# Control Strategies of Microgrid at Micro-source Level and System Level

Shuang Zhao, Jie-Sheng Wang *, Hong-Yu Wang, An He

*Abstract*—**The control mode of microgrid is generally divided into micro source level control, system level control and dispatching level control. Off-grid mode and grid-connected mode can be called the two steady-state modes of microgrid, and switching from off-grid mode to grid-connected mode and from grid-connected mode to off-grid mode can be called the transient process of microgrid. In this paper, the system equivalent structure of AC microgrid is studied, and the basic micro source level and system level control strategies of AC microgrid in off-grid operation mode and grid connected operation mode are studied. Firstly, the structure of microgrid is simplified into a microgrid system composed of multiple micro source converters, and the voltage and frequency at the AC bus are the key indexes to ensure the stable operation of microgrid. Then, PQ control, VF control and droop control are used to realize micro-source level control in microgrid. The master-slave control and peer control are adopted to realize the system level control in microgrid. Simulation results show that PQ control is used for grid connected operation of micro source converters, VF control and droop control are used for off-grid operation in each micro-source converter controller of microgrid. In the system level control of microgrid, the master-slave control is simple, but its stability is poor, but the droop control is generally adopted to peer control and to make the microgrid have good stability.**

*Index Terms*—**AC microgrid; PQ control; VF control; droop control**

## I. Introduction

ENERGY is an important material basic for social development, and the reliable power supply is essential to support the construction of modern civilization. Electricity is the core of secondary energy, and primary energy is transformed into secondary energy in the form of electric energy, which is sent to the user side by various substations, transmission and distribution networks as the ultimate energy[1]. Currently, the global energy Internet promoted by state grid corporation is becoming an important comprehensive intelligent electrical platform for China to promote energy industry upgrading, high-end power equipment construction and advanced power grid control optimization technology. The energy Internet not only contains the traditional power system, but also contains the advanced electronic power system[2]. The energy Internet is an intelligent, information-based and modular integrated ecological energy system with multiple energy sources participating and users leading. The intermediary and volatility of renewable energy power generation equipment will be regulated and stabilized by power electronic equipment and energy storage equipment, so as to realize the extensive participation of distributed power generation equipment in electric energy interaction. Due to the high proportion of new energy connected to the power system, the operation characteristics and control mode of the power system will be significantly different from the past, which brings a series of new scientific and technological problems. Considering the operation characteristics of distributed power generation equipment, especially its uncertainty and randomness, electromagnetic coupling of power system, power flow calculation, load prediction and relay protection will be the hot spots of future research [3]. The energy Internet will be a highly integrated information system and physical system, involving big data and cloud computing, so it will be one of the most complex network institutions in human history. Energy Internet embodies a high degree of energy integration, cross-regional interconnection and muti-energy access will become more and more common.

The structure of the microgrid depends on how the distributed generation devices and loads are connected to the AC/DC bus of a microgrid system. Microgrids can be divided into AC hybrid, DC hybrid, and AC-DC hybrid microgrids. In the AC hybrid microgrid, various distributed generation units and renewable energy units are connected to the AC bus through their power interface converters [4]. Renewable energy units need two-way converters to provide two-way flow capacity [5]. In this configuration, AC and DC loads are also connected to common bus-bars, generally through power electronic converters. This structure is commonly used in microgrids where the dominant power source generates AC voltage through an interface power converter. In such an AC hybrid system, the control strategy and power management scheme mainly focus on power generation consumption balance and AC bus voltage frequency control, especially in off-grid operation mode. AC hybrid Microgrid is the main structure at present, whose structure is simple, bus control

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and power management implementation is simple. Therefore, the whole system can be regarded as a single power processing unit with multiple interface ports.

Aiming to the operation of AC-DC hybrid microgrid, the microgrid control strategy and power management scheme are the most important research directions. The power management strategy determines the active and reactive power of distributed generation units and renewable energy units, and realizes the regulation of voltage and frequency [6]. Hybrid microgrid control strategies can be divided into grid-connected control strategies and off-grid control strategies [7]. In grid-connected mode, power management strategy can be divided into dispatching power mode and unassigned output power mode. In the distributed output power mode, the microgrid behaves like a controllable source or main load and can provide valuable grid support or load management as a whole [8]. In this mode, the distributed generation units and renewable energy units operate in the power control mode [9]. Power control can be achieved by current control or voltage control. Current control mode is the common grid-connected operation control mode at present, which controls the output current of distributed generation units and renewable energy units, so as to track and determine the reference power, output voltage and frequency [10]. In the voltage control mode, both the distributed generation unit and the renewable energy unit can operate and control the output voltage, whose regulating the output power of the distributed equipment is similar to the synchronous generator in the power system [11].

In off-grid mode, the power management strategies of microgrid mainly include voltage regulation, frequency regulation, reactive power regulation and active power regulation [12]. In off-grid mode, there is usually one or more dominant nodes in the microgrid to regulate the voltage and frequency of the microgrid, so as to ensure that the voltage and frequency run in a stable interval [13]. The secondary regulation of frequency and voltage can bring the voltage and frequency of the microgrid back to the stable operation range from the verge of collapse, which will enhance the stability of the microgrid [14]. Reactive power regulation and active power regulation are the basis to ensure the stability of voltage and frequency of microgrid, and the average distribution control of general reactive power is a research hot spot of off-grid operation mode of microgrid [15]. In addition, the off-grid switching strategy is also an important research point so as to ensure the synchronization of voltage, frequency and phase between the microgrid and improve the stability of the connection between the Microgrid and the main grid, and at the same time improve the optimal power distribution of the system [16]. In off-grid operation mode, reactive power distribution is an important regulation to ensure the voltage stability of microgrid. General reactive power sharing strategies can be divided into communication-based reactive power regulation and non-communication-based reactive power regulation [17]. In the communication based reactive power regulation, there is a dominant node in the system, and the reactive power distribution control is realized through interactive communication. The non-communication based reactive power sharing strategy has good communication stability and cost control, but its general control strategy is complex, and also needs to consider the hierarchical control to ensure the stable operation of microgrid [18].

The control modes of microgrid are generally divided into micro source level control, system-level control and dispatching level control. The micro-source level control is mainly to ensure the stability of micro source operation, including regulating the output voltage, frequency, active and reactive power of micro sources. The system-level control is generally to ensure the stable operation of the microgrid system, which is generally based on voltage and frequency regulation at the AC bus to improve the operation stability of the system [19]. The dispatching level control is to ensure the optimal use of energy in the whole microgrid system, generally, optimization algorithm is adopted to consider the economy [20]. This paper mainly studies the system equivalent structure of AC microgrid, the basic micro source level and system level control strategies of AC microgrid in off-grid operation mode and grid-connected operation mode. The structure of the paper is described as follows. Section 2 introduces the simplified structure of multi-energy system of Microgrid. Section 3 introduces the micro-source control strategy in microgrid. Section 4 shows the system control strategy in microgrid. Section 5 described the experimental simulation and result analysis. The last is the conclusion.

## II. Simplified Structure of Microgrid Multiple Energy System

### A. Basic Principle of Bat Algorithm

The key to stable operation of microgrid system is to ensure that the voltage and frequency of AC BUS are within a stable range, and the general frequency fluctuation range is $\pm 0.5Hz$ , the voltage fluctuation range is $\pm 10\%$ . To ensure the stable operation of the microgrid is to ensure the system power balance, that is to say that the power provided by the micro-sources and the load demand power remain stable, so that the voltage and frequency at the AC bus will remain stable. The operation mode of AC microgrid is divided into grid-connected operation and off-grid operation. Under grid-connected, the AC Bus is connected to the distribution network through circuit breakers, and the voltage and frequency at the AC Bus are controlled by the distribution network. Under off-grid operation, the circuit breaker of the AC Bus is disconnected, and the voltage and frequency at the AC Bus are adjusted by each micro-source in the microgrid. When the microgrid is switched from grid-connected operation mode to off-grid operation mode, the circuit breaker at the AC Bus is disconnected, and the AC microgrid is operated in off-grid mode. When the microgrid is switched from off-grid operation mode to grid-connected operation mode, the voltage and frequency at the AC Bus should be adjusted to keep it consistent with the distribution network. The circuit breaker can be closed to make it works under the grid-connected operation mode.

The simplified structure of AC microgrid is shown in Fig. 1. When $n$ micro-sources are connected to the AC bus by independent micro-source converters, the output power of micro-source 1 is $\left[v_{a1} \quad v_{b1} \quad v_{c1}\right]$ and $\left[i_{a1} \quad i_{b1} \quad i_{c1}\right]$ , the line impedance is $Z_1$. By this analogy, the output power of micro source n is $\left[v_{an} \quad v_{bn} \quad v_{cn}\right]$ and $\left[i_{an} \quad i_{bn} \quad i_{cn}\right]$ , and the line impedance is $Z_n$.

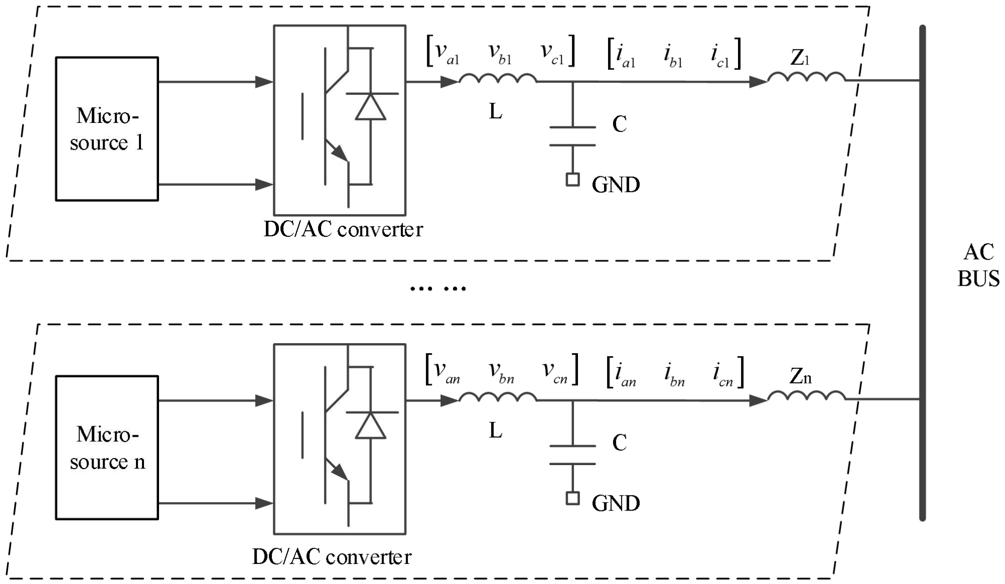


Fig. 1 The simplified architecture of AC microgrid.

Suppose the output voltage of distributed generation unit is $[v_a \quad v_b \quad v_c]$ and the output current is $[i_a \quad i_b \quad i_c]$, then the output power of the distributed generation unit can be expressed as:

$$S = P + jQ = v_a i_a + v_b i_b + v_c i_c \tag{1}$$

Eq. (1) is the power calculation method of distributed power generation unit in the static coordinate system, but this calculation method is relatively complex. The output voltage and output current are sinusoidal functions, and there is an angel difference. Therefore, the active and reactive power of distributed generation units are generally calculated in the rotation coordinate system. The power calculation of three-phase micro source converter in the rotating coordinate system requires the following steps.

1) Voltage and current parameters are converted to two-phase static coordinate system.

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3}$$

2) Voltage and current parameters are converted to the two-phase rotating coordinate system.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{5}$$

After the above transformation, the apparent output power of the distributed generation unit can be expressed as:

$$S = P + jQ = \frac{3}{2}\left(v_d i_d + v_q i_q\right) + j\frac{3}{2}\left(v_q i_d - v_d i_q\right) \tag{6}$$

## III. MICRO-SOURCE CONTROL IN MICROGRID

The control mode of micro-source level in microgrid generally includes the PQ control to ensure the stability of output power of micro source, the VF control to ensure the stability of output voltage and frequency of micro source, and the Droop control to ensure that the output power and voltage frequency of micro source show droop characteristics.

### *A. PQ control*

PQ control is a typical control mode of distributed generation units, whose control core is to ensure the stability of the output power of distributed generation units, even if the voltage and frequency at the AC bus change, the distributed generation unit ACTS as a constant power element in the system, which is a typical PQ node. The typical operation mode of PQ control can be represented by Fig. 2, which respectively corresponds to the output characteristic between active power P and AC bus frequency *f* in PQ operation mode, and the output characteristic between reactive power Q and AC bus voltage *V*.

According to the P-*f* and Q-V operation curves, when the distributed generation unit runs at point A at the AC bus (voltage $V_0$, frequency $f_0$), the active power output of the distributed generation unit is $P_{ref}$, and the reactive power is $Q_{ref}$. When the distributed generation unit runs at point B, that is at the AC bus (voltage $V_{max}$, frequency $f_{min}$), the active power output of the distributed generation unit is $P_{ref}$, and the reactive power is $Q_{ref}$. When the distributed generation unit runs at point C at the AC bus (voltage $V_{min}$, frequency $f_{min}$), the active power output of the distributed generation unit is $P_{ref}$, and the reactive power is $Q_{ref}$.

Therefore, the distributed generation unit running in PQ mode cannot realize voltage and frequency regulation at the AC bus, and its voltage and frequency in control depend on the AC bus. PQ operation mode, generally applied in grid-connected mode, acts as constant power supply to provide power to microgrid. For micro-source converter, the control block diagram of PQ control is shown in Fig. 3.

Firstly, after coordinate transformation of output voltage and current of distributed generation unit, the real-time power calculation is carried out to obtain active power P and reactive power Q. The deviation between the active power given value $P_{ref}$ and instantaneous value P is fend into the PI controller, then the current reference value $i_{dref}$ can be obtained. The deviation of the given value of reactive power $Q_{ref}$ and instantaneous value Q is fend into PI controller to obtain the current reference value $i_{qref}$. The voltage reference value $U_{ref}$ is is obtained through current loop control and coordinate transformation based on the  of $i_{dref}$ and $i_{qref}$ in static coordinate system.

### B. VF control

VF control mode ensures that the output voltage and frequency of distributed generation unit remain unchanged, but its output power changes. In contrast to PQ mode, the operating point of micro source moves horizontally and stabilizes the voltage and frequency of the system by adjusting the active power and reactive power output of the system. As shown in Fig. 4 and Fig. 5, the operating point of the micro-source is switched between A, B and C to ensure that the output voltage of the micro source is stable at $V_0$ and the output frequency is stable at $f_0$. VF control mode is generally used in off-grid operation mode to control the voltage and frequency at the AC bus.

### C. Droop control

Droop control is the most widely used control method in microgrid. Compared with the first two control methods, it is suitable for both off-grid control and grid-connected control, which takes into account the characteristics of both methods.

Droop characteristic is a power converter control method that simulates the running characteristic of synchronous generator in power system. According to Fig. 6, the output terminal voltage of the micro source converter is $V\angle\theta$, the output power is $S=P+jQ$, the line impedance is $Z=R+jX$, and the voltage at the AC bus is $E\angle 0$.

The derivation process of droop control principle is described as follows:

$$\begin{aligned} S &= EI^* = E\left(\frac{V\cos\theta + jU\sin\theta - E}{R+jX}\right)^* \\ &= \frac{1}{Z}\left(EV\cos\theta\cos\varphi - E^2\cos\varphi + EV\sin\theta\sin\varphi\right) \\ &+ j\frac{1}{Z}\left(EV\cos\theta\sin\varphi - E^2\sin\varphi + EV\sin\theta\cos\varphi\right) \end{aligned} \quad (7)$$

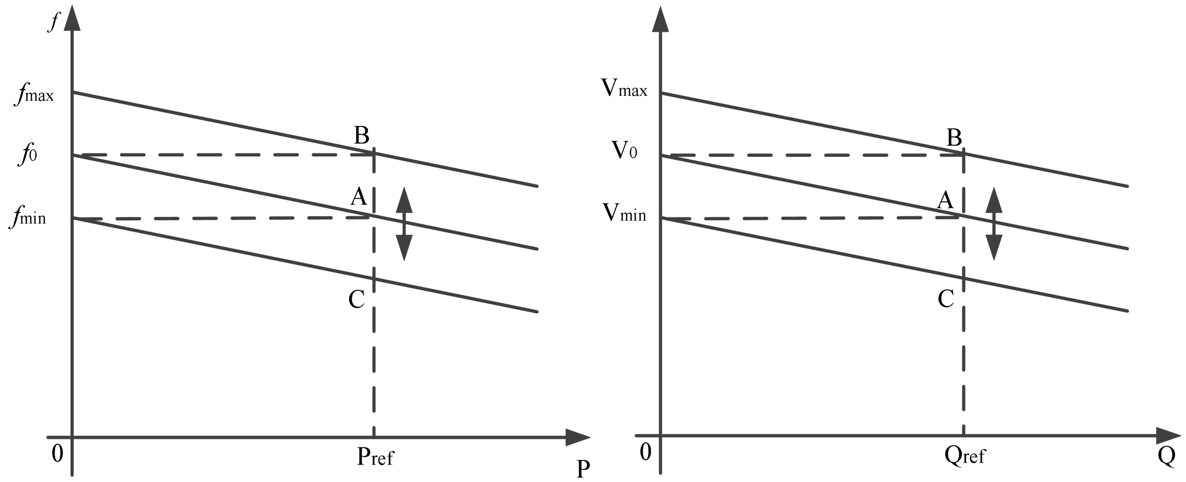

Fig. 2 Typical operation mode of PQ control.

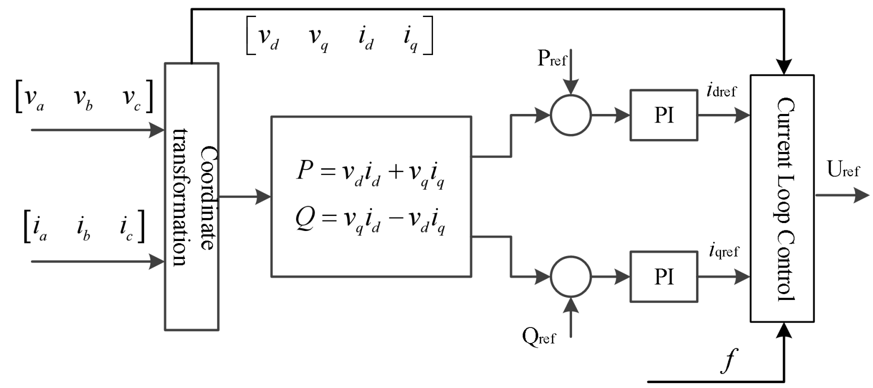

Fig. 3 The block diagram of PQ control.

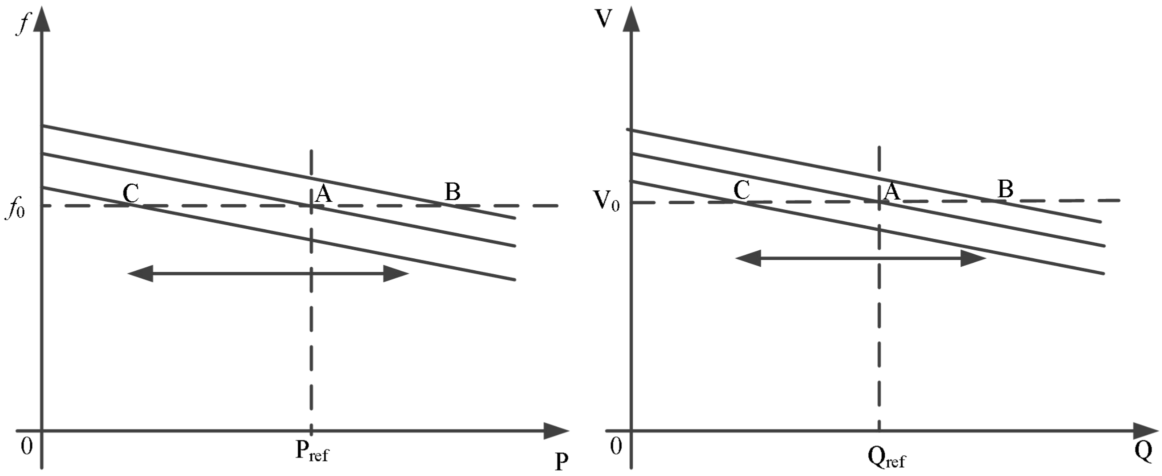


Fig. 4 Typical operation mode of VF control.

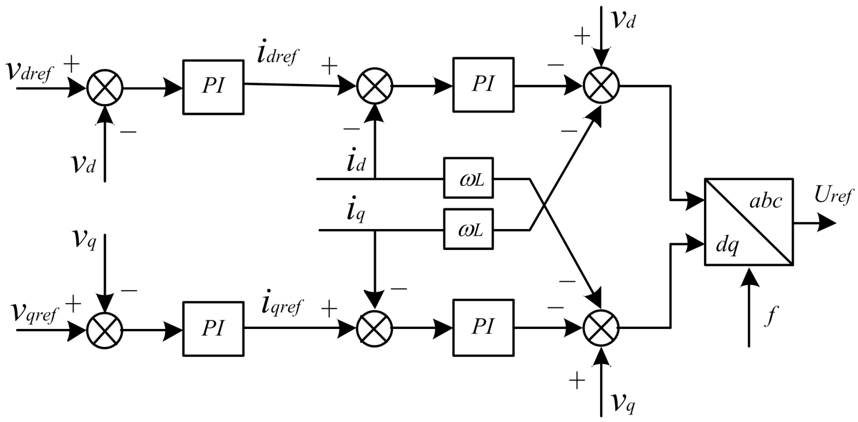


Fig. 5 Control block diagram under VF control mode.

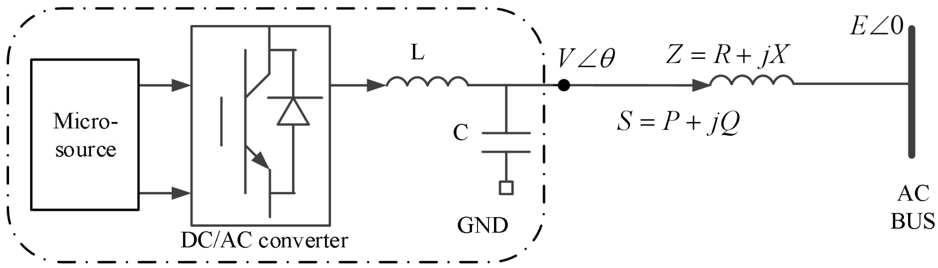


Fig. 6 The equivalent circuit of microgrid.

Then, the active power P and reactive power Q of the micro source are calculated by:

$$\begin{cases} P = \dfrac{1}{Z}\left(EV\cos\theta\cos\varphi - E^2\cos\varphi + EV\sin\theta\sin\varphi\right) \\ Q = \dfrac{1}{Z}\left(EV\cos\theta\sin\varphi - E^2\sin\varphi + EV\sin\theta\cos\varphi\right) \end{cases} \quad (8)$$

In microgrid, the above equation can be classified according to the characteristics of line impedance, including the virtual inductive sag characteristic equation, the virtual inductive sag characteristic equation, and the virtual inductive sag characteristic equation. In general, in the microgrid, the virtual sagging characteristic equation is chosen. That is to say that the line impedance in the system can be regarded as X, so $\sin\varphi \approx 1$, and $\theta$ is small at the same time, so $\cos\theta \approx 1$ and $\sin\theta \approx \theta$. Therefore, the active power P and reactive power Q of the micro-source can be simplified as:

$$\begin{cases} P = \dfrac{EV}{X}\theta \\ Q = \dfrac{EV - E^2}{X} \end{cases} \quad (9)$$

The output frequency of micro-source can be expressed as:

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\frac{d\theta}{dt} \quad (10)$$

By combining Eq. (9) and Eq. (10), it can be seen that when the line impedance is inductive, the active power P of the micro-source is related to the output voltage $V$, and the reactive power Q of the micro-source is related to the output frequency $f$. Therefore, the active frequency and reactive voltage characteristics of the micro-source can be expressed as:

$$\begin{cases} f = f_n - m\left(P - P_n\right) \\ V = V_n - n\left(Q - Q_n\right) \end{cases} \tag{11}$$

where, $P_n$ and $Q_n$ are the reference values of active power and reactive power, $f_n$ and $V_n$ are the reference values of frequency and voltage, m and n are active and reactive droop coefficients.

As shown in Fig. 7, at point A, the output power of micro-source is $P_0$ and $Q_0$, and the working voltage and frequency of the system are $V_0$ and $f_0$, respectively. At point B, the output power of the micro-source is $P_1$ and $Q_1$, and the working voltage and frequency of the system are $V_1$ and $f_1$, respectively. Therefore, it can be deduced that the values of active power droop coefficient $m$ and reactive power droop coefficient $n$ can be calculated by:

$$\begin{cases} m = \dfrac{\left(f_0 - f_1\right)}{\left(P_1 - P_0\right)} \\ n = \dfrac{\left(V_0 - V_1\right)}{\left(Q_1 - Q_0\right)} \end{cases} \tag{12}$$

Generally, in the AC microgrid, the amplitude range of voltage at the AC bus is $311V \pm 10\%$ , and the frequency range is $50Hz \pm 0.5Hz$ . Therefore, the maximum point of output power of general system corresponds to the lowest point of voltage and frequency value. By comparing droop control and VF control, it can be seen that VF control is a special droop control, that is to say when droop coefficients m and n are 0, the droop control is VF control. The control block diagram of droop control is shown in Fig. 8.

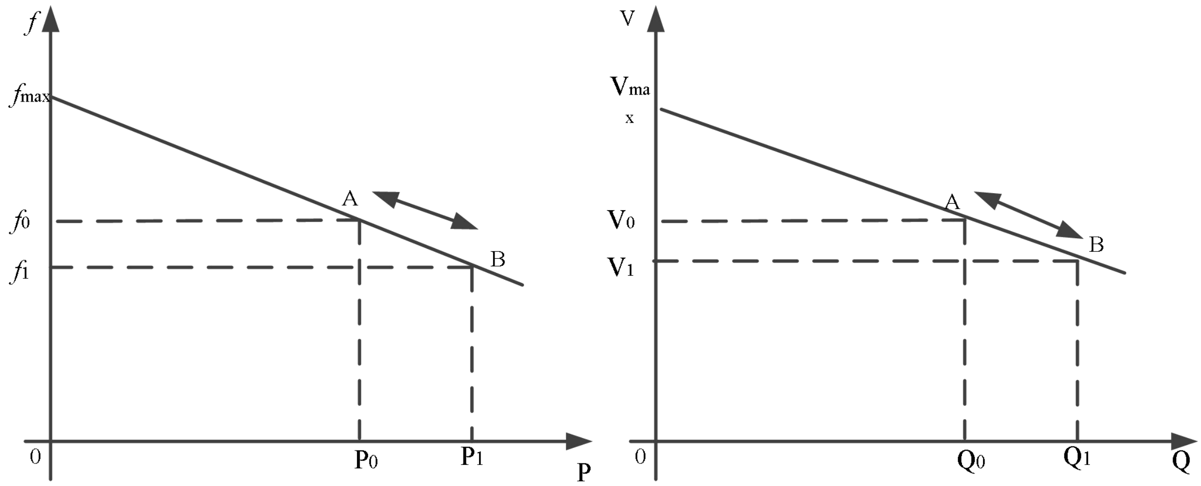

Fig. 7 The typical operation mode of droop control.

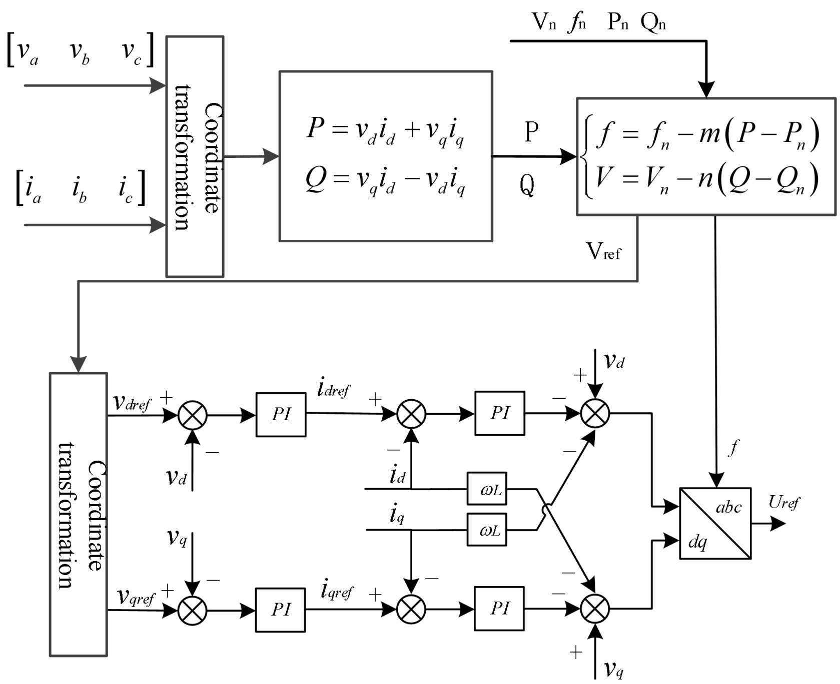

Fig. 8 Control block diagram of droop control.

Firstly, after coordinate transformation of output voltage and output current of distributed generation unit, the real-time power calculation is carried out to obtain active power P and reactive power Q. Then the voltage reference value $V_{ref}$ and frequency reference value f of the current working point are calculated according to P-f and Q-V sag curves. Then, the voltage reference values of axis d and axis q are obtained through the voltage and current double-loop controller, and $U_{ref}$ is obtained by putting in the reference frequency and through coordinate transformation.

## IV. System Control in Microgrid

The characteristics, capacity and control methods of distributed generation in a microgrid system are inconsistent. Therefore, how to realize the stability control of multiple distributed power generation devices in microgrid is the focus of current research. In a power system, there are three types of nodes: PQ node, PV node and equilibrium (Vf) node. PQ node, that is, the output power of the device remains unchanged, but its output voltage and frequency change dynamically with the system. This kind of nodes can correspond to distributed equipment under PQ control mode in the microgrid. PV node, that is, the active power and voltage output of the equipment remain unchanged, but its reactive power and frequency change dynamically, generally acting as a link of reactive compensation in the system. Finally, there are balance nodes, which have stable output voltage and frequency. These nodes can correspond to distributed devices under VF control or droop mode in Microgrid. Microgrid system-level control strategies generally fall into two categories: master-slave control and peer-to-peer control.

### A. *Master-slave Control*

Fig. 9 shows the block diagram of typical master-slave control structure of microgrid. In master-slave control, there is a dominant VF node in the Microgrid, and the others are all PQ nodes. Generally, in the grid-connected operation mode, the distribution network acts as the VF dominant node of the microgrid, while other distributed devices adopt PQ control and act as the PQ nodes. In off-grid operation mode, distributed power generation equipment with large capacity in the microgrid are selected to act as VF nodes, and the dominant node adopts VF control or droop control to adjust the voltage and frequency at the AC bus of the microgrid. Other nodes still adopt PQ control. Therefore, in off-grid mode, the grid-connected synchronization signal is used as the switching signal of PQ control and droop control. However, it is difficult to find distributed equipment with large enough capacity in general microgrid, so it is difficult to achieve steady state by using master-slave control when the system voltage and frequency are out of balance.

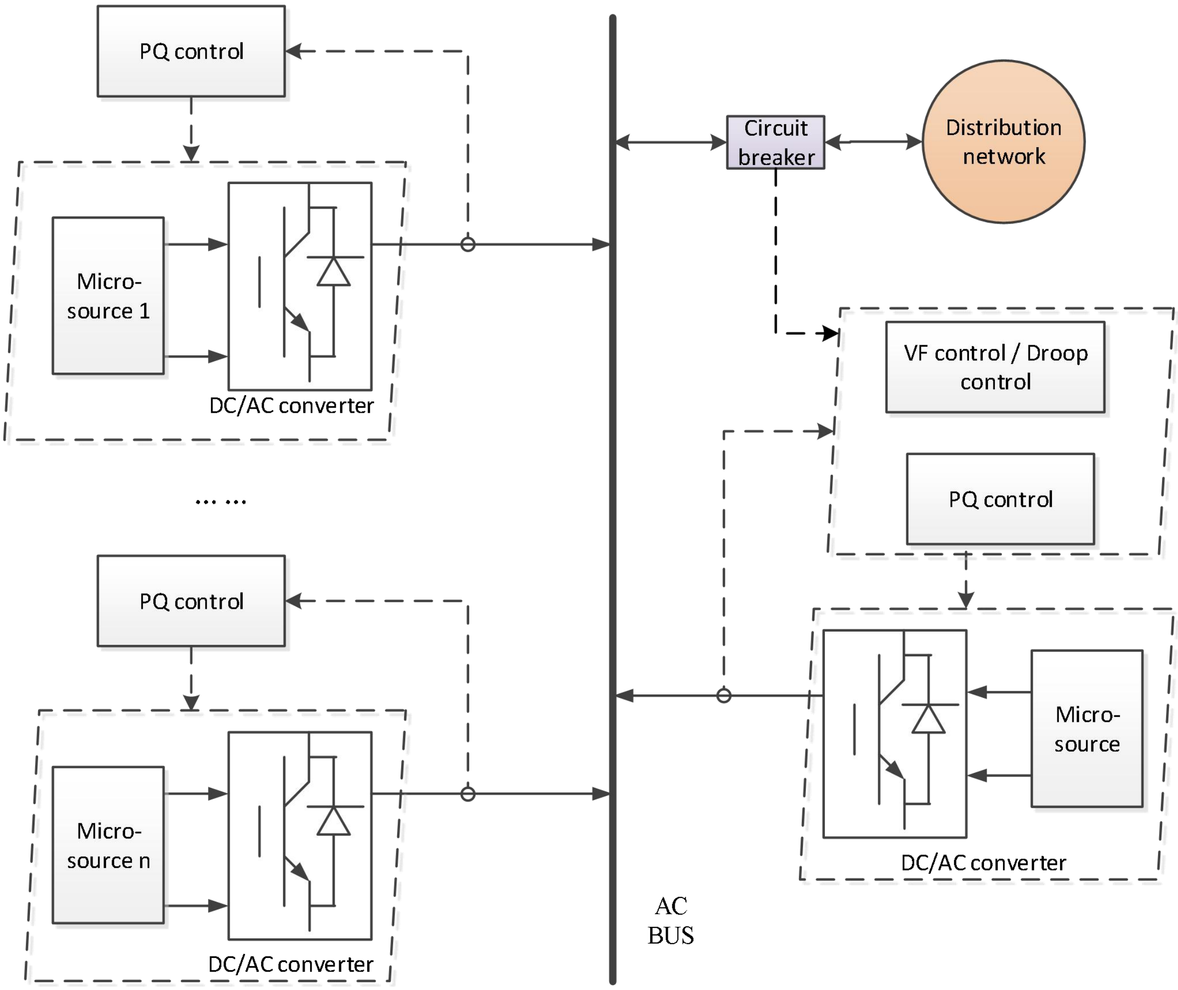


Fig. 9 Typical master-slave control structure block diagram.

*B. Peer-to-pear Control*

Fig. 10 shows a typical microgrid peer control structure block diagram. Peer control is the same control method used by all distributed generation devices in microgrid. Generally, in the grid-connected operation mode, the distribution network acts as the VF dominant node of the microgrid, while other distributed devices adopt PQ control and act as the PQ nodes. In off-grid operation mode, all nodes in the microgrid adopt VF control or droop control to jointly adjust the voltage and frequency at the AC bus of the microgrid. In addition, a small number of nodes in the system are also allowed to adopt PQ control. Therefore, in off-grid mode, the grid-connected synchronization signal is used as the switching signal of PQ control and droop control. The use of peer control can effectively solve the problem of insufficient regulating voltage and frequency caused by insufficient capacity of single distributed power generation equipment in master-slave control.

## V. Simulation Verification

Based on the above discussed control strategies, micro source level control strategy simulation is carried out, including PQ control, VF control and droop control.

*A. Simulation of PQ Control*

PQ control circuit model built in MATLAB is shown in Fig. 11, which includes reference current calculation link, decoupling link of current inner loop, and PWM generation link. Parameters of PQ control model are shown in Table 1.

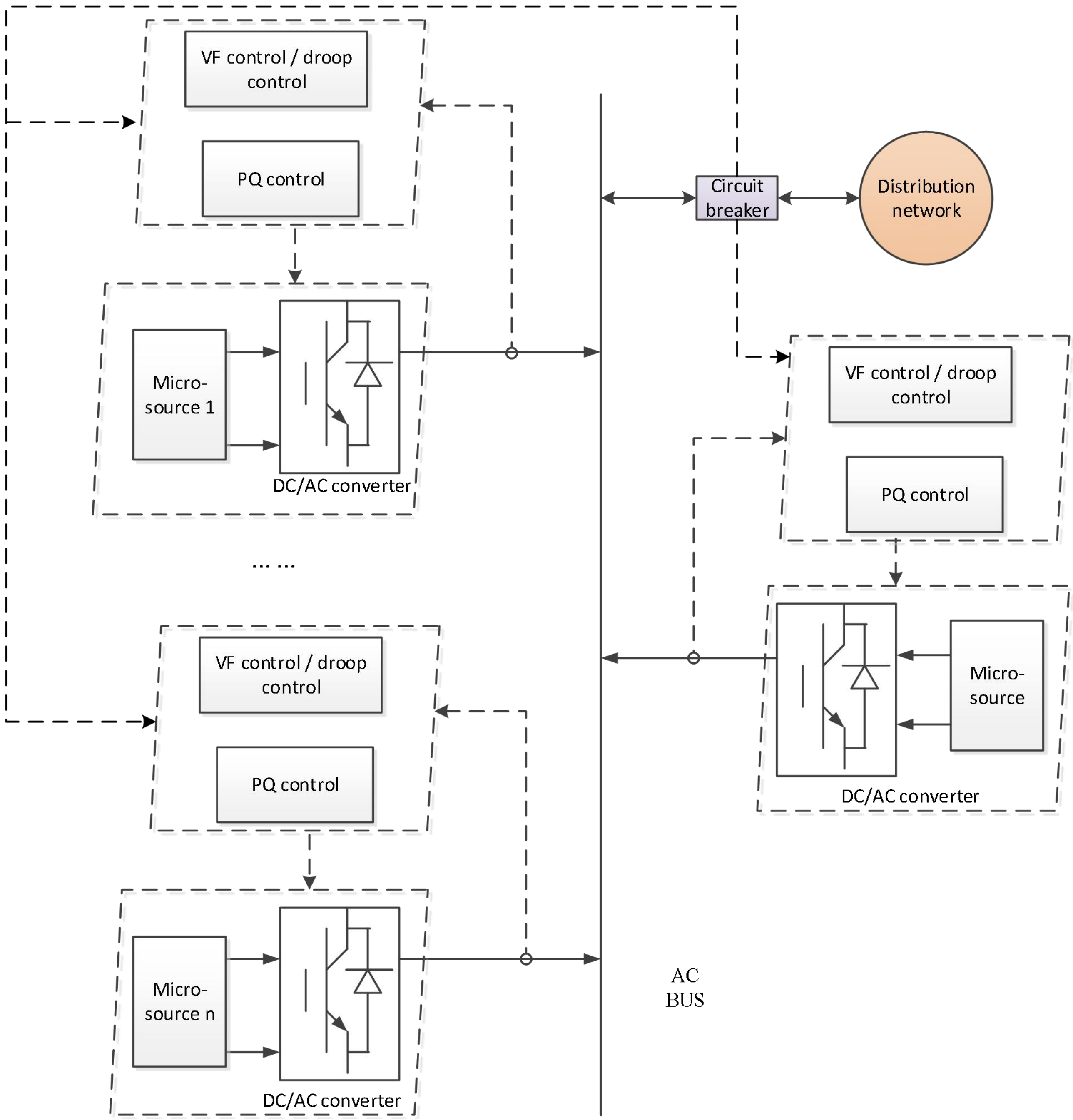


Fig. 10 Typical peer control structure block diagram.

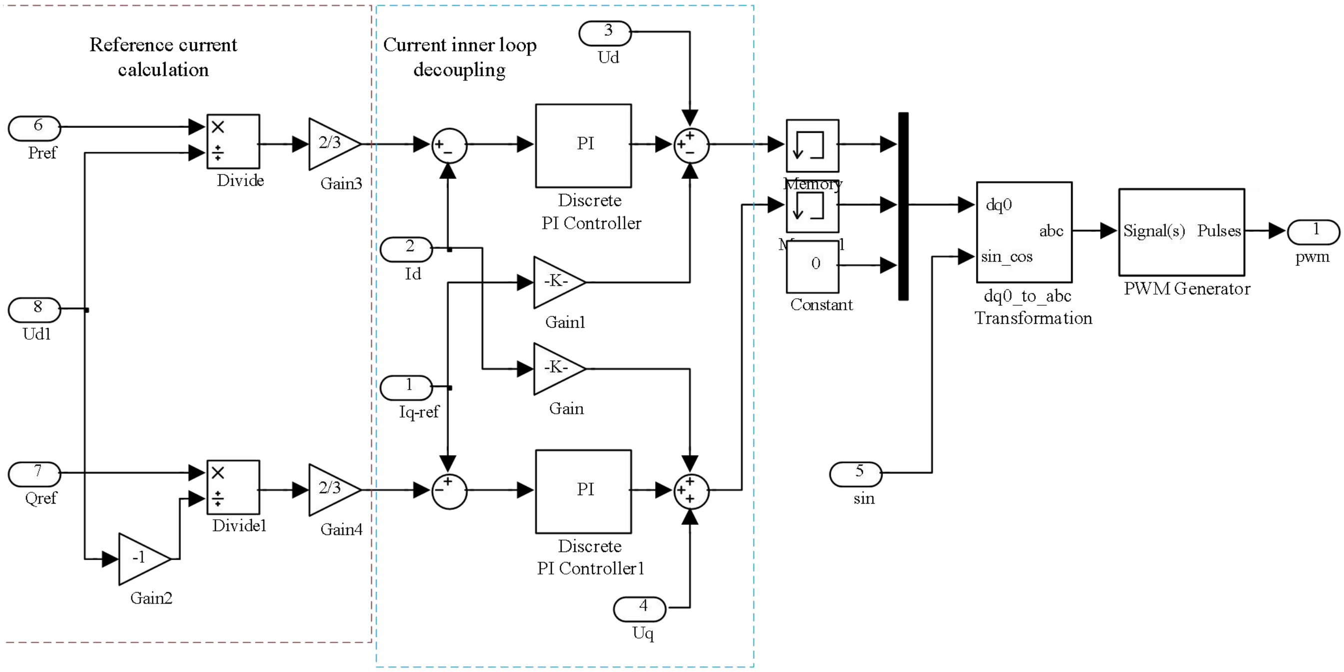


Fig. 11 PQ control circuit model.

TABLE 1. PARAMETERS OF PQ CONTROL SIMULATION MODEL

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| PI parameter | Kp=3，Ki=100 | Filter parameters | L=3mH，C=10uF |
| Power (0s~2s) | P=11kW，Q=6kVar | Power (2s~4s) | P=7kW，Q=2.5kVar |
| Power (4s~6s) | P=11kW，Q=4kVar | DC voltage | 700V |
| AC voltage | 380V | Grid frequency | 50Hz |

The active power waveform and reactive power waveform of the micro-source inverter under the PQ control are shown in Fig. 12. In the simulation process, at time 0~2s, the reference values of active power and reactive power are P=11kW and Q=6kVar. At moments 2~4s, the reference values of active and reactive power are P=7kW, Q= 2.5kvar. At moments of 4~6s, the reference values of active power and reactive power are P=11kW and Q=4kVar. According to the simulated power waveform, the dynamic response speed of PQ control is better, but the fluctuation at the steady-state moment is larger.

Fig. 13 shows the simulation waveform of grid voltage and grid-connected current at the time of 1~1.1s, and the grid voltage contains only three harmonic amplitudes of 10V. According to the current waveform, it can be seen that the current waveform works well in the steady state. At the same time, it can be seen that the grid-connected current contains a large number of harmonics, and burr is more obvious. Therefore, the power waveform fluctuations are relatively larger.

Fig. 14 shows the simulation waveform of grid voltage and grid-connected current at the time of 2~2.1s, which is used to verify the dynamic characteristics when the reference power changes. According to the waveform of the current, it can be seen that the dynamic adjustment time of the current inner loop is about 1~2 cycles.

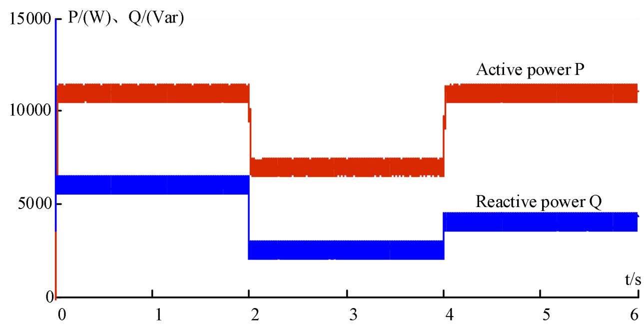


Fig. 12 The output power waves of micro source.

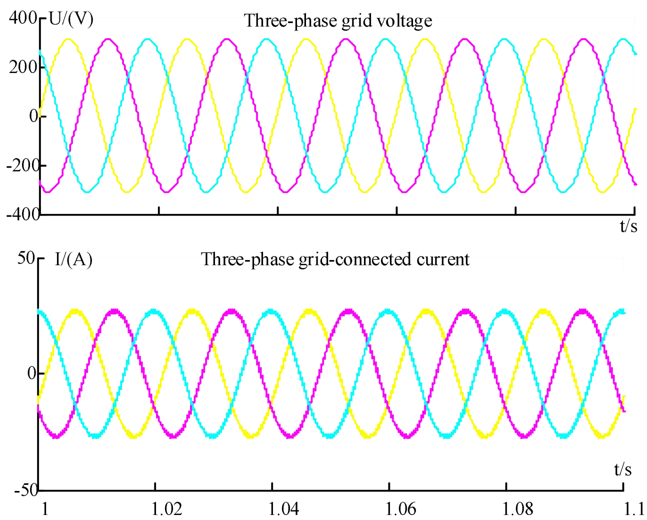


Fig. 13 The output voltage and current waves of micro source in steady state.

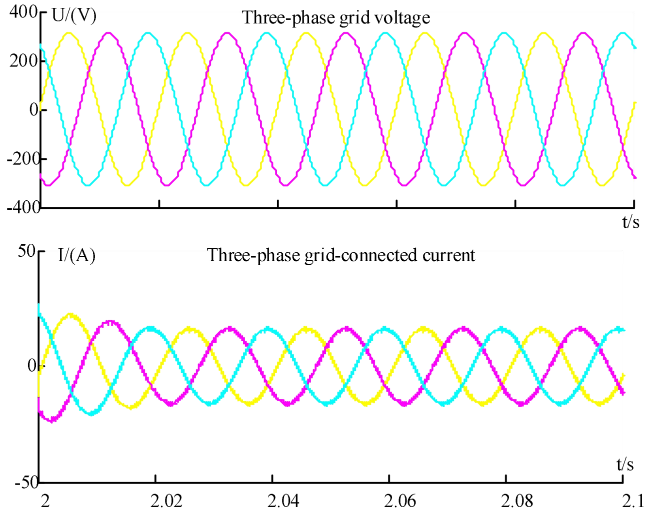


Fig. 14 The output voltage and current waves of micro source in transient state.

## B. *Simulation of VF Control*

The parameters of VF control simulation model are listed in Table 2. The VF control circuit model built in MATLAB is shown in Fig. 15, which includes voltage outer loop link, current inner loop decoupling link, and PWM generation link.

TABLE 2. PARAMETERS OF VF CONTROLS SIMULATION MODEL

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| PI parameters of voltage loop | Kp=0.2，Ki=200 | PI parameters of current loop | Kp=0.0471 |
| Filter parameters | L=3mH，C=10uF | DC voltage | 700V |
| AC reference voltage | 380V | Grid reference frequency | 50Hz |

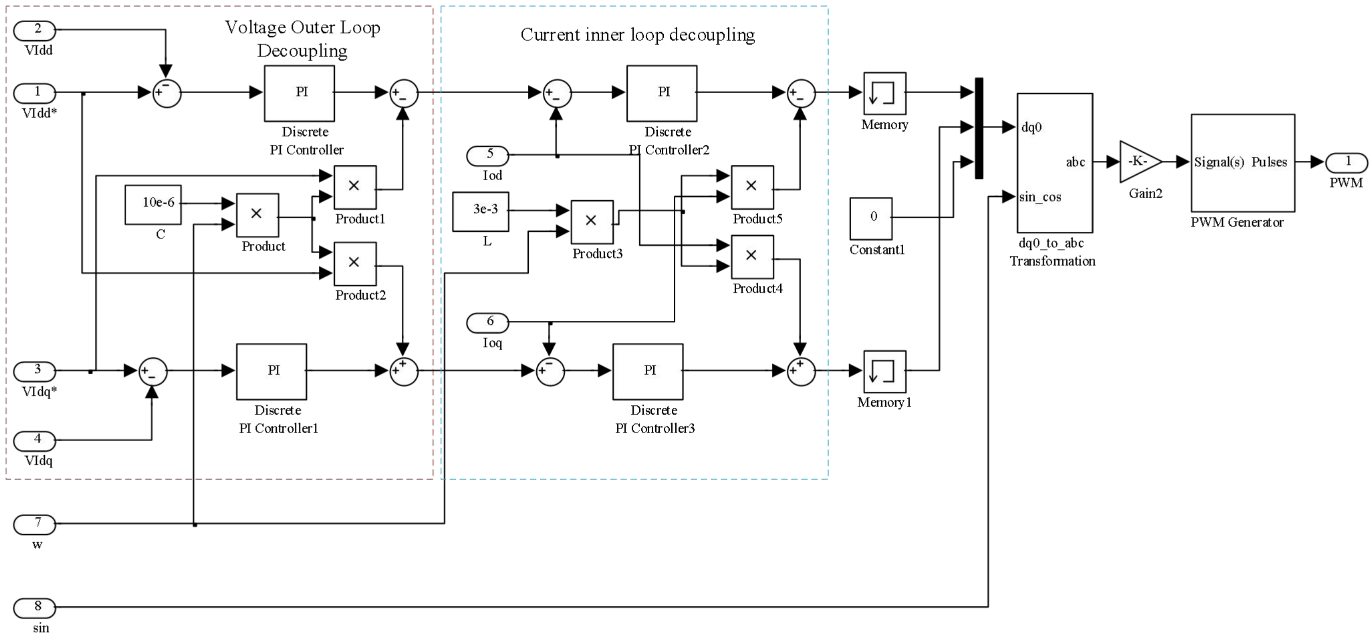


Fig. 15 VF control circuit model.

In order to verify the VF control, the on-state characteristics of voltage, current and power when the load is connected and the load is cut off are set as follows. At the time of 0s, access load 1 with power is 2kW, 700Var; At 0.2s, access load 2 with power 3kW, 1kVar; At the moment of 0.4s, access load 3 with power 4.5kw, 1.9kvar. At 0.8s, remove load 3 with power 2kW, 700Var. Fig. 16 shows the waveform diagram of output power of micro-source inverter. It can be seen that when the load increases, the dynamic response speed of active power and reactive power is faster, and the steady state performance of the power waveform is also better. At the time of load removal, the dynamic and steady state characteristics also maintain higher level. Fig. 17 shows the waveform diagram of output voltage and frequency of micro-source inverter. The reference value of voltage is 380V, and the effective value is 220V. According to the voltage waveform, it can be seen that the AC bus voltage basically remains constant at 220V, and the voltage fluctuation range is between 215V and 225V, with better stability performance. The frequency waveform is also stable at 50Hz, and the fluctuation range is around 0.1hz. Fig. 18 shows the instantaneous value waveform of voltage and current output of micro-source inverter. According to the current waveform, it can be seen that the dynamic response speed of the current waveform is faster when the load changes.

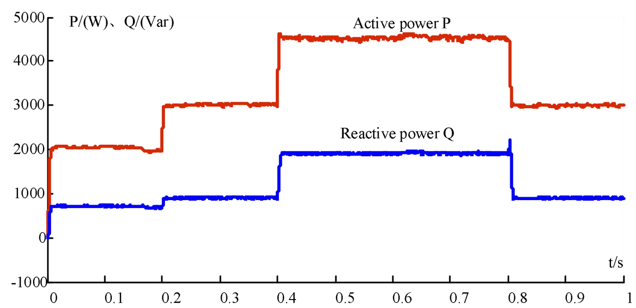


Fig. 16 The output power waves of micro source in VF control.

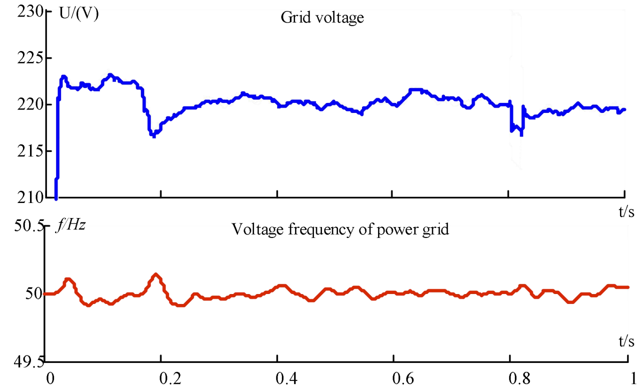


Fig. 17 The voltage and frequency waves of micro source.

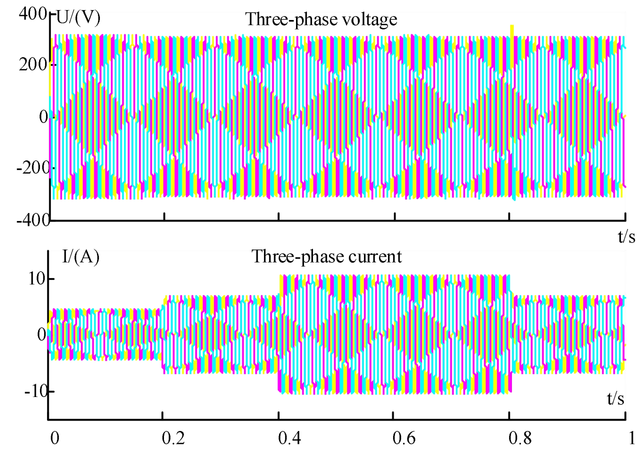


Fig. 18 The voltage and current waves of micro source.

### *C. Simulation of Droop Control*

The droop control circuit model built in MATLAB is shown in Fig. 19. The parameters of the droop control simulation model are listed in Table 3. The droop control circuit model includes reference power calculation and droop control. Reference voltage and reference frequency are generated through these two links, and PWM control signal is generated through the voltage and current double closed-loop control link shown in Fig. 15. In the power calculation step, the voltage and current signals are firstly converted to the dq coordinate system, and then the active power and reactive power of the micro-source converter are calculated. In the droop control link, the active power deviation signal is superimposed on the reference frequency to get the reference frequency, and the reactive power deviation signal is superimposed on the reference voltage to get the reference voltage value. At 0~0.3s, the load power is P=7kW, Q= 3.5kvar. At 0.3~0.5s, the load power is P=5kW, Q= 2.5kvar. Fig. 20 shows the waveform of active and reactive power of micro-source inverter. When 0~0.3s, the output power of micro-source inverter is P=7kW and Q= 3.5kvar, which can quickly match the power required by the load. At 0.3-0.5s, the output power of micro-source inverter is P=5kW and Q= 2.5kvar. According to the waveform, the dynamic response time and steady-state error of the power waveform are relatively lower. The voltage and frequency waveform of the micro-source inverter is shown in Fig. 21.

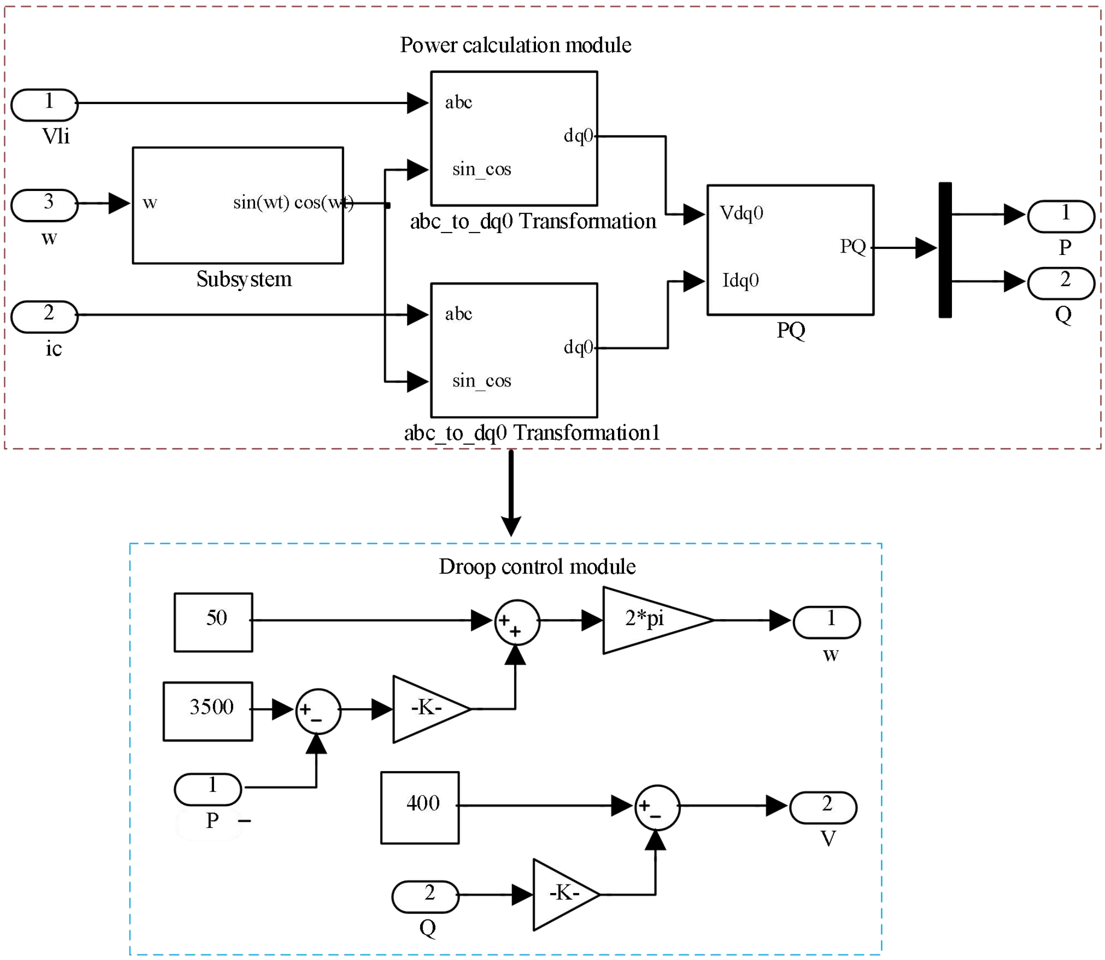


Fig. 19 Droop control circuit model.

TABLE 3. PARAMETERS OF DROOP CONTROL SIMULATION MODEL

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| PI parameters of voltage loop | Kp=0.2, Ki=200 | PI parameters of current loop | Kp=3, Ki=10 |
| Filter parameters | L=3mH, C=10uF | DC voltage | 700V |
| AC reference voltage | 400V | Reference frequency | 50Hz |
| Frequency sag coefficient | 1e-5 | Voltage sag coefficient | 3e-4 |
| Base value of active power | 3.5kW | Base value of reactive power | 0 |

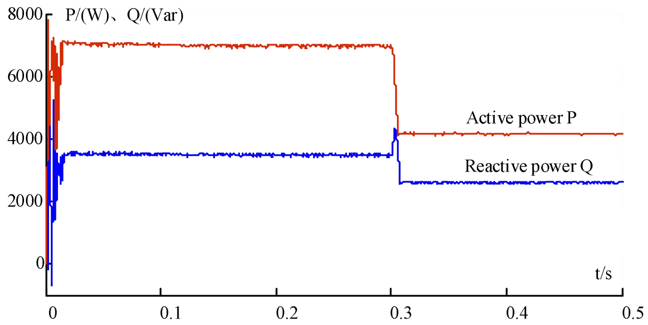


Fig. 20 The output power of micro source in droop control.

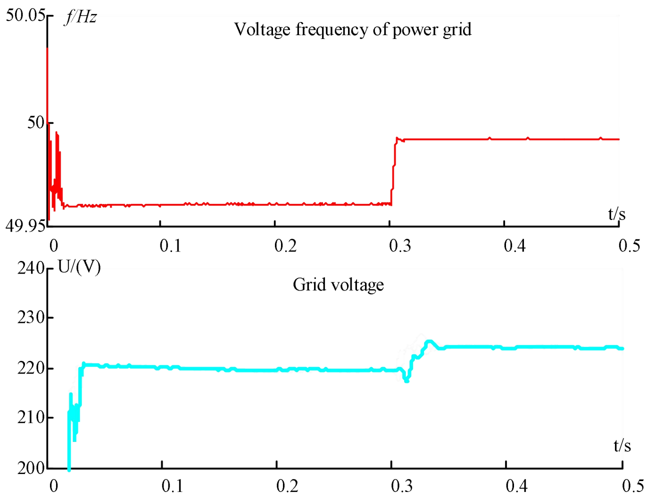


Fig. 21 The voltage and frequency waves of micro source in droop control.

At 0~0.3s, the frequency of the output voltage of the micro-source inverter is 49.96hz, and the difference between the active power and the reference power is -3.5kw. At 0.3~0.5s, the frequency of output voltage of micro-source inverter is 49.8hz, and the difference between the active power and the reference power is -1.5kw. At 0~0.3s, the RMS value of output voltage of micro-source inverter is 220V, and the deviation between reactive power and reference power is -3.5kvar. At 0.3~0.5s, the RMS of output voltage of micro-source inverter is 225V, and the difference between reactive power and reference power is -2.5kvar. According to the simulation waveform, the actual running voltage and frequency values are consistent with the reference values calculated by the droop controller.

## VI. CONCLUSION

This paper mainly studies the simplified structure model of microgrid and the control methods of micro-source level and system level. Firstly, the structure of microgrid is simplified into a microgrid system composed of multiple micro-source converters. Then, the micro-source level control methods, including PQ control, VF control and droop control, are analyzed and deduced in details. Finally, the system level control methods, including master-slave control and peer control, are introduced in details, and their advantages and disadvantages are explained. MATLAB simulation verifies the control results of micro-source level control strategy in off-grid mode or grid-connected mode, as well as the output characteristics of voltage, frequency and power.

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