Research in system design of AC and DC distribution network based on flexible substation

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Abstract. In recent years, distribution network is developing rapidly from current to future advanced form. Under the tendency, this article puts forward a new AC and DC distribution network technology based on flexible substation. There is no mature design experience and complete theory for designing, equipment manufacturing and engineering construction, etc. in this technology. In this paper, system design method of AC and DC distribution network based on flexible substation are given systematically. And design of overall system, key equipment parameters, control and protection are researched and discussed. All of the research results above are adopted in the first AC and DC distribution network demonstration project based on flexible substation. The paper will provide theoretical and experimental experience for system design in the future AC and DC distribution network projects.

1. Introduction

In recent years, distributed renewable energy access and energy users put forward new demands, it requires distribution network to become electronic and Internet of Things to provide all-round services [1, 2]. Comparing with traditional distribution network, flexible DC technology has remarkable advantages such as friendly access to new energy, adaptability to multi-load demand, convenient control, high power quality and strong transmission capability [3-5]. On the basis of the current situation of AC distribution network, combining application scenarios, the construction of AC and DC distribution network becomes an important development trend. Technical research and engineering practice have been carried out at home and abroad [6-11]. But these AC and DC distribution networks are based on converters, and there is no engineering practice based on flexible substation.

Flexible substation is the key node in the integrated energy application system characterized by the widely applied of power electronics. The flexible substation takes power electronic transformer (PET) as its core, mixing together control and protection technology, information and communication technology, as well as advanced computing technology, highly integrating various functions, realizing energy transmission, power grid regulation and load regulation functions. Flexible substation has many advantages, such as flexible power flow control, plug and play of renewable energy, AC and DC graded power supply, load control, flexible reactive power control, highly intelligent and so on. AC and DC distribution network based on flexible substation considers flexible substation as its core, multi-voltage level coordination and interaction [12].
It is the first time in research, design, equipment manufacturing, engineering construction and commissioning for AC and DC distribution network based on flexible substation. Here is no ready-made engineering experience, standard and specification for reference. The AC and DC distribution network based on flexible substation needs not only to solve the new characteristics of the urgent demand for new energy absorption and highly demand for multi-component electricity, but also to overcome the new features, such as the unique networking scheme, the difficulty of equipment development and the complexity of control and protection.

In consideration of the above difficulties, it is necessary to systematically study the technical scheme and related equipment parameters of AC and DC distribution network based on flexible substation. Carrying out a system design research becomes an effective way. System design in DC engineering is mostly applied in the field of HVDC and VSC-HVDC. In the field of AC and DC distribution network, there is no precedent for systematic system design [11]. This paper will put forward the system framework of system design of AC and DC distribution network based on flexible substation. According to design system, relevant research will be carried out around solving technical difficulties and combining with Zhangbei AC and DC distribution network and flexible substation demonstration project.

2. A framework of system design for AC and DC distribution network based on flexible substation

The system design is to solve the design of work scope, procedure, technical requirements, depth regulation and working method in the process of designing AC and DC distribution network based on flexible substation technology. The frame of system design research of AC and DC distribution network based on flexible substation is shown in Figure 1.

![Figure 1. Framework of system design of AC and DC distribution network based on flexible substation.](image)

According to the framework and the process, research contents are divided into three parts: design of overall system, equipment parameters, as well as control and protection. On the basis above, it guides engineering site selection, system integration, modeling and analysis, equipment development, engineering construction and test.

In view of the difficulties of AC and DC distribution network based on flexible substation proposed in the introduction, this paper focuses on the innovative work done from three aspects according to a set of design framework system. The first one is the AC and DC distribution network system scheme based on flexible substation, which combines typical new energy generation scenarios and typical AC and DC load scenarios. The second is the functional requirement of core equipment. The third is the control and protection method, which combines high-power power electronics technology with distribution automation technology.

3. System scheme

The AC and DC distribution network based on flexible substation, relying on highly integrated power and power electronic equipment, needs to design a new system scheme. Combined typical new energy
generation and AC/DC load scenarios, the system design proposes to build a flexible AC and DC distribution network based on flexible substations with coordinated and interactive "source, network, and load".

This paper analyzes the application of DC voltage levels at home and abroad in various industries and related standards [13-15]. On this basis, the selection of medium voltage level focuses on three factors: power supply distance, electrical insulation and protection, system cost and design difficulty. The selection of the low-voltage DC voltage level focuses on DC load of the power supply area, the access voltage level requirements of various distributed power sources and energy storage devices, as well as the capacity ratio relationship.

The DC medium voltage side of flexible substation is DC bipolar symmetry mode. For this mode, the voltage loss is calculated according to the limit operating condition that the load is concentrated at the end of the line:

$$\Delta U = \frac{2PR}{2U_{DC2}} = \frac{PL_0}{U_{DC2}}$$  

In the formula: $U_{DC2}$ - Bipolar DC supply voltage, kV; $P$ - transmission power of line, kW; $r_0$ - unit resistance of line, $\Omega/km$; $L$ - length of line, km.

Then the voltage deviation is:

$$\Delta U\% = \frac{2PL_0}{10\times2U_{DC2}^2}$$  

The power transmitted by the DC bipolar line is:

$$P = 2U_{DC2}I$$  

Then, the relationship between the power supply distance of the DC bipolar line and the voltage loss can be obtained.

$$L = \frac{10\Delta U\%U_{DC2}}{r_0I^2}$$  

It can be known from Equation (4) that the power supply distance is proportional to the voltage deviation, and appropriately increasing the voltage deviation limit is advantageous for increasing supply distance. Considering the surrounding power grid environment, relevant factors and actual conditions, the medium voltage DC voltage level of Zhangbei AC and DC distribution network and flexible substation demonstration project is chosen to be ±10kV. Similarly, considering the access requirements of various AC and DC load, distributed power supply and electric vehicles, the low voltage DC voltage level is selected as ±375V.

The system topology structure is shown in Figure 2. AC power comes from one 110kV substation, and 10kV side is grounded by arc suppression coil. The load is data center [12], with a total load of 2.5MW, of which the server-based DC load is about 1.8MW. A flexible substation with a capacity of 10kV 5MVA/ ±10kV 5MW/ ±375V 5MW/ 380V 2.5MVA was built. The new energy source comes from one photovoltaic power station. A DC booster station with a capacity of ±10kV 2.5MW/±375V 2.5MW is built.

PET, the core equipment of flexible substation, has the ability of cutting off DC fault. It eliminates the configuration of DC circuit breaker. In order to achieve fast recovery of DC line faults, a fast disconnector is configured.

In order to meet the reliability requirements of load power, in conjunction with the fault blocking function of PET, according to the load capacity and protection action time, and considering a certain margin, a 1.5MW capacity super capacitor is arranged on the ±375V DC bus. It supports power during PET blocking, ensuring continuous and reliable power.

The DC side fluctuates at high frequency, and the voltage source converter does not have the problem of current interruption at low current. Using double clamp modular multilevel converter (MMC) topology, DC short circuit current can be suppressed. 10kV cable is short, the capacitance to ground is only 1uF. Insulated wires are used for DC lines. There is no need to configure a smoothing reactor for the project.
Because there is no magnetic isolation between 10kV AC and ±10kV DC sides, the neutral point of AC and DC is equipotential, so unipolar operation of DC side is not allowed. The pseudo-bipolar structure is chosen for DC system.

Only one end of the demonstration project is connected to the AC grid, and the blocking type converter valve can block the fault path between AC and DC. To reduce equipment, the connection transformer is not configured in this project. Since there is no connection transformer, the potential of the AC side is shifted after the single-pole ground fault occurs on the ±10kV DC side, as shown in Figure 3. The neutral point of the AC system is clamped to 10kV DC, resulting in a neutral point overcurrent.

Figure 2. Schematics of system topology structure in demonstration project.

Figure 3. 10kV AC waveforms when ±10kV DC lines occur single-pole grounding fault.

The current waveform of neutral point is shown in Figure 4 when the single-pole grounding fault occurs on the ±10kV DC side.
4. Functional requirements of core equipment

The AC and DC distribution network based on flexible substation relies on highly integrated core equipment. Many devices, including power electronic transformer, are newly developed. There is no ready-made experience for reference, which increases the difficulty of determining equipment parameters. The system design completes the parameter formulation and type design of PET, which realizes the high integration of converter, DC circuit breaker, reactive power compensation and other equipment functions.

According to the functional design of the flexible substation, PET should have the following functions:

(1) Flexible power flow control: Active power flow can be flexibly controlled, PET ports flow can be bidirectional and controlled. PET can be used as a flexible control node for distribution network. Reactive power of AC port can be flexibly controlled to realize static or dynamic reactive power support.

(2) DC fault isolation: there is no need to rely on DC circuit breaker to achieve fast DC side fault removal, and the fault current clamping time is less than 5ms. After the external faults are removed, the system state can be automatically distinguished and the function of self-healing can be realized. The load power supply can be quickly restored, and the reliability of power supply can be improved.

(3) Both highly integrated and scalable: Realize the unification of functions of several devices. On the unified hardware platform, the function configuration is optional, the capacity is expandable.

(4) Energy saving and high efficiency: Efficient access to new energy sources, users have high power efficiency and low transmission loss.

Figure 5. Schematic diagram of PET topological structure.
According to the functional requirements, the schematic diagram of PET topology in the demonstration project is shown in Figure 5.

Figure 6. Schematics of PET’s structure.

Multi-port integration is realized in the design of PET as Figure 6. The PET designed in the demonstration project has four ports, namely 10kV AC, ±10kV DC, ±375V DC and 380V AC. The power between ports can flow bidirectionally to realize flexible control.

Using clamping double sub-module (CDSM) topology structure, the fault current of medium voltage DC can be cut off, and the fault isolation can be realized without DC circuit breaker.

PET adopts highly integrated, modular and compact design. It integrates the functions of medium voltage AC/DC converter, DC/DC converter, AC/AC transformer, low voltage DC/AC converter and reactive power compensation device. As shown in Figure 7, PET 10kV AC, ±10kV DC and low voltage ±375V DC are integrated design, including high-power intermediate frequency link, and low-voltage 380V AC converter port expands according to load conditions.

Figure 7. Schematic of control system structure.
The overall power transmission efficiency of PET is not less than 95%. Under rated power, the conversion loss of medium voltage AC to low voltage DC is not higher than 4%, and the conversion loss of low voltage DC to low voltage AC is not higher than 2%.

For the selection of power devices of PET, the two components, 3300V/500A and 1700V/600A are compared.

The highest operating voltage of AC is considered as 12kV. Due to the half-bridge structure, each module bears the minimum allowable DC voltage of half of the whole bridge:

$$U_{dc_{min}} = \frac{12}{\sqrt{3}} \times \sqrt{2} \times 2 = 19.59\text{kV}$$  \hspace{1cm} (5)

DC voltage fluctuation is considered at 4%, measurement and control error is considered at 5%, then DC bus operating voltage is:

$$U_d = \frac{U_{dc_{min}}}{0.96/0.95} = 21.48\text{kV}$$  \hspace{1cm} (6)

For 3300V power component with rated DC voltage of 1.65kV, each bridge arm needs the number of SM is:

$$21.8/1.65 \approx 14$$  \hspace{1cm} (7)

For 1700V power component with rated DC voltage of 1kV, each bridge arm needs the number of SM is:

$$21.48/1 \approx 22$$  \hspace{1cm} (8)

According to calculation, the number of bridge arm modules of 3300V power component used in PET is 14, and the carrier frequency is 600Hz. The number of bridge arm modules of the 1700V power component is 22, and the carrier frequency is 1000Hz. 1700V power component has more modules, more levels, higher carrier frequency and easier harmonic suppression. At the same time, the on-state voltage drop and switching energy consumption of 3300V power component is larger than 1700V. Therefore, 1700V/600A power component is selected in this project.

Photovoltaic booster transformer has the function of constant output power control, medium voltage DC voltage is controlled by flexible substation, and low voltage DC bus voltage has the function of maximum power point tracking (MPPT). The photovoltaic booster transformer realizes that the megawatt-level capacity of photovoltaic power generation does not go through the inverter link, and is directly sent to the ±10kV DC through the DC line, which shortens the conversion link and reduces the conversion loss by about 2%.

In order to reduce the cost, overhead insulated lines are used in ±10 kV DC lines in this project. The influence of lightning overvoltage is fully considered in the overvoltage part to ensure the reliability.

5. Control and protection methods
The AC and DC distribution network based on flexible substation not only needs to realize the coordinated optimization and flexible interaction of source, network, load and storage, but also achieve high integration of multiple information and energy. Thus, the control protection strategy is significantly different from the past. This paper proposes a control and protection method combining high-power power electronics technology with power distribution automation technology.

The system design creates the system architecture based on collaborative control of “data flow” and “power flow”, and realizes the on-demand distribution of power distribution network and the optimal configuration of energy. The structural diagram of the demonstration project control system is shown in Figure 8. The control system adopts the layered optimization control method and is divided into two layers of system layer and equipment layer.

PET control system is shown in Figure 8. It adopts layered structure, which is divided into three layers: main control, valve base control and module drive control protection. PET function is realized by main control, including constant DC voltage control, reactive power control, start and stop, cross, etc. The main control generates the duty ratio of the isolation stage and modulation wave of the input stage (MMC level) for Valve Base Control (VBC), and VBC generates the pulses of each module.
Each module drives control to execute the VBC command and realize the overvoltage, overcurrent protection of module.

![Diagram](image-url)

**Figure 8.** Schematic of PET control system structure.

The DC/AC converter in PET realizes functions such as DC voltage regulation and on/off-grid switching. Increasing the active voltage control function is to prevent the 380V sectional switch from being closed to the bus fault or the permanent fault of the outgoing line.

In the AC and DC distribution network based on flexible substation, the DC fault relies on PET blocking to realize the truncation, and the action coordination is significantly different from the previous engineering. At the same time, without the connection transformer configuration, the interaction between the DC system and the AC system of this project is obvious, and the response speed, timing coordination, protection setting of the AC and DC system are very complicated. The integrated configuration of the control and protection system requires scheme to meet the characteristics of this distribution network.

**Table 1.** Switching table of control mode for each port failure condition.

| Index               | 10kV AC Port | 380V AC Port | Photovoltaic ±375V DC Port | ±10kV DC Port |
|---------------------|--------------|--------------|----------------------------|---------------|
| Normal Operation    | Active Control | Active Control | Voltage Control            | Voltage Control |
| 10kV AC Failure     | Blocking      | Active Control | Voltage Control            | Voltage Control |
| 380V AC Failure     | Active Control | Blocking      | Voltage Control            | Voltage Control |
| Photovoltaic ±375V DC Failure | Active Control | Active Control | Blocking                   | Voltage Control |
| ±10kV DC Failure    | Active Control | Active Control | Voltage Control            | Blocking       |
The system design constructs the hierarchical partition protection system architecture of the AC and DC strong coupling distribution network. Under the coordination of control and protection, the AC and DC distribution network with hierarchical locking and hierarchical recovery can fulfill self-healing.

In order to meet the maximum consumption of photovoltaics in the system, the ±10kV DC port in the demonstration project operates in a constant DC voltage control mode. And the photovoltaic is connected at maximum power. On this basis below, the control mode of each port's fault condition is switched as shown in Table 1.

In order to meet the uninterrupted power supply requirements, the equipment should have self-healing capability in the case of transient disturbance or fault. In the design process of the control and protection system, not only fault isolation but also recovery after failure should be considered.

PET is a multi-voltage class equipment, so the concept of hierarchical locking is proposed. It can ensure a highly integrated design, and the flexibility of the control protection system is also taken into consideration. In the process of fault recovery, the control and protection system cooperates with the equipment of energy storage, DC automatic closing emergency source, and adopts a method of hierarchical recovery.

The system is divided into two types: fast restart, and low-voltage charge restart. When the system has a transient short-term voltage drop, according to the overcurrent value, and considering the tolerance of the converter valve, the fault severity is distinguished by the fixed value and time coordination, the control system adopts two-stage short-time blocking protection, which can latch the converter capacitor energy and create more favorable conditions for the device to resume operation. Short-term blocking for fault crossing does not change the operation of the DC/AC, at which point the super capacitor will supply power to the load.

The demonstration project protection configuration follows the basic principles of simple and overlapping partitions. Each area protection cooperates to achieve rapid detection and isolation of faults in various areas. Dividing the protection into five areas as shown in Figure 9, it makes suitable protection configuration for each area. In order to ensure that any faults are placed in the protection zone, overlapping configurations are required between the protection zones.

![Figure 9. Map of protection partition.](image-url)
6. Conclusions
This study fully considers the requirements of new energy power generation and power users, and proposes a unique topology structure of AC and DC distribution network, establishing the system design method, and gives the concept, principle and framework of the system design including overall system, equipment parameters, control and protection. The research results were successfully applied in the first demonstration project of AC and DC distribution network based on flexible substation. This research will help to standardize the technology of medium and low voltage AC and DC distribution network, standardize the process, and promote the versatility of design, economy and technological advancement. Thereby, this research ensures design quality, improves design efficiency, lays the theoretical foundation and implementation path guidance for the application of AC and DC distribution network, and may promote the development of a new generation of power systems.

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