Research and Analysis on Relay Protection of AC-DC Hybrid Distribution Network

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Abstract: The construction of Alternating Current and direct current (AC-DC) hybrid distribution networks is the future development trend. Due to the large number of distributed generation (DG) and power electronic devices, the fault characteristics on the AC side are more complicated. At the same time, due to the control strategy and topology, conventional protection methods has adaptability problems to the power system containing power electronics equipment. Therefore, it is of great significance to study the adaptability analysis of AC-DC hybrid distribution network protection to ensure the safe and reliable operation. This paper summarizes the research on the topological structure, fault characteristics, and protection principles, then analyzes the impact of AC-DC interactions on the protection configuration of the AC-DC hybrid distribution networks.

1. Introduction
In the face of the increasingly serious energy crisis and environmental pollution, countries around the world are vigorously developing clean energy based on wind and solar energy. At the same time, DC power is also used in many equipment for office power, commercial power and residential power. With the rapid development of power electronics technology, the advantages of DC distribution networks have become increasingly apparent. However, the AC distribution network is mature, and AC power and loads are still the main components. Therefore, the DC distribution network cannot completely replace the AC distribution network. The construction of AC-DC hybrid distribution networks is the future development trend of distribution networks. On the basis of retaining the advantages of the existing AC, AC-DC hybrid distribution network give full play to the advantages of the DC power distribution network. This paper analyzes and summarizes the control strategies, fault characteristics analysis, and relay protection of AC-DC hybrid distribution networks for large-scale power electronic equipment in detail. It is hoped that the research on related protection issues will be helpful.

2. Interconnected converter control strategy
As a bridge for power exchange between AC and DC, interconnected converters play an important role in stabilizing voltage and improving power quality. The structure of the interconnected converter generally uses a two-way AC-DC converter, which plays a dual role in the actual application process including rectifier and inverter.

At present, interconnected converters are based on line commutated converter (LCC) and voltage source converters (VSC). The basic control methods of LCC include constant current control, constant arc angle control and constant voltage control [1]. The control strategies based on VSC mainly include constant active power(P) reactive power(Q) control, constant voltage and constant frequency control.
(V/f control), and Droop control. Reference [2] introduced PQ control and V/f control in detail. The inner loop is a current loop, and the difference is in the outer loop, as shown in Figure 2. PQ control outer loop generally runs in maximum power tracking mode or given active and reactive power output according to instructions. For the V/f control outer loop, it is controlled by voltage, which assumes the regulation of voltage and frequency to maintain the stability of voltage and frequency, at the same time, it adjusts own output power according to the load demand, so that it changes with the change of load. Generally, it is used as the control strategy of the main power source when it is running in an island, providing frequency and voltage support for other subordinate distributed power sources.

![Diagram of Dual-loop Controller Based on dq Decoupling](image)

Reference [3] stated that the Droop control strategy is to realize the automatic distribution of load power among the inverters. Reference [4] uses a modular multilevel converter (MMC) for wind field interconnection, and the results show that the low-voltage ride-through (LVRT) capability of the wind field is improved. Literature [5] proposed a hybrid DC transmission system composed of LCC on the rectifier side and MMC on the inverter side, and analyzed that the ability of the hybrid system to have fault ride-through and rapid recovery. The control strategy of the interconnected converter station can not only realize the stable operation of the power system, but also have important significance for relay protection.

3. Fault characteristics of AC-DC hybrid distribution network
Compared with traditional distribution networks, AC-DC hybrid distribution networks have significant features such as high-density access to DG and AC-DC hybrid connections, which the distribution network show different fault characteristics.

DG can be divided into partial power conversion type (Doubly-fed Induction Generator, DFIG) and full power conversion type (Permanent Magnetic Synchronous Generator, PMSG, Photovoltaic generation, PVG). Its fault characteristics depend on the control strategy. DFIG achieves LVRT control through a crowbar protection circuit. Its fault current will have a frequency offset and generate a high content of second harmonic. This causes the deviation of the Fourier algorithm based on the power frequency to extract the signal. As a result, the traditional power directional elements and three-stage current protection have malfunctioned. At the same time, resulting in a small short-circuit current, which will reduce the sensitivity of the protection. PMSG implements LVRT control through an Chopper protection circuit, and its fault current will not have frequency shift phenomenon, but the short-circuit current output is also limited due to the inverter current limiting effect. Reference [6] discussed the fault characteristics of DFIG. As the grid-side converter has a capacity of only 20% -30% of the rated capacity of the generator, its fault current is relatively small. Therefore, only the fault current provided by the generator itself can be considered. The literature [7] analyzed the short-circuit current characteristics of DFIG under the crowbar protection circuit, and obtained the conclusion that the short-circuit current would have frequency offset and weak feed. The literature [8] analyzed the component expressions of the DFIG current in the fault situation and the change law of the short-circuit current after the Crowbar was turned on. Reference [9] analyzed the short-circuit current of PMSG maintains the power frequency and can provide a stable short-circuit current that does not exceed 1.1 times the rated current. Literature [10] analyzes the impact of PVG due to inverter
current limiting. The short-circuit current capability provided is limited, and the maximum does not exceed 1.3 times the rated current. As shown in Figure 3, the short-circuit current characteristics of a wind power system can be divided into two stages. Both stage 1 and stage 2 show weak feedback characteristics under control.

![Figure 2. Controllability and weak feedback of short-circuit current](image)

The access of DC distribution network has further increased the difficulty of fault analysis. Their fault characteristics are affected by both the control strategy and the topology of interconnected converters. Due to the constant current control strategy adopted in LCC, their fault characteristics mainly depend on the topology change by the fault. It has controlled characteristics and discrete nonlinear characteristics. At the same time, when commutation failure occurs, the occurrence of low-frequency components and harmonics will reduce the protection reliability. Different from the pure AC system, the nonlinearity of the power electronics of the converter station and the fast and stable response characteristics of the DC control may affect the AC system, and the closer the fault point is to the converter station, the more complex the fault characteristics[11]. Limited by the control strategy and topology of the converter, characteristics such as weak feed, harmonics, and positive and negative sequence impedance differences will appear. Reference [12] analyzed that when a single-phase short-circuit fault occurs on the AC side of the AC-DC hybrid, the short-circuit current provided by the DC system will reduce the initial value of the power-frequency short-circuit current. And compared to the AC system, the short-circuit current provided by the DC system is limited. Literature [13] simulation results show that when commutation failure occurs, the content of non-characteristic harmonics will be greatly increased. Non-characteristic harmonics can cause the transformer to saturate and cause incorrect operation of the protection configuration on the AC side. Literature [14] experiments show that the nonlinear characteristics of inverter-side converters and the influence of fast control strategies of DC systems will make the converters become a complex non-linear power supply when AC system fails. At the same time, a large number of transient harmonics will be introduced into the system, which will have a greater impact on the calculation of power frequency. Compared with pure AC systems, the amplitude and phase of the positive and negative sequence impedances in AC-DC hybrid power grids are significantly different, and they no longer meet the assumption that the positive and negative sequence are approximately equal. In summary, due to the influence of DG control strategies and DC systems on the AC side, fault characteristics different from traditional power grids will occur, which will cause a series of problems such as reduced sensitivity and insufficient selectivity based on traditional protection devices.

4. Relay protection of AC-DC hybrid distribution network
The AC-DC hybrid distribution network brings many practical problems to existing relay protection. Especially prominent are the three-stage current protection and power directional components. The fault characteristics of frequency offset and harmonics will cause errors in the Fourier algorithm based on the power frequency to extract the signal, which will cause the traditional power directional components and three-stage current protection to malfunction.

Reference [15] proposed a scheme for limiting the access capacity, adaptive current three-stage protection, and island detection division of distributed power access to AC distribution networks to achieve protection in two states: grid-connected operation and island operation. Reference [16] proposed a directional element for the upstream protection of the wind power to prevent the reverse
current provided by wind power from causing the current protection to malfunction, at the same time, adaptive current protection is used to ensure correct operation. Literature [17] aimed at the phenomenon of dead zone of power directional elements, and proposed a new principle of directional elements based on positive sequence fault current and voltage phase before fault. Reference [18] established the equivalent power frequency variation model of the DC system. And use the traditional full-period Fourier algorithm to extract the power frequency variation. Furthermore, the equivalent impedance of the DC system is analyzed when commutation fails. Literature [19] When the AC side fails, the DC side is equivalent to a weak power source, which causes the ratio of the system's equivalent impedance to the set impedance to become larger.

The three-stage protection currently widely used in AC power distribution networks. Due to a large number of low-order harmonics invading into the AC side when DC commutation fails, the current transformer will be saturated, causing the incorrect operation of the three-stage protection. In AC-DC hybrid systems, AC side fault location, fault type, and fault time all have effects on commutation failure [20]. AC transients easily cause DC commutation failures, and DC commutation failures will cause incorrect actions of the AC side protection. It can be seen that the transient process of AC-DC hybrid distribution networks is complex and requires higher protection. New energy grid-connected and flexible DC systems appear as large-scale access of power electronic equipment to power systems. The inverter is an excitation power source that provides fault current. The controllability of the inverter and the diversity of control strategies lead to the complexity of the fault characteristics. This leads to problems with relay protection based on the characteristics of power frequency electrical quantities. As shown in Figure 4, the principle of relay protection based on electrical quantities such as current and voltage is affected by the control strategy, while the principle of relay protection based on the identified object model will not be affected by the control strategy. Therefore, we should consider using the model topology of the protected component and the changing characteristics of the model parameters to implement fault identification to protect it.

Figure 3. Comparison of electrical quantity protection and model protection

5. Conclusions and research prospects
In summary, the AC-DC hybrid distribution network has huge advantages in absorbing DG and improving energy utilization, but relay protection is one of the important factors restricting its development. Research on this aspect at home and abroad is still in its infancy. This paper summarizes the topology, control strategy, fault analysis, and relay protection of AC-DC hybrid distribution networks with large-scale power electronics equipment. Also this paper summarized the research advances in the analysis of fault characteristics. I hope it will be helpful for the research on related relay protection issues.

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