Modular Multi-terminal Flexible DC Micro-grid and Its Hierarchical Control Method

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Abstract. In the traditional DC micro-grid, the structure is complex, the control is difficult and there is no fixed networking mode. Thus the construction of micro-grid is expensive and the output is slow. In this paper, a hierarchical control method of modular multi-terminal flexible DC micro-grid is proposed, which simplifies the structure and control method of DC micro-grid and is beneficial to the construction of micro-grid. The structure of flexible multi-terminal DC micro-grid and the modularized method of network construction are discussed. The feasibility of the study is confirmed by a specific example of DC micro-grid. On the basis of the above research, the hierarchical control method of DC micro-grid, the specific control method and control logic in each layer are determined. PSCAD/EMTDC simulation is established to verify the effectiveness of the proposed theory and control method.

1. Introduction

Large-scale development and utilization of renewable energy has provided a new way to solve the problems of the world energy shortage. Micro-grid is the effective way and development trend of distributed power supply [1]. With the development of power and load, their composition has obvious changes, and the concept of DC micro-grid is emerging [2]. Compared with AC distribution network, DC distribution network has great economic and technological advantages in facilitating new energy access, improving transmission capacity and ensuring the quality of power supply [3]. Flexible transmission is widely used in HVDC transmission network, because it changes the structure of internal converter [4].

Literature [5] proposed a new multi-terminal flexible hierarchical control strategy. Based on hierarchical control, decentralized control and energy optimal dispatch at different time scales, a basic control mode for multi-terminal flexible DC micro-grid is proposed. Reference [6] utilized the flexible multi-state switch SOP instead of traditional contact switch has the advantages of continuous power control and flexible control mode.

Modular design of micro-grid can be basically divided into two categories. The first category is functional division, which facilitates the internal balance and control of micro-grid and reduces the number of contacts with the central controller. Documents [7-8] modularize the AC-DC hybrid micro-grid into three categories: all energy storage devices, all AC devices and all DC devices. The second is to divide the devices according to their geographical environment, so as to facilitate the coordination, balance and stability within each region of the micro-grid, reduce the area occupied, and make it more convenient to control the balance near the same region. Documents [9-10] regard a building as a module to coordinate the balance of distributed generators, DC energy storage and various AC and DC loads in the building.

This paper presents a modular multi-terminal flexible DC micro-grid networking and hierarchical control method. The hierarchical modular control method is used in the control. The multi-terminal flexible DC micro-grid is divided into three kinds of modules: controllable module, uncontrollable module and large grid. The hierarchical and modular control method includes three layers: central control layer, module layer and component layer. This modular control method ensures that the internal load can be totally absorbed and the internal self-balance of the controllable module can be completed. Finally, based on PSCAD/EMTDC simulation software, the proposed content is verified, and a multi-terminal flexible DC micro-grid simulation system is built. Three examples are given to demonstrate the effectiveness of the proposed control strategy.

2. Flexible multi-terminal DC micro-grid structure

In order to simplify the structure and control objectives of DC micro-grid and facilitate precise control, flexible multi-state switch technology is applied to connect distributed power supply, energy storage devices and loads in the system to DC buses through flexible multi-state switch. The DC network is then connected to the external AC network through power electronic inverters.

Fig. 1 is the structure of flexible multi-terminal DC micro-grid. The converters connected by the large grid, distributed generators, energy storage and AC loads are flexible multi-state switches (FMSS), and the converters constituting FMSS are modular multi-level converters (MMC). The internal structure of MMC is shown in Figure 2.

Among them, the specific structure of FMSS is as follows.

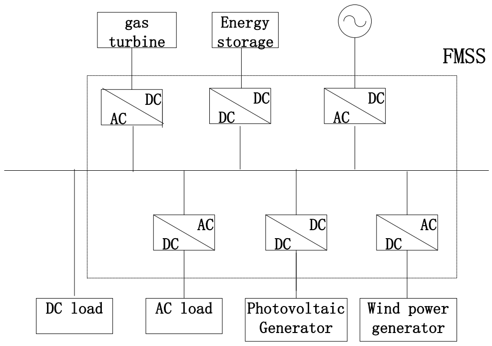

Figure 1. Structural Chart of Flexible Multi-terminal DC Micro-grid.

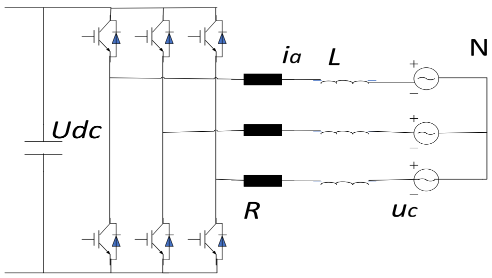

Figure 2. The concrete structure of FMSS.

In the figure, L is the line inductance; R is the line resistance; C is the line capacitance; Uc is the system volt-age; N is the neutral point.

Compared with the traditional DC micro-grid, the flexible multi-terminal DC micro-grid uses FMSS to enhance the stability of the grid, simplifies the structure of the micro-grid and is easy to be built later, and simplifies the control objective to control the voltage stability of the DC bus, which is conducive to the selection of control methods.

3. Composition of each module

3.1. Modular structure

Flexible multi-terminal DC micro-grid is divided into three types: controllable module, uncontrollable module and large grid based on the controllability of each part. Each part is connected with DC bus by converter in each module. Three kinds of modules can exist in one, many or none DC micro-grid.

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3.2. Composition of each module

3.2.1. Controllable module.
The controllable module is composed of a single-axis micro gas turbine, battery energy storage, AC load and DC load. Single-axis micro-gas turbine's output power should not only meet the internal load demand, but also ensure that the DC bus voltage is in a stable range. Battery energy storage simulates the primary frequency modulation characteristics of large power grid. Therefore, it is necessary to balance the power of single-axis micro-gas turbine to supply power for its internal load and DC micro-grid. This compensates for the voltage deviation caused by sag control. Controllable module itself belongs to small self-balanced micro-grid. On the basis of local load absorption, it responds to power fluctuation of micro-grid.

3.2.2. Uncontrollable module.
The uncontrollable module is composed of uncontrollable distributed power (wind turbines, photovoltaic generators, etc.) and AC and DC loads. Because each part of the uncontrollable module can't control the output power, that is, it can't maintain the stability of DC bus voltage, so the whole uncontrollable module can be treated as a net load.

3.2.3. Power grid.
The large power grid is connected to the DC micro-grid by bi-directional converter. In the connected state, the large power grid assists the controllable part of the DC micro-grid to adjust the DC bus voltage. When the large power grid requests the DC micro-grid, the large power grid is equivalent to the uncontrollable module. In the isolated island state, the bidirectional converter is disconnected from the DC micro-grid.

3.3. Types of distributed power storage system with different modules
Because different modules play different roles in DC micro-grid, the types of distributed generation and energy storage in different modules are different. In the controllable module, the selected distributed power can be single-axis micro-gas turbine, diesel genera-tor, wind power plant with energy storage, photovoltaic power station and so on. The uncontrollable module of DC micro-grid has no regulation function, so the distributed generators in this module are wind power plants, photovoltaic power plants and so on.

4. Operation mode and hierarchical control method

4.1. Operation mode
The multi-mode operation of modular multi-terminal flexible DC micro-grid includes three modes: coordinated control mode between large grid and controllable module in grid-connected state, independent control mode of controllable module and island mode in island state. Its operation characteristics are as follows.

4.1.1. Coordination control mode between large power grid and controllable module.
This mode is applied to the grid-connected state. The bus voltage balance of the DC micro-grid is controlled by the controllable part of the large grid and the DC micro-grid. Bidirectional converter receives the signal from top-level central controller. When the power grid is running normally, bidirectional converter chooses droop control. This ensures the maximum utilization of resources in the DC micro-grid, reduces the dependence on the large grid and reduces the operation cost of the DC micro-grid.

4.1.2. Controllable Module Independent Control Mode.

When this mode is applied to grid-connected state, there are requirements for DC micro-grid in large power grid, and it doesn't participate in bus voltage regulation of DC micro-grid. The bi-directional converter receives the signals from the top-level central controller and inputs the reference values of P_{ref} and Q_{ref} of PQ control according to the requirements.

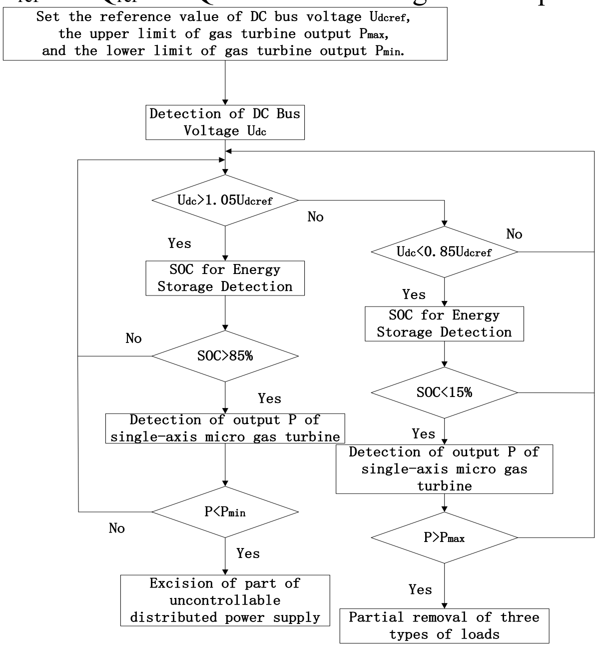


Figure 3. Module Layer Control Block Diagram.

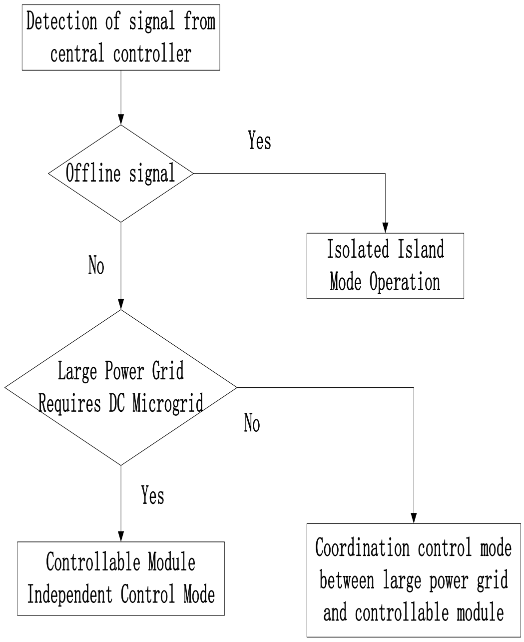


Figure 4. Logic Control Block Diagram of Central Controller Conversion Mode.

4.1.3. Isolated Island Operation Mode.

Under the normal operation of the interconnected grid, if the fault of the large power grid or the power quality does not meet the requirements, the large power grid is disconnected from the DC micro-grid. The specific control block diagram is shown in Fig.3.

4.1.4. Switching of Running Mode.

The control mode of bi-directional converter includes droop control and PQ control. The control mode is switched according to the command signal from the top-level central controller. The specific control block diagram is shown in Fig.4.

4.2. Hierarchical control method

Based on the above structure, a three-layer control method including central control layer, module layer and component layer is adopted.

4.2.1. Component Layer Control Method.

The component layer determines the control mode of each device in each module, adjusts the internal control parameters of droop control and constant voltage control.

4.2.2. Modular Layer Control Method.

Module layer controls the coordinated control in each module. Controllable module must ensure that it responds to the fluctuation of external uncontrollable module on the basis of satisfying the internal load power, and ensure the stability of DC bus voltage.

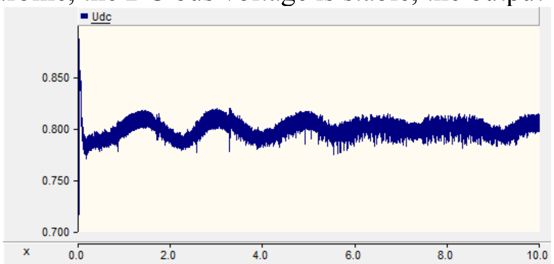
4.2.3. Central Control Layer.
The central control layer is controlled by the signals of the large power grid. It judges whether the large power grid has requirements for the DC micro-grid and whether the power quality of the large power grid meets the standard. The central control layer sends out signals to control the control mode of the bidirectional converter and determines the operation mode of the DC micro-grid.

5. Simulation

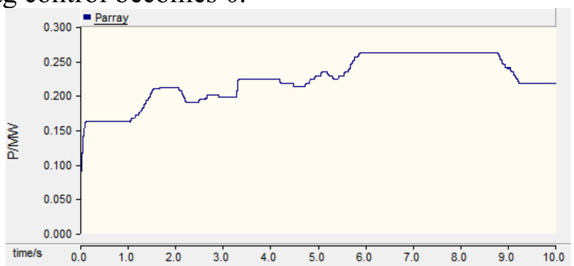
In order to verify the feasibility of the proposed multi-terminal flexible modular control, this paper takes four-terminal FMSS as an example. The uncontrollable module includes DC load and photovoltaic; the controllable module includes energy storage and single-axis micro-gas turbine; and the large power grid module includes AC source and bidirectional converter. Based on PSCAD/EMTDC, the parameters of the system are: DC Bus Voltage U_{dc}: 0.8 kV; AC Bus Voltage U: 10 kV; Inductance of AC Bus L: 0.001H; DC load P_{load}: 0.4MW. Batteries are controlled by sagging; single-axis micro gas turbine is controlled by constant voltage; photovoltaic is controlled by MPPT. P_{arrary} is photovoltaic output power; Pbat1 is battery storage output power; P_{grid} is large grid output power; P_g is single axis micro gas turbine output power; U_{dc} is DC bus voltage.

5.1. Example 1: Coordination control mode between large power grid and controllable module
The energy storage of bidirectional converter is controlled by sagging. Change the output power of uncontrollable module. The simulation results are shown in Figure 5.

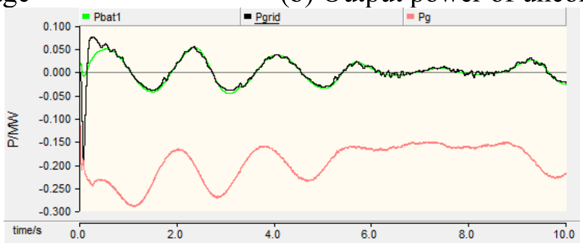
When the net load of uncontrollable module changes, the sag control of large power grid and storage battery react immediately. After the constant voltage response action of single-axis micro gas turbine, the DC bus voltage is stable, the output of sag control becomes 0.



(a) DC Bus Voltage

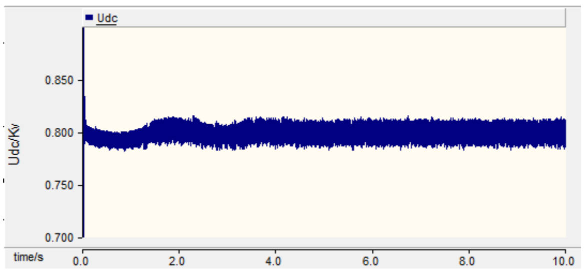


(b) Output power of uncontrollable module

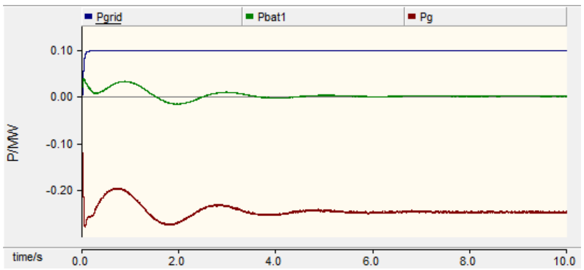


(c) Controllable Module Output Power

Figure 5. Diagram of coordinated control mode between large power grid and controllable module.



(a) DC Bus Voltage



(b) Controllable Module Output Power

Figure 6. Simulation Diagram of Independent Control Mode of Controllable Module.

5.2. Example 2: Controllable Module Independent Control Mode

The bidirectional converter is controlled by PQ, whose P and Q are controlled by the central controller. Change the reference P value of bi-directional converter from 0 to 0.1.

As shown in Fig. 6, the sag control of storage battery reacts immediately. After the constant voltage response action of single-axis micro gas turbine, the DC bus voltage is stable, the output of sag control becomes 0. The DC bus voltage can be maintained in a stable range when the power fluctuates.

6. Conclusion

- The flexible multi-terminal DC micro-grid simplifies the structure and facilitates the later construction. The control objective is simplified to the bus voltage control of the DC micro-grid, which facilitates the selection of the control mode. The modularization of micro-grid is transformed from "design micro-grid" to "assembly micro-grid". It is convenient to save the construction cost of micro-grid and facilitate the expansion of micro-grid construction.
- The control layers are three layers. The central control layer is controlled by the signal of the large power grid, which controls the operation mode of the whole power grid. Module layer controls the coordination of devices in each module to ensure the stability of each module. The component layer mainly determines the control method of each device in each module and ensures the speed of voltage stability.
- The controllable part must ensure that the internal load of the module layer and the output power of the generator can be self-balanced. The controllable module is as net loads. Power fluctuation affects bus voltage.
- Three operation modes should deal with all kinds of operation conditions. When the large power grid is involved in regulation, droop control is chosen to save operation costs. The two states of large power grid are not involved in regulation. It operates as an uncontrollable module with the same control mode, which simplifies the control mode and avoids the bus voltage fluctuation caused by too complex control means.

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