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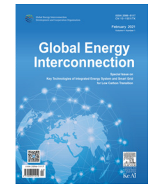

Full-length article

Key technologies for medium and low voltage DC distribution system

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Abstract: Development of the medium and low voltage DC distribution system is of great significance to a regional transmission of electric energy, increasing a penetration rate of new energy, and enhancing a safety of the operation of the AC/DC interconnected grid. This paper first summarizes the medium and low voltage DC distribution system schemes and plans put forward by many countries, and then elaborate status of under-construction medium and low voltage DC distribution system project cases in China. Based on these project cases, this paper analyzes key issues involved in the medium and low voltage DC distribution system topologies, equipment, operation control technologies and DC fault protections, in order to provide theoretical and technical reference for future medium and low voltage DC distribution system-related projects. Finally, this paper combines a current China research status to summarize and give a prediction about the future research direction of medium and low voltage DC distribution system, which can provide reference for the research of medium and low voltage DC distribution system.

Keywords: Medium and low voltage DC distribution system, System topology, Key equipment, DC fault protection, Operation control technology.

0 Introduction

With the growing penetration of distributed power generation energy, as well as a increasing demand for electric energy from DC loads such as electric vehicle charging piles, intelligent data and computing centers, and communication equipment, source-load characteristics of current medium and low voltage DC systems become more obvious [1-3].

Compared with the traditional AC power distribution system, the medium and low voltage DC distribution system has unique advantages of the DC power distribution system such as higher system capacity, longer transmission distance, and better power quality. It can also be constructed by retrofitting the AC power distribution system, which can save 25% to 30% of corridor resources [4-6]. At the

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same time, there are still some shortcomings in the DC distribution system [7-10]: (1) The lack of standardization requirements for a topology research of DC distribution system is reflected in that the planning and design of various projects is still based on the traditional AC power distribution system; (2) The internal structure of key AC and DC equipment is complicated, and the manufacturing cost is too high. These will lead to higher amount of manpower and material resource in the early construction stage and the maintenance of equipments; (3) The research on an operation control strategy of DC distribution system mainly focuses on the high-voltage transmission process but these researches are not yet mature for medium and low voltage power distribution systems.

Therefore, this article first summarizes research projects on DC distribution system in the United States, Europe, East Asia [11-13] for reference. Then, the medium and low voltage DC distribution system project cases [14, 15] in China are presented to explain the current development status, topology and the key equipment, and provide related operation control technology. The future research directions are given in the end.

1 Development status of medium and low voltage DC distribution system

At present, many countries have put forward many research plans for DC distribution systems, but the number of practices is small. In China, by renovating and retrofitting the AC power distribution network, a series of medium and low voltage DC distribution system demonstration projects have been completed.

1.1 The United States

In 2007, the CPES Center of Virginia Tech proposed the “Sustainable Building Initiative (SBI)” research plan [16]. The aim was to connect a variety of DC distributed energy sources to the original AC system to provide electric energy for future houses and buildings. With the in-depth study of the SBI project [17], the CPES Center developed the SBI project into a “Sustainable Building and Nanogrids (SBN)” research plan in 2010 [18]. It proposed to use 380V DC as the standard voltage level for industrial electricity and 48V DC was mainly used in communications, thus forming a multi-voltage level AC and DC distribution system [19].

In 2011, the North Carolina State University proposed the “The Future Renewable Electric Energy Delivery and Management (FREEDM)” system structure [20, 21] to provide a foundation for building an automatic and flexible renewable energy and management network. The FREEDM system included a “plug and play” interface, which was connected to a 400V DC bus and a 120V AC bus. It can be used to connect distributed energy and energy storage equipment to the system. At the same time, the system also had an Intelligent Energy Management (IEM) equipment [22], which was connected to a 12kV medium voltage AC distribution bus, a 120V low voltage AC distribution bus and a 400V low voltage DC distribution bus. The IEM equipment made the medium and low voltage AC power distribution system and the low voltage DC power distribution system coexist, that is, the medium and low voltage AC and DC distribution system.

1.2 Europe

In 2007, the Romanian Bucharest University of Technology proposed a dual-bus power distribution system structure [23] with two alternating power supplies of AC and DC. It connected various distributed power generation units such as photovoltaic power generation, wind power generation and biogas power generation to a 750V DC bus, and then connected the bus to the traditional AC power distribution system, thereby improving the power supply capacity and reliability of the power distribution system.

In 2008, the United Kingdom, Switzerland, Italy and other countries carried out “Universal and Flexible Power Management (UNIFLEX)” project research [24]. It researched power conversion technology of novel power electronic equipment for energy management of the European power grid with a large number of distributed power sources [25].

Aachen University in Germany put forward the “City of Tomorrow” power distribution system construction plan [26, 27]. With the medium voltage DC ring network as the backbone of the power distribution system, the original AC network and other levels of DC networks were exchanged with the medium voltage and DC ring networks through AC/DC converters and DC/DC transformers.

In 2014, Finland Elenia Oy applied low voltage DC power distribution technology in rural areas to connect low voltage 400V DC with traditional medium voltage 20kV AC and low voltage AC 400V to form a medium and low voltage DC distribution system [28, 29]. This system used power electronic technology to connect distributed power sources and energy storage equipment in parallel, which not only reduced commutation losses, but also improved the power quality, power supply reliability and economy in rural areas.

In 2015, SP Energy Networks successfully applied for the ANGLE-DC project which would construct the first medium-voltage direct current (MVDC) link in Europe

[30-32]. It demonstrated novel network reinforcement by converting an existing 33 kV double-circuit AC to DC operation.

1.3 East Asia

In 2006, Osaka University in Japan proposed a low-voltage bipolar structure AC-DC hybrid microgrid suitable [33-35] for residential buildings. It connected the ±170V DC to the 230V AC system through inverters, and integrated the energy storage equipment and distributed power supply through DC/DC transformers on the DC side, and the gas turbine was connected to the AC side through the back-to-back inverter.

In 2007, Mingzhi University took the lead in establishing the Intelligent Power Distribution System Research Center. It was expected to establish a DC microgrid power [36] supply system from 2007 to 2012, and conducted research on DC power distribution, power conversion technology. It also had control and communication technology.

In China, experts and scholars have jointly drafted and issued national standards, China Electric Union standards and corporate standards on DC power distribution systems. In the national standard GB/T 35727-2017 “Medium and Low Voltage DC Distribution Voltage Guidelines”, simplifying the voltage level, reducing the transformation level, and optimizing the network structure, which are the principles for determining the voltage level of the DC distribution system. When selecting the voltage levels, it is necessary to obey the principle proposed in [37]. It says that the ratio of the two adjacent voltage levels should be close to or exceed 3. One of the two adjacent voltage levels should be removed if their ratio is close or less than 2. In this situation, both the ratio of the transformer capacity and the reasonableness of the power supply distance are appropriate. For instance, low voltage level can be ±375 V, ±110 V and the medium voltage level can be ±35 kV, ±10 kV, ±3 kV. In addition, China Electricity Union Standard T/CEC 107-2016 “DC Distribution Voltage”, China Electricity Union Standard T/CEC 166-2018 “Medium Voltage DC Distribution Network Typical Grid Structure and Technical Guidelines for Power Supply Schemes”, CEC Standard T/CEC 167-2018 “Technical Requirements for Interconnection of DC Distribution Network and AC Distribution Network”, Enterprise Standard Q/GDW 11722-2017 “Guiding Principles for Planning and Design of AC and DC Hybrid Distribution Networks” all put forward normative requirements for the DC distribution system and provide instructions for the construction of demonstration projects. Since 2009, China has started research on the installation of DC power distribution system. At present, preliminary research results have been made on the overall planning, dispatch operation, control and protection and economic analysis of DC distribution systems which contain a large number of distributed power sources and energy storage equipment. They have been applied in demonstration projects.

At present, although DC distribution system technology is gradually becoming mature, it is of vital importance to the development of future power distribution systems. There are still many demonstration projects in China under planning, design and operation. This article will combine the existing domestic demonstration projects to introduce the system topology, key technologies, operation control technologies and DC fault protections in the medium and low voltage DC distribution system and provide theoretical and practical basis for future demonstration projects.

2 Topology of medium and low voltage DC distribution system

It is important to construct a reasonable medium and low voltage DC distribution system network topology structure which ensure the economy of system operation and improving the reliability of power supply. In this way, the technical advantages of DC distribution system can be given full play. This chapter will summarize and analyze radial, hand-in-hand, ring and multi-port structures with the current domestic DC distribution system.

2.1 Radial topology

The radial topology structure can be used as the basic structure in the medium and low voltage DC distribution system. It is the most widely used in the current projects. This structure connects the traditional medium voltage AC distribution network to the medium voltage DC system through a voltage source converter, which makes the one-time investment cost less, and is more suitable for upgrading the traditional AC distribution network. When a failure occurs on the DC side of the hand-in-hand, ring, and multi-port topology, the contactor on the DC line needs to be disconnected to ensure the continuous power supply of the load at the non-faulty location. This will split the original system into a radial topology, realizing uninterrupted power supply to loads. At the same time, the relay protection configuration of the radial medium and low voltage DC distribution system is relatively easy to facilitate fault identification. However, when the AC/DC main bus fails, it will affect the power supply reliability of the entire DC distribution system network. Therefore, this structure can be used in occasions where the power supply range is small, the AC and DC loads are relatively concentrated, and the original system needs to be re-upgraded and constructed through technological transformation. The DC microgrid demonstration project in Shangyu uses a radial topology [38, 39], as shown in Fig. 1.

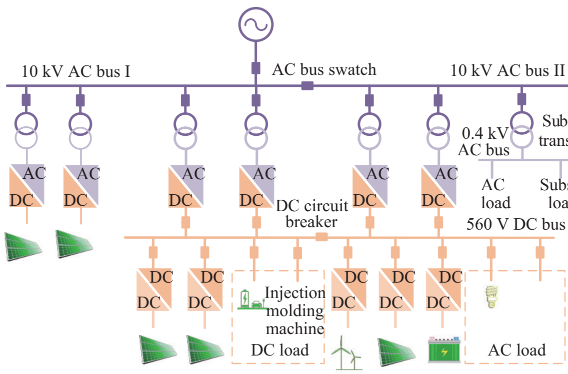


Fig. 1 Topology of the DC microgrid demonstration project in Shangyu

The DC microgrid demonstration project in Shangyu is located in Shangyu economic development zone, Shaoxing city, Zhejiang province. The company is mainly engaged in the production of automotive plastic parts. The main DC loads in the field including injection molding machines, LED lightings and DC power supplies are distributed photovoltaics. In the process of constructing and reconstructing project, it is necessary to fully consider the distributed characteristics of DC loads and DC power, and issues such as ensuring power supply to important loads in the site when a failure occurs outside the plant area. Through comprehensive analysis, the DC microgrid demonstration project in Shangyu can adopt transformation and reconnection methods to combine the original medium voltage AC system with the medium voltage DC network. In this way, the project construction could upgrade the plant area and reduce the impact on the enterprise. Therefore, the radial topology was chosen for this demonstration project.

2.2 Hand-in-hand topology

The hand-in-hand topology has relatively higher power supply reliability than the radial topology. The reason is that the medium voltage DC distribution system is connected to the medium voltage AC distribution network through two connection points. The bus of the medium voltage DC distribution system between two AC connection points can be connected to distributed power sources, energy storage equipment and DC loads according to actual conditions. A low voltage DC grid can then be connected to the medium voltage DC grid through DC/DC converters that adopt the input series output parallel (ISOP) multiple modular structure in order to form a medium and low voltage DC distribution system. Although the hand-in-hand topology can improve power supply reliability and quickly locate faults, thereby reducing power outage losses, it also puts forward higher requirements for the coordination of protection control and fault identification. Therefore, this topology can be used for user groups with higher power quality requirements. The DC distribution demonstration project in Baolong industrial district adopts a hand-in-hand topology [40-43], as shown in Fig. 2.

The DC distribution demonstration project in Baolong industrial district is located in the middle of Longgang district, Shenzhen. There are 41 state-level high-tech enterprises in this area which are characterized by abundant renewable energy, concentrated sensitive loads and DC loads. Based on the above analysis, the DC distribution demonstration

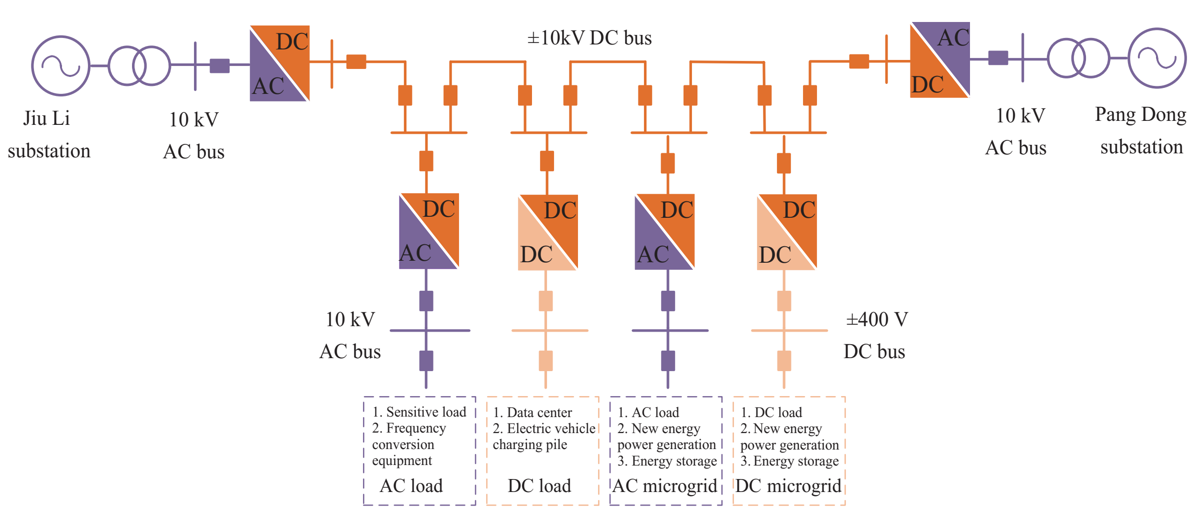


Fig. 2 Topology of the DC distribution demonstration project in Baolong industrial district

project in Baolong industrial district adopts the hand-in-hand topology to improve the absorption capacity and energy storage capacity of renewable energy in the region. It guarantees high-tech manufacturing companies different voltage levels of DC voltage and high-quality power quality.

2.3 Ring topology

The ring topology can connect the medium voltage DC power distribution system and the traditional medium voltage AC power distribution network in a single-ended or multi-ended manner. In addition, distributed renewable energy, energy storage systems, and AC and DC loads can be connected to the medium and low voltage DC power distribution system at multiple points, so that the system can supply power to a wider area. Compared with radial and hand-in-hand topologies, the coordination requirements for fault identification and protection control of ring topology in the medium and low voltage DC distribution system are the most challenging. Therefore, this structure is suitable for occasions with high requirements for power supply reliability and multi-point access to sources and loads. The medium-voltage DC distribution system demonstration project in Suzhou adopts ring topology structure [44], as shown in Fig. 3.

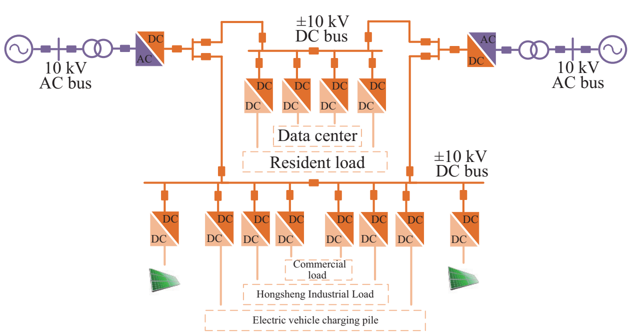


Fig. 3 Topology of the medium-voltage DC distribution system demonstration project in Suzhou

The medium-voltage DC distribution system demonstration project in Suzhou is located in Wujiang district, Suzhou city. This area is rich with DC power and load resources but there are problems with uneven distribution of DC sources and loads. At the same time, the area has 6 typical DC power consumption scenarios, such as civil loads, commercial loads, municipal government office areas, data centers, etc. They should be promised to ensure the reliability of power supply to important loads. Therefore, consideration should be given to the location of converter stations, the distribution of DC sources and loads and the access to renewable energy sources during planning. Through comprehensive analysis, the medium-voltage DC distribution system demonstration project in Suzhou can adopt a ring topology to meet the multi-terminal access of distributed new energy to the medium and low voltage DC grid so as to accommodate nearby renewable energy and meet the power demand of DC loads.

2.4 Multi-port topology

Compared with the other three topologies, the multi-port topology has a more flexible way of AC and DC energy exchange, that is, the conversion between AC and DC is realized through the converter of each port. It can ensure that the load in the system works normally when one of the ports or several ports exit operation. This topology has the characteristics of flexible control strategy, high reliability of power supply, and good scalability, so it is also widely used in various domestic demonstration projects. The flexible DC distribution system demonstration project in Guizhou and the three-terminal flexible DC distribution system demonstration project in Zhuhai Tangjiawan [45, 46] adopts the multi-port topology, as shown in Fig. 4 and 5.

It can be seen that the topology selection of the medium and low voltage DC distribution system should fully consider the geographical environment, the distribution characteristics of renewable energy, and the importance of DC load, and maximize the advantages of the medium voltage DC distribution system to ensure the reliability and economy of operation.

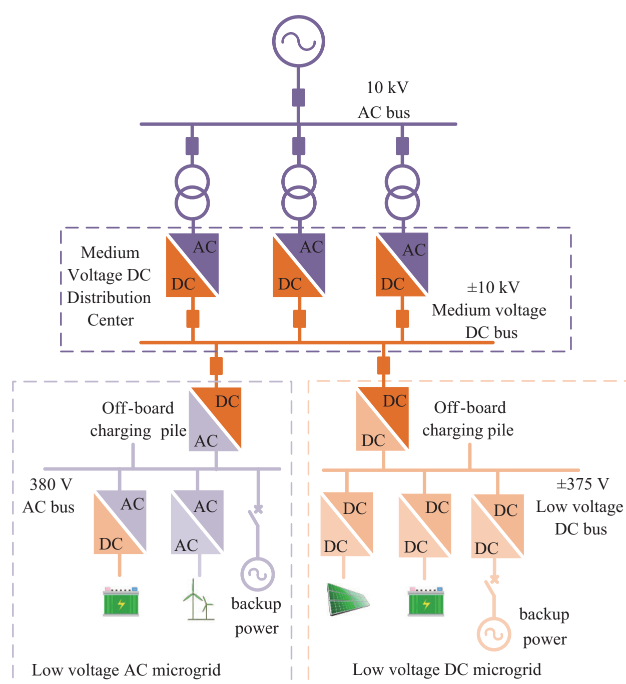


Fig. 4 Topology of the flexible DC distribution system demonstration project in Guizhou demonstration project

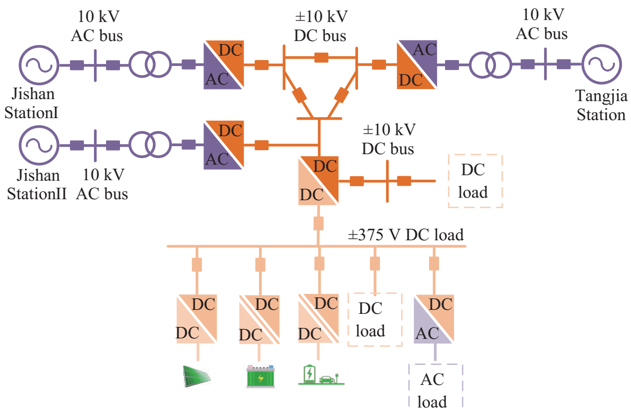


Fig. 5 Topology of the three-terminal flexible DC distribution system demonstration project in Zhuhai Tangjiawan

3 Key equipment of medium and low voltage DC distribution system

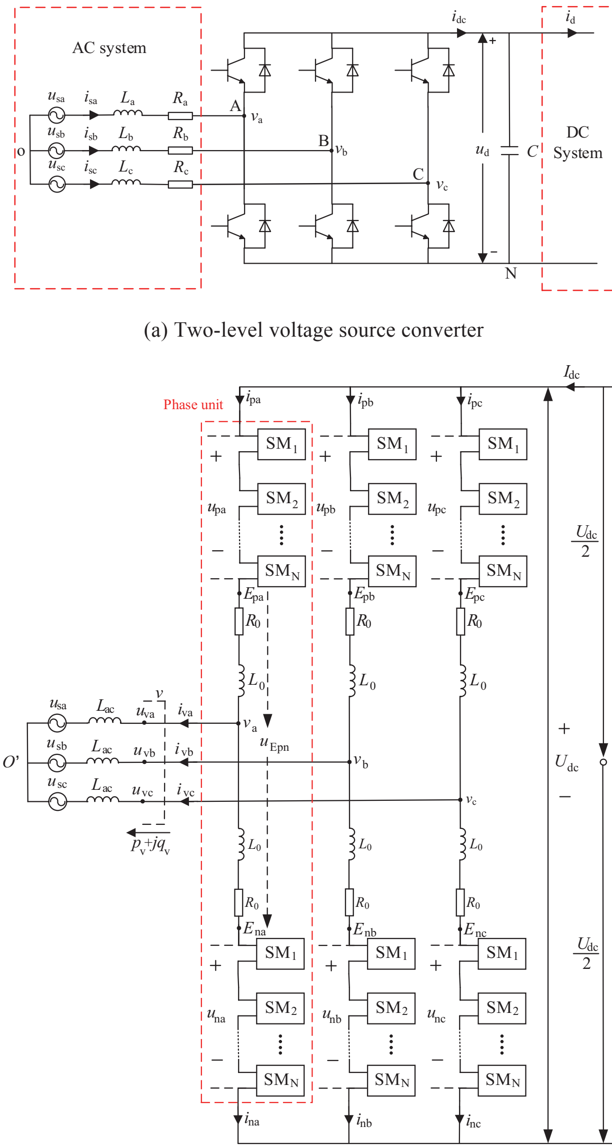
The medium and low voltage DC distribution system is a flexible power distribution system containing the variety of power electronic equipment. The power electronic equipment plays a vital role in the medium and low voltage DC distribution system.

3.1 Voltage source converter

At present, in the medium and low voltage DC distribution system, the voltage source converter (VSC) as the key equipment can realize energy exchange between AC and DC buses. And the AC and DC systems can support each other through its internal energy flow. According to different engineering configuration requirements, VSCs mainly have three topological structures which are two-level, three-level and modulator multilevel converter (MMC). When choosing a suitable VSCs type, factors such as equipment rated capacity, reliability, harmonic indicators, and investment costs need to be considered.

The DC distribution demonstration project in Baolong industrial district uses two-level converters and MMC [47, 48], as shown in Fig. 6. Among them, a VSC needs to connect AC and DC systems with two voltage levels that are low voltage and medium voltage, respectively. When considering the small capacity of VSC equipment connected to the low-voltage AC and DC system, and the lower requirements for voltage and reactive power control a two-level VSC is selected to reduce the investment cost. A VSC requires a large capacity and has high requirements for reliability and harmonics at that time it connects to the medium-voltage AC/DC system, so the MMC converter is selected.

The medium-voltage DC distribution system demonstration project in Suzhou uses a hybrid sub-module MMC converter. The two medium voltage AC and DC converters are respectively selected based on the half bridge submodule MMC (HBSMMC) topology and the half/full-bridge hybrid MMC (HMMC) topology. Fig. 7 shows the submodule topology. The design takes into account both the requirements for power supply reliability, and the fault ride-through capability and the converter fault self-clearing capability. It also reduces the high investment cost brought by the hybrid MMC design to a certain extent.



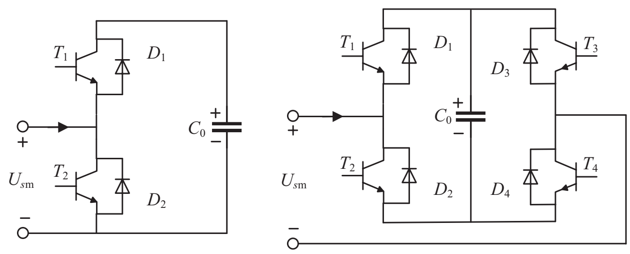
(a) Two-level voltage source converter

(b) Modulator multilevel converter (MMC)

Fig. 6 Topology of two-level voltage source converter and MMC

3.2 DC transformer

Generally, DC transformers usually adopt the input series output parallel (ISOP) multiple modular structure in the



(a) Half bridge submodule (b) Full bridge submodule

Fig. 7 MMC submodule topologies

medium and low voltage DC power distribution system. This structure has the advantages of a small number of modules, easy realization of soft switching characteristics and high power density. It can be applied to medium and low voltage DC voltage conversion occasions in actual projects.

Each module in the ISOP type uses a high-frequency isolation dual active bridge (DAB) structure, as shown in Fig. 8. Usually, each submodule is connected in series on the high voltage side to make it evenly divide the voltage on this side, and then through the H-bridge circuit and high frequency isolation transformer, the high voltage obtained on the high voltage side is converted into the DC current on the low voltage side. Finally, it is connected in parallel on the low voltage side to improve power transmission. Each sub-module can adopt DAB non-resonant, CLLC resonant and LLC resonant soft switching technologies, which have the characteristics of phase shift control, simple control, and two-way power transmission, which achieve the advantages of reducing device loss, reducing equipment volume, and electrical isolation on the high and low voltage sides. The Shangyu AC/DC demonstration project, the Baolong Industrial City DC distribution demonstration project, the Suzhou medium and low voltage DC power distribution system demonstration project, and the Guizhou distribution network flexible DC transmission demonstration project all used ISOP DC transformers.

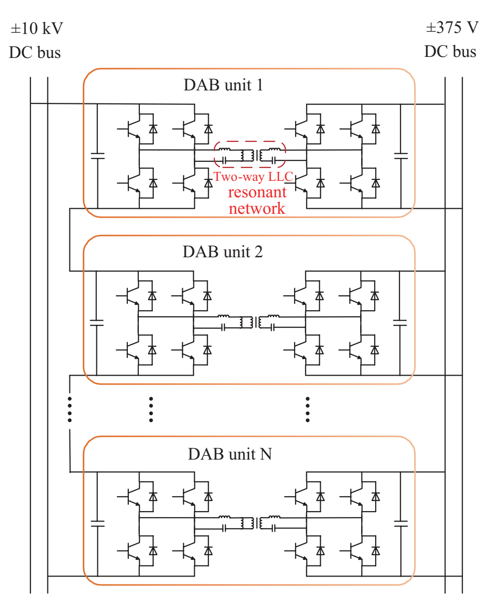


Fig. 8 Topology of DC/DC converter based multi structure

3.3 DC circuit breaker

The DC circuit breaker faces two major problems in the development process. On one hand, when the current is interrupted, the arc cannot be extinguished since the DC current does not have a natural zero crossing point. On the other hand, a large amount of energy is stored in inductive components in the DC system, which will increase the difficulty of DC fault current interruption. Therefore, hybrid DC circuit breakers have been proposed. The hybrid DC circuit breaker, as shown in Fig. 9, adopts a mechanical and power electronic hybrid structure, which combines the good static and dynamic characteristics of the two. It has the characteristics of rapid breaking, high reliability, simple control and low operating loss. At present, the DC distribution demonstration project in Baolong industrial district adopted hybrid DC circuit breakers, which can meet the needs of medium and low voltage DC power distribution systems.

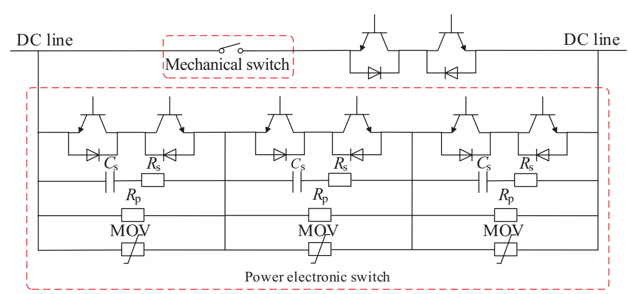


Fig. 9 Topology of hybrid DC circuit breaker

At the same time, the new city smart flexible DC distribution network demonstration project in Hangzhou Jiangdong develops a DC circuit breaker based on the principle of magnetic coupling transfer. As shown in Fig. 10, the main branch of this scheme has no power electronic equipment switches and the magnetic coupling equipment

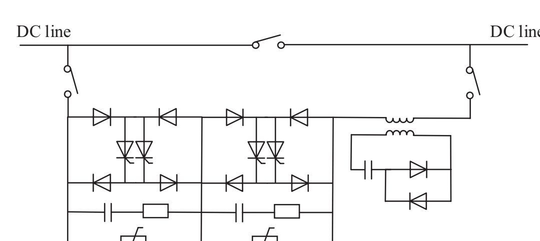


Fig. 10 Topology of DC circuit breaker based on magnetic coupling transfer principle

realizes current transfer and electrical isolation of the high and low voltage sides which improves the reliability of power supply. At the same time, the bridge diode structure realizes bidirectional current breaking, reducing the cost of the DC circuit breaker.

It can be seen that when selecting equipment for medium and low voltage DC distribution systems. It is necessary to consider voltage matching and energy interaction issues between AC and DC grids of different voltage levels to ensure safe and reliable operation of the system.

4 Operation control technology of medium and low voltage DC distribution system

The traditional medium voltage AC network is connected to the medium voltage DC network through VSCs to realize the parallel operation of the two networks, and the operation control strategy is determined according to the network topology of the medium voltage AC and DC distribution system and the power electronic equipment. The DC distribution demonstration project in Baolong industrial district has typical features, so this chapter takes this project as an example.

4.1 Control strategy under grid-connection mode

Under normal circumstances, the system runs in grid-connected mode through VSCs. In this mode, it can be divided into 6 operation modes. They are multi-terminal power supply operation mode, single-ended power supply operation mode, multi-terminal isolation operation mode, power support operation mode, STATCOM operation mode and back-to-back operation mode respectively.

The DC power distribution demonstration project of Baolong industrial city has 4 types of typical loads. As shown in Fig. 2, they are AC and DC loads that need to absorb power from the power distribution system and AC microgrids and DC microgrids with distributed power generation technology and energy storage technology that perform two-way power transmission with the power distribution system. It can be seen that in the medium and low voltage DC distribution system. According to different load types, power electronic equipment needs to have corresponding control strategies, as shown in Table 1.

In the multi-terminal power supply operation mode, the network topology of the DC distribution demonstration project in Baolong industrial district is hand in hand, that is, the power supply operation mode at both ends. According to the pre-determined priority, one end adopts constant DC voltage control and the other end adopts droop control or constant power control.

Table 1 Typical power electronic equipment in the medium and low voltage AC/DC power distribution system

Category	Equipment	Connection object	Control ability
1	Unidirectional DC/AC Inverter	AC load that only absorbs power in the bus of medium voltage DC power distribution system	AC side: constant voltage, constant power control
2	Unidirectional AC/DC Inverter	Independent AC generating equipment for busbar of medium voltage DC power distribution system	DC side: constant voltage, constant power control
3	Unidirectional DC/DC Inverter	DC load or DC microgrid where the bus of medium voltage DC power distribution system only absorbs power	DC load side: constant voltage control or DC microgrid side: constant voltage and constant power control
4	Two-way AC/DC converter	AC microgrid with two-way power transmission in bus of medium voltage DC power distribution system	DC side: constant voltage control AC side: constant voltage, constant power control
5	Bidirectional DC/DC transformer	DC microgrid with two-way power transmission in the bus of medium voltage DC power distribution system	DC distribution network and load side: constant voltage and constant power control

When the VSC at one end of the medium-voltage DC distribution system fails, the AC/DC system can only transmit power through another bidirectional AC/DC converter which is a single-ended power supply operation mode. In this case, the non-fault side AC/DC converter controls the voltage of the medium voltage DC bus and other equipment connected to the medium voltage DC system maintain the original control strategy.

When the medium voltage DC bus is disconnected, the original hand-in-hand topology is transformed into two radial topologies and the AC/DC converters at both ends are controlled by constant DC voltage to ensure that each medium voltage DC power distribution system has voltage stable. At this moment, it is a multi-terminal isolation operation mode. In this demonstration project, it is a dual-terminal isolation operation mode.

When the AC system at one end fails, the premise of the DC power distribution system can provide power support to the AC grid. At the same time, the DC system will provide short-term support in the power support operation mode to ensure that the faulty AC system provides uninterrupted power supply to important loads. The AC/DC converter on the fault side uses a constant AC voltage control strategy and the other end uses a constant DC voltage control strategy.

When operating in STATCOM mode, the two AC/DC converters connect to the medium-voltage AC/DC system operate in STATCOM mode. They respectively provide reactive power compensation for the AC side, but they do not provide active power transmission for the system.

In the back-to-back operation mode, the AC and DC loads are both off-grid in the medium voltage DC distribution network and the microgrid. At this moment, the two medium voltage AC distribution networks realize asynchronous interconnection. Without changing the original AC system structure, the AC/DC converter adopts constant DC side voltage control and power control strategies which can improve the reliability of power supply and power quality.

4.2 Control strategy under islanding mode

When the medium voltage AC power distribution system has a permanent failure or the VSC connected to the medium and low voltage AC and DC system fails, the medium voltage AC and DC system needs to be decoupled to operate, that is, the island operation mode. The control strategy is also different from grid operation.

In island operation, the distributed power and energy storage equipment in the system need to support the bus voltage stability of the medium voltage DC system. This kind of operation needs coordinate control strategies to realize the recovery of the medium voltage bus voltage, maintain the stability of the important load voltage and control the power of distributed energy.

When restoring the medium voltage DC bus voltage, the AC and DC microgrid needs to provide power to the bus. Among them, the VSC connected to the AC microgrid and the medium voltage DC bus is a two-way AC/DC equipment. The AC side uses voltage control and the DC side uses voltage control and reactive power control. At the same time, the DC transformer connected to the DC microgrid and the medium voltage DC bus also has the function of bidirectional power flow. These voltages on the high voltage side and the low voltage side are both controlled to ensure the voltage stability of the medium voltage DC bus.

In island operation, maintaining the stability of important load voltage is crucial. The load in the system needs to supply power to the important load according to the pre-determined priority while disconnecting the load with low priority. The useful work power only flows from the medium voltage DC bus to the load side. At this moment, the VSC AC side connects to the important AC load and the low voltage side of the DC transformer connected to the important DC load need to be controlled by voltage. Using this method can ensure uninterrupted power supply to important loads during island operation.

Distributed power generation and energy storage equipment are the only energy supply unit in island operation. It can issue active power transmission instructions according to the state of energy storage state of charge (SOC). At the same time, the distributed power generation unit needs to coordinate the energy storage equipment not only to prevent the SOC from being too high but also to ensure the supply of stable electric energy to the medium voltage DC bus.

5 DC fault protection of medium and low voltage DC distribution system

The protection technology is one of the key technologies to ensure the high efficiency and reliable operation of low and medium voltage DC distribution system. It can promote the development of DC distribution system. At present, the protection technology of medium voltage DC power distribution system is divided into two aspects that are device level and system level. Whether to use the DC circuit breaker to cut off the fault current has become a hot topic.

Form the protection level of equipment, circuit breakers cut off the DC side fault current when VSCs adopt topological structures which are two-level, three-level and

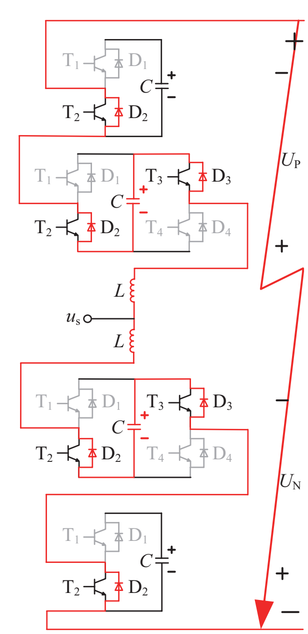


Fig. 11 Blocking current limiting operation

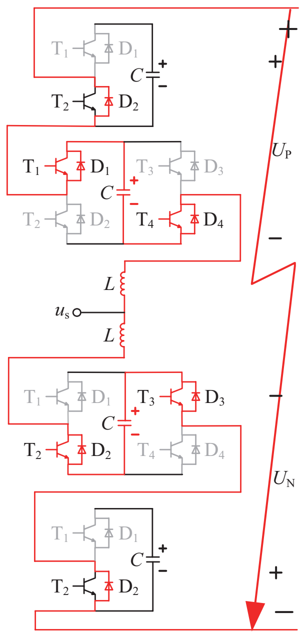


Fig. 12 Fault ride-through limiting operation

half bridge submodule MMC. Form the protection level of equipment, circuit breakers cut off the DC side fault current when VSCs adopt topological structures which are two-level, three-level and half bridge submodule MMC.

VSCs adopt full and half bridge submodule hybrid MMC in the medium-voltage DC distribution system demonstration project in Suzhou. Fig. 11 adopts blocking current limiting operation. After detecting the fault, all the switching devices of SMs of the converter are blocked, so that the sub-module capacitors are reversely connected into the fault circuit. The fault current charges the sub-module capacitors. The fault point is subjected to reverse voltage, thereby blocking the DC fault current.

Fig. 12 adopts fault ride-through operation. Under this operation, the converter controls and limits its DC side current actively by reducing the DC side voltage of the converter station. The converter is still operating in STATCOM mode during the fault period, which can provide reactive power support to the AC system. After the fault is isolated, the power supply can be quickly restored through this operation mode.

Form the protection level of system, although medium and low voltage DC distribution system can use the protection strategies of AC distribution system and HVDC transmission system, DC distribution system has more complex features such as lots of electronic equipment, loads and faults. That is to say, the overall optimal configuration of medium and low voltage DC distribution system protection will be the key research direction of DC protection technology.

6 Conclusion

This article summarized the demonstration projects of China's medium and low voltage DC distribution system. It analyzed and discussed system topologies, the key equipment, operation control technology and DC fault protection.

(1) In terms of system design, this article describes 4 system topologies, analyzes the advantages and disadvantages of various topologies, then gives their applicable scenarios. It is pointed out that the AC and DC distribution network is a DC system with multiple voltage levels which can realize the safe and reliable access of a large number of distributed power sources, energy storage equipment, and AC and DC hybrid loads to the system. These can provide references for the differentiated needs of future demonstration projects.

(2) The development of medium and low voltage DC distribution systems requires the support of equipment, such as VSCs, DC transformers and DC circuit breakers. These development speeds largely determine the development level of the system. At present, the key equipment still has problems such as inability to coordinate control, low efficiency and inability to be applied in projects. As a result, the DC distribution network cannot meet the requirements of power supply reliability. Therefore, it is necessary to accelerate the speed of research on the key equipment of medium and low voltage DC power distribution systems.

(3) The medium and low voltage DC distribution system has multiple voltage levels and also includes DC loads, AC loads, DC microgrids, AC microgrids. This article only provides equipment-level control technology. It is necessary to study the optimal operation and stable control of the system based on the ideas of "local autonomy" and "regional coordination".

(4) Protection with the purpose of reliability and selectivity not only relies on equipment to isolate faults, but also adopts applicative configuration in medium and low voltage DC distribution systems. The protection strategy of DC distribution system can refer to few regulations. In the future, feasible protection strategies can be provided for projects according to various operating conditions.

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Declaration of Competing Interest

We declare that we have no conflict of interest.

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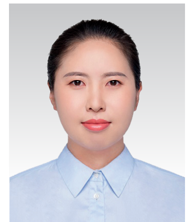
Biographies



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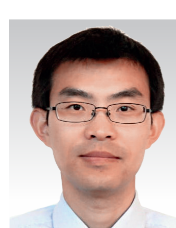

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