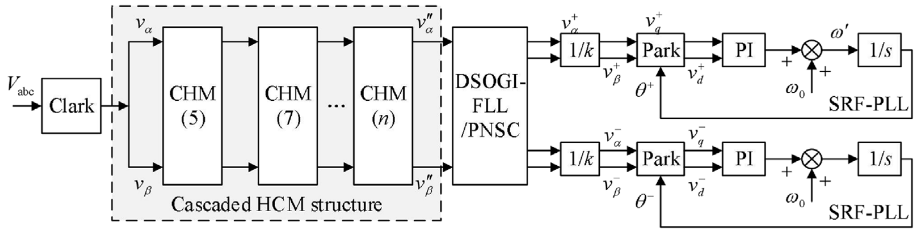


Fig. 16. Overall structure of the upgraded DSOGI-PLL system.

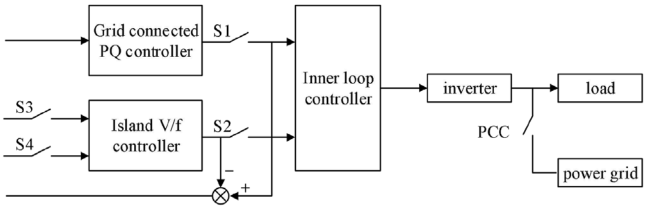


Fig. 17. Block diagram of switching structures of the upgraded controller.

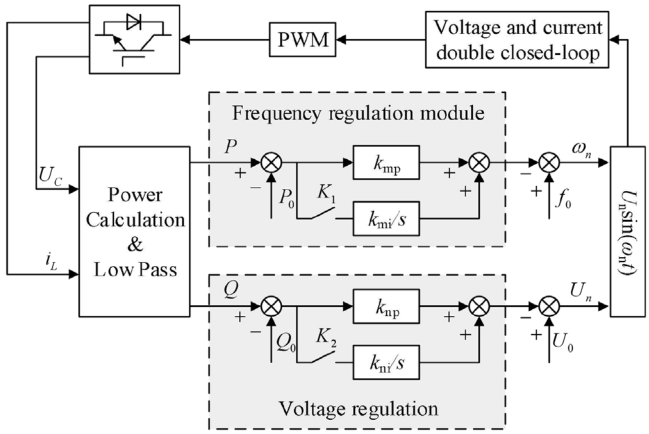


Fig. 18. Schematic diagram of upgraded droop control.

addresses the problem that the recovery time of frequency will become longer in a bid to slow down the frequency by the control strategy of the VSG with given parameters.

This paper [68] addresses the significant threat posed by the randomness of wind power system output and abrupt load changes to the stability of microgrid frequency and voltage. Through extensive research, this paper proposes a control approach for the battery energy storage system that combines VSG technology with deep reinforcement learning. This combined approach is aimed at preserving microgrid stability. A virtual governor is designed using the deep deterministic policy gradient (DDPG) algorithm within deep reinforcement learning. The upgraded VSG technology introduced by DDPG enables real-time regulation of active and reactive power, yielding a highly effective control impact on system voltage and frequency stability.

This paper [69] focuses on a photovoltaic energy storage VSG grid-connected power generation system, addressing the issues of power oscillations and frequency overshoot. An adaptive VSG control strategy is proposed to adjust rotational inertia and damping. The system's front end employs Maximum Power Point Tracking (MPPT) control for the photovoltaic system and energy storage control strategies. Subsequently, the paper analyzes the dynamic impact of rotational inertia on VSG frequency in a traditional photovoltaic energy storage VSG grid-connected power generation system. It then applies Radial Basis Function (RBF) neural network control to the VSG for adaptive adjustment of rotational inertia. Additionally, based on a fixed damping ratio, the damping coefficient is adaptively adjusted as the rotational inertia changes. Although the use of the RBF neural network algorithm increases the computational load of the system, it overcomes the shortcomings of fixed rotational inertia. This approach not only suppresses frequency overshoot and power oscillations but also accelerates the system's response speed.

4.3 Upgrade of droop control

This paper [70] employs a PQ control strategy in grid-connected mode, while the light-storage integrated converter follows the V/F control strategy in off-grid mode. However, when switching between grid-connected and off-grid modes, the system faces instability challenges. To address this issue and achieve a unified control strategy for both grid-connected and off-grid modes, an upgraded droop control strategy is proposed. This ensures smooth and seamless mode transitions between off-grid and grid-connected modes. The working principle of the upgraded droop control is illustrated in Figure 18.

In the paper [71], to address issues arising from traditional dual-mode and single-mode switching processes, a single-mode switching strategy with transient adaptive nonlinear sag curves for control is implemented. Prior to switching, the inverter output voltage, frequency, and power are pre-adjusted, effectively mitigating voltage and current anomalies that typically occur during traditional dual-mode and single-mode switching processes.

In the article [72], the whale algorithm is employed to enhance sag control. This approach calculates optimal dynamic sag coefficients based on real-time data using an optimization algorithm during system operation. It facilitates the system's normal operation, enables rapid response and control adjustments in the event of sudden load changes, ensures smooth mode transitions, reduces switching time, enhances system stability during the switching process, and overall improves the reliability of the system's power supply.

The article [73] takes the microgrid system with master-slave structure as the research object, and in order to ensure that the microgrid frequency is stabilized at the rated value, it is proposed to use the fuzzy sag-based V-F control, *i.e.*, in the case of grid-connected operation, the main controller adopts the PQ control that outputs active and reactive power with a specified reference; in the case of islanded operation, the main controller adopts the fuzzy-sag-based V-F control, in which case the main controller plays a role of frequency support for the whole microgrid system. The slave controller adopts PQ control in both states to ensure the maximum power output, which better solves the problems of oscillation and impact that occur during the switching process of master-slave inverter output voltage and current and system frequency in both states.

In the article [74], the SPLL technique is employed to achieve precise phase and frequency phase locking with the input signal [75]. Additionally, an enhanced sag control strategy is proposed, which utilizes the phase difference between the two sides of the PCC for grid-connected synchronous regulation. Particularly, during the "islanding-grid-connected" transition, an incremental phase correction algorithm is introduced alongside the improved sag control strategy. This approach facilitates non-differential control of the microgrid's voltage, frequency, and phase alignment with the main grid throughout mode transition, ensuring seamless microgrid switching during grid-connected operation.

5 Future research directions and prospects of microgrid frequency stabilization problems

Current research has revealed the importance of the microgrid frequency stabilization problem and made some progress in the control strategies. However, there are still some pending problems and some new research directions. With the large-scale access of renewable energy sources to microgrids, research should focus on frequency stability under multi-energy systems. Attention should be paid to how to coordinate and dispatch multiple energy sources, such as solar and wind, to improve the frequency stability of microgrids. There is still room for improvement in frequency control techniques such as VSGs and PLLs, and efforts should be made to improve the algorithms and control strategies in order to enhance their performance and accuracy and to ensure reliable frequency synchronization during the frequency switching process. In addition, the sag control strategy needs to be further optimized to cope with different load types and changing conditions, and new control algorithms can be explored to improve the performance and stability of sag control by combining other strategies. The application of artificial intelligence and machine learning technology is an important direction for future research, using big data analysis and intelligent algorithms, accurate frequency prediction models and intelligent frequency control systems can be established to realize automated and intelligent frequency regulation. The exploration of these research directions will promote the improvement of microgrid frequency stability, facilitate the sustainable development and intelligent operation of microgrids, and further promote the application of clean energy and the upgrading of power systems.

6 Conclusion

The frequency stability problem is becoming an important challenge in microgrid research. In this paper, starting from several frequency security accidents that occurred in recent years, we introduce the generation, operation state, and frequency stability problem faced by microgrids. We analyze the control strategies for the frequency stability problem of microgrids in islanding mode as well as in the switching state between islanding and grid-connectedness. Based on this analysis, we propose and evaluate improvement measures for frequency stability in these two states. The study's main findings include the identification of key challenges in maintaining frequency stability in microgrids, particularly under the dynamic conditions of islanding and switching states, the evaluation of current control strategies and their limitations in ensuring frequency stability, and the proposal of enhanced control measures, such as improved master-slave control, advanced droop control, optimized PLLs, and VSGs, which significantly improve frequency stability during transitions.

Future research directions should focus on developing more robust and adaptive control algorithms that can handle the high variability and uncertainty of renewable energy sources, investigating the integration of advanced energy storage systems to provide additional support for frequency regulation, exploring the potential of machine learning and artificial intelligence to predict and mitigate frequency stability issues in real-time, and conducting large-scale simulations and field tests to validate the proposed control strategies and their effectiveness in diverse microgrid configurations. This paper provides a foundation for future research by highlighting the critical areas that require further exploration and development, aiming to enhance the frequency stability of microgrids and support their reliable integration into modern power systems.

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Conflicts of interest

The author declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Data availability statement

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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