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A Novel AC-DC Hybrid Distribution Network Topology and its Characterization Analysis

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Abstract:
With the extensive access of distributed new energy and the continuous growth of new loads, AC/DC hybrid distribution network has become a research hotspot of new distribution network. The choice of topology is very important for the construction of AC/DC hybrid distribution network. Accordingly, this paper proposes a new AC/DC hybrid distribution network topology based on the actual needs of a demonstration project. The structure combines the advantages of annular structure and radial structure, which can provide a more efficient and stable construction scheme for AC and DC power supply systems with multiple voltage levels and multiple bus structures. In this paper, various characteristics of the structure are studied through simulation analysis. The results show that the topology distribution network can quickly recover to a stable working state in the face of voltage changes caused by source-load switching and can effectively cope with the fluctuation of photovoltaic output in the system due to environmental changes, which in turn leads to voltage fluctuations. In addition, the distribution network of this structure has a high power transmission efficiency.

Keywords: AC-DC hybrid distribution network; topology; converter; voltage sag; voltage pulsation

1.INTRODUCTION

With the large-scale access of distributed new energy sources and the continuous input of new types of loads such as electric vehicles, the traditional AC distribution network is facing a unprecedented challenge. In order to improve the transmission efficiency and power supply reliability of power grids, AC/DC hybrid distribution networks emerged. In the construction of AC/DC hybrid distribution networks, the choice of topology will directly affect the operation efficiency and power supply reliability of the grid, and the ability to consume renewable energy. Therefore, it is crucial to dig deeper in the research of the topology of AC/DC hybrid distribution grids.

Nowadays, for the AC-DC hybrid distribution network topology, literature [1] establishes a DC distribution network topology optimization and control method based on battery energy storage, which effectively improves the reliability and economy of the distribution network by determining the optimal reactive power compensation point and using the continuous tidal current method to calculate the load threshold. Literature [2] proposes a new single conductor AC/DC hybrid distribution network topology, which can realize the coupling and decoupling of AC/DC power avoiding iron core saturation. Literature [3] puts forward the concept of AC-DC hybrid microgrid for renewable energy, and four typical grid structures are summarized and analyzed. Literature [4] puts forward a new type of AC/DC microgrid structure for the smart energy station power supply system of "multiple stations in one", which improves the power supply reliability by adopting a DC load switch, optimizing the sequence of voltage levels, and designing the power supply equipment. Literature [5] analyzed the AC/DC hybrid distribution network with different wiring methods and proposed an AC/DC hybrid distribution network model based on intelligent soft switches and flexible ring devices. Literature [6] summarizes the typical application scenarios of AC-DC hybrid distribution networks. Literature [7] proposes a novel single conductor AC/DC distribution network topology, aiming to solve the problem of interconnecting renewable energy with distribution networks. Literature [8] proposes an emergency control method based on Deep Graph Reinforcement Learning (DGRL) for the emergency control problem in the topology change scenario of the AC-DC hybrid grid. Literature [9] proposes a new topology based on Hybrid Active Power Filter (HAPF), which effectively solves the harmonic problem in AC-DC hybrid distribution networks. Literature [10] designs three new types of AC-DC hybrid microgrid topologies, one-to-many type, many-to-one type, and many-to-many, from topology design. Literature [11] proposes three types of new AC-DC hybrid microgrid topologies considering the composition and operation mode of AC-DC hybrid microgrids. Literature [12] analyzes two typical application scenarios for urban distribution grids and industrial park distribution grids. Literature [13] proposes a three-stage type PET (Power Electronic Transformer) topology with multiple types of interfaces, which provides a new solution for power conversion and power quality control in AC/DC distribution networks. Literature [14] proposes a new modular AC-DC hybrid microgrid topology for the design and operation requirements of microgrid modular access and friendly interaction with the larger grid.

Hybrid AC-DC distribution grids integrate the advantages of AC and DC systems and can adapt to growing distributed power sources and DC loads. Despite the progress made in topology research, there are still challenges in practical applications, especially in ensuring power quality and promoting the effective utilization of renewable energy. In this paper, we address these issues and design a new hybrid AC-DC distribution network topology with practical engineering examples. The structure combines the advantages of ring and radial topologies to provide an efficient and stable solution for multi-voltage and multi-bus systems and verifies its performance by simulation

2.SELECTION OF VOLTAGE LEVELS FOR AC-DC HYBRID DISTRIBUTION NETWORKS

Since the demonstration project is a DC transformation on a 10kV AC system, we only need to select the voltage level of the new DC distribution network. According to the requirements of the national standard "Medium and Low Voltage DC Distribution Voltage Guidelines" (GB/T35727-2017), it is necessary to carry out the selection of low-voltage voltage levels and medium-voltage voltage levels.1.1Low-voltage voltage level selection

As shown in Figure 1, the selection of low-voltage voltage levels should mainly consider the access voltage level requirements of DC loads in the power supply area, various types of distributed power sources, and energy storage devices. Therefore, this paper fully considerates the demonstration project area of various types of DC equipment interface voltage (electric vehicle charging pile interface voltage level, storage battery voltage level, data center power supply voltage level, etc.) and the interface device voltage withstand level, personal and equipment safety in combination with the existing DC power distribution voltage standards. Then we initially determine that the low voltage voltage level of the alternative values should be ± 1.5kV, ± 750V, 380V, ±375V, 220V, ±190V, and 48V. According to the requirements of simplifying the voltage level, reducing the transformer level, and optimizing the network structure of the "Medium and Low Voltage DC Distribution Voltage Guidelines" (GB/T35727-2017), this paper, by the principle of "sacrificing the less to achieve more" and the principle of "geometric mean", further selects the alternative value of low voltage level. And we get the optimal low voltage voltage level program： ±1.5kV, ±0.75kV, ± 0.375kV.

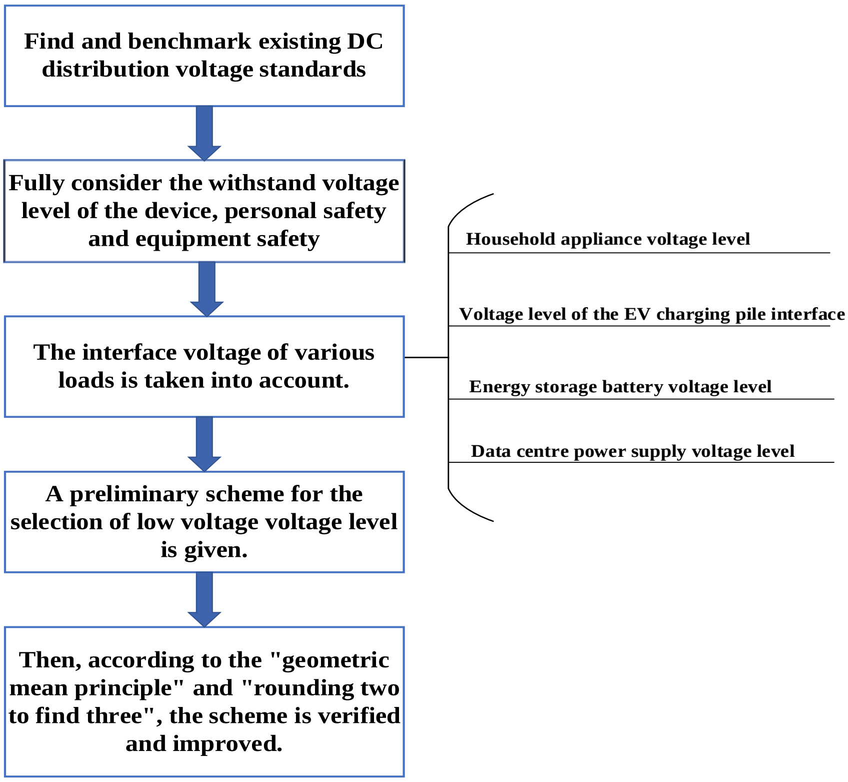

Fig. 1 Low-voltage DC voltage level selection process.

2.1 Medium voltage level selection

For the 10KV AC system that exists in the demonstration project area according to the AC-DC conversion relationship, this paper comprehensively considers the economy, reliability, and adaptability of the construction of a medium-voltage DC distribution network. Combined with the “medium and low voltage DC distribution voltage guidelines” for medium voltage distribution voltage standards (as shown in Table 1), we determine the ±6kV, ±10kV, and ±20kV three voltage levels as alternative values. Then, a comprehensive analysis is carried out from three aspects, such as construction cost and operation cost, reliability of some devices like converter stations and DC transformers, and adaptability to loads and power sources, etc. Finally, the comprehensive evaluation of different voltage levels of distribution networks is carried out according to the process of establishing the architecture, comparing and examining the importance of each layer of elements, and obtaining the overall weight of the system [15], and the MV voltage level of ±10kV is obtained as the final selection scheme.

Tab. 1 The voltage level of the medium voltage DC distribution network recommended by the "Medium and Low Voltage DC Distribution Voltage Guidelines" standard

Preferred value (kV)	Alternative value (kV)
—	±50
±35	—
—	±20
±10	—
—	±6
±3	—
3（±1.5）	—

3.HYBRID AC/DC DISTRIBUTION SYSTEM ARCHITECTURE

3.1Converter Selection

Currently, the main converters that have been maturely applied in the field of flexible DC transmission are PWM two-level converters, three-level converters, and Modular Multilevel converters (MMC). We select the MMC converter with six submodules as the current converter for AC/DC hybrid distribution networks because of its higher power factor, lower harmonic content of the AC measured current, higher transmission capacity, and higher voltage withstand level. The topology of its main circuit is shown in Fig. 2 [16], where the MMC rectifier will generate seven levels of voltage on the AC side due to six submodules in each bridge arm [17]. The equations for the upper and lower bridge arms of the MMC rectifier are obtained from the KVL equation:

$$-\frac{\mathrm{U_{dc}}}{2}+u_{pj}-R_0 i_{pj}-L_0\frac{di_{pj}}{dt}-L_{sj}\frac{di_{vj}}{dt}+u_{sj}-u_{oo'}=0 \tag{1}$$

$$\frac{\mathrm{U_{dc}}}{2}-u_{nj}+R_0 i_{nj}+L_0\frac{di_{nj}}{dt}-L_{sj}\frac{di_{vj}}{dt}+u_{sj}-u_{oo'}=0 \tag{2}$$

Through Eq. (1) and Eq. (2), we can further obtain the difference equation:

$$-u_{diff\,j}-\frac{R_0}{2}i_{vj}-(\frac{L_0}{2}+L_{sj})\frac{di_{vj}}{dt}=u_{oo'}-u_{sj} \tag{3}$$

In order to facilitate the modeling control, let L=L0/2+Lsj, and the Raschel transform is obtained:

$$\begin{cases}(sL+R)i_{vd}=u_{sd}-u_{diffd}+\omega Li_{vq}\\(sL+R)i_{vq}=u_{sq}-u_{diffq}+\omega Li_{vq}\end{cases} \tag{4}$$

In the control part of the MMC converter, the carrier phase-shift modulation technique of PWM modulation is used to generate the control signals for six submodules in a bridge arm. To enable the converter to complete the current exchange task efficiently and maintain the equalization of the sub-module capacitor voltages, this paper adopts a hierarchical additional equalization algorithm applicable to carrier-phase-shift modulation to keep the equalization of the sub-module capacitor voltages. The working principle is based on the difference between the actual value of the submodule capacitance-voltage and the given value, as well as the nature of the current in the main circuit, and adds a corresponding component to the modulating signal generating part in the control circuit, to realize the maintenance of the equalization of the submodule capacitance voltage.

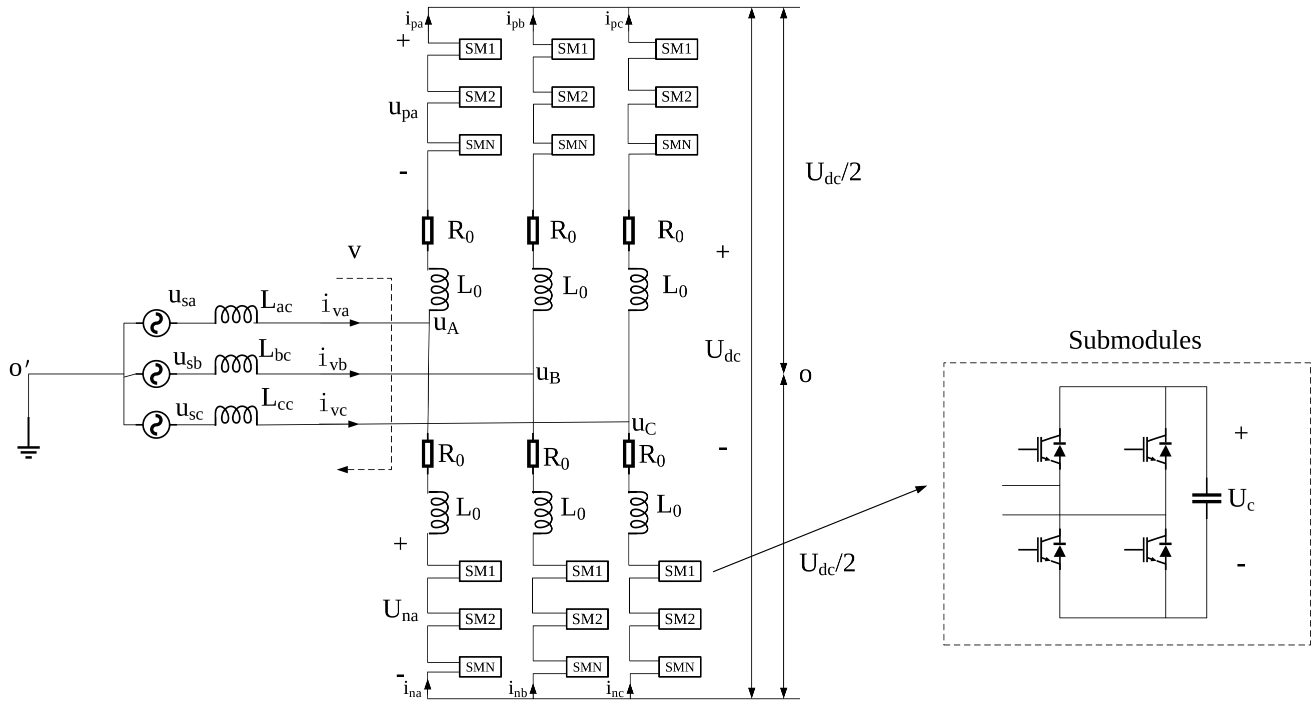

Fig. 2 MMC Topology Diagram

3.2 Selection of wiring method

Considering the high demand for power transmission capacity in the demonstration project area and the high demand for power supply reliability of important loads such as data centers, this paper adopts a true bipolar wiring method as shown in Fig. 3.On the one hand, the true bipolar wiring method has a larger transmission capacity compared with other wiring methods to meet the power supply needs of the region; on the other hand, when a converter or a pole of the DC bus in the system fails, the true bipolar wiring method of the distribution network can also realize the single-pole operation, which ensures the reliability of the power supply for important loads. In addition, the true bipolar wiring system can also provide positive and negative symmetrical DC transmission lines, which can not only match the selection of voltage level but also provide the necessary power supply flexibility.

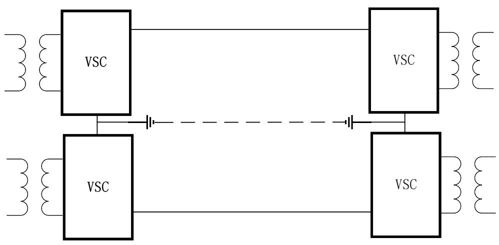

Fig. 3 True bipolar wiring

3.3 Selection of busbar construction

According to the load characteristics and the true bipolar wiring of the demonstration area method, in the same voltage, we select a double busbar structure. In addition, because the distribution network has four voltage levels, DC10kV, DC1.5kV, DC750V, and DC375V, the overall hierarchical bus structure shown in Figure 4 is adopted. In this structure, the interconnection of DC buses of adjacent voltage levels is implemented through DC transformers, which makes the distribution network adapt to all kinds of DC loads and reduces the use of adapters for loads. At the same time, this structure can also realize the isolation between different voltage levels, which improves the security of the power supply.

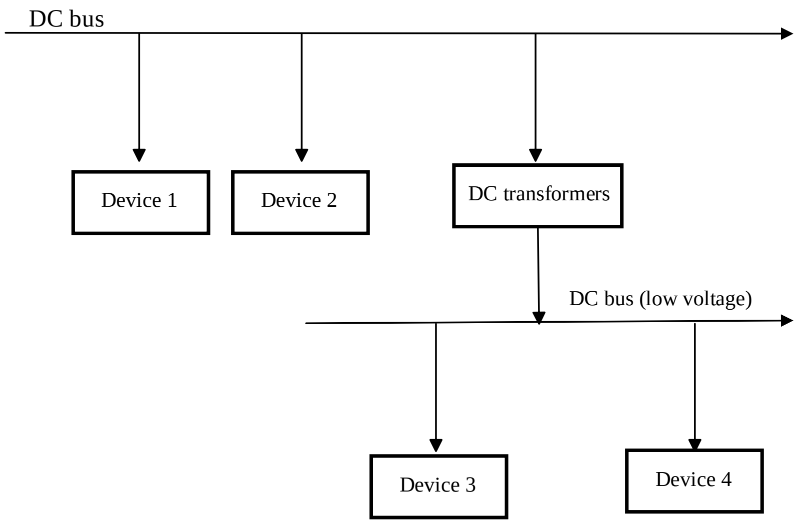

Fig.4 layered bus structure

3.4 New AC-DC hybrid distribution network topology

Currently, the main topologies are radial, two-end distribution, and ring [24]. Among them, the radial structure distribution network has a lot of advantages: simple structure, low requirements for control and protection, easy operation, and high efficiency of power transmission, but this structure is less reliable and not applicable to power supply scenarios containing important loads. The reliability of the two-end distribution type and the ring structure has been improved, but it is relatively difficult to identify faults and cooperate with protection and control. In addition, due to the extensive use of power adapters, the power transmission efficiency of the distribution network under these two structures is low. In summary, combining the characteristics of multi-voltage level and multi-bus structure in the demonstration project area, this paper designs a hybrid structure of DC power supply system topology, as shown in Fig. 5. In this structure, the ring-like distribution network structure is adopted to guarantee the reliability of the power supply of the 10kV bus. Provide bipolar voltage to improve the power supply capacity of the distribution network. Select the other voltage levels that are similar to the radial DC distribution network structure, giving full use of its simple structure, low cost, high efficiency of power transmission, and relative ease of identifying the faults and protecting and controlling the coordination, which is different from the typical radial topology. The DC transformer in this structure is connected to a bipolar DC bus at one end, and after transforming, the other end also outputs the corresponding bipolar voltage, which improves the power supply capacity of the low-voltage part. Also, it provides a backup voltage interface, which improves the reliability of supplying power to low-voltage equipment.

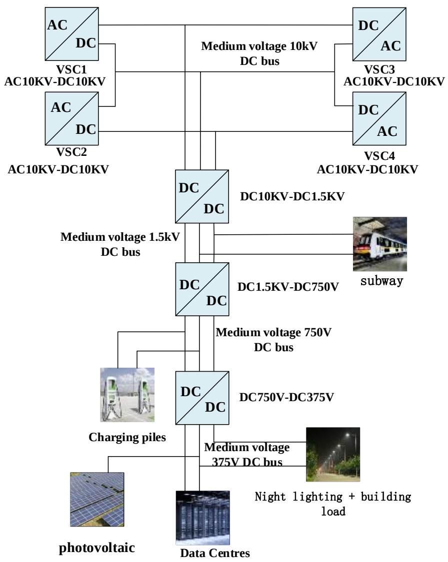

Fig. 5 hybrid AC/DC distribution grid

3.5 Modeling of Main Functional Modules

Major equipment in the area includes utility loads, data centers, and photovoltaic systems. Among them, the utility loads cover charging piles, night lighting, and building loads (lighting, air conditioning, fire pumps, etc.). In the modeling simulation of DC loads, a constant power model as shown in Fig. 6 is used to replace the loads such as charging piles, data centers, and night lighting. The module uses a feedback control system to ensure consistency between the actual power and the set power. By monitoring the voltage changes in the grid in real-time, the load module can dynamically adjust the current output to cope with the changes in the grid conditions, thus achieving the effect of consuming constant power.

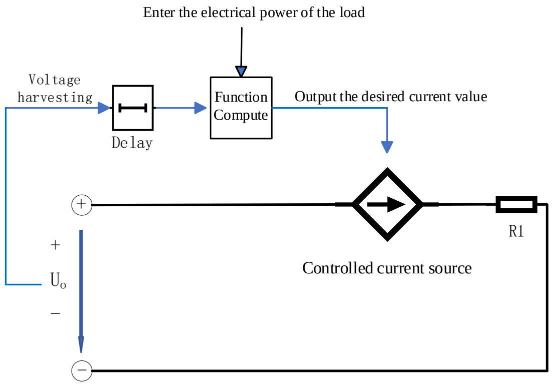

Fig.6 Constant power load model

The PV module utilizes a model structure as shown in Figure 7. The structure mainly contains a PV array and a Boost DC/DC converter. The input parameters in the PV array are irradiation value and temperature, and when these two parameters are given, the module can be regarded as a power supply whose output power varies with the port voltage. The Boost DC/DC converter is used to interconnect the PV array to the 375V bus, and Maximum Power Point Tracking (MPPT) is used in the control section to dynamically adjust the operating point of the PV cells to ensure that they operate at their maximum power output as much as possible in order to optimize the efficiency of the PV system.

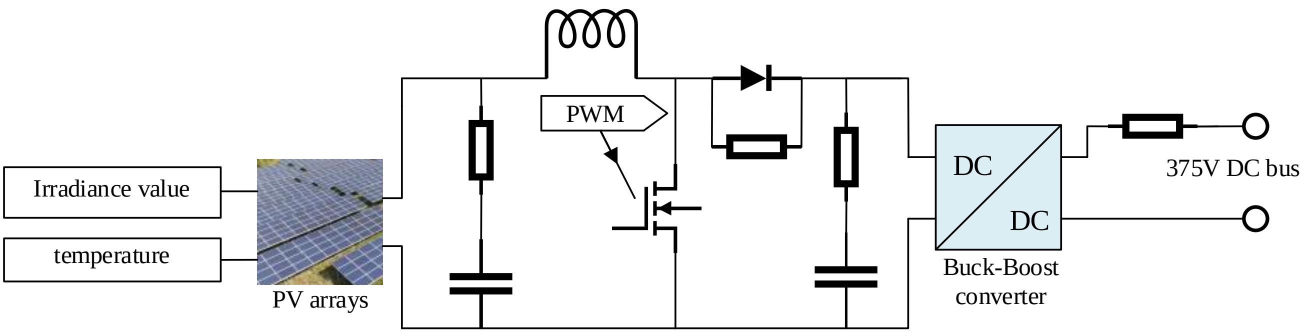

Fig.7 Schematic of photovoltaic mode

The DC converter module in the distribution network, on the other hand, adopts the structure shown in Fig. 8. In this structure, the control signals of the primary side switching tubes PWM1 and PWM3 are the same, PWM2 and PWM4 are the same, and the two sets of signals differ by half a cycle so that each switching tube operates at a constant duty cycle of 0.5.

The voltage conversion of the DC transformer is realized by adjusting the transformer ratio. In this module, the voltage closed-loop control strategy is used for the adjustment of the transformer ratio.

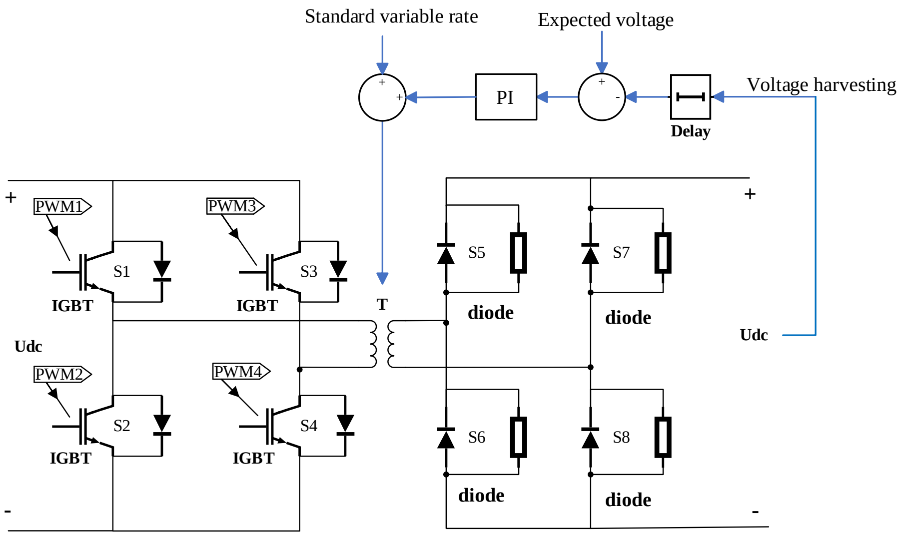

Fig.8 DC-DC Transformer Module

4.SIMULATION ANALYSIS

4.1 Distribution network power supply efficiency analysis

4.1.1 DC Transformer Efficiency Analysis

Since the distribution network power losses are mainly concentrated in each DC transformer, the transformer efficiency is calculated according to equation (5) after simulation.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{5}$$

Where P_{out} and P_{in} respectively represent transformer output and input power.

The power conversion efficiency of each transformer is shown in Table 2. The results show that all transformers exhibit very high efficiency and very low losses. The power transfer efficiency in the negative voltage portion of the transformer from 750V to 375V significantly decreases, which indicates the room for optimization in the voltage conversion process in the low voltage range. Overall, the new topology provides excellent performance in terms of DC transformer efficiency, which contributes to the reduction of energy conversion losses and improves the overall energy efficiency of the hybrid AC-DC distribution network.

Tab.2 DC Transformer Efficiency Simulation Results

transformers	Transformer modules	Input power/kW	Output power/kW	Transformer loss/kW	Transformer efficiency/%
10KV-1.5KV DC Transformer	positive voltage	760	757	3	99.67
	negative voltage	1355	1351	4	99.70
	the total	2114.2	2107.7	6.5	99.69
1.5KV-750V DC Transformer	positive voltage	756.7	752.5	4.2	99.44
	negative voltage	1351	1340	11	99.19
	the total	2107.7	2092.5	15.2	99.28
	positive voltage	272.5	270	2.5	99.08

750V-375V DC Transformer	negative voltage	1340	1300	40	97.01
	the total	1612.5	1570	42.5	97.36

4.1.2 Analysis of power supply efficiency of 10KV DC distribution network

The power supply efficiency of the DC part of the whole system can be obtained as shown in Table 3, which indicates the high efficiency of this power supply system in actual operation, According to the loss and power transmission efficiency of each transformer and the output power of the DC 10KV bus and the power consumed by each type of load. Among them, the photovoltaic power generation system provides 150KW of power, which not only reduces the dependence on traditional power sources but also improves the energy utilization efficiency of the whole system. In addition, the constant power load module used in the simulation model can dynamically adjust the current output according to the changes in grid voltage, ensuring that the power consumed by the loads is maintained at the set value, which further improves the stability and reliability of the power supply.

Tab.3 Simulation results of 10KV DC distribution network efficiency

10KV bus output power/kW			Load power consumption/kW					efficiency
Positive Voltage Output Power	Negative voltage output power	The total	Charging Pile Load	Night lighting and building load	data center	photovoltaic power generation	The toeal	96.96%
759.2	1355	2114.2	480	1300	420	-150	2050	

4.2Analysis of Voltage Transient Droop due to Source Load Shedding

The PV output in this distribution network is subject to oscillations in PV power due to external environmental factors, which produce voltage changes while charging loads generate changes in bus voltage. As a result, the voltage variations produced by source load casting are studied using the new AC-DC hybrid distribution network topology presented in this research. In the simulation model, the charging pile module is connected. The PV system is disconnected after 0.8 seconds, and the curves of 375V and 750V bus voltage variations in this structure are depicted in Figs. 9 and 10.

According to Fig. 9, the 750V bus causes a voltage transient decrease of 2.3 V with a duration of 0.159 seconds. According to calculations, the voltage transient drop has a maximum magnitude of 99.46% of the drop to the rated value, within the tolerance range of most power-consuming equipment.

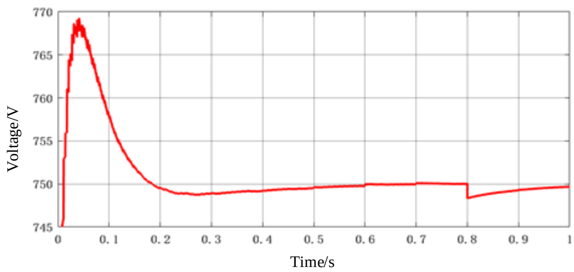

Fig.9 Temporary drop of 750V bus voltage at 0.8s for excision of PV access charging pile

4.3 Analysis of voltage fluctuations due to environmental changes

The output power and other parameters of the photovoltaic system in this model will change in response to changes in temperature and light intensity in the surrounding environment, resulting in DC bus voltage swings. As a result, this research examines the voltage fluctuations caused by the real temperature and light intensity of the region on a given day. First, the voltage variation of each bus voltage is examined using actual temperature, light intensity, and other data (see Figure 10). Figure 11 illustrates the voltage fluctuation curve of a 750V bus. According to the voltage fluctuation calculation formula, the voltage variation d is 2.5%, which is within the acceptable limit. By analogy, the voltage fluctuation of other voltage levels can be obtained as shown in Table 4. The table shows that the voltage fluctuations are within the national guidelines.

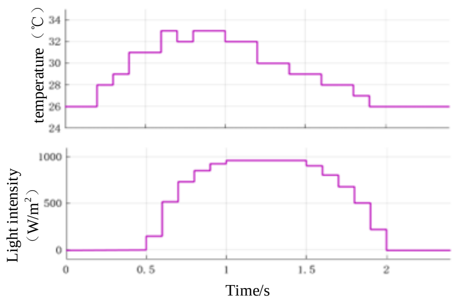

Fig.10 Plot of actual temperature versus light intensity on 750V buse for a given day in the region

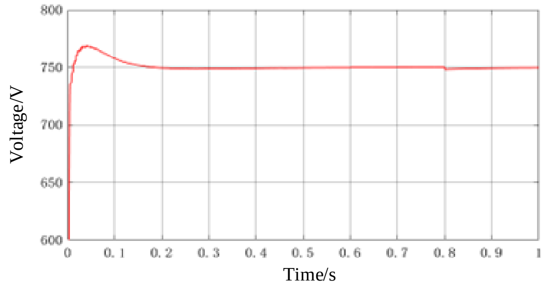

Fig.11 Amplitude of voltage pulsations generated

Tab.4 Voltage fluctuation results at each voltage level

voltage level	Voltage variation d (%)
10kV	0.1
1.5kV	1.2
750V	2.5
375V	2.6

5.CONCLUSION

This paper takes a demonstration project as an object and focuses on the construction of AC/DC hybrid distribution network in this region. It completes the selection of voltage level and the setting of distribution network system architecture and then proposes a new topology of the AC/DC hybrid distribution network on the basis of analyzing the current mainstream topology. The study finds that the new topology can quickly restore the bus voltages to the normal working values for the scenarios of PV system removal and charging pile load input, and the voltage drop amplitude and duration are within the tolerance range of the equipment. The topology can cope with voltage fluctuations brought by light amplitude and temperature changes. The power supply efficiency of the 10KV DC distribution network under the new topology can reach 96.96%. In summary, the new topology has significant practical application value and promotion prospects in improving the performance of AC-DC hybrid distribution networks.

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