Topology Research of Flexible DC Distribution Network Based on Different PV Operation Scenes

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Abstract. With the increase of load types and power consumption, the scale of power grids continues to expand. Traditional AC distribution networks face a series of problems, such as distributed power grid-connected power generation, low power quality, and DC power distribution technology. There are clear advantages in these areas. This paper first analyzes the advantages of analyzing flexible DC distribution networks, and clearly analyzes several common topologies of flexible DC distribution networks. Secondly, the distributed photovoltaic model is established, and its way of accessing the AC grid and DC grid is analyzed. It is learned that the DC distribution network has great economic significance. Finally, the four-terminal toroidal DC distribution network in different scenarios is simulated. The simulation results show that the DC distribution network can effectively adjust the voltage through the energy regulation of the energy storage module and the photovoltaic module, and quickly realize the power balance of the DC distribution network.

1. Introduction
With the rapid development of the economy, the density of urban electricity load is increasing, and the operating characteristics, topology and control methods of the power grid are becoming more and more complex. The traditional AC distribution network faces a series of problems [1-3]. On the one hand, when distributed power supplies, such as electric vehicles, photovoltaic power generation, wind power and other DC equipment are connected to the AC distribution network on a large scale, a large number of configurations of the inverter are added due to the need to pass through the structure and control of complex inverters. Loss of the grid. On the other hand, distributed power sources have volatility, intermittency, and instability, which seriously endanger the safe operation of the AC distribution network [4]. Flexible DC distribution network is an AC/DC hybrid wide area network with advanced energy management system [5].

In this context, many countries have launched research and exploration of flexible DC distribution networks. The relevant research institutions in the United States conducted research earlier and explored their system structure and power supply form [6-7]. At present, China has built a number of DC active distribution network demonstration projects based on flexible DC interconnection, including the world's first multi-terminal flexible DC project - South Australia multi-end flexible DC normal engineering, and the first medium-voltage five-end flexible in China. The DC power distribution project was officially put into operation in Guizhou in 2019[8-9].
This paper first analyze the advantages of DC distribution network, briefly describes the typical application scenarios of existing DC distribution networks, and then studies the difference between photovoltaic power generation and energy storage equipment respectively connected to DC distribution network. Finally, a four-port ring DC distribution network structure is designed. The design of the design is simulated and the operating conditions of three typical operating conditions are described in detail. Through simulation, some useful conclusions are obtained, which has certain reference value for further research on flexible DC distribution network.

2. Advantage Analysis of Flexible DC Distribution Network

2.1. Easy access to distributed power
For the current AC distribution network, the photovoltaic power supply and the energy storage device are all DC working methods, and the primary condition for grid connection is DC/AC conversion. If these distributed power sources are connected to the DC distribution network, the DC/AC conversion link can be omitted, the power transmission loss can be reduced, and the power transmission efficiency can be improved [10]. Figure 1 shows a schematic diagram of a distributed power supply and energy storage device incorporated into a DC distribution network.

![Figure 1. New energy and energy storage access to DC distribution network](image)

2.2. Improve power quality
Good power quality is the basic guarantee for the normal operation of the power grid and the power supply of the load. Due to the fragility of the traditional distribution network, the impact load and harmonic load in the power grid cause the grid voltage to flicker and the waveform to be distorted, which seriously damages the power quality and stability. With the improvement of the performance of power electronic devices, the DC distribution network can improve the power quality, including the converters composed of power electronic switching devices, which are the key interfaces of the DC distribution network, and can quickly and accurately maintain the power balance of the power grid. Stabilize the grid voltage.

2.3. Easy to invest and manage
At present, there is little research on the investment and maintenance costs of DC distribution networks, because there is no large-scale DC distribution network actual engineering and network topology, voltage grades, lines and converters have not yet been determined, for DC distribution networks. Some economic assessments are based on assumptions. This paper evaluates the investment and maintenance costs of ±750V DC system and 400V AC system. As shown in Table 1, the table mainly considers the price of the converter, investment and maintenance costs, power outage and other factors, and finally calculates the LVDC technology and medium. The economic loss of the pressure line.
Table 1. Economic comparison of DC distribution network

| Cost factor (10^3 EUR) | investment | loss | Fault repair | maintain | converter | total |
|------------------------|------------|------|--------------|----------|-----------|-------|
| 20/0.4kV AC distribution network | 104 | 9 | 7 | 8 | 0 | 128 |
| ±750VDC distribution network | 45 | 19 | 3 | 3 | 56 | 126 |
| Loss difference | 59 | -10 | 5 | 5 | -56 | 3 |

3. Flexible DC distribution network topology

3.1. Radiation structure

Figure 2 shows the structure of a radiating DC distribution network. The radiating structure is the simplest network structure. As can be seen from the figure, the DC bus is connected to the upper AC, DC grid, and distributed power source through AC/DC and DC/DC converters to obtain electric energy.

![Figure 2. Radiation structure of DC distribution network.](image)

3.2. Simple double-ended structure

Figure 3 shows the structure of a double-ended DC distribution network. The double-ended structure is a radiation-type network powered by dual power supplies, and has a structure of segmentation and bridge. In the case of a power supply side failure, the power supply at both ends can be continuously powered by another power supply, thereby ensuring the reliability of the DC distribution network.

![Figure 3. Two-terminal structure of DC distribution network.](image)

3.3. Ring structure

Figure 4 shows the structure of a ring-type DC distribution network. There are two tidal current paths between any two points of the ring-shaped DC distribution network, and the two tidal current paths may be mutually redundant. When one line has an open or short circuit fault, it is necessary to cut off
the load and supply power from another line, thus improving the reliability of the power supply. Therefore, the multi-terminal ring DC distribution network is more suitable for the actual power supply system.

![Figure 4. Ring structure of DC distribution network](image)

4. Distributed photovoltaic and energy storage

Photovoltaic cells are the most basic components of photovoltaic power generation modules. The voltage and current generated by a single photovoltaic cell are small, the stability and adaptability are weak, and the output mechanical characteristics are poor. Generally, it cannot be directly used [13]. Therefore, by serially connecting the photovoltaic cells in series, a practical photovoltaic power generation module can be obtained.

![Figure 5. Photovoltaic power generation equivalent circuit](image)

The equivalent model for establishing photovoltaic power generation is shown in Figure 5. In the figure, \( I_{ph} \) is the short-circuit current at a given light intensity; \( I_d \) is the diode saturation current; \( R_s \) and \( R_{sh} \) are equivalent resistances; \( I_{pv} \) is the battery component output current; \( U_{pv} \) is the battery component terminal voltage. Considering the variation of the light intensity \( S \) and the temperature \( T \) of the photovoltaic cell, the photovoltaic cell output is as follows:

\[
I_{pv} = I_{ph} - I_d - I_{ph} \tag{1}
\]

\[
I_{ph} = \frac{G}{G_{ref}} [I_{SCR} + K_i(T - T_r)] \tag{2}
\]

\[
I_d = I_{ph} \exp\left(\frac{q(V + I_{pv}R_s)}{AKT}\right) - 1 \tag{3}
\]

\[
I_{sh} = \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \tag{4}
\]


\[ I_{pv} = I_{sc} \left[ 1 - m_1 \exp \left( \frac{V_{pv}}{m_2 V_{oc}} \right) \right] \]  

(5)

\[ m_1 = (1 - I_{sc}) \exp \left( \frac{V_{pv}}{I_{sc} V_{oc}} \right) \]  

(6)

\[ P_{pv} = I_{pv} V_{pv} \]  

(7)

Where \( G \) is the light intensity; \( G_{ref} \) is the rated light intensity; \( I_{SC} \) is the rated light intensity and the short-circuit current at temperature; \( K_I \) is the short-circuit current temperature coefficient; \( T_r \) is the reference temperature, 25 °C. \( R_{sh} \) is the ground resistance; \( m_1, m_2 \) are two intermediate coefficients. \( P_{pv} \) is the output power. The output characteristics are shown in Figure 6.

\[ \text{Figure 6. Output characteristics of photovoltaic cells.} \]

5. DC distribution network simulation system

In order to study the operating characteristics of DC distribution network under various working conditions, this paper establishes a four-terminal ring DC distribution network, in which the maximum power of the AC system is 160kW, DC load is 40kW, and the maximum output power of PV is 80kW. The maximum charge and discharge power is 30 kW. This section studies the working characteristics of DC distribution network through simulation of several working conditions. The power variation of each port of DC distribution network in each working condition is shown in Table 2.

| Simulation case | DC system | AC system | PV 1 | PV 2 | DC load | ESN |
|----------------|-----------|-----------|------|------|---------|-----|
| 1/kW           | -100→-80  | 80        | 80   | 40   | -20→0   | 30  |
| 2/kW           | -10→20    | 0         | 0    | -20  | 30→0    |     |
| 3/kW           | 10→-90    | 0→80      | 0→80 | -40  | 30→30   |     |

5.1. Photovoltaic power fluctuations and energy storage charging

This scenario simulates the PV fluctuation and energy storage charging. The figure includes the voltage waveform of the quality distribution network and the power output or absorption of each module. The simulation results are shown in Figure 7.
5.2. Photovoltaic power supply off-network and energy storage discharge
This scenario simulates the photovoltaic off-network and energy storage discharge. The figure includes the voltage waveform of the mass distribution network and the power output or absorption of each module. The simulation results are shown in Figure 8.

5.3. Photovoltaic power grid connection and energy storage device charging and discharging
The simulation case is a simulation of the charging and discharging of the photovoltaic power grid and the energy storage device. The figure includes the voltage waveform of the mass distribution network and the power output or absorption of each module. The simulation results are shown in Figure 14.
6. Conclusion
In this paper, the basic principle, advantage analysis and topology of DC distribution network are studied in detail, and the photovoltaic power supply model is studied. Finally, a four-port ring distribution network is designed. The simulation structure proves the design. The correctness and feasibility of the program. The simulation results show that the flexible DC distribution network can quickly achieve power balance and the voltage rises rapidly when the photovoltaic power supply is in fluctuation, off-grid, grid-connected, and energy storage unit charging and discharging. These scenarios basically contain the possible operating states of the DC distribution network, and have a high reference value for the operation and management of the DC distribution network.

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