Research on key technologies of highly reliable flexible distribution facing tidal load

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Abstract. Under the background of steady development of DC transmission and distribution technology, a series of pilot projects and demonstrations have been carried out gradually in the Engineering application of DC distribution network. In this paper, the typical mode of low voltage DC distribution network- flexible distribution system, is taken as the main research object. The interface between low voltage DC distribution and AC distribution, the distributed energy resource and electric vehicle, and the characteristics of electrical load is considered synthetically. The DC voltage level, power supply radius and capacity, the mode of grounding and connection, and topology structure are analyzed and studied. The typical DC distribution structure is analyzed by simulation. And the DC network load mutual supply experiment system suitable for different scenarios is constructed.

1. Introduction

In recent years, new energy, DC load and conventional AC load developed rapidly [1]. On the one hand, the controllable and adjustable demand of new energy and DC load is Growing continually, on the other hand, the uneconomic operation is common in conventional load [2]. DC distribution is based on flexible DC technology and communication technology, which can effectively solve the above problems of traditional AC distribution, flexible distribution is one type of DC distribution technology [3]. When multiple electric vehicle loads are connected to different platforms, there is the characteristic of tidal power, which requires the distribution network to reasonably control the charging power [4].

Flexible distribution is a composite technology, which is based on voltage source converter based high voltage direct current (VSC-HVDC) and Distribution network operation control [5]. Flexible distribution is equipped with AC/DC converters (PCS) in the distribution station area, the converters in multiple stations are connected by the DC bus, photovoltaic and energy storage are connected directly to the nearby DC bus through the DC/DC converters. Flexible distribution operation control system collects the operation data of each station and optimizes the power flow [6]. The converter (PCS) of Flexible platform area converter does not need H-bridge cascade or modular multilevel, but only needs two/three level technology to realize the transformation from low-voltage distribution voltage to DC supply voltage. Flexible distribution could solve the "two-way" problem caused by the new energy access to the distribution network, realize the efficient absorption of new energy, and improve the convenient access and orderly regulation of new loads such as electric vehicles [7].
2. System architecture of flexible distribution

Flexible distribution is based on AC distribution network, AC/DC converters are installed on the side of the AC feeder in each distribution station to form several independent AC/DC distribution networks. DC distribution systems are connected by the DC bus to form a multi-terminal AC/DC distribution network system, DC loads such as charging piles and distributed power supply are connected to the DC bus. The typical system architecture of flexible distribution is shown in figure 1, the DC bus voltage usually choose 750~900V.

![Figure 1. The typical system architecture of flexible distribution.](image)

The main operating modes of flexible distribution include multi-terminal power supply, single-terminal power supply and fault isolation, as shown in figure 2. When the grid operating boundary or load condition changes, the multi-terminal AC/DC system can automatically switch to the operating mode suitable for the new operating conditions, forming the switching relationship between the operating modes and corresponding specific conditions. Each VSC works in single-end power supply mode when there is no sudden large capacity load and the distribution transformer load rate is in economic interval. When sudden large-capacity load is connected, power flow can be transferred to the sudden load through the dc interconnection system, and the power flow can be withdrawn when the capacity demand is small. The converter at the fault end would be removed for fault isolation when fault occurred in multi-terminal AC-DC system, and reconnect the DC grid after fault recovery.

![Figure 2. The main operating modes of flexible distribution.](image)
3. System analysis of flexible distribution

The design of flexible distribution topology need according to the data of grid and load. The optimal interconnection of nearby zone node is obtained by using the genetic optimization algorithm. The capacity of flexible station system for electric vehicles could be fully increased by capacity complementation. In this way, the voltage of overload area could be improved and the network loss could be decrease. Specific optimization steps are as follows:

3.1. Objective function

The optimal object of this project considers three aspects: 1) Largest active capacity during the whole time of the day when the network is added; 2) Minimum overall voltage deviation of the network; 3) Minimum network loss.

As follows:

(1) Maximum active capacity during the whole time of the day.

\[
\max \sum_{i=1}^{T} \sum_{t=1}^{N} \Delta P_{i,t}
\]

Where: \(\Delta P_{i,t}\) is the capacity increased of node \(i\) in time period \(t\) after optimization of interconnected, \(N\) is the number of network nodes, \(T\) is the number of study periods. Considering the timing sequence characteristics of distribution transformer load at different nodes, it is assumed that the time period when the load rate of heavy and overload distribution transformer is less than 70% can be independently undertaken, otherwise the interconnection node output is required, in this way, the active capacity of the network increased by interconnection is calculated.

(2) Minimum overall voltage deviation of the network

\[
\min \sum_{i=1}^{T} \sum_{t=1}^{N} \left| U_{i,t} - U_n \right|
\]

Where: \(U_n\) is nodal standard voltage, generally selected as 1; \(U_{i,t}\) is voltage amplitude of node \(i\) in time period \(t\).

(3) Minimum network loss

\[
\min \sum_{i=1}^{T} \sum_{j,B} P_{\text{loss},i,j}
\]

Where: \(B\) is the collection of network branches, \(P_{\text{loss},i,j}\) is the loss of network in branch \(j\).

3.2. Constraint condition

(1) Constraints of distribution transformer capacity

\[
\sqrt{P_{i,t}^2 + Q_{i,t}^2} \leq S_i
\]

Where: \(S_i\) is distribution transformer capacity of node \(i\), \(P_{i,t}\) and \(Q_{i,t}\) is distribution transformer active and reactive load of node \(i\) in time period \(t\).

Further, for interconnected nodes, the load rate of both nodes after binding interconnection is lower than 70% to ensure the load balance. As follows:

\[
\sqrt{P_{j,t}^2 + Q_{j,t}^2} \leq 0.7 \cdot S_i
\]

Where: \(j\) is the collection of interconnection nodes.

(2) Constraints of power flow voltage and current

\[
U \leq U_{i,j} \leq \bar{U}
\]

\[
L \leq I_{i,j} \leq \bar{I}
\]
Where: $U_{i,t}$ is the voltage amplitude of node $i$ in time period $t$, $U$ and $\overline{U}$ is lower bound and upper bound of voltage, $I_{ij,t}$ is the current amplitude of branch $i-j$ in time period $t$, $I$ and $\overline{I}$ lower bound and upper bound of current.

3.3. Solution algorithm
Genetic optimization algorithm is used to solve the optimal interconnection of this scheme. The solution steps are as follows:

1. Input basic network parameters, including node parameter matrix, line parameter matrix, 24 time period load matrix of distribution transformer.
2. Generating the initial population randomly with the size of 50.
3. Calculating the fitness value of each individual, Fitness value is obtained by weighting the three objective function values.
4. New individuals are generated by selection, crossover and mutation operations, and calculating the fitness value of new individuals. Compared with the fitness value of original individuals, the new population is gradually generated by retaining the larger one.
5. Setting the maximum number of iterations to 100, finally decode and output the result.

4. Key technologies of flexible distribution

4.1. Planning and design

4.1.1. Design of voltage. The basic requirements of selecting DC supply voltage are to meet the relationship of load supply demand, capacity and operation economy. (1) Power supply capacity and radius. The higher the DC distribution voltage level, the stronger the power supply capacity, the larger the power supply radius. (2) Compatibility with AC grid. The DC voltage level should match the AC distribution network voltage level, such as 35kV, 10kV and 380V. (3) Power supply efficiency and operating loss. The overall efficiency of energy conversion should be the highest. (4) Compatibility with converters. The DC voltage level is closely related to the efficiency and stability of converters.

4.1.2. Design of capacity. The capacity design of PCS in the flexible distribution system should fully consider the large-scale access requirements of renewable energy and electric vehicles, especially the access demands of large-capacity distributed power sources such as light and storage and charging stations. The capacity design methods are as follow: Firstly, the DC load of each station area is calculated and analyzed, and a certain DC mutual supply capacity is considered. And then, the transfer capacity of AC load is calculated and analyzed, the system capacity is designed based on DC load, DC transfer capacity and AC transfer capacity. Lastly, the PCS capacity of each station is configured according to Historical average available capacity.

4.1.3. Network architecture. The basic requirements of selecting DC supply voltage are to meet the relationship of load supply demand, capacity and operation economy. The Architecture of flexible distribution system includes star power supply structure, ring power supply structure, bus power supply structure and tree power supply structure. The design principles are as follows: the interconnection selection results of the station area, the power supply reliability demand, power supply radius and system design cost. Grounding mode needs to consider grounding mode of AC side filter and DC side, the design principles are as follows: (1) Provide reference potential for DC distribution system. (2) Restrain the zero-sequence current by designing zero sequence circuit. (3) Improve the transient characteristics of DC system in case of AC/DC fault.

4.2. Operational control
The operation control system of the flexible distribution is composed of three levels: system level, operation level and equipment level. The flexible distribution system can ensure the economic
operation and stable operation of the region through the regulation of PCS, energy storage and DC load, and realize the coordination and interaction between regions through inter-region scheduling.

4.2.1. System management layer. Including energy management and operation control, operation mode switch, flow scheduling between different platform, source-grid-load and storage coordination control, start-stop control, grid tied/off control, single/multiple terminal control. The main task of the system management is to realize the system level functions of larger spatial scale and time scale, and to provide auxiliary decision-making for the coordination and scheduling between regions.

4.2.2. Centralized coordination control layer. Including every operation mode, such as control and distribution of flow in the platform, multi-terminal coordinated control(slope control or droop control), AC/DC load transfer, fault isolation, fault operation(emergency power support), fault recovery, stable control. The main task of centralized coordination control layer is to determine and issue the control instructions of local device according to the operating objectives of the system management layer, adjust the operation mode, working mode and power instructions of each local device, and summarize and analyze the status of each local device and upload it to the system layer.

4.3. Key equipment
The key equipment of DC distribution includes AC/DC converter, coordinating controller.

4.3.1. AC/DC converter(PCS). PCS usually use VSC(Voltage Source Converter). In DC distribution network, low voltage PCS mainly have the following applications: (1) As the supply power of the low-voltage dc bus, it is commonly seen in the low-voltage dc distribution network. (2) As the backup power supply circuit, it is often seen in multilevel dc distribution network. (3) As the reverse power loop from DC to AC. The controller of converters could adopt master-slave control or independent control, and the independent control adopts bi-directional active power (P)-DC voltage (Udc) slope control. The P-Udc droop strategy proposed in this paper is aimed at the active bi-directional flow VSC, as shown in figure 3 Slope independent variable is Udc and dependent variable is active power flow P. When the active power flow control target is adjusted, the DC bus voltage level is changed to achieve instantaneous active power and DC voltage rebalancing.

4.3.2. Coordinating controller of flexible distribution. Flexible station coordinate controller can detect the information of the distribution network, such as running data, power grid status, the information would be summarized and analyzed by communication system. In this way, the working state of the current distribution network and the most suitable system operation mode are obtained. The flexible distribution coordination controller can also realize the distribution network control objectives, including: (1) Load concentration method for low load state of system. (2) Recovery mechanism for temporary failure states.

Figure 3. Diagram of droop control strategy
5. Simulation experiment system

In this paper, a flexible distribution simulation experiment system based on DC network technology is built to conduct load mutual supply experiment of distribution network. The scheme of operation control and safety protection is verified on the experiment platform. In this experiment system, the capacity simulation ratio is 80:1, the AC voltage simulation ratio is 10:1, the DC voltage simulation ratio is 1:1. The wiring layout of the experiment system is shown in figure 4. The experiment platform consists of one dynamic mode booster transformer, four sets of analog transformer stands, six panel cabinets, three V2G AC load cabinets and battery cabinets. The six panel cabinets consists of an incoming line cabinet, four converters and one DC feedback load cabinet, among them, four converter cabinets have the same structure, and each AC/DC converter cabinet contains one AC/DC converter.

![Diagram of experiment platform](image)

**Figure 4.** Structure chart of experiment platform

The DC load of the flexible distribution platform system is set to be low, the PCS in the two areas will be used to conduct the DC load transfer experiment to meet the DC load power supply. The experimental waveform is shown in figure 5. The experiment results show that the DC voltage is stable at 750V, the active power flow in the station is controlled according to the set target, and the deviation from the active power target value in the respective stations is less than 3%, and a good dynamic response process is indicated.

![Waveform of DC load transfer](image)

**Figure 5.** Experimental waveform of DC load transfer
6. Conclusion

The application of DC distribution technology can promote the adjustable and controllable in distribution network, and realize the transfer of distribution network load and inter-regional power flow. In this paper, the typical mode of low voltage DC distribution network-flexible distribution system is taken as the main research object. The method of selecting points and capacity is studied, and key technologies such as topology architecture, voltage, operation control and key equipments are studied. The simulation experiment platform is set up for experimental verification, the experimental results verify the feasibility of the flexible distribution and the control strategy.

7. References

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