

Improved Controller for Interlinking Converter in Hybrid AC/DC Microgrids

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ABSTRACT

The AC/DC hybrid microgrids are a feasible solution to provide both AC and DC power to electrical equipment. However, the control problem to maintain voltage and frequency stability in AC/DC hybrid microgrids is essential. This paper proposes a control method for the converter to maintain voltage and frequency stability for AC/DC hybrid microgrids. The power converter will operate bidirectionally to transfer power back and forth between AC and DC subgrids in the AC/DC hybrid microgrid operating in standalone mode. The proposed control method not only controls the bidirectional power flow between AC and DC subgrids to stabilize voltage and frequency as well as balance active power and reactive power. In addition, the proposed method can restore voltage and frequency for the microgrid in the event of sudden load surges or power failures in AC and DC subgrids. This method is established based on the relationship between active power and frequency, because active power is present in both AC and DC subgrids, while frequency is only present in AC subgrid. However, in AC subgrid, frequency depends on active power, while in DC subgrid, DC bus voltage depends on active power. Therefore, the proposed method is designed based on adaptive frequency shifting to adjust the power flow exchange between the two subgrids in order to maintain the stability of the frequency and voltage of the buses. The suitability and feasibility of the method are demonstrated by simulating the AC/DC hybrid microgrid using Matlab/simulink software.

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1. Introduction

The issue of power control for power converters in microgrids has received significant attention in research, with many studies both domestically and internationally developed to address this problem. Currently, there are numerous research works on power control for AC microgrids or DC microgrids [1]-[6]. These studies focus on power sharing among parallel-connected power converters to reduce circulating currents in isolated microgrids, stabilizing frequency and voltage when the microgrid is disconnected from the grid. Additionally, there are studies aimed at stabilizing the power flow into the grid for grid-connected microgrids [7]-[10]; these studies have been conducted for purely AC or DC microgrids and have not yet been applied to hybrid AC/DC microgrids. With the advantages of DC and AC household appliances and devices, providing both AC and DC power for electrical devices, a hybrid AC/DC microgrid appears to be a viable solution. Alternating current is typically available for electrical devices. However, by using a hybrid AC/DC microgrid, DC power can be supplied to DC devices without significant conversion losses. The power obtained from renewable sources such as photovoltaics and fuel cells is in DC form. Therefore, it is necessary to integrate AC and DC microgrids through a bidirectional power converter and establish a hybrid AC/DC microgrid, which helps alleviate power sharing across different networks as well as both types of loads. Furthermore, it takes into account the stability of the electrical system.

This paper proposes a power control method for a hybrid AC/DC microgrid containing supply sources and loads structured as shown in Figure 1. This structure enhances the flexibility of power distribution and utilizes distributed energy resources. The AC/DC converter, which manages the power transfer between the AC and DC buses in the AC/DC microgrid, is referred to as the Interlinking

Converter (IC). The IC needs to manage the bidirectional power flow between the AC and DC subnetworks, coordinating and controlling the power transfer between the AC and DC grids to maintain the stability of the frequency and bus voltages for both AC and DC. This means that when a power imbalance occurs in one subnetwork, the other networks will be affected, necessitating the provision of essential support power to ensure electricity supply for all critical loads in the hybrid AC/DC microgrid system.

The focus of this paper is on studying power control for Interlinking Converters (ICs) to maintain stable voltage frequency on both AC and DC sides for a hybrid AC/DC microgrid in standalone mode, as well as the balance of active and reactive power. The control method also enhancing the resilience of the hybrid AC/DC microgrid during sudden load increases or power source failures in the AC and DC subgrids.

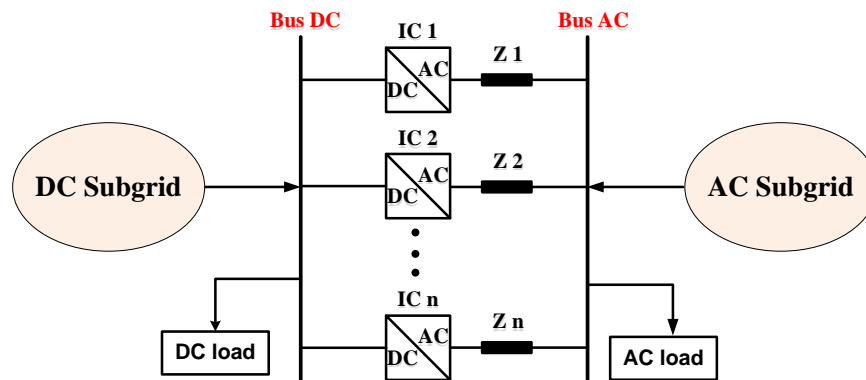


Figure 1. Structure of AC/DC hybrid microgrid

2. Proposed controller

The simplified structure of the AC/DC microgrid is shown in Figure 1. It includes both AC and DC subnetworks. The AC subnetwork consists of distributed generators (DG), alternating current loads, nonlinear loads, and transmission lines. Similarly, the DC subnetwork includes direct current sources, direct current loads, and transmission lines. The two buses, AC and DC, divide the entire microgrid system into three parts: the AC grid, the DC grid, and the IC. The IC converter is controlled to ensure that voltage and frequency remain stable under various operating conditions, linking both the AC and DC subnetworks, and facilitating the bidirectional power flow. Due to sudden fluctuations in AC load, the microgrid system exhibits a frequency drop. Likewise, significant changes in DC load result in a voltage drop. These spontaneous changes in frequency and voltage are not only detrimental to the performance of the microgrid system but also severely affect the lifespan of electrical equipment.

In standalone operating mode, without power from the grid, the IC needs to be controlled to maintain a constant frequency and voltage at the AC and DC buses, thus a suitable control method needs to be proposed. Figure 1 shows that the DC load is directly dependent on the consumer, and there may be cases where the required DC load capacity exceeds the capacity of the DC sources. In this situation, power transmission from the AC source to the DC side will be needed to compensate for the DC load power demand. Similarly, in the case of an increase in AC load, if the AC load demand exceeds the AC supply, it will also require power transmission from the DC source to the AC side to meet the demand. Therefore, maintaining bus voltage stability and power balance is the control objective for the IC.

In this paper, we combine the $P/f - Q/V_{ac}$ droop control method and the P/V_{dc} droop control method to manage bidirectional power for the inverter controller (IC) in different operating modes. The proposed control strategy aims to enhance the stability of the microgrid and to address the power flow of the IC, ensuring that the AC frequency and DC voltage of the microgrid remain within permissible limits. At the same time, the proposed method also improves the resilience of the microgrid in the event of faults in the AC and DC grid sources. The control scheme designed to meet these two objectives will be presented in the following section.

2.1. Design of the droop control method for AC subgrid

Droop is a power control method that does not require communication [10]-[11]. The ability for droop to operate without communication is essential for connecting remote power converters. It can avoid complexity and high costs, enhancing the reliability of the system. Additionally, such a system is easier to scale due to the plug-and-play features of the modules, allowing for the replacement of an inverter without stopping the entire system. According to the droop principle, active power and reactive power are controlled by two independent variables: frequency and voltage amplitude. Here, active power controls by the system frequency, while reactive power controls by the voltage amplitude (droop P/f and droop Q/V). This droop method has the advantages of being simple to implement, requiring no communication, being flexible, and easily accommodating the expansion of microgrids.

The active and reactive power of distributed generators (DGs) in the AC subgrid in the Figure 1 is calculated as follows [11]-[15]:

$$P = \frac{V}{R^2 + X^2} [R(V - V_{AC} \cos \delta) + X V_{AC} \sin \delta] \quad (1)$$

$$Q = \frac{V}{R^2 + X^2} [-R V_{AC} \sin \delta + X (V - V_{AC} \cos \delta)] \quad (2)$$

In which: V is the output voltage of the distributed source in the AC subgrid, I is the current flowing along the line connecting the distributed source to the common AC bus, δ is the phase angle difference between the output voltage of the distributed source in the subgrid and the AC bus voltage, V_{AC} is the common AC bus voltage, and R and X are the impedance on the line.

In the distribution network, the line typically has X much larger than R, and the phase angle δ is usually very small; thus, equations (1) and (2) can be rewritten as follows:

$$\delta \cong \frac{XP}{VV_{AC}} \quad (3)$$

$$V - V_{AC} \cong \frac{XQ}{V} \quad (4)$$

Equations (3) and (4) show that the active power (P) depends on the frequency (f), and the reactive power (Q) depends on the voltage (V). From this, we can establish the droop controller P/f and Q/V to control the power for power converters as follows: Equations (3) and (4) show that the active power (P) depends on the frequency (f), and the reactive power (Q) depends on the voltage (V). From this, we can establish the droop controller P/f and Q/V to control the power for power converters as follows:

$$f = f_0 - m_p P \quad (5)$$

$$V = V_0 - m_q Q \quad (6)$$

The slope coefficients m_p and m_q are selected based on the allowable voltage deviation and frequency compared to the nominal values.

$$m_p = \frac{f_0 - f_{min}}{P_{max}} ; m_q = \frac{V_0 - V_{min}}{Q_{max}} \quad (7)$$

P_{max} is the maximum active power that the distributed energy resource allows; Q_{max} is the maximum reactive power that the distributed energy resource allows; P_0 and Q_0 are the rated active and reactive power of the distributed energy resource; P and Q are the actual active and reactive power values that the distributed energy resource generates; V_0 and f_0 are the rated voltage and rated frequency of the microgrid system; V and f are the voltage and frequency at the output of the distributed energy resource.

Equations (5) and (6) are droop formulas for power control for DGs in the AC sub-grid, these DGs have the same or different rated power, so droop equations (5) and (6) have different slope factors determined by equation (7). According to research [4], the P/f droop curve in equation (5) for the DGs is shown in figure 2a, the Q/V droop curve in equation (6) for the DGs is shown in figure 2b. The DGs are connected in parallel so they have the same rated frequency f_0 and rated voltage V_0 .

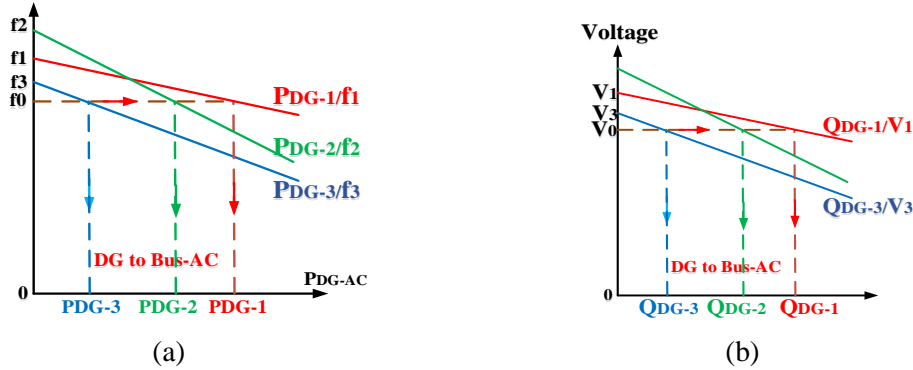


Figure 2. Droop graph for AC subgrid, (a) Droop P/f, (b) Droop Q/V

2.2. Design of the droop control method for DC subgrid

The active power of the DGs in the DC subgrid in the Figure 1 is calculated as follows:

$$V_{dc,DG} = i_{dc}R_{dc} + V_{dc} \quad (8)$$

In which: $V_{dc,DG}$ is the output voltage of the distributed power source; V_{dc} is the common DC bus voltage; R_{dc} is the resistance of the line connecting the distributed power source to the common DC bus, and i_{dc} is the current flowing through the line. On the other hand, we have:

$$V_{dc} = \frac{P_{L,dc}}{i_{L,dc}} \quad (9)$$

In which: $P_{L,dc}$ is the power consumption of the DC load; $i_{L,dc}$ is the current flowing through the DC load. Combining (8) and (9) we have:

$$V_{dc,DG} = i_{dc}R_{dc} + \frac{P_{L,dc}}{i_{L,dc}} \quad (10)$$

From equation (10), the droop method for the DC microgrid can be implemented according to the equation P_{dc}/V_{dc} :

$$V_{dc} = V_{dc0} - m_{dc}P_{dc} \quad (11)$$

In which m_{dc} is the slope coefficient, calculated using the following formula:

$$m_{dc} = \frac{V_{dc0} - V_{dc,min}}{P_{dc,max}} \quad (12)$$

In which $P_{dc,max}$ is the maximum active power that the distributed energy source is allowed to output when the voltage on the DC bus drops to the minimum allowable voltage $V_{dc,min}$.

2.3. Design of the improved droop method for IC

Figure 1 shows that the DC load depends directly on the consumer, it may happen that the DC load power required exceeds the power generated by the DC sources. In this situation, the transmission power from the AC source side to the DC will be needed to compensate for the DC load power demand. Similarly, in the case of an increased AC load, the AC load demand may exceed the AC supply, it also

requires transmission power from the DC sources side to the AC to meet the demand. Therefore, maintaining stable bus voltage and power balance is the control goal for the IC. In addition, if the power source in the AC or DC subgrid fails, the frequency and voltage at the buses will also drop sharply, the sharp change in frequency and voltage will seriously affect the performance of the microgrid, affecting the protection system and the life of the equipment in the microgrid. Therefore, improving the voltage and frequency recovery ability when the power source fails is also the control goal for the IC. Equation (5) is the droop P/f for the AC side, equation (11) is the droop P/Vdc for the DC side. These equations show that P is present in both AC and DC sides. On the other hand, P is exchanged in both directions by IC. When the AC side load increases or the AC source fails, the AC bus frequency and voltage will decrease, at this time the AC side needs power support from the DC side to restore the AC bus frequency and voltage. When the DC side load increases or the DC source fails, the DC bus voltage decreases, at this time the DC side needs power support from the AC side to restore the DC bus voltage.

In this paper, the droop P/f and droop P/Vdc control methods are combined to control the bidirectional power for ICs in different operating modes, which are responsible for linking the AC and DC buses to operate automatically. The idea of the proposed control method is that each subgrid will manage its own power flow. The surplus power will be distributed to other subgrids depending on the power shortage or surplus of both subgrids. When the power flows from the AC side to the DC side, the IC works as a parallel DC source, and the IC also works in the opposite direction when the power flows from the DC side to the AC side. The frequency and voltage at the buses must be within the allowable range. To unify the AC and DC grids, the frequency f in the alternating current grid and the voltage V_{dc} in the direct current grid are standardized as follows:

$$\Delta f = \frac{f - (f_{max} + f_{min}) / 2}{(f_{max} - f_{min}) / 2} \quad (13)$$

$$\Delta V = \frac{V_{dc} - (V_{dc,max} + V_{dc,min}) / 2}{(V_{dc,max} - V_{dc,min}) / 2} \quad (14)$$

Combining Δf and ΔV to generate the reference voltage for the IC output through the proposed controller, they represent the quantity and direction of power flow between the AC and DC subgrids. The frequency on the AC side will be balanced with the voltage on the DC side. Thus, any change in the power level at any bus will affect the entire AC/DC microgrid, since the IC is the connecting element between the two subgrids of the AC/DC microgrid. Therefore, controlling to achieve $\Delta f = \Delta V$ can be accomplished using a proportional-integral (PI) controller in the power controller for IC. Consequently, IC is controlled as an alternating current voltage source with two-dimensional droop. To achieve frequency and voltage stability in the AC/DC microgrid, a PI controller is used to shift the droop curve along the axis f , ensuring that Δf and ΔV are equal. Therefore, this paper proposes a method to improve the equation droop P/f (5) by shifting the graph of equation (5) along the f axis as shown in Figure 3. Figure 3 shows that when the load increases or the power source in the subgrids fails, the voltage and frequency at the buses in the AC/DC microgrid are restored around the allowable value. The proposed frequency shifting method as shown in Figure 3 can be written in the following equation:

$$f = f_0 - m_{p,ic} P_{ic} + k_p \int (\Delta V - \Delta f) dt \quad (15)$$

$$V = V_0 - m_{q,ic} Q_{ic} \quad (16)$$

The slope coefficients $m_{p,ic}$ and $m_{q,ic}$ are selected based on the allowable voltage deviation and frequency compared to the nominal values.

$$m_{p,ic} = \frac{f_{max} - f_{min}}{P_{ic,max}} \quad (17)$$

$$m_{q,ic} = \frac{E_{max} - E_{min}}{Q_{ic,max}} \quad (18)$$

Figure 3 shows that the operating region of (5) is in the first and second quadrants. In the first quadrant, when $P > 0$ ($P = P_1$), the power flows from the DC side to the AC side, the BIC operates in the inverter mode ($f_1 < f_0$), when the AC load increases or the AC source fails ($P = P_2$), the voltage also decreases ($f_2 < f_1 < f_0$). At this time, the AC/DC hybrid microgrid needs to be controlled to restore the frequency and voltage within the allowable range. In the second quadrant, when $P < 0$ ($P = P_3$), the power flows from AC to DC, BIC works in rectification mode ($f_3 > f_0$), when the DC load increases or the DC source has a problem ($P = P_4$), the AC bus voltage increases ($f_4 > f_3 > f_0$), the DC bus voltage drops. At this time, the AC/DC hybrid microgrid needs to be controlled to restore the AC bus voltage and frequency within the allowable range. At this time, the AC/DC hybrid microgrid needs to be controlled to restore the frequency and voltage within the allowable range.

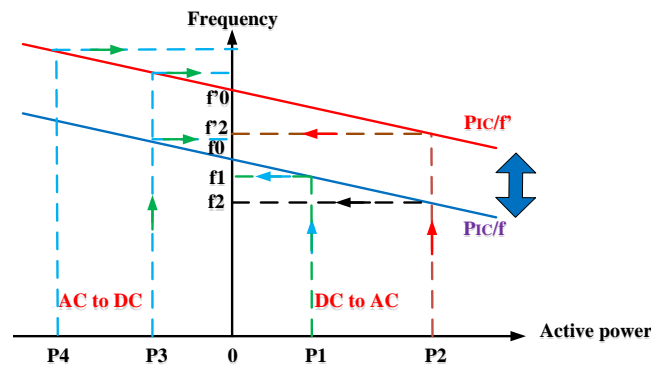


Figure 3. Improved droop plot by frequency shifting ($P_{ic}/f \Rightarrow P_{ic}/f'$)

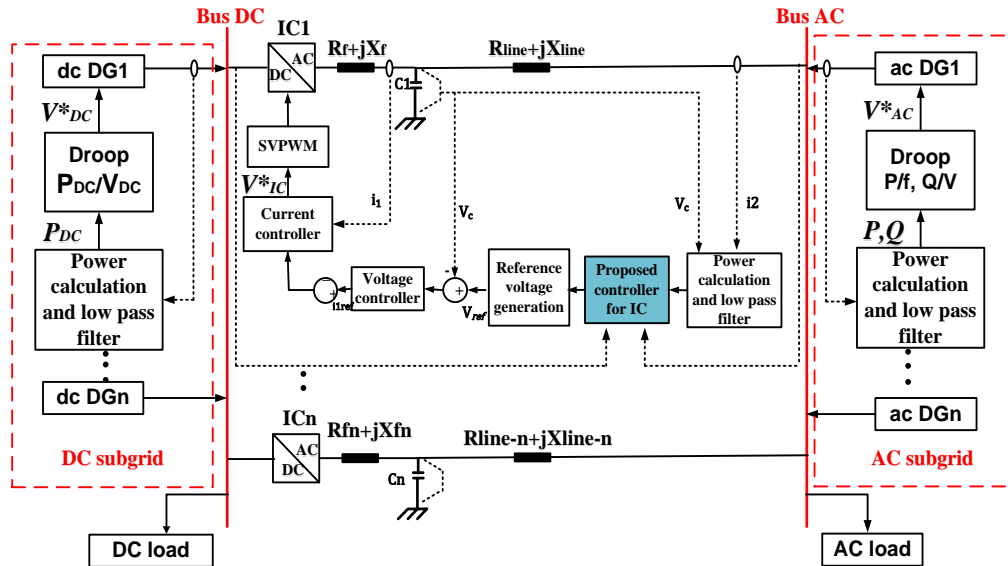


Figure 4. Block diagram of the proposed control for the IC

In which $P_{ic,max}$ is the maximum active power allowed by the inverter controller (IC); $Q_{ic,max}$ is the maximum reactive power allowed by the IC; P_0 and Q_0 are the rated active and reactive power of the IC; P and Q are the actual active and reactive power values produced by the IC; V_0 and f_0 are the rated voltage and frequency of the microgrid system; V and f are the voltage and frequency at the output of the IC; k_p is the integration coefficient, ΔV and Δf are calculated according to (13) and (14).

By adjusting the output active power from the IC, the voltage of the DC grid can be supported around its acceptable range. The power control scheme for the proposed IC can adjust the alternating current or

direct current voltage as implemented in equations (15) and (16), aiming to maintain stable voltage frequency on both AC and DC sides for the AC/DC hybrid microgrid in standalone mode, as well as the balance of active and reactive power, enhancing resilience when sources in the subgrid experience faults, avoiding mode switching, and achieving smooth operation. The block diagram of the power control scheme for the IC is shown in Figure 4.

2.4. Block of power calculation and low-pass filter

The active and reactive power produced by converters are calculated in a stationary $\alpha\beta$ frame [13]:

$$p = \frac{3}{2} (i_{2\alpha} v_{c\alpha} + i_{2\beta} v_{c\beta}) \quad (19)$$

$$q = \frac{3}{2} (i_{2\alpha} v_{c\beta} - i_{2\beta} v_{c\alpha}) \quad (20)$$

The active P and reactive power Q at the output of low-pass filter (LPF)

2.5. The current controller and voltage controller

Based on Figure 4, the following equations can be obtained:

$$i_1 = i_2 + C \frac{dv_c}{dt} + i' \quad (21)$$

$$v_{inv} = L_f \frac{di_1}{dt} + R_f i_1 + v_c \quad (22)$$

Where: R and R_f are line resistor and the filter (Ω), L and L_f are line inductor and the filter (H)

According to [13], the equation (21) can be written:

$$i_{1d} = i_{2d} + C \frac{dv_{cd}}{dt} - \omega C v_{cq} + i'_d = \Delta i_d + i_{2d} - \omega C v_{cq} + i'_d \quad (23)$$

$$i_{1q} = i_{2q} + C \frac{dv_{cq}}{dt} + \omega C v_{cd} + i'_q = \Delta i_q + i_{2q} + \omega C v_{cd} + i'_q \quad (24)$$

Where:

$$\Delta i_d = k_{pv} (v_{cd}^* - v_{cd}) + k_{iv} \int (v_{cd}^* - v_{cd}) dt \quad (25)$$

$$\Delta i_q = k_{pv} (v_{cq}^* - v_{cq}) + k_{iv} \int (v_{cq}^* - v_{cq}) dt \quad (26)$$

Equations (23) to (24) are the voltage controller.

According to [13], the equation (22) can be written:

$$v_{invd} = L_f \frac{di_{1d}}{dt} + R_f i_{1d} - \omega L_f i_{1q} + v_{cd} = \Delta v_d - \omega L_f i_{1q} + v_{cd} \quad (27)$$

$$v_{invq} = L_f \frac{di_{1q}}{dt} + R_f i_{1q} + \omega L_f i_{1d} + v_{cq} = \Delta v_q + \omega L_f i_{1d} + v_{cq} \quad (28)$$

Where:
$$\Delta v_d = k_{pi} (i_{1d}^* - i_{1d}) + k_{ii} \int (i_{1d}^* - i_{1d}) dt \tag{29}$$

$$\Delta v_q = k_{pi} (i_{1q}^* - i_{1q}) + k_{ii} \int (i_{1q}^* - i_{1q}) dt \tag{30}$$

Equations (27) to (28) are the current controller.

3. Simulations Results

The proposed controller is simulated by Matlab/Simulink, this controller performs power-sharing for 2 inverters 4kVA, parameters of the controller are presented in Table 1.

Table 1. Parameters for the controllers

Parameters	Values	Parameters	Values
$V_{cd} (V)$	600	$f_o (Hz)$	50
$L_f (mH)$	4,2	$f_{max} (Hz)$	51
$R_f (\Omega)$	0,1	$V_{AC,p} (V)$	311
$C (\mu F)$	2,2	$f_z (kHz)$	10
$V_{cd,max} (V)$	610	$f_{min} (Hz)$	49
$V_{cd,min} (V)$	590	k_p	0,9

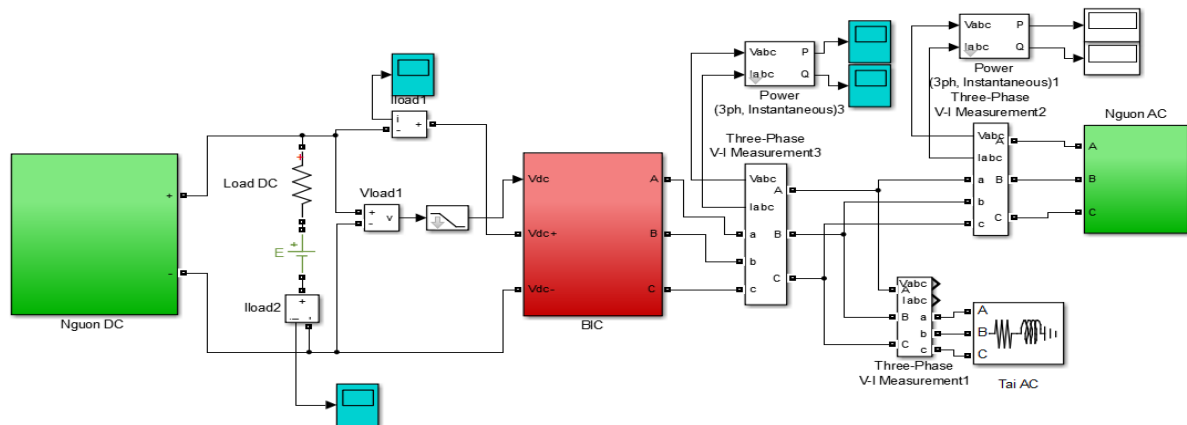


Figure 5. Simulation model using Matlab/Simulink software

Simulate the AC/DC microgrid configuration as shown in Figure 4 for the following case: Enhance the resilience of AC voltage regulation when the AC sources in the AC subgrid experience a fault and AC loads suddenly increase. The DC load with a power consumption of 3.6kW and the AC load with a power consumption of 4+j3kVA are connected at the DC and AC buses respectively. The DC sources in the DC sub-grid generates a DC voltage at the DC bus of $V_{dc} = 600V$, the AC sources in the AC sub-grid generates a phase voltage amplitude of 311V, the AC sub-grid and the DC sub-grid are connected to each other through two parallel ICs, the 2 BICs have the same rated power. At the 11th second, the sources in the AC sub-grid have a fault and lose connection to the AC bus, at this time the AC load increases to 6.3+j4.6 kVA. The simulation results for this case are shown in Figure 6.

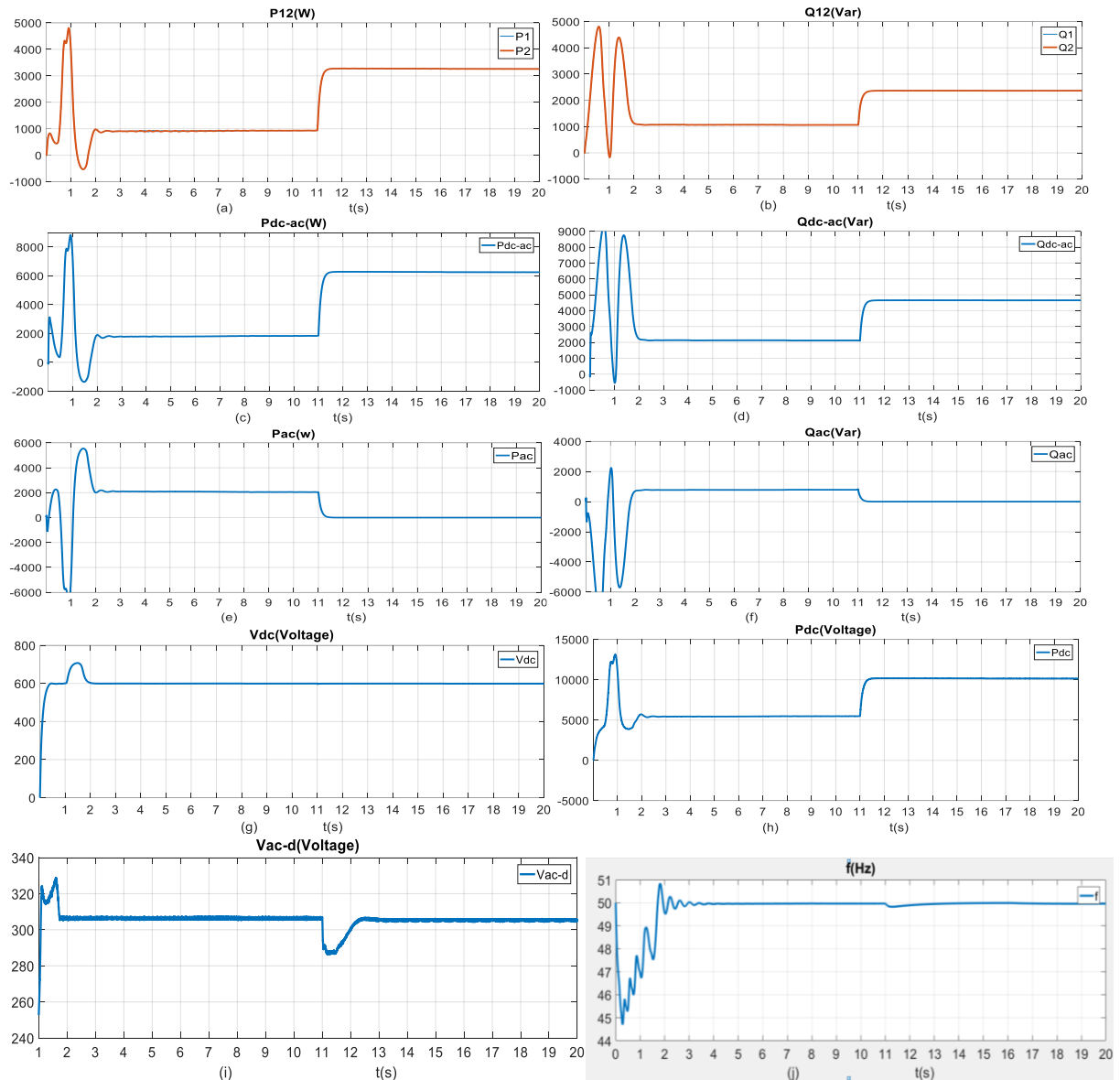


Figure 6. Simulation results

During the period from 0-11s, Figure 6a and 6b show that the two ICs share the power equally $P_1=P_2=940W$, $Q_1=Q_2=1100Var$. Figure 6c and 6d show that the power transmitted from the DC side to the AC side is $P_{dc-ac}=1880W$ and $Q_{dc-ac}=2200Var$. Figure 6e shows that the AC power generated in the AC sub-grid is $P_{ac}=2120W$ and $Q_{ac}=800Var$, all of which is to supply the AC load. Figure 6h shows that the power generated by the DC source in the DC sub-grid is $P_{dc}=5480W$ to supply the DC load and the remaining will be transferred from the DC side to the AC side. According to the proposed control diagram in equations (13), (14) and (15), the power in the AC/DC hybrid microgrid is balanced, each IC shares the power equally. Figures 6g, 6i and 6j show that the DC bus voltage is $V_{dc} = 599V$, $V_{ac} = 309V$ and the frequency is $f = 49.9Hz$. Thus, we can see that the frequency and voltage at the buses in the AC/DC hybrid microgrid are stable within the allowable range.

At 11 seconds, the AC source in the AC subgrid has a fault and is disconnected from the common AC bus, and the AC load also increases suddenly at this time. Figure 6i shows that at this time the AC voltage drops to 287V, and the DC bus voltage also drops to 596.2V. We can see that the AC bus voltage drops below the allowable range when the AC source has a fault and the AC load increases. According to the proposed control diagram in equations (13), (14) and (15), at 12s the AC bus voltage is restored to 308.9V and the DC bus voltage is 598.9V, the proposed controller helps the AC bus voltage follow the DC bus voltage to restore the voltage. At that time, the DC power in the DC subgrid increases to P_{dc}

= 10000W to supply the DC load, the remaining load is transferred from DC to AC is $P_{dc-ac}=6300W$ to support the AC load and restore the AC bus voltage. The two ICs also share the same power $P_1=P_2=3150W$, $Q_1=Q_2=2300Var$. Figure 6j shows that at this time the frequency in the microgrid is 49.6Hz. Thus, we can see that the frequency and voltage at the buses in the AC/DC microgrid are stable within the allowable range, the system's resilience has been enhanced during the AC power failure in the AC subgrid and the sudden increase in AC load.

4. Conclusions

In this paper, an improved droop controller by adaptive frequency shifting for AC/DC hybrid microgrid is proposed, which can ensure that the controller makes the converter operate in bidirectional power exchange. The simulation results show that the control method has maintained the stability of voltage and frequency, as well as the balance between active power and reactive power in the AC/DC hybrid microgrid system. Moreover, the proposed method recovers the system frequency and voltage when the load surges or power failures in subgrids, improving the quality of transmitted power. In addition, the bidirectional power flow, as an essential requirement for hybrid AC/DC networks, is realized by the bidirectional converter. The proposed method is independent of communication, thus reducing the system cost and facilitating the integration of distributed power sources, which brings significant benefits to the economic efficiency and resilience of the hybrid microgrid system.

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Conflicts of Interest

All of the authors there aren't in conflict of benefit and data in the research.


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