

Analysis of the Transition Between Multiple Operational Modes for Hybrid AC/DC Microgrids

Lihu Jia, Yongqiang Zhu, Shaofei Du, and Yinshun Wang

Abstract—There are four basic operational modes for the hybrid AC/DC microgrid, including AC grid-connected while interconnecting, both off-grid while interconnecting, AC grid-connected without connection, and both off-grid without connection. How to achieve a seamless operational mode transition is an urgent technical need to overcome. First, this paper describes the typical structure of the hybrid microgrid, and places a detailed focus on the power balance and transition strategy. Secondly, it takes the master-slave control structure as an example, and designs the transition logic for different operational modes, and then a method for selecting the slack bus and transition time-sequence is proposed. Based on the different roles that the interlinking converter (IC) plays in the process of modes transition, a voltage-power (U-P) control method for a hybrid AC/DC microgrid is proposed, and the exchanged power is calculated based on the voltage deviation between the rating value and measured value. Finally, a control flowchart for the transition between the four operational modes in transition is designed. Using the PSCAD/EMTDC platform, this paper takes a typical seven-point microgrid structure as an example, the proposed transition strategy is carried out, and the results show that the transition method and time sequence can achieve smooth transition between different operational modes.

Index Terms—Hybrid AC/DC microgrid, mode transition, slack bus, transition time-sequence, voltage-power control.

I. INTRODUCTION

THE hybrid AC/DC microgrids are gaining a high momentum to facilitate the penetration of renewable energy resources into the utility grid, compared with the individual AC or DC microgrid. The main characteristics of the hybrid AC/DC microgrid is higher energy conversion efficiency, because it can directly integrate the AC and DC distributed generations (DG), energy storage units (ESU) and AC or DC loads, which reduces the power conversion process. Additionally, power can smoothly flow between the two microgrids through the interlinking converter (IC), which can improve the power supply reliability [1], [2].

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Since the hybrid AC/DC microgrid is a great solution for the integration of smart grids in the conventional distribution network, there are several studies related to the IC control strategy in [3]–[7], energy management in [8]–[10], and power flow calculation in [11], [12]. However, there are almost no studies related to the transition between the multiple operational modes. The current microgrid demonstration project is still the master-slave control structure [13], [14]. Master-slave control means one or more DGs (or storage systems) with large capacity in a microgrid as the slack bus units. Since hybrid AC/DC microgrids contain both AC microgrids and DC microgrids, it involves a lot of control strategies for different types of slack bus in the transition process between multiple operational modes, and the control complexity is greatly increased compared with the individual AC or DC microgrid.

The individual AC or DC microgrid transition control strategy is mature at present [15]–[20], however, there are few studies involving two or more microgrids [21]. In order to solve the volatile and overshoot problem of the controller and bus voltage, reference [15] proposes an improved voltage loop controller and it can estimate the output states of the switch regulator to achieve the seamless transition process. Reference [16] proposes a hybrid control method based on the master-slave control, where an in grid-connected mode of the master unit adopts the droop control and in the off-grid mode it uses the V/f control. In order to ensure smooth switching between operational modes and reduce the impact of transient switching, reference [17] propose a new software phase locked loop (PLL) control, which includes the instantaneous grid phase detector, off-grid phase-locked technology and frequency compensation for the phase pre-synchronization algorithm. Considering timing-sequence-coordination between the physical state switching and the control mode switching, reference [20] proposes the effective time-coordination criterion, which can guarantee the smooth transition between the multiple operational modes, and reduce the switching transient impact caused by the unsynchronized switching process. From the above analysis, we can conclude that these papers adopt the improved control algorithms and hardware circuit design method in order to realize the smooth transition. However, they only take the AC microgrid as an example, and the circuits are too simple to represent the real microgrid because of the diversity of the circuit parameters, network topologies and other factors in actual situations. In [21], a preliminary research of the transition switch between the grid-connected

and off-grid mode of the hybrid AC/DC microgrid is conducted, yet the power relations between the AC microgrid and DC microgrid are not analyzed in-depth. Therefore, further comprehensive study on the transition of the hybrid AC/DC microgrid multiple operational modes is needed. This paper addresses the master-slave control structure of the hybrid AC/DC microgrid, and analyzes its transition control strategy between the multiple operational modes. The power relations and transition control strategies are analyzed among the multiple operational modes in Section II. In Section III, this paper proposes a method of time-sequence transfer for the slack bus in order to realize smooth switching between multiple operational modes. In Section IV, a voltage-power (U-P) control method for the IC is proposed, and in addition, a voltage/current reference compensation algorithm is introduced in order to reduce the transient of the PI controllers during the switching between the PQ control and V/f control. In Section V, the performance of the proposed time-sequence transfer strategy is demonstrated through time-domain simulations. Finally the conclusion is given in Section VI.

II. TYPICAL TOPOLOGY OF THE HYBRID AC/DC MICROGRID

A typical topology of the hybrid AC/DC microgrid is shown in Fig. 1. It contains seven points, including three AC points, three DC points and one utility grid point, respectively. Each microgrid contains DGs, ESUs, and loads. An IC links the AC microgrid and DC microgrid together. The magnitude of the AC microgrid bus voltage is 0.38 kV, while the DC is up to 0.8 kV. In addition, during normal grid operations the hybrid microgrid is connected to the main utility grid through the bus_{1AC}. In the grid-connected mode, the voltage and frequency of the AC microgrid are governed directly by the main utility grid and the IC primarily regulates the DC microgrid voltage and supports the power balance, as well. In the off-grid mode, the DC slack bus supports the voltage of the DC microgrids, while the frequency and voltage of the AC microgrid is supported by the AC slack bus.

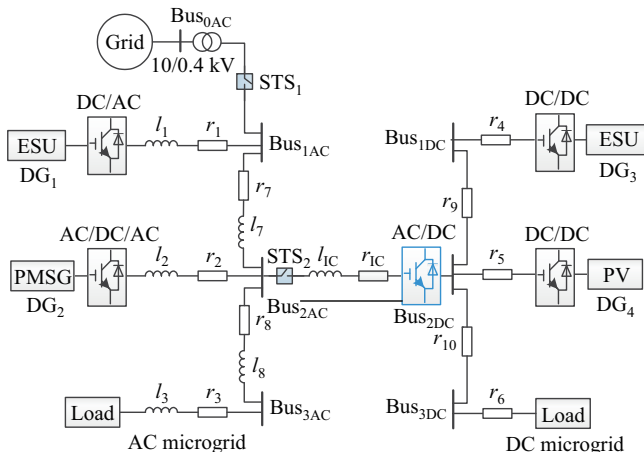


Fig. 1. A typical topology of seven-point hybrid microgrid.

III. OPERATIONAL MODES AND TRANSITION RELATIONSHIPS

A. Classification of the Operational Mode

Compared with the traditional individual AC or DC microgrid, the operational modes of the hybrid AC/DC microgrid are more diverse. According to the state of the static transfer switch (STS) in Fig. 1, operational modes can be classified into four types: AC grid-connected while interconnecting, both off-grid while interconnecting, AC grid-connected without connection, and both off-grid without connection.

1) *AC Grid-connected While Interconnecting (Mode 1, STS₁ = 1, STS₂ = 1)*

The “1” means the STS is closed, while “0” means STS is open. The hybrid AC/DC microgrid is connected to the utility grid, and the voltage and frequency of AC microgrid is determined by the utility grid. The DGs of AC microgrid operate on the MPPT mode and the ESUs are in charging or standby mode, while the voltage of DC microgrid can be governed by the IC which is working on the constant voltage control mode. Power exchange between the two microgrids is realized by the IC, and the relations of the power exchange is shown in Table I.

TABLE I
POWER EXCHANGE OF IC (STS₁ = 1, STS₂ = 1)

Position	Situation I ($P_{IC} < 0$)	Situation II ($P_{IC} > 0$)
DC side	$\sum P_{dc,i} > \sum P_{dc,j}^{load}$	$\sum P_{dc,i} < \sum P_{dc,j}^{load}$
IC	$P_{ILC} = \sum P_{dc,i} - \sum P_{dc,j}^{load} - P_{dc}^{loss}$	$P_{ILC} = \sum P_{dc,j}^{load} + P_{dc}^{loss} - \sum P_{dc,i}$

In Table I, P_{IC} denotes the power exchange between the AC microgrid and DC microgrid. In Situation I, the generated power in the DC microgrid is sufficient for the DC load demand, so the surplus power can be transferred to the AC side through the IC. In Situation II, the power relationship is reverse, and the power generated in the DC microgrid is deficient, so the required power should be supplied by the IC.

2) *AC Grid-connected Without Connection (Mode 2, STS₁ = 1, STS₂ = 0)*

The AC microgrid is grid-connected, while DC microgrid is off-grid. The operation states of the DGs and ESUs in the AC microgrid are similar to the DC-AC-grid mode, while the voltage of the DC microgrid is supported by the ESUs. When the power generated in the DC microgrid is sufficient or deficient, the power regulation can be realized by the charging and discharging of the ESUs, or cutting off some loads to ensure the voltage stability of the DC microgrid. The power relationship can be described,

$$\text{AC microgrid: } P_{grid} = \sum P_{ac,j}^{load} + P_{ac}^{loss} - \sum P_{ac,i}$$

$$\text{DC microgrid: } \sum P_{dc,j}^{load} + P_{dc}^{loss} = \sum P_{dc,i}$$

$$\text{IC: } P_{IC} = 0.$$

3) *Both Off-grid While Interconnecting (Mode 3, STS₁ = 0, STS₂ = 1)*

The DC microgrid is connected with the AC microgrid, but the AC microgrid is disconnected with the utility grid. The power balance is determined by the coordinate control of the “DGs-ESUs-Loads” in the hybrid microgrid. Specifically,

TABLE II
POWER EXCHANGE RELATIONSHIP ($STS_1 = 0, STS_2 = 1$)

Position	Situation I	Situation II	Situation III	Situation IV
DC side	$\sum P_{dc,i} > \sum P_{dc,j}^{load}$	$\sum P_{dc,i} < \sum P_{dc,j}^{load}$	$\sum P_{dc,i} > \sum P_{dc,j}^{load}$	$\sum P_{dc,i} < \sum P_{dc,j}^{load}$
AC side	$\sum P_{ac,i} > \sum P_{ac,j}^{load}$	$\sum P_{ac,i} > \sum P_{ac,j}^{load}$	$\sum P_{ac,i} < \sum P_{ac,j}^{load}$	$\sum P_{ac,i} < \sum P_{ac,j}^{load}$
IC	$P_{IC} = C_1$	$P_{IC} = \sum P_{dc,j}^{load} + P_{dc}^{loss} - \sum P_{dc,i}$	$P_{IC} = \sum P_{ac,j}^{load} + P_{ac}^{loss} - \sum P_{ac,i}$	$P_{IC} = C_2$

the power balance relationship of the four types are shown in Table II.

In Table II, C_1, C_2 are constant. 1) when $C_1 = C_2 = 0$, the sufficient power and deficient power generated by the DGs should be shared and managed autonomously by the existing DGs in both microgrids, which involves battery charging and discharging, and the loads shedding. 2) when C_1 and $C_2 \neq 0$, which means there exists power exchanging between the AC microgrid and DC microgrid, and it involves the optimizing energy management of the whole hybrid AC/DC grid, which needs the unified scheduling, and this problem does not belong to the scope of this paper.

4) *Both Off-grid Without Connection (Mode 4, $STS_1 = 0, STS_2 = 0$)*

The AC microgrid and DC microgrid are both disconnected with the utility grid, so there is no power exchanged through the IC. The stability of the AC and DC-subgrids are maintained by the cooperation control of the internal “DGs-ESUs-Loads” and the power balance relationships are expressed by,

$$\text{AC microgrid: } \sum P_{ac,i} = \sum P_{ac,j}^{load} + P_{ac}^{loss}$$

$$\text{DC microgrid: } \sum P_{dc,i} = \sum P_{dc,j}^{load} + P_{dc}^{loss}$$

$$\text{IC: } P_{IC} = 0.$$

B. Transition Relations Between Different Operational Modes

The transition relationships of the four basic operational modes are shown in Fig. 2. The operational rule of the switching action between the four basic operational modes is that: only one STS can take an action at one time. According to this rule, the switching between adjacent operational modes can be realized by the one step action [22], [23].

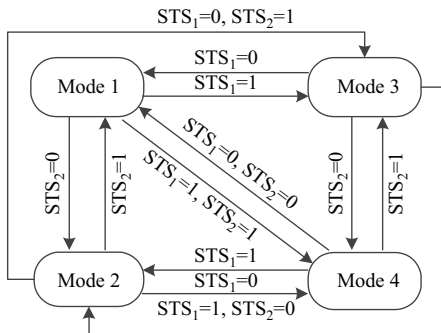


Fig. 2. The transition relationship of multiple operational modes.

From the above analysis, it is seen that the purpose of mode transition is to reduce the influence of the utility grid failures on the hybrid AC/DC microgrids. When grid failures have been dealt with well, then the microgrid can be re-connected to the utility grid again. As to these four basic operational modes, the specific purposes are as follows:

Mode 1 and Mode 2: When the failure occurs in the DC microgrid, in order to reduce the influence on the AC microgrid, the STS_2 changes to the open state. After the failure has been handled well, the DC microgrid re-connected to the AC grid again.

Mode 2 and Mode 4: In Mode 2, if there exist some grid failures in the AC microgrid, the AC microgrid have to disconnect with the utility grid in order to limit the spread of the failures to the utility grid.

Mode 4 and Mode 3: When the power generation cannot meet the load requirements in Mode 4, the AC microgrid and DC microgrid have to connect with each other, so that they can get the power exchange to maintain the power balance.

Mode 1 and Mode 3: In Mode 3, the hybrid AC/DC microgrid operates on the off-grid mode, and there is no power exchange between hybrid microgrid and the utility grid. When the failures of the utility grid have been either dealt with well or the hybrid microgrid appears to have a power shortage and cannot solve the power generation by itself, then the hybrid microgrid switches to Mode 1.

From Fig. 2, we can conclude that the operational modes and transition relationships of the hybrid AC/DC microgrid are more complicated and varied compared with the individual AC and DC microgrids.

IV. CONTROL LOGICAL OF SMOOTH TRANSITION

It is necessary to design a reasonable control logic for the switching of operational modes. Based on the master-slave control structure, this paper develops a set for the switching control logic, which includes two parts: 1) Design of the transfer time sequence of the slack bus in the hybrid AC/DC microgrid. 2) The compensation of control algorithms between different control strategies.

A. Design of the Transfer Time-sequence of the Slack Bus

The appropriate transfer time-sequence of the slack bus is the key to different operational modes. In this paper, we choose bus_{0AC} and bus_{1AC} as the slack bus of AC microgrid, and bus_{1DC} and IC as the slack bus of DC microgrid, which is shown in Table III. It is important to note that the IC is chosen as the slack bus only when the hybrid is in the Mode 1, and in reality the utility grid is the slack bus of the DC microgrid through the IC.

From Table III, we can conclude that it involves the transition of software and hardware in the process of the slack bus transferring, therefore, it is necessary to design a reasonable transfer time-sequence. In order to reduce the influence of the slack bus transferring on the stability of the microgrid, this paper adopts the control strategy in a step by step approach.

TABLE III
SELECTION OF SLACK BUS IN DIFFERENT MODES

Operational Mode	AC Microgrid	DC Microgrid
Mode 1	Bus _{0AC}	IC
Mode 2	Bus _{0AC}	Bus _{1DC}
Mode 3	Bus _{1AC}	Bus _{1DC}
Mode 4	Bus _{1AC}	Bus _{1DC}

For example, when Mode 1 transfers to Mode 3, transferring of the slack bus in the DC microgrid has higher transferring priority than the slack bus in the AC microgrid. Fig. 3 gives the transfer time-sequence diagram of the four basic operational modes. $T_0, T_1, T_2, \dots, T_7$ denote the delay time. It is important to note that the delay time is determined by the fault ride-through time, communication and actuation delay. In this paper, we set $T_0 = T_1 = T_2 = T_4 = T_7 = 10$ ms, considering the transition delay between different control strategies, and set $T_3 = T_5 = T_6 = 50$ ms, taking the turn-on and turn-off time delay of the STS into account.

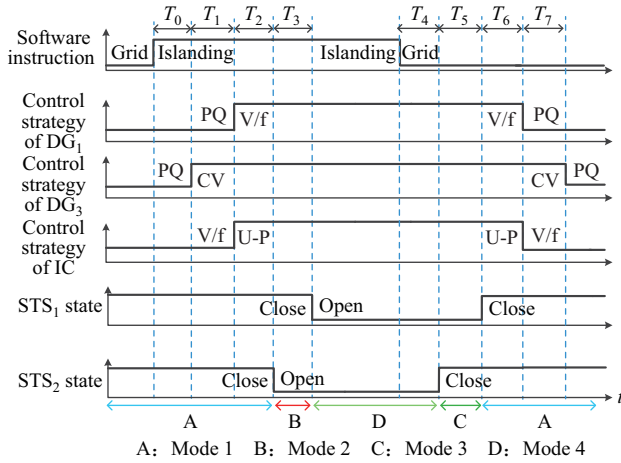


Fig. 3. Time-Sequence control diagram of the slack bus.

In Fig. 3, A, B, C, D denotes the basic operational modes separately. PQ denotes that the converter adopts constant power control, and V/f denotes the constant voltage and frequency control. CV denotes the constant DC voltage control, and U-P denotes the voltage-power control. When the hybrid AC/DC microgrid switches to off-grid mode, the control strategy of the slack bus transfers firstly, and then STS takes action, which means that software operation takes priority to the hardware operation. However, when the hybrid AC/DC microgrid switches to grid-connected mode, the situation is different, the STS takes action firstly, and then the control strategy begins to switch. That means the hardware operation takes priority to the operation of the software.

B. Design of the Switching Control Strategy

In the process of the modes transition, the key is the transferring of the slack bus and the switching of the control strategy for the master source under different operational modes. In this paper, DG₁ is switching between PQ control and V/f control, and DG₃ is switching between CV control and PQ control. However, IC is switching between CV control and U-P control.

1) Compensation Algorithm for PQ Control and V/f Control

In the grid-connected mode, the voltage and frequency of the AC microgrid are supported by the utility grid, so DG₁ adopts the PQ control. When hybrid AC/DC microgrid switches to the off-grid mode, the role of the slack bus should be transferred from the utility grid to DG₁. At the same time, the control strategy of DG₁ switches from PQ control to V/f control. The current reference of the inner loop is in the steady state in PQ control, but when the controller changes to V/f control, the current reference of the inner loop need to adjust the state from zero to the new steady state with a transient, which will lead to the current and voltage fluctuation [18], [21]. In order to solve the problem, this paper adopts the compensation algorithm, as shown in Fig. 4.

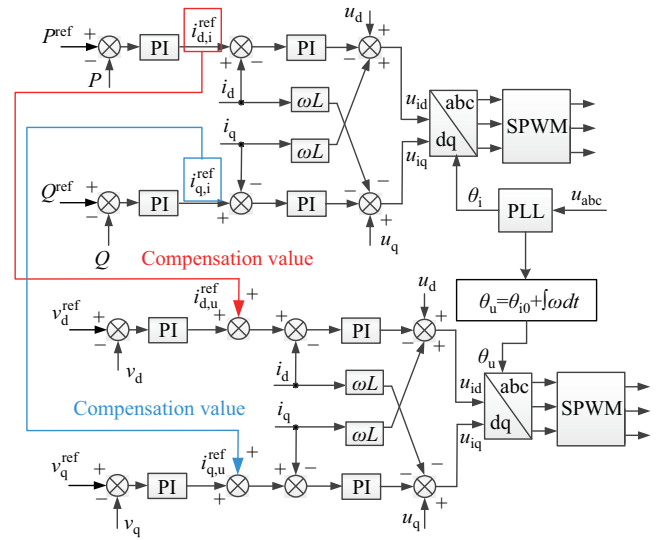


Fig. 4. Schematic diagram of the transition between PQ control and V/f control.

1) PQ control switches to V/f control: The current reference can be compensated as the following equations:

$$\begin{cases} i_{Ud}^{\text{ref}} = i_{d,u}^{\text{ref}} + i_{d,i}^{\text{ref}} \\ i_{Uq}^{\text{ref}} = i_{q,u}^{\text{ref}} + i_{q,i}^{\text{ref}} \end{cases} \quad (1)$$

where, $i_{Ud}^{\text{ref}}, i_{Uq}^{\text{ref}}$ denote the current reference of the V/f control.

2) V/f control switches to PQ control:

$$\begin{cases} i_{Id}^{\text{ref}} = i_{d,i}^{\text{ref}} + i_{d,u}^{\text{ref}} \\ i_{Iq}^{\text{ref}} = i_{q,i}^{\text{ref}} + i_{q,u}^{\text{ref}} \end{cases} \quad (2)$$

where, $i_{Id}^{\text{ref}}, i_{Iq}^{\text{ref}}$ denote the current reference of the PQ control.

The phase relationship between PQ control and V/f control is shown in Fig. 4. It is known that both the PQ control and V/f control are based on the synchronous dq frame, so a d-axis orientation is required. For PQ control in the grid-connected operational mode, the d-axis is oriented to the utility grid voltage vector. While for the V/f control, the d-axis is oriented to an arbitrary rotating reference vector with a constant reference frequency. Therefore, the difference between the two types of orientation will definitely cause a transient, and it is better to remember the phase message of the last control mode in the control switching process. For

example, when PQ control switches to the V/f control, the phase θ_i is switching from the utility grid voltage vector to the constant 50 Hz rotation vector. Therefore, it is necessary to memorize the grid voltage phase θ_{i0} and makes it is as the initial phase of the V/f control. When V/f control switches to PQ control, the constant 50 Hz rotation vector can switch to the grid voltage phase only when the phase of bus_{1AC} is equal to the grid voltage.

2) Compensation Algorithm for CV Control and U-P Control

U-P Control Principle: The controller calculates the power exchange between AC microgrid and DC microgrid based on the voltage of both sides, in order to keep the power balance of the hybrid microgrid.

Considering the capacity of the AC microgrid and DC microgrid, this paper defines α and β as follows,

$$\begin{cases} \alpha = P_{ac}^{sum} / (P_{ac}^{sum} + P_{dc}^{sum}) \\ \beta = P_{dc}^{sum} / (P_{ac}^{sum} + P_{dc}^{sum}) \end{cases} \quad (3)$$

where P_{ac}^{sum} and P_{dc}^{sum} represent the capacity of the AC microgrid and DC microgrid respectively, and α and β are the weight factors of the capacity. In this paper, the weight factors are pre-defined. The capacity of the AC microgrid is set as 45 kW, while the DC microgrid is 40 kW, so $\alpha = 0.53$ and $\beta = 0.47$. The droop characteristic of the IC can be represented by the (4). Note that, the impedance characteristic of the whole hybrid AC/DC microgrid is resistive, which is up to 5 ($r/x > 5$), therefore, the active power transmission is determined by the AC bus voltage to a large extent [24].

$$\begin{cases} P_{IC}^{dc} = k_{dc} (u_{dc} - U_{dc}^N) \\ P_{IC}^{ac} = k_{ac} (u_{ac} - U_{ac}^N) \end{cases} \quad (4)$$

where k_{DC} , k_{AC} represent the droop coefficient of the DC microgrid and AC microgrid respectively.

The power exchange of IC between the two sides is calculated by using (3) and (4), as is shown in (5).

$$P_{ref} = k_{ac} \cdot \alpha \cdot \frac{u_{ac} - U_{ac}^N}{U_{ac}^N} - k_{dc} \cdot \beta \cdot \frac{u_{dc} - U_{dc}^N}{U_{dc}^N} \quad (5)$$

Finally, after the exchanged power (P_{ref}) is calculated by using (5), which will be the reference power for the double closed loop control, the drive signal for IC can be produced, as shown in Fig. 5.

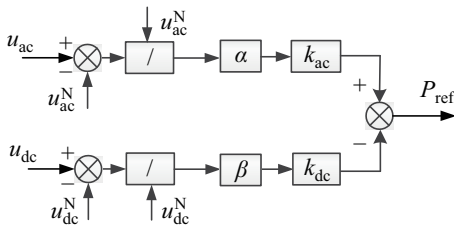


Fig. 5. Schematic diagram of the U-P control strategy.

Unlike the switching principle of the PQ control and V/f control, the phase reference used in the transformation of the CV control and U-P control is based on the utility grid, and does not need to regulate, as shown in Fig. 6. The inner control

loop of the CV control and the U-P control both adopt the current loop, and the difference is that the goal of the CV control is to stabilize the DC bus voltage, while the U-P control is to maintain the voltage fluctuation of both the DC side and AC side in a reasonable range. It can be concluded that the role of the IC is just exchanging the power between the AC side and DC side. To this end, this paper designs the U-P control. According to this method, the power exchanged between the two sides can be calculated from the DC voltage and AC voltage, and the direction of the power flow can also be determined at the same time.

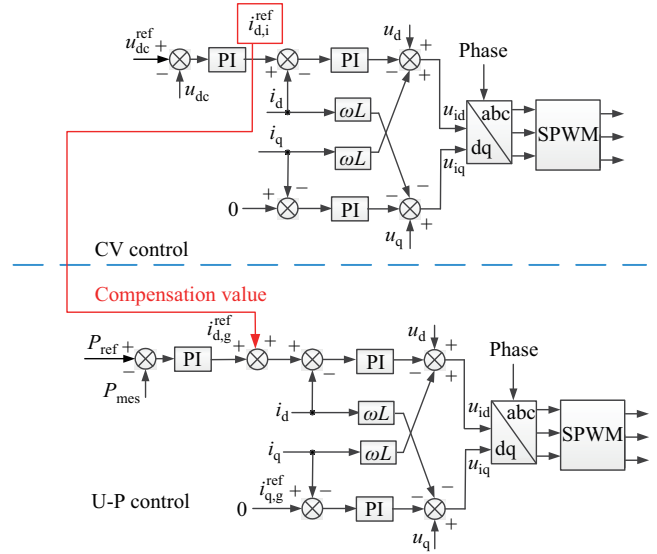


Fig. 6. Schematic diagram of the transition between CV control and U-P control.

3) The Schematic Diagram of the Communication Network and Logic Circuit

The schematic diagram of the communication network and logic circuit is shown in Fig. 7. The measuring device represented by the red circle in the figure measures the electrical parameters, such as voltage, current, frequency, etc. The measured data are sent to the controller, and are processed in the controller. Then the triggered signal from the controller is produced to control the converter. Concretely, the controllers of DG_1 , DG_2 and IC adjust the control strategy according to the instructions of the operational mode controller. The STS controller controls the state of STS_1 and STS_2 . In addition, the transition between multiple operational modes for the hybrid AC/DC microgrid can be performed manually or automatically. The STS trips automatically in a failure for state transition, while under normal circumstances they can also operate manually with an instruction.

4) Control Flow

In order to realize the smooth switch between the basic four operational modes, this paper designs a case of which the transition process is ① Mode 1 $\rightarrow$ ② Mode 2 $\rightarrow$ ④ Mode 4 $\rightarrow$ ③ Mode 3 $\rightarrow$ ① Mode 1. The corresponding control process is shown in Fig. 8 and Fig. 9.

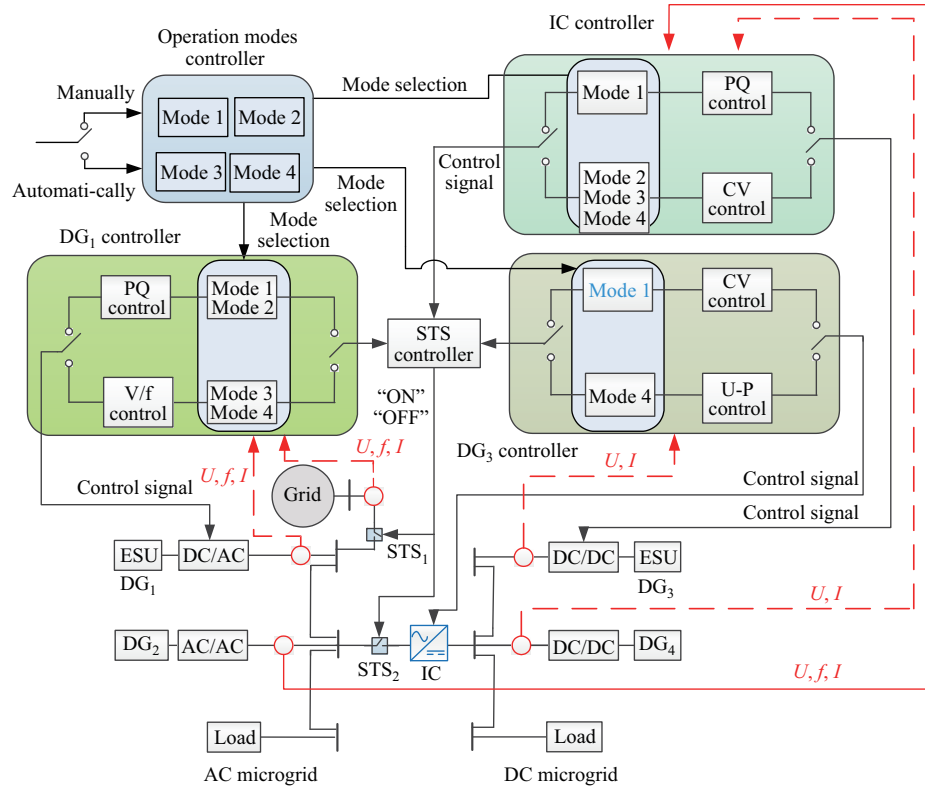


Fig. 7. Schematic diagram of the communication network and logic circuit.

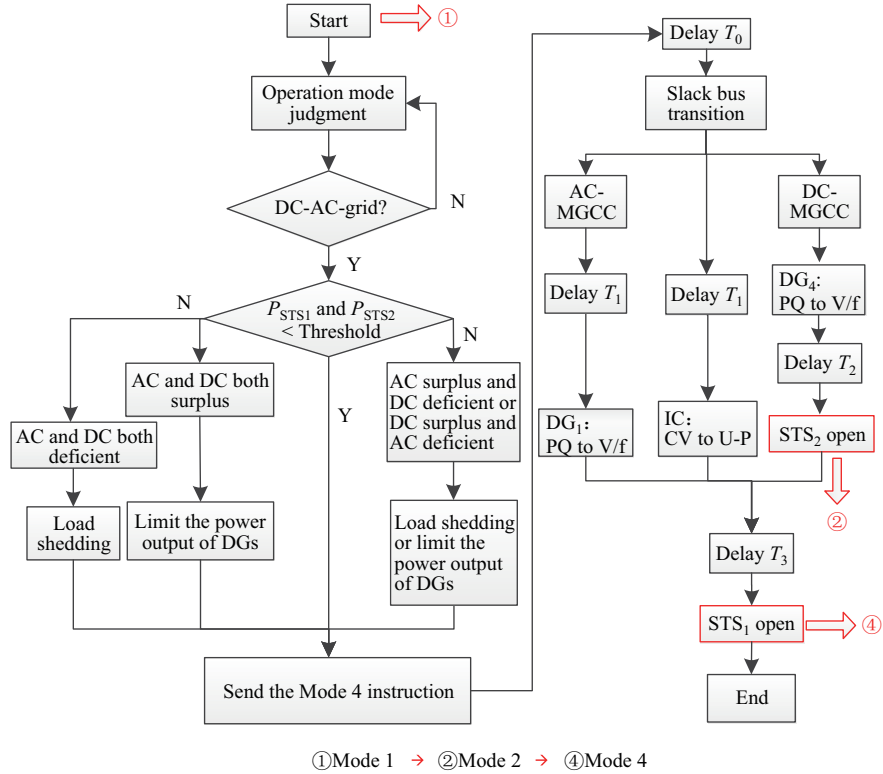


Fig. 8. Control flow chart of transition from Mode 1 to Mode 4.

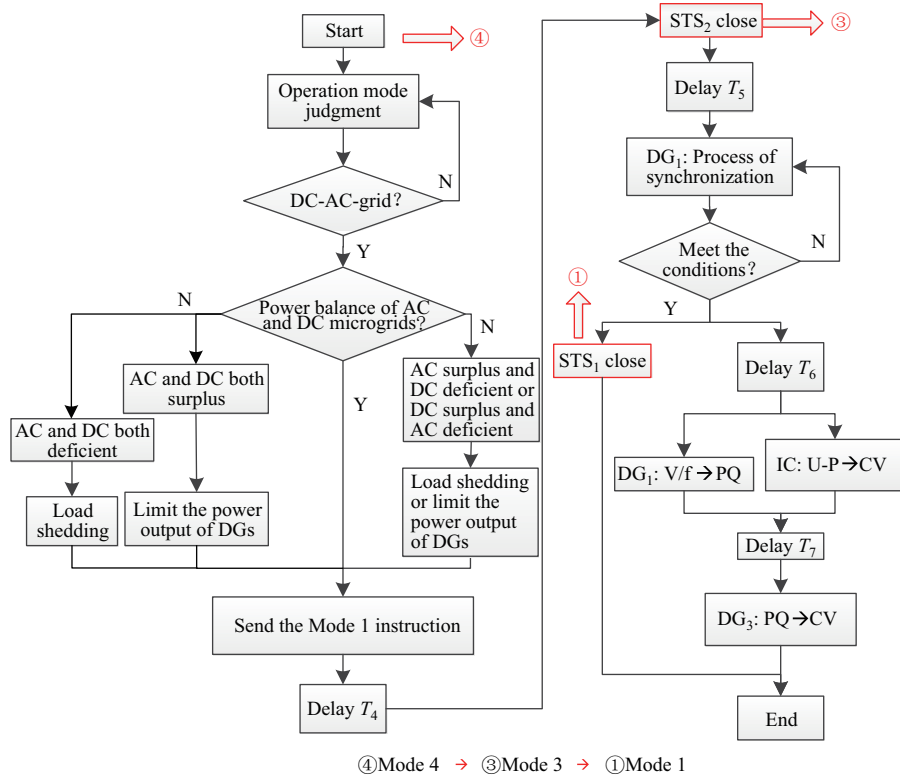


Fig. 9. Control flow chart of transition from Mode 4 to Mode 1.

V. SIMULATIONS

In order to verify the correctness and effectiveness of the proposed switching control strategy, a seven-bus hybrid AC/DC microgrid system has been built on the PSCAD/EMTDC platform, and the simulation circuit is shown in Fig. 1. The parameters used for simulation are given in Table IV and Table V.

TABLE IV
PARAMETERS OF THE DGs AND LOAD

AC Microgrid		DC Microgrid		IC	
DG ₁	25 kWh	DG ₁	25 kWh	AC side	0.4 kV
DG ₂	10 kVA	DG ₂	5 kW	DC side	0.8 kV
Load	10 kVA	Load	10 kW		

TABLE V
LINE PARAMETERS FOR THE 7-BUS HYBRID MICROGRID

AC Microgrid				DC Microgrid		
From	To	r (Ω)	x (Ω)	From	To	r (Ω)
Bus _{1AC}	Bus _{2AC}	0.0962	0.0152	Bus _{1DC}	Bus _{2DC}	0.0641
Bus _{2AC}	Bus _{3AC}	0.0641	0.0152	Bus _{2DC}	Bus _{3DC}	0.0320
Bus _{2AC}	Bus _{2DC}	0.0320	0.0076			

The specific process of the simulation is to make a recycle among the four basic operational modes: ① Mode 1 → ② Mode 2 → ④ Mode 4 → ③ Mode 3 → ① Mode 1.

The time-sequence of the control strategy switching and states of STS are designed based on the Fig. 3. The simulation results are shown from Fig. 10 to Fig. 13.

STS₁ and STS₂ switch from the “ON” to “OFF” state at 1.0 s and 1.5 s respectively, while at 2.0 s and 2.5 s, they switch from the “ON” to “OFF” state, which realizes the

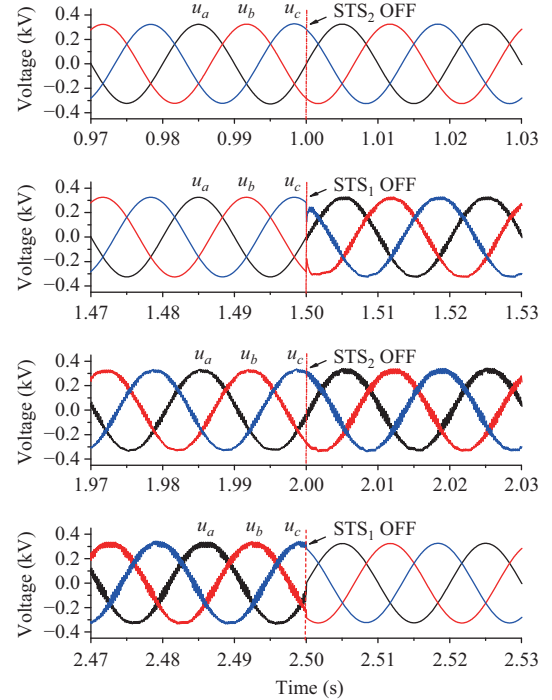


Fig. 10. Voltage of the DGs in the AC microgrid.

transition between the four basic operational modes. From Fig. 10, we can see that the fluctuation of the amplitude and the phase of the AC voltage are in a reasonable range ($\pm 5\%$), and the voltage and current impact on the utility grid can be ignored. At 0.98 s, 0.99 s, 2.51 s and 2.52 s, the control strategy conversion of DG₁, DG₃ and IC have adopted the

proposed switching control strategy as shown in Fig. 4 and Fig. 5. From the wave of the voltage, we can see that the AC voltage is a three-phase sine wave, which indicates that the control algorithm can realize the smooth switching between the four basic operational modes.

Fig. 11 shows the power output of the micro source (DG₁, DG₂), load, IC and the utility grid respectively. From Fig. 10, we can conclude that DG₁ is a storage unit and is in charging mode at 0.5–1.0 s, and the charging power is 5 kW. DG₂ is a constant power source, and the output power is up to 10 kW. The power of the resistive AC load is about 10 kW, and the power exchange from the AC microgrid to DC microgrid is up to 10 kW, so the utility grid has supplied the power shortage, which is 15 kW.

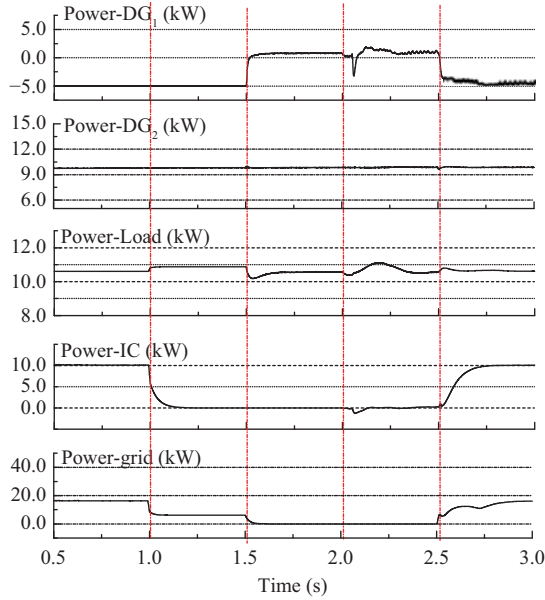


Fig. 11. Output power of DGs in the AC microgrid.

At 1.0 s, STS₂ is in the OFF state. The operational mode of the hybrid AC/DC microgrid is changed from Mode 1 to Mode 2. And the slack bus of the DC microgrid is transferred from IC to DG₃, so the IC is in idle mode, and the exchange of the power between the AC side and DC side is zero. DG₁ is still in charging mode, and the output power of the utility grid drops to 5 kW. At 1.5 s, STS₁ is in OFF state, the operational mode of the hybrid AC/DC microgrid is changed from Mode 3 to Mode 4. And the slack bus of the AC microgrid is transferred from the utility grid to DG₁. At this time, the output power of the utility grid is zero, and the control strategy of DG₁ is changed from PQ control to V/f control and is in the discharging mode, which plays a role of maintaining the stability of the AC microgrid.

At 2.0 s, STS₂ is in the OFF state. The operational mode of the hybrid AC/DC microgrid is changed from Mode 4 to Mode 3. In Mode 3, the exchange power of the IC is zero, and the power of the AC microgrid is in a balanced state, that is to say, $P_{DG2} = P_{Load}$. At 2.5 s, STS₁ is in the ON state. The operational mode of the hybrid AC/DC microgrid is changed from Mode 3 to Mode 1. And the slack bus of the DC microgrid is transferred from DG₃ to IC. At the same time,

the slack bus of the AC microgrid is transferred from DG₁ to the utility grid. The power output of micro-source, load, and IC are recovered to the initial state.

Fig. 12 shows the output power of the DC microgrid when the hybrid AC/DC microgrid is in the transition of operational modes. From Fig. 11, we can see that the power of the DC load is constant ($P_{Load} = 10$ kW), DG₄ is also a constant power source ($P_{DG4} = 5$ kW), and DG₃ is a storage unit, which will maintain the stability of the DC voltage when the STS₂ is in the OFF state. At that time the control strategy of DG₃ is changed from the PQ control to constant voltage control. At 0.5–1.0 s, the DG₃ is in charging mode, and the charging power is 5 kW. At 1.0 s, STS₂ is in OFF state, and DC microgrid is in the off-grid mode. At that time, DG₃ is operating on the voltage control strategy in order to support the DC microgrid. While at 2.5 s, STS₂ is in the ON state, and DG₃ has recovered to the charged mode.

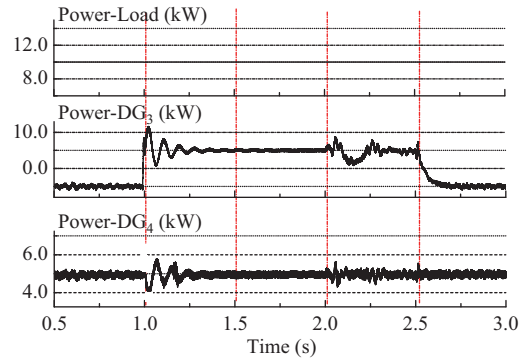


Fig. 12. Output power of DGs in the DC microgrid.

Fig. 13 shows the fluctuations of the AC and DC voltage and the frequency of the AC microgrid when the hybrid AC/DC microgrid is in the transition process of operational modes. From Fig. 13, we can see that the DC voltage is ranging from 0.95 p.u. to 1.05 p.u., while the AC voltage is ranging from 0.96 p.u. to 1.06 p.u., and the frequency of the AC microgrid is ranging from 49.5 Hz to 50.5 Hz, which can meet the power quality requirements of the load.

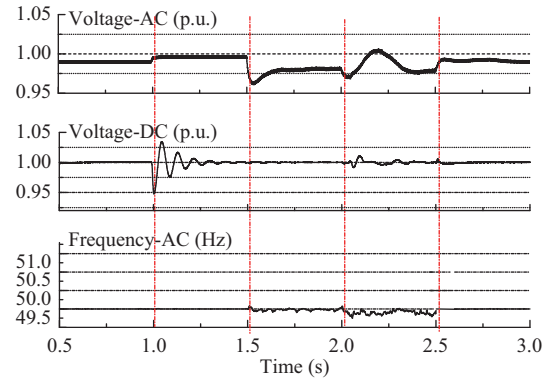


Fig. 13. Voltage per unit of the AC and DC microgrid.

It can be seen from the simulation results that the proposed switching algorithm of the control strategy and time-sequence transferring method of the slack bus in this paper are correct

and effective, and can realize the smooth switching between the four basic operational modes.

VI. CONCLUSION

1) This paper has proposed the switching algorithm of the control strategy and the time-sequence transferring method, which takes the delay time of the conversion of the control strategy and the circuit breaker into consideration. According to this method, the hybrid AC/DC microgrid can overcome the difficult problem of the operational modes transition, and realize the smooth switching process.

2) Based on the different roles that IC plays in the process of modes transition, a U-P control method of the hybrid AC/DC microgrid is proposed. By using this control strategy, the hybrid AC/DC microgrid can realize the power exchanging in different operational modes.

A more sophisticated transition control strategy for multiple hybrid AC/DC microgrids can be extended from the result of this work, which is under investigation by the authors for a future study. However, there are still problems, which need to be further researched.

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