A Review of Synchronous Fixed-Frequency Microgrid Control Methods and Power Allocation Strategies

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Abstract. Guided by the dual-carbon goal, new energy generation has become the focus due to its environmentally friendly, renewable and low-emission characteristics. As a bridge for the transformation of the smart grid, the microgrid effectively integrates distributed energy resources and loads to promote the green transformation of the energy system. This paper focuses on the AC microgrid, especially its fixed-frequency control method, which aims to ensure frequency stability. The article first examines the shortcomings of traditional control methods and then introduces the concept of fixed-frequency control. The fixed-frequency control strategy is then refined into three categories: phase angle droop, voltage fixed-frequency VI droop, and virtual impedance droop. Targeted improvement measures to optimize power distribution are outlined. Finally, a comparative analysis of the characteristics of each method points the way forward for future research.

Keywords: microgrid; fixed frequency control; power distribution; droop control.

1. Introduction

In recent years, under the goal of “double carbon”, new energy power generation has attracted much attention due to its environmentally friendly, renewable and low-carbon characteristics. Microgrids have become a research hotspot due to their flexible acceptance of new energy sources, efficient use of distributed energy sources, high reliability and flexibility[1-2]. AC microgrids are divided into grid-connected and off-grid modes. When off-grid, they are particularly dependent on inverter power sources to build voltage and frequency support [3]. Although there are currently various control methods, centralized [4], hierarchical [5], and master-slave control [6] rely on communication networks, which affects cost and flexibility. Peer-to-peer control is favored because it does not require communication lines [7]. The most studied peer-to-peer control is the classic frequency droop control [8], but it is difficult to balance power sharing and stability.

Optimization strategies for traditional droop control focus more on secondary control, but are prone to transient frequency fluctuations. Advances in GPS technology have provided new ideas to solve the frequency fluctuation problem by ensuring the system's constant frequency operation by providing a global phase angle. However, precise regulation of inverters operating in parallel poses a new challenge. This paper classifies fixed-frequency control strategies into three categories: phase-angle droop, voltage fixed-frequency VI droop, and virtual impedance droop control. It also provides an in-depth analysis of improvement measures for each strategy and demonstrates the advantages and limitations of GPS fixed-frequency control. Given the limited literature at the beginning of the research, this paper aims to comprehensively sort out the existing results and present the current situation in the field. Although the literature [9-10] proposes the equivalence between control methods, this paper discusses them separately based on their applicable scenarios, characteristics, and compensation differences.

Overview of the structure of this article: Section 2 details the core control architecture of the AC fixed-frequency microgrid; Sections 3 to 5 respectively discuss in depth the three mainstream fixed-frequency control strategies of phase angle droop, voltage fixed-frequency VI droop and virtual impedance droop; Section 6 summarizes and compares the aforementioned strategies and looks ahead to the research directions of fixed-frequency microgrid technology; and Section 7 concludes the whole article.

2. Basic Concepts of AC Fixed-Frequency Microgrids

2.1 Basic Structure of AC Microgrid

The AC microgrid is modeled as Fig. 1 shown, which integrates various distributed generation units, energy storage units, etc [11].

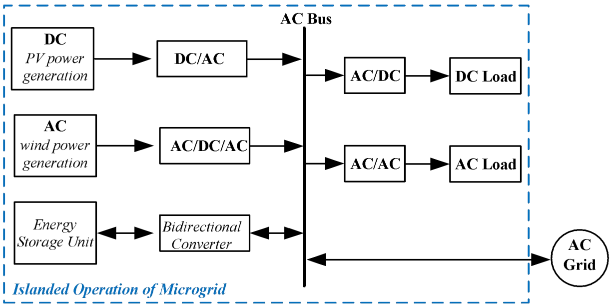

Fig. 1 Basic structure of microgrid

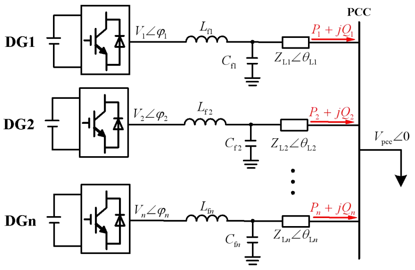

Fig. 2 Diagram of multiple parallel inverter power supply to the same load

In the microgrid system shown in Fig. 2, when multiple distributed power generation units work together to supply power to the same load, a fine and balanced distribution of power generation ratios must be carried out based on the capacity size of each power generation unit and the current real-time demand of the load. For off-grid microgrids, it is especially critical to optimize the load distribution ratio by accurately setting the reference voltage command of the converter. In this paper, we will introduce the reference voltage generation principle of inverter power supply under three kinds of fixed-frequency control strategies.

2.2 Fixed-Frequency Control Architecture of Inverter

Under the synchronized fixed-frequency control system described in this paper, the controller coordinate transformation phase angle θ_g is generated by the GPS real-time signal. The control block diagram is shown in Fig. 3. The inverter power is supplied to the load after passing through the inverter, LC filter and line. The control loops in the process include droop control for generating the reference voltage and voltage and current control.

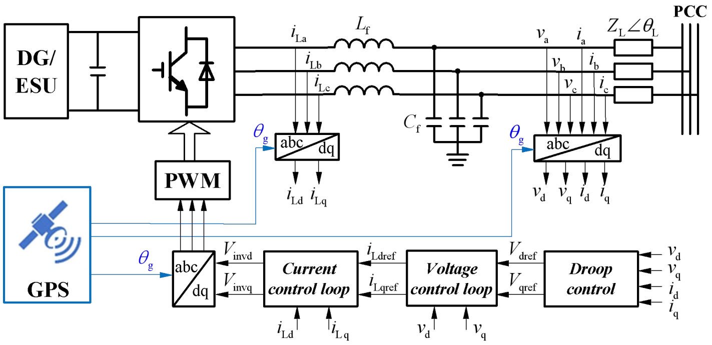

Fig. 3 Inverter power supply model and control loop

In Fig. 3, the droop control loop outputs the reference voltage signal required for each inverter control based on the capacity of the inverter and the actual demand of the load at the moment. Phase-angle droop control calculates the active and reactive power based on the inverter output voltage and current, and then generates a reference voltage command based on the phase-angle droop curve; while voltage fixed frequency VI droop control and virtual impedance droop control can directly determine the reference voltage signal based on the inverter output current.

A PI controller can be used for the voltage-current loop, and in addition, a PR controller can be used in order to ensure a high-quality waveform of the voltage and current under non-linear load conditions. The output signal of the controller is processed by the fine PWM (Pulse Width Modulation) technique to realize the precise control of the inverter output. Meanwhile, in scenarios where large-capacity power needs to be transmitted, multilevel modulation can be used in order to significantly improve the quality and stability of power.

2.3 Generation of GPS Synchronized Fixed-Frequency Signal θg

The introduction of GPS synchronization technology can realize the uniform generation of global phase angle among the controllers of each inverter, effectively eliminating the transformation error due to the phase angle difference, and improving the control accuracy and stability. Literature [12-13] firstly applied this control idea to multi-inverter microgrid control.

The GPS receiver calculates Coordinated Universal Time (UTC) and the deviation between the local clock and UTC by comparing the time delays of the signals received from four satellites, and then generates 1 pulse per second[14]. The inverter's local controller's timer module captures the rising edge of the pulse signal generated by the GPS receiver, and its offset from the GPS receiver's pulse signal is denoted as the t_{offset}, the phase angle of the local rotating coordinate system of the distributed power supply can be expressed as equation (1).

$$\theta_{\text{g}} = \mathrm{mod}[\omega_{\text{n}}(t - t_{\text{offset}}), 2\pi] \tag{1}$$

where $\omega_{\text{n}} = 2\pi f_{\text{n}}$, is the nominal angular frequency of the system, and when the receiver is stabilized, the t_{offset} tends to 0 and the system outputs a globally uniform phase angle.

3. Phase Angle Droop Control

3.1 Principle of Phase Angle Droop Control

The principle of the phase angle droop control method is similar to that of the classical droop control, and the key lies in taking the frequency stability as the core, and dynamically adjusting the phase angle by introducing the frequency integration link, so as to guarantee the stability of the system frequency. Literature [15] analyzes the output impedance model of the inverter power supply and obtains its equivalent circuit as shown in Fig. 4.

Literature [16] proposes a phase-angle droop control strategy that directly controls the phase angle of the inverter output voltage. This strategy directly controls the phase difference between the inverter output voltage phase and the synchronization signal θ_{g} according to the size of the inverter output active power. When the network is inductive, the relationship between active power and phase angle droop P-φ, and the relationship between reactive power and voltage amplitude droop Q-V, are established. The droop relationship is as follows (2).

$$\begin{cases} \varphi_{i,\text{ref}} = \varphi_0 - m_i(P_i - P_{i,\text{rated}}) \\ V_{i,\text{ref}} = V_0 - n_i(Q_i - Q_{i,\text{rated}}) \end{cases} \tag{2}$$

where φ_0 and V_0 refer to the initial phase and no-load voltage of the inverter power supply, respectively; m and n denote the active and reactive droop coefficients, respectively, and different DG droop coefficients should be selected inversely proportional to their rated capacities. The voltage amplitude reference and phase angle reference in polar coordinates are transformed to d and q coordinates to obtain the voltage reference of the inverter in d and q axis.

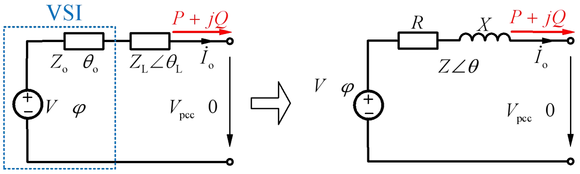

Fig. 4 Inverter equivalent circuit model

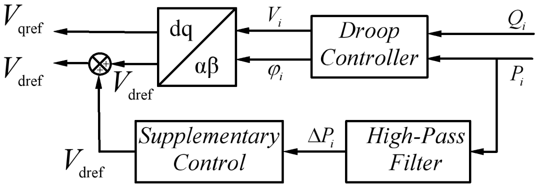

Fig. 5 Reference voltage generation with auxiliary voltage controller

Phase angle droop control is also derived based on the fact that the network is inductive, and in general the network needs to be decoupled for control. At present, the most widely used for decoupling methods is the virtual impedance method[17], which sets the virtual impedance and compensates the network as resistive or inductive; literature [18] mentions power decoupling through the transformation matrix, which is composed of impedance to regulate the droop coefficients; literature [19] introduces the power decoupling factor to correct the active phase angle droop coefficient for decoupling. In addition, the decoupling methods in the classical frequency droop control methods can also be borrowed[20-21].

The problem with phase angle droop control is that the phase angles are not globally unified, resulting in active power not being distributed inversely according to rated capacity. Although it improves frequency deviation and power quality, it is greatly affected by system impedance, and does not solve the problem of reasonable distribution of reactive power. It needs to be supplemented by other control methods.

3.2 Phase Angle Droop Control Improvement Strategy

After decoupling the general network, scholars have proposed some methods to improve the accuracy of power distribution. These methods can be divided into two categories: compensation control methods and addition of auxiliary voltage controller method.

3.2.1 Compensatory control method

Traditional droop control ensures consistent frequency and thus accurate active power distribution. Active compensation control, proposed in [22], achieves more accurate active power distribution by reducing the phase angle difference between the inverter and PCC through a secondary control strategy. This method relies on a synchronized phasor measurement unit (uPMU) to measure and synchronously share the voltage phase angle of the PCC to each DG unit in real time, and adjusts the reference phase angle with a PI controller. This process ensures time synchronization with the help of GPS, precisely controls active power distribution, but does not directly involve reactive power distribution.

Literature [23] adds the PCC point voltage magnitude to the compensation control loop as well on this basis, and when all the inverter power sources are controlled with the PCC voltage magnitude and phase angle as the reference, the effect of the line impedance mismatch on the active and reactive power can be completely eliminated. It can be seen that this compensation control method requires the deployment of a communication network from the PCC point to each controller, which reduces the economy of the system.

3.2.2 Addition of auxiliary voltage controller method

A large droop coefficient allows for more accurate power distribution, and literature [24] suggests that the addition of an auxiliary voltage controller can reduce the effect due to increasing the droop coefficient to some extent, indirectly increasing the droop coefficient. The reference voltage generation control block diagram with auxiliary voltage controller is shown in Fig. 5.

The active output of the inverter P is filtered through a high pass filter to obtain the RMS value of the high frequency fluctuation component ΔP_i , and the auxiliary voltage controller generates an auxiliary control voltage increment ΔV_{dref} , which is superimposed on the d-axis voltage generated by the original droop controller to generate a new d-axis reference voltage V'_{dref} , to obtain the correction equation as in equation (3).

$$\begin{cases}\varphi_{i,\mathrm{ref}} = \varphi_0 - m_i(P_i - P_{i,\mathrm{rated}}) + \Delta\varphi_i \\ V_{i,\mathrm{ref}} = V_0 - n_i(Q_i - Q_{i,\mathrm{rated}}) + \Delta V_i\end{cases} \tag{3}$$

where $\Delta\varphi$ and ΔV are the phase angle increments and amplitude increments of the voltage produced equivalently by the introduction of ΔV_{dref}. The article mentions an auxiliary voltage controller design

that configures an independent compensation control loop for each DG . Because it is difficult to

Table 1. Comparison of two improved methods for phase angle droop control

Modalities for improvement	communication method	Whether the power can be distributed accurately	specificities

Compensatory control	low-bandwidth communication	Yes	Requires a secondary controller with reduced dynamic performance
Addition of auxiliary voltage controller	No communication method	No	Auxiliary controller parameters are numerous and more difficult to determine

determine the initial value of optimization, and it is difficult to analytically solve for unknown gains and time constants, a group optimization method is often used to determine the parameters. This method is more suitable for weak systems, and the droop coefficient needs to be increased to ensure reasonable load distribution, but it is difficult to achieve accurate power distribution. In summary, the two improvement methods were compared and the results are as follows Table 1 shown.

4. Voltage Fixed-Frequency VI Droop Control

4.1 Voltage Fixed-Frequency VI Droop Control Principle

Mohammad S. Golsorkhi first proposed the voltage fixed-frequency VI droop control method in [25]. Compared with phase-angle droop control, VI control converts the nonlinear problem of power distribution into a linear problem of current distribution, eliminating the inherent delay of droop control power calculation and low-pass filter, and improving the dynamic performance of the system. The linear droop control expression is as in Equation (4). In addition, this paper also uses a piecewise linear droop function to reduce the error of current sharing under heavy load conditions.

$$\begin{bmatrix} V_{i,\mathrm{dref}} \\ V_{i,\mathrm{qref}} \end{bmatrix} = \begin{bmatrix} V_0 \\ 0 \end{bmatrix} - \begin{bmatrix} m_i & -l_i \\ k_i & n_i \end{bmatrix} \begin{bmatrix} i_{i\mathrm{d}} \\ i_{i\mathrm{q}} \end{bmatrix} \tag{4}$$

The essence of voltage fixed-frequency VI droop control is to control the output current by equivalent output impedance of the inverter. Among them, *m* and *n* adjust the equivalent output impedance of the inverter. If the value is selected to be small, the system may generate an underdamped response. *l* and *k* adjust the equivalent output reactance of the inverter. The value represents the degree of coupling between the d and q axis currents. According to the power calculation formula, the power delivered by the inverter to the common load is inversely proportional to the output current of the inverter. When the voltage fluctuation at each node is limited to a small range, the output current can be considered to be inversely proportional to the total system impedance. When the droop coefficient is much larger than the total system impedance, the output current of the inverter can be controlled by configuring the droop coefficient, thereby controlling the reference voltage and achieving reasonable power distribution.

Based on the droop control of a voltage fixed-frequency VI control, literature [26] proposes the droop control of a synchronous current fixed-frequency IV control. However, its essence is a current-source inverter, and when applied to a system with large load changes, the voltage distortion is serious.

Due to the high impedance ratio characteristics of low-voltage distribution networks, the design of droop control parameters is often simplified in the literature. In reference [27], the dq-axis currents are set to be uncoupled, so that *l* and *k* are 0, to achieve decoupled control. In reference [28], the design is further simplified. Based on the assumption that the steady-state voltage is in phase with the d-axis and the transient q-axis component is small, only the resistance droop coefficient *m* is configured, but the error that may be caused by the transient q-axis current fluctuation when the load fluctuates greatly is ignored.

For low-voltage distribution networks, voltage-fixed VI droop control can be applied, because the line impedance is small due to the short circuit, and the line and output impedance can be ignored by using a large droop coefficient. However, in medium and high voltage distribution networks, a larger droop coefficient is required to ignore the line impedance, but this will cause a significant voltage drop, which will affect the PCC voltage. Therefore, it is important to choose the droop coefficient reasonably and take necessary measures.

4.2 Voltage Fixed-Frequency VI Control Improvement Strategy

In response to the problem that the line impedance of medium and high voltage systems significantly affects current distribution, scholars have proposed three types of solutions: compensated line impedance method, addition of voltage correction term method, and correction of droop coefficient method to optimize current distribution.

4.2.1 Compensated line impedance method

Medium and high voltage distribution network, for the line impedance on the impact of power distribution, the line impedance can be compensated for the line impedance into the generated reference voltage to compensate for the voltage drop generated by the line, after compensation of the reference voltage as equation (5).

$$\begin{bmatrix} V_{i,\mathrm{dref}} \\ V_{i,\mathrm{qref}} \end{bmatrix} = \begin{bmatrix} V_0 \\ 0 \end{bmatrix} + \begin{bmatrix} R_{\mathrm{L}i} & -X_{\mathrm{L}i} \\ X_{\mathrm{L}i} & R_{\mathrm{L}i} \end{bmatrix} \begin{bmatrix} i_{i\mathrm{d}} \\ i_{i\mathrm{q}} \end{bmatrix} - \begin{bmatrix} m_i & -l_i \\ k_i & n_i \end{bmatrix} \begin{bmatrix} i_{i\mathrm{d}} \\ i_{i\mathrm{q}} \end{bmatrix} \tag{5}$$

In the complex process of long-distance power transmission, the lines are indispensably equipped with step-up and step-down transformers, and the impedance parameters of these transformers are precisely set at the factory to ensure the reliability and efficiency of power conversion. In order to further optimize power distribution and reduce the power distribution errors that may occur due to differences in transformer characteristics, the idea of the compensated line method can be borrowed, and the compensated transformer impedance method can be used to carry out the fine adjustment of the power[25].

The virtual negative impedance compensation method mentioned in reference [29] is also essentially a compensation line impedance method, which addresses the problem of uneven line impedance and uneven power sharing among inverters. However, it only solves the problem of power sharing in systems with equal inverter capacity, controller parameters, and LC filter parameters, and lacks generality.

4.2.2 Addition of voltage correction term method

Adding a voltage correction term is equivalent to shifting the droop curve up and down to ensure that the output current is in the right proportion. Two inverter power supplies with the same parameters in a low-voltage resistive AC microgrid are used as an example to illustrate the principle. As shown in Fig. 6 shown, if the line impedance connected to the two inverters is not equal, assuming that $R_1 > R_2$, then DG1 works at point a and DG2 works at point b, it can be seen that the two inverters which should have equalized currents do not have equalized output currents at this time; if the incremental $\Delta V_{\mathrm{d}1}$,$\Delta V_{\mathrm{q}1}$ are compensated for the droop curves of DG1 respectively, and after compensating for the incremental $\Delta V_{\mathrm{d}2}$, $\Delta V_{\mathrm{q}2}$ for the droop curves of DG2, DG1 will work at point c, and DG2 will work at point d, and both currents reach equal, realizing power equalization.

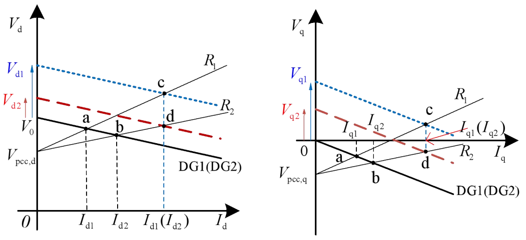

Fig. 6 Schematic diagram of adding voltage offset term

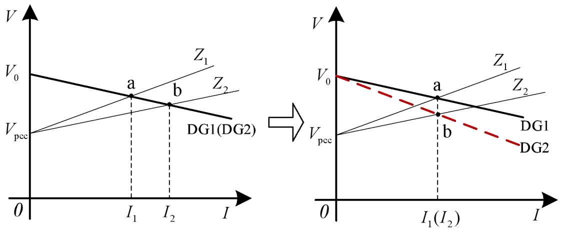

Fig. 7 Principle diagram of changing the droop coefficient method

The core of the increased voltage corrected phase method is to compensate the proper voltage. After compensation, the reference voltage expression is shown in equation (6).

$$\begin{bmatrix} V_{i.\mathrm{dref}} \\ V_{\mathrm{i,qref}} \end{bmatrix} = \begin{bmatrix} V_0 \\ 0 \end{bmatrix} - \begin{bmatrix} m_i & -l_i \\ k_i & n_i \end{bmatrix} \begin{bmatrix} i_{i\mathrm{d}} \\ i_{i\mathrm{q}} \end{bmatrix} + \begin{bmatrix} \Delta V_{i\mathrm{d}} \\ \Delta V_{i\mathrm{q}} \end{bmatrix} \tag{6}$$

A method for obtaining dq-axis voltage correction terms using a distributed approach in a low-voltage resistive microgrid is described in literature [30]: The local controllers of individual inverters are interconnected via a network to allow information exchange between adjacent units, and the information status is shared between the inverters via a sparse communication network. The state of each secondary controller updates the voltage correction terms based on the information received from adjacent units.

Literature [31] designs a voltage recovery compensation control based on traditional VI control for secondary regulation without difference. By designing an additional PI control loop in the power outer loop to compensate for the rise of the inverter output voltage to the rated value, the dynamic performance of the system will inevitably deteriorate due to the addition of the redundant loop.

In summary, the method of correcting the current distribution error by adding a voltage correction term can achieve accurate power distribution if the compensation value is properly designed, but it inevitably requires the use of a communication network.

4.2.3 Correction of droop coefficient method

For the convenience of description, the principle of correcting the droop coefficient is described in the stationary coordinate system based on the resistive network. Different droop coefficients result in different reference voltages for the same output current, and the larger the absolute value of the droop coefficient, the steeper the droop curve. Correcting the droop coefficient method aims to control the inverter output current by changing the slope of the droop curve, thus controlling the inverter reference voltage. As shown in Fig. 7, two inverters with equal droop coefficients have unequal output currents due to line impedance mismatch, assuming that $Z_1>Z_2$, DG1 works at point a and DG2 works at point b. After changing the droop coefficient of DG2, the output currents of the two inverters reach an equal share to realize the precise distribution of power.

In a stationary coordinate system, literature [32] proposes an adaptive droop coefficient method to modify the droop coefficient, which is updated adaptively according to the peak value of the inverter output current. This scheme emphasizes the accurate sharing of instantaneous currents and to some extent avoids the unreasonable current distribution caused by mismatched line impedances. In [33], the droop slope is changed using a quadratic control. An adaptive droop coefficient correction term based on the communication line is added to the droop coefficient, which is obtained in a similar way to the voltage correction term in [30], so it will not be repeated here.

It can be seen that if the droop coefficient correction term is well designed, accurate power allocation can also be achieved. To summarize, the comparison of the three modes of improvement of voltage fixed-frequency VI control is as follows Table 2 described.

Table 2. Comparison of Three Improved Methods for Voltage Fixed-Frequency VI Control

Modalities for improvement	communication method	Whether the power can be distributed accurately	specificities
Compensated line impedance	non-communicating	Yes	Precise line impedance information is required, but the compensation principle is simple
Addition of voltage correction	neighboring communications	Depends on the accuracy of the voltage compensation term	Line impedance information is not required
Correction of droop coefficient	neighboring communications	Depends on the accuracy of the droop coefficient correction term	Line impedance information is not required

5. Virtual Impedance Droop Control

5.1 Principle of Virtual Impedance Droop Control

Virtual impedance was first used for power decoupling in medium voltage microgrids. Literature [30] mentions that in voltage fixed-frequency VI droop control, it is equivalent to increase the output impedance of the inverter equivalently by designing a large droop coefficient, thus ignoring the difference in line impedance. However, the virtual impedance method introduced in this section aims to compensate the exact virtual impedance value for more accurate power allocation . After the introduction of virtual impedance, the equivalent circuit model of the inverter is shown in Fig. 8.

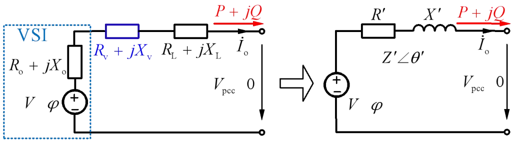

Fig. 8 Equivalent circuit model of inverter after adding virtual impedance

In Fig. 8, $Z_v\angle\theta_v=R_v+jX_v$ is the introduced virtual impedance. As can be seen from the preceding analysis, when the system is operating normally and the inverter voltage fluctuation is small, the power delivered by the inverter to the common load is approximately inversely proportional to the total system impedance. Since the inverter output impedance R_o+jX_o is small, it is generally ignored. Assuming that the compensated ideal total system impedance is $R'_i+jX'_i$, the value of the virtual impedance to be compensated is given by Equation (7).

$$\begin{cases} R_{vi} = R'_i - R_{Li} \\ X_{vi} = X'_i - X_{Li} \end{cases} \tag{7}$$

After virtual impedance introduction, droop loop outputs reference voltage as per Equation (8).

$$\begin{bmatrix} V_{i,\text{dref}} \\ V_{i,\text{qref}} \end{bmatrix} = \begin{bmatrix} V_0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_{vi} & -X_{vi} \\ X_{vi} & R_{vi} \end{bmatrix} \begin{bmatrix} i_{id} \\ i_{iq} \end{bmatrix} \tag{8}$$

Literature [34] Consider a low-voltage distribution network in which the total impedance is resistive and a virtual resistance much larger than the line impedance is introduced to solve the problem of unequal line impedance. This method is a special case of the virtual impedance method in low-voltage distribution networks, and too large virtual resistance, although simple to design, is improperly designed and can cause system instability.

5.2 Adaptive Virtual Impedance Droop Control

In principle, as long as the impedance value of the line is known, the virtual impedance to be compensated can be calculated. However, the magnitude of the line impedance in practice varies with the load access situation, and its trend cannot be predicted. In order to solve the problem of the actual line impedance change of the inverter, literature [35-37] proposes a two-layer virtual impedance control strategy, the lower layer is the basic virtual impedance control, which aims at compensating the total impedance to be resistive first; and the upper layer is the virtual resistance rectification network based on the principle of consistency, which is used to compensate for the power allocation error introduced by the change of the line impedance.

Literature proposes that under the premise of compensating the line impedance as resistive first, the specific expressions for the d-axis virtual resistance compensation amount ΔR_{vdi} and the q-axis virtual resistance compensation amount ΔR_{vqi} are shown in Equation (9).

$$\begin{cases} \Delta R_{\text{vdi}} = k_d \int_0^t \sum\limits_{j\in N, j\neq i} m_{ij}(x_j(\tau)-x_i(\tau))d\tau \\ \Delta R_{\text{vqi}} = k_q \int_0^t \sum\limits_{j\in N, j\neq i} n_{ij}(y_j(\tau)-y_i(\tau))d\tau \end{cases} \tag{9}$$

Where $x_i=P_i/P_{i,\text{rated}}$ and $y_i=Q_i/Q_{i,\text{rated}}$ are the normalized active reactive power and k_d and k_q are the dq-axis tuning coefficients, respectively. The values of m_{ij} and n_{ij} are taken as 1 if there is a communication line connecting inverter sources i and j, and 0 otherwise. The total virtual impedance to be compensated after adding the compensation amount is shown in Equation (10).

$$\begin{cases} X_{\mathrm{v}i} = -X_{\mathrm{L}i} \\ R_{\mathrm{vd}i} = R_i' - R_{\mathrm{L}i} + \Delta R_{\mathrm{vd}i} \\ R_{\mathrm{vq}i} = R_i' - R_{\mathrm{L}i} + \Delta R_{\mathrm{vq}i} \end{cases} \tag{10}$$

This method does not need to get the specific line impedance value, and although it can achieve more accurate power allocation, the control process also needs to calculate the output active reactive power of each inverter, and it needs communication lines and integration links, and the dynamic performance of the system is reduced.

Literature [38] proposed adaptive virtual impedance control to cope with stability and power allocation accuracy under microgrid disturbances, considering that the dynamic response of the system becomes faster under virtual impedance control. However, if not properly designed, it will deteriorate the dynamic performance of the system.

6. Comparison and Prospects of Control Methods for Fixed-Frequency Microgrids

6.1 Comparison of Three Fixed-Frequency Control Methods

This paper explores new peer-to-peer control methods based on GPS signals. It proposes various control strategies to address the problem of insufficient state monitoring after the system frequency is fixed in an AC microgrid. Phase angle droop control adjusts the frequency integral in a complex manner to maintain frequency stability. It is suitable for high-resistance or high-inductive systems, and requires power decoupling for medium-voltage networks. Improvements include compensation control to globalize voltage amplitude and phase angle, and an auxiliary voltage controller to deal with weak systems. Voltage-fixed frequency VI droop control simplifies phase angle control, switching to linear voltage and current control, improving dynamic performance, and optimizing power distribution by compensating line impedance, adding voltage correction terms, and dynamically adjusting droop coefficients. Virtual impedance droop control adapts to a wide range of microgrid types through virtual impedance compensation, but requires accurate measurement of line impedance and compensation of virtual resistance through power information to cope with impedance fluctuations, improving control accuracy. Its adaptive virtual impedance method provides an improved method that does not require the precise impedance of the line. With the popularization of GPS technology, these control methods are easier to implement. A comparison of the three fixed-frequency control methods is shown in Table 3.

Table 3. Comparison of three fixed frequency control methods

control method	Applicable occasions	System Dynamic Performance	Whether line impedance is required text
P-φ droop	Highly inductive or highly resistive	There are power calculation modules, filtering links, not very fast	The virtual impedance method is needed for decoupling the system, and the accuracy is not required to be high
V-I droop	Low impedance line network	High speed, but reduced when improved control is involved	Compensating for the line resistance method requires the use of precise information about the line
Virtual impedance droop	almost all networks	High speed, but reduced when improved control is involved	The more accurate the line impedance value, the more accurate the power distribution

6.2 Perspectives on Fixed-Frequency Control of Microgrids

In the future,fixed-frequency microgrid control is expected to make progress in the following areas:

1) AC-DC microgrid integration: Voltage regulation strategies for DC microgrids may provide new ideas for AC microgrid control, especially the commonality of VI and DC microgrid control. In

addition, in-depth research into the fixed-frequency control characteristics of AC-DC hybrid microgrids is expected to improve system flexibility and load response speed.

2) Intelligent algorithm integration: By introducing intelligent algorithms such as reinforcement learning and neural networks, the secondary control strategy can be optimized to achieve more accurate control compensation and improve control accuracy and efficiency.

3) Grid stability and pre-synchronization technology: In view of the challenges of grid connection in fixed-frequency microgrids, the pre-synchronization between the two needs to be considered, and innovative control parameters or mechanisms need to be developed to ensure effective management of power flow after grid connection and improve the overall coordination of the system.

7. Summary

1) Fixed-frequency control is divided into three types: phase-angle droop, voltage-fixed-frequency VI droop, and virtual impedance droop control. Improvement measures for each method are summarized. 2) For frequency fluctuations, phase angle droop control is used; to improve system response speed, voltage-fixed frequency VI droop control is used; and to ensure accurate power distribution, virtual impedance droop control is used. Each method has its own advantages and needs to be selected according to the system characteristics and control requirements. 3) This paper reviews the research results at home and abroad, and is expected to be helpful for future research.

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