Operating mode analysis of hybrid AC/DC microgrids

Yongqiang Zhu, Fuyuan Wang\(^1\) and Kang Liu

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 100026, China

\(^1\) E-mail:youngwfy@qq.com

Abstract. This paper presents a typical topology considering the line parameters of hybrid AC/DC microgrids. There are four basic operation modes of hybrid AC/DC microgrids, such as AC/DC grid-connected mode, AC grid-connected and DC off-grid mode, AC/DC both off-grid mode and AC/DC off-grid mode respectively. And then the power balance relationship of various operating modes was analyzed. According to the number of circuit breaker need to change when the system switch its operation mode, the relationship of the operation mode is divided into two categories, such as Type I and Type II. To reduce the impact on the system and improve system stability, we proposed three principles of operating mode switching and took its mathematical qualitative analysis and simulation validation. The simulation results show that the switching principle does improve the stability of the system to a certain extent and provides some reference for the application development of AC/DC microgrid.

1. Introduction

Microgrid provides a good solution for distributed power connected to the power grid [1]. It has been proved through practice that distributed power supplies access to the distribution network in the form of microgrid can achieve higher conversion efficiency and reduce the adverse impact on the traditional distribution network [2-3]. At present, according to the difference of grid structure and power supply mode of microgrid, it can be divided into AC microgrid, DC microgrid and hybrid AC/DC microgrid [4]. The hybrid AC/DC microgrid connects the AC microgrid to the DC microgrid through the Interlinking Converter (ILC) which combines the advantages of the AC microgrid and the DC microgrid, has greater efficiency and compatibility in integrating distributed micro-sources and AC and DC loads. Relying on ILC to achieve mutual support of power and improve the reliability of power supply of the system, hybrid AC/DC microgrid has become a hot topic in recent years [5-7].

The research on the control strategy of hybrid AC/DC microgrid ILC [8-11], energy management [12-14], power flow calculation [15] and other aspects are still in the initial stage. In addition, since the hybrid AC/DC microgrid contains both the AC microgrid and the DC microgrid, the switching control of multiple balanced nodes is involved in the handover process. Compared to the simple AC microgrid and DC microgrid, the complexity of control has greatly increased. In [16], taking the hybrid AC/DC microgrid pilot as an example, it is proposed that the sequential control of the automatic strategy set can be used to switch between multiple operation modes of the hybrid microgrid, but no in-depth discussion has been made from the theoretical aspect. The literature [17] introduced the operation mode switching of hybrid AC/DC microgrid under master-slave control structure, peer-to-peer control structure and hierarchical control structure, and analyzed the regulation function of micro power supply and energy storage unit under various control structures. The literature [18] classifies the operation modes of multiple AC microgrids based on the bus voltage and the operation...
mode of energy storage converters, and designs timing relationships between hardware switches and software control strategies. However, the priority of the switch in the switching process has not been analyzed yet. Therefore, it is necessary to analyze the operation mode of hybrid AC/DC microgrid and its switching relationship in detail, so as to provide a theoretical basis for the design of hybrid AC/DC microgrid control system.

2. Operation mode classification and power balance analysis

This paper takes AC-coupled model as an example to analyze and design the operation mode and switching control system of hybrid AC/DC microgrid, the specific topology is shown in figure 1. The hybrid AC/DC microgrid AC part consists of ‘m’ AC subnets, and the DC part consists of ‘n’ DC subnets. The AC part is incorporated into the distribution network through the breaker CB1 and the transformer, the DC part is connected to the AC part through the ILC and the breaker CB2. Subnets in a hybrid microgrid can be composed of distributed power supplies, loads, and energy storages.

![Figure 1. A typical topology of hybrid microgrid.](image)

**Table 1.** The classification of operation modes.

| CB1 | CB2 | operation modes                                      | number |
|-----|-----|-----------------------------------------------------|--------|
| 1   | 1   | AC/DC grid-connected                                 | A      |
| 1   | 0   | AC grid-connected and DC off-grid                    | B      |
| 0   | 0   | AC/DC off-grid respectively                          | C      |
| 0   | 1   | AC/DC both off-grid                                  | D      |

Where CB$_i$=1 means closing breaker, CB$_i$=0 means opening breaker, i=1, 2.

2.1. Operating mode classification

Compared with the traditional AC microgrid and DC microgrid operating modes, hybrid AC/DC microgrids operate more diversified. According to the switch status of the breakers CB1 and CB2, the operation modes of the hybrid AC/DC microgrid can be divided into four types: AC/DC grid-connected (A), AC grid-connected and DC off-grid (B), AC/DC off-grid respectively (C), and AC/DC both off-grid (D), as shown in table 1.

2.2. Power balance relationships for each operation mode

In the AC/DC grid-connected operation mode, the hybrid AC/DC microgrid is connected to the distribution network. The voltage and frequency of the AC microgrid are generally determined by the distribution network, the DC microgrid voltage is generally determined by the ILC. Non-controllable distributed power supplies (such as direct-drive wind turbines, photovoltaic generations, etc.) in hybrid AC/DC microgrid are generally operated at maximum power. Controllable distributed power supplies (such as energy storage systems, gas turbines, etc.) are in charging or standby state. The power balance relationship within the system is shown in equation (1).

Where $P_{ILC}$ represents the exchange power between AC side and DC side; $P_{ILC}>0$ indicates that the AC side power flows through the ILC to the DC side; $P_G$ represents the exchange power between the grid-connected inverter and the AC side; $P_G>0$ indicates that grid power flows to the AC side through grid-connected inverters; $P_{dc}$, $P_{ac}$ represent DC-side and AC-side power output; $P_{dc}^{load}$, $P_{ac}^{load}$ represent DC-side and AC-side load power consumption; $P_{dc}^{loss}$, $P_{ac}^{loss}$ represent DC-side and AC-side loss power.
\[
\begin{cases}
P_G = \sum_{i}^{m} P_{\text{load},j} + P_{\text{loss}} + P_{\text{ILC}} - \sum_{i}^{m} P_{\text{ac},i} \\
\sum_{i}^{n} P_{\text{dc},i} + P_{\text{loss}} - \sum_{i}^{n} P_{\text{dc},j} 
\end{cases}
\]

(1)

In the AC grid-connected and DC off-grid operation mode, the AC microgrid is connected to the distribution network, the voltage and frequency are determined by the distribution network, distributed power supplies operation is the same as mode A. The DC microgrid runs in island mode and the system voltage is maintained by the internal main power supply (energy storage unit). The power balance relationship of AC/DC side is shown in Equation (2).

\[
\begin{cases}
\sum_{i}^{n} P_{\text{dc},i} = \sum_{i}^{n} P_{\text{dc},i} + P_{\text{loss}} \\
P_{\text{ILC}} = 0 \\
P_G = \sum_{i}^{m} P_{\text{load},i} + P_{\text{loss}} - \sum_{i}^{m} P_{\text{ac},i} 
\end{cases}
\]

(2)

In the AC/DC off-grid respectively operation mode, AC/DC subnets are in island operation respectively. The stability of the subnet systems are completely controlled by the "source-storage-load" coordination control within the microgrid. Here, the power balance relationship of AC/DC side is shown in Equation (3).

\[
\begin{cases}
P_G = 0 \\
P_{\text{ILC}} = 0 \\
\sum_{i}^{m} P_{\text{ac},i} = \sum_{i}^{m} P_{\text{ac},i} + P_{\text{loss}} \\
\sum_{i}^{n} P_{\text{dc},i} = \sum_{i}^{n} P_{\text{dc},i} + P_{\text{loss}}
\end{cases}
\]

(3)

In the AC/DC both off-grid operation mode, the AC and DC microgrid are interconnected and disconnected from the distribution network. The stability of the hybrid AC/DC microgrid is completely controlled by the "source-storage-load" coordination control within the hybrid AC/DC microgrid. Here, the power balance relationship of AC/DC side is shown in Equation (4).

\[
\begin{cases}
P_G = 0 \\
\sum_{i}^{m} P_{\text{ac},i} = \sum_{i}^{m} P_{\text{ac},i} + P_{\text{loss}} + P_{\text{ILC}} \\
P_{\text{ILC}} = \sum_{i}^{n} P_{\text{load},i} + P_{\text{dc},i} \quad \sum_{i}^{n} P_{\text{dc},i} - \sum_{i}^{n} P_{\text{dc},j}
\end{cases}
\]

(4)

3. Switching relationship between operating modes and rules

3.1. Switching relationship between operating modes

The four operating modes of the hybrid AC/DC microgrid involve the changes in the operating states of the two breakers CB1 and CB2. When the hybrid AC/DC microgrid is switched between the four operating modes, we can divide the switching relationships into Type I and Type II, which is distinguished by the number of breakers requiring action.
Type I: When switching between the two operating modes, only one breaker action is required.
Type II: When switching between the two operating modes, two breaker actions are required.

The switching relationship between the four operating modes is shown in figure 2.

Table 2. The unbalanced power corresponding to operating mode switching.

|       | A   | B   | C   | D   |
|-------|-----|-----|-----|-----|
| A     | 0   | |    | |    |
| B     | | 0  | |    | |    |
| C     | |   | 0  | |    |
| D     | |   |   | 0  |

Figure 2. The relationship of operation mode switching.

3.2. Operating mode switching rules
When the hybrid AC/DC microgrid switches the operation mode, the impact of the switching process on the system should be minimized. For this reason, three principles of operating mode switching are proposed:

1. Only one breaker action at a time;
2. Type I relationship switching follows the principle of proximity;
3. Type II relationship switching reference breaker operation priority, priority from high to low are: CB1 closing, CB2 closing, CB2 opening, CB1 opening. The higher the priority, the earlier the operation is done.

To illustrate the three principles, we first define the following two concepts.

1. Unbalanced power \( \Delta S_{ij} (i = A, B, C, D, j = A, B, C, D, i \neq j) \): Indicates the power that needs to be changed when switching between two operating modes (For example, \( \Delta S_{AB} \) represents the unbalanced power when mode A is switched to B), which is numerically equal to the sum of the absolute values of the powers of the two operating modes that have changed. Therefore, there are \( \Delta S_{ij} = \Delta S_{ji} \). Table 2 shows the unbalanced power of each operating mode switching.

2. Impact strength \( F_{ij} = \Delta S_{ij}/t_{ij} (i = A, B, C, D, j = A, B, C, D, i \neq j) \): indicates the degree of disturbance to the entire system by the switching process. \( t_{ij} \) is the switching time, including the breaker operating time \( t_{CBi} \) and the breaker operating interval time \( t_{CBj} \). In single-step operation, \( t_{ij} = t_{CBi} \), in step-by-step operation, \( t_{ij} = 2t_{CBi} + t_{CBj} \). Obviously, the greater the value of impact strength, the greater the unbalanced power in the system per unit of time and the stronger the impact on the system.

3.2.1. Description of rules (1). When Type II switching is required, you can choose to perform Type I switching twice (step-by-step operation), or you can select two breakers to complete at the same time (single-step operation). The former produces an impact strength of \( F_1 \), the latter produces an impact strength of \( F_2 \), then:
\[ F_i = \frac{\Delta S_{ij}}{2t_{CBi} + t_{CBij}} \]  
\[ F_i = \frac{\Delta S_{ij}}{t_{CBi}} \]  

Obviously, the impact strength produced by the step-by-step operation is much smaller than the single-step operation. In addition, the switching time of single-step operation needs to be kept in synchronization, which inevitably demands high communication systems, resulting in an increase in the construction cost of microgrid construction. In summary, it is the reason why the “only one breaker action at a time” rule is proposed.

3.2.2. Description of rules (2). When the switching relationship between the two operating modes belongs to Type I, the switching path may have multiple. For example, there are two switch paths between ADs: ① A → D; ② A → B → C → D. The impact strength of path ① is \( F_j \), and the impact strength of path ② is \( F_4 \) (according to rule(1), step-by-step operation should be taken), then:

\[ F_j = F_{AD} = \frac{|P_0|}{t_{CB1}} \]  
\[ F_4 = \frac{2|P_{ILC}| + |P_0|}{t_{CB1} + 2t_{CB2} + 2t_{CB12}} \]  

Although path ② may produce less impact strength than path ①, the switching time used for path ② is almost 5 times that of path ①, and generates more unbalanced power. On the one hand, too long operating time reduces the real-time performance of the system reflecting external faults; on the other hand, frequent switching operations increase the probability of failure due to misoperation and cause extremely adverse effects on the breaker itself. It is the reason why the “Type I relationship switching follows the principle of proximity” rule is proposed.

3.2.3. Description of rules (3). The hybrid AC/DC microgrid is designed to solve the problem of the grid-connected operation of AC/DC distributed power supplies with different characteristics. Therefore, ensuring that all parts of the system are connected to the grid as much as possible and the voltage and power support functions of the grid are fully utilized has a very positive effect on improving the utilization efficiency of the distributed power supply and power supply quality. The breaker operation priority given in Rules (3) is intended to use as much of the support from the grid as possible to offset the impact of the switching process on the system and maintain the stability of the system. For example, when switching from A to C, there are two paths: ③ A → B → C; ④ A → D → C. Through the above analysis, it can be seen that the unbalanced power and the impact strength generated by the above two paths are equal in value, and the difference lies in the order of the operation of the breaker at the grid connection point and the interconnection point. If the breaker at the grid connection point is operated first (path ④), the impact generated by the switching process is entirely borne by the micro-source within the system; If the breaker at the interconnection point is operated first (path ③), the impact generated by the switching process is shared by the large power grid and the micro-source within the system, which has a very positive effect on maintaining the stability of the system. Corresponding to rules (3), we can see that by querying the priority, the opening priority of CB2( A → B ) is higher than that of CB1( A → D ). Therefore, the path ③ is selected for switching so as to ensure that the AC part in the hybrid AC/DC microgrid can obtain more voltage support.
4. Simulation verification

In order to verify the rationality and effectiveness of the proposed operating mode switching principle, the simulation system shown in figure 3 was built in PSCAD/EMTDC. See Appendix A for simulation system parameters and the initial operating parameters of the simulation system.

![Simulation system diagram](image)

**Figure 3.** Simulation system diagram.

In this simulation system, when the hybrid AC/DC microgrid is operated in the state of AC/DC grid-connected (CB1 is closed and CB2 is closed), DG1 and DG3 are in charging or standby state. After CB1 is disconnected, DG1, as a balanced node in the off-grid operation of the AC microgrid, must change from the constant-power control to the constant-voltage constant-frequency control to maintain the stability of the AC microgrid. Similarly, when CB2 is disconnected, DG3, as a balanced node in the off-grid operation of the DC microgrid, should also be converted from constant-power control to constant-voltage control to maintain the stability of the DC microgrid. DG2 and DG4 have been running at constant-power control; DCLOAD and ACLOAD obtain power from the microgrid according to their own needs. When the CB2 is not disconnected, the ILC is under constant-voltage control to maintain the DC microgrid voltage stable; after the CB2 is disconnected, the ILC exits operation.

4.1. Switching rules (1) verification

Take two different switching modes from mode A to mode C as examples for simulation. The two modes are Mode 1 (Jump from A to C, and two breakers move at the same time) and Mode 2 (Switch from A to B and then to C, and only one breaker acts per step) respectively. According to the analysis, when the two modes are switched, the unbalanced power of the DC side of the system is the same, so the waveform of the DC side parameters is the same too; however, the unbalanced power of the AC side caused by switching is different. Considering that the power fluctuation is related to the frequency of the AC system, we give the system frequency fluctuation diagram caused by these two switching modes, as shown in figure 4.

![Frequency waveform](image)

**Figure 4.** Frequency waveform.
It can be seen from the figure that the impact of Mode 1 on the AC side is much greater than Mode 2, which demonstrates the rationality of Rule (1).

4.2. Switching rules (2) verification
The simulation of the mode A to mode D switching process is taken as an example. Figure 5 and figure 6 give the AC and DC voltage waveform diagrams of the system via the path 1 (A-D) and the path 2 (A-B-C-D) respectively.

Figure 5(a) and figure 5(b) respectively shows the voltage waveform of the AC side when the system is switched by path 1 and path 2. The comparison of the diagrams shows that the impact of the AC side caused by path 1 is much smaller than path 2, which means the path 1 switching system is more stable.

Figure 6 shows that the DC voltage disturbance generated by path 1 is much less than that generated by path 2. From the analysis, we can see that the difference between path 1 and path 2 is whether the ILC branch is involved. The ILC branch is required when the system switches through path 2, which involves the disturbance of the transmission power. Figure 7 shows that the ILC disturbance generated by switching path 2 is much larger than path 1.

From the above analysis, we can see that when the two operation modes belong to Type I, it is reasonable and necessary to select the nearest path switch.

4.3. Switching rules (3) verification
Take the switching process from Mode A to Mode C as an example for simulation analysis. Figure 8 is the DC side voltage when the system operation mode is switched by A → B → C (path 3) and A → D → C (path 4) respectively. Figure 9(a) and 9(b) show the AC side voltage when the system operation mode is switched by path 3 and path 4 respectively.

0-0.5s, the system operates in the ac-dc grid-connected (A). When the path 3 is selected for switching, the breakers CB2 and CB1 are disconnected successively at 0.51s and 0.53s, completing the transition to the Mode C. When the path 4 is selected for switching, the breakers CB1 and CB2 are
disconnected successively at 0.51s and 0.53s, completing the transition to the Mode C. As shown in figure 8, under the same initial conditions, the amplitude of the disturbance generated by the two switching modes is basically the same, but the disturbance time of the path 3 is obviously shorter than the path 4. From figure 9(a) and figure 9(b), it can be seen that, under the same initial conditions, the voltage disturbance on the AC side caused by the switching of path 3 is significantly less than that of the path 4.

![DC side voltage waveform](image)

**Figure 8.** DC side voltage waveform.

![AC side voltage waveform](image)

**Figure 9.** AC side voltage waveform.

![DG1, DG3 power waveform](image)

**Figure 10.** DG1, DG3 power waveform.

Figure 10 shows the power variation of the balanced node microsource during the operation mode switching. DG1 and DG3 are balanced nodes in the off-grid operation of AC microgrid and DC microgrid respectively. Since the system mode switching process involves balancing node transfer problems, their control method and output power need to be changed according to the different operating modes of their respective microgrids. Figure 10(a) and 10(b) respectively show the output power of DG1 and DG3 in different path switching. From figure 10(a), it can be seen that DG1 not only bears the unbalanced power of the AC microgrid, but also provides the ILC transmission power when switching from path 4, therefore, a large power mutation occurs at the moment of disconnecting CB1. However, when switching from path 3, the abrupt power is completely absorbed by the grid, so that the power output of the DG3 is more stable. Figure 10 (b) shows that by path 3 switching, DG3 output power tends to be stable earlier under the same amplitude.

To sum up, when the operation mode switching belongs to the type II relationship, switching according to the operation priority of the breaker can make the system more stable.
5. Conclusions
The hybrid AC/DC microgrid adapts to the trend of distributed power supplies grid connection and has a very broad space for development. On the basis of this, three principles for switching operation modes of hybrid AC/DC microgrids are proposed. Through mathematical analysis and simulation verification, the validity and practicability of the three principles are proved, in order to provide some reference for the application development of hybrid AC/DC microgrid.

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Appendix A

Table A1. AC side parameters.

| Parameter name | Parameter value |
|----------------|-----------------|
| DG1 AC bus voltage | 0.4kV |
| Rated Capacity | 50A·h |
| DG2 AC bus voltage | 0.4kV |
| Rated Capacity | 30kW |
| ACLOAD AC bus voltage | 0.4kV |
| Rated Capacity | 10kW |

Table A2. DC side parameters.

| Parameter name | Parameter value |
|----------------|-----------------|
| DG3 Rated Capacity | 50A·h |
| Rated voltage | 0.8kV |
| DG4 Rated voltage | 0.8kV |
| Rated power | 30kW |
| DCLOAD Rated voltage | 0.8kV |
| Rated power | 10kW |

Table A3. Line parameters.

| number | Node interval | Voltage | Length | Resistance | Reactance |
|--------|---------------|---------|--------|------------|-----------|
| Line1  | Bus1-2        | 0.4kV   | 0.1km  | 64.1mΩ    | 10.1mΩ   |
| Line2  | Bus2-3        | 0.4kV   | 0.15km | 96.1mΩ    | 15.15mΩ  |
| Line3  | Bus2-5        | 0.4kV   | 0.05km | 32mΩ      | 5.05mΩ   |
| Line4  | Bus4-5        | 0.4kV   | 0.1km  | 64.1mΩ    | 10.1mΩ   |
| Line5  | Bus5-6        | 0.4kV   | 0.1km  | 64.1mΩ    | 10.1mΩ   |

Table A4. Initial operating parameters.

| Parameter name | Parameter value |
|----------------|-----------------|
| CB1 state | 1 |
| CB2 state | 1 |
| DG1 output power $P_{DG1}$ | -5kW |
| DG2 output power $P_{DG2}$ | 5kW |
| DG3 output power $P_{DG3}$ | -5kW |
| DG4 output power $P_{DG4}$ | 5kW |
| AC_LOAD absorption power $P_{ACL}$ | 10kW |
| DC_LOAD absorption power $P_{DCL}$ | 10kW |
| ILC output power (AC→DC is Positive) $P_{ILE}$ | 10kW |