Fault Analysis of VSC Single-pole Ground Fault in Flexible AC/DC Hybrid Distribution Network

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Abstract. The stable operation of the flexible AC-DC hybrid distribution network is inseparable from the configuration of the relay protection device, while the fault analysis and simulation research is the basis for the protection scheme selection. This paper introduces the current situation of fault analysis and protection research of flexible AC-DC Hybrid distribution network, and set up a model of radiated flexible AC-DC hybrid distribution network on PSCAD/EMTDC platform, then deeply analyzed the grounding fault of VSC single-pole short circuit of DC side. According to the simulation results, the trend and characteristics of the transient state after the fault are studied, which lays a foundation for the research of the subsequent relay protection method and the configuration of the protection device.

1. Introduction
Recently, with the large scale of renewable energy accessed into the grids and the increasing quantity of DC load, the traditional AC distribution network can no longer meet the needs of the power system. The rapid development of power electronics technology provides convenient conditions for DC power, DC load and energy storage equipment to access DC distribution networks. As a new form of power distribution technology, it has the characteristics of large transmission capacity, high power quality and good stability, and there is no reactive power compensation and problem of frequency [1]. In the meantime, the DC distribution network has economic merit, when the DC equipment is connected to the grid, a large amount of DC/AC converters will be saved, so the DC distribution network has received widespread attention. At present, many Chinese and foreign scholars have conducted in-depth research on DC distribution networks.

In this paper, the fault response mechanism and transient state changes of a single-pole short-circuit grounding fault in a VSC converter station in a flexible AC-DC hybrid distribution network are studied. In section 1, the status of fault analysis and protection research on flexible AC/DC hybrid distribution network at China and abroad is mainly described. In section 2, the flexible AC/DC hybrid power distribution system applied in this paper is briefly introduced. In section 3, the failure mechanism and the characteristics of fault transients are studied based on the simulation results, which were obtained on the PSCAD/EMTDC platform. In Section 4, the whole fault analysis is summarized. And pointed out the inadequacies of this study and the aspects which need to be improved in the future.

2. Research Status of Fault Analysis and Protection of Flexible AC/DC Hybrid Distribution Network
After long-term research and development, the AC distribution network has matured its protection and configuration technology. Unlike the AC grid, the relay protection technology of the DC distribution network is still in the theoretical research stage. The topology, operation mode and fault characteristics of the DC distribution network are different from those of the AC grid, therefore the protection technology of the AC grid cannot be directly applied to the DC distribution network [2]. Therefore, the fault analysis and protection technology of the DC distribution network still needs to continue in-depth study. At present, the research on DC distribution network protection is mainly divided into the following aspects: fault characteristics analysis, fault location and isolation, and protection methods and strategies [3-4]. Different types of fault electrical transients in different locations of the DC distribution network will exhibit different characteristics, how to detect and analyze these transient quantities is the main content of fault characteristics analysis [4-6]. Reference [7] introduced several protection devices for DC distribution networks, and summarized the research status of DC distribution network protection and its application in subways and ships. Reference [8] pointed out that high-proportion distributed power is connected to AC/DC distribution network, and the grid fault exhibits nonlinear correlation characteristics. Reference [9] establishes a three-terminal ring-shaped DC power distribution structure, analyzes the topology structure of the existing DC power distribution field, compares the advantages and disadvantages. In general, the research on the protection of DC distribution network is still in the theoretical research stage, and has not reached the requirements of practical application, so further research and exploration are needed.

3. Introduction of the Flexible AC/DC Hybrid Distribution System
In this paper, a flexible AC/DC hybrid distribution network is built on the PSCAD/EMTP platform. The way of the wiring on the DC line is pseudo-bipolar wiring. VSC converter is a key device for connecting AC and DC systems. It can realize four-quadrant operation of active and reactive power on AC system, and can also optimize the system operation through effective control strategies [10]. The converter station used in this paper adopts a three-phase two-level VSC converter, in which the converter 1 and the converter 2 are controlled by a constant DC voltage, so that the DC side voltage is ±10 kV, while the converter 3 adopts PQ control and output active power is 6kw. The schematic diagram and specific parameters of the system are shown in figure 1 and table 1 respectively:

![Figure 1. Schematic diagram of the flexible AC/DC hybrid distribution network](image-url)
Table 1. Parameters of the flexible AC/DC hybrid distribution network system

| Parameter name                  | Parameter value |
|---------------------------------|-----------------|
| Rated Capacity / Mva            | 100             |
| Generator rated power / kV      | 10              |
| Output power of VSC1 / km       | 1.6             |
| Output power of VSC2 / km       | 1.98            |
| Output power of VSC3 / km       | 6               |
| Load on DC side / km            | 9.4             |
| Length of Line 1 / km           | 59.34           |
| Length of Line 2 / km           | 75.45           |
| Length of Line 3 / km           | 16.51           |

4. The response and analysis of single-pole grounding short-circuit fault at VSC grid-connected converter station

The quantity of electrical transient variables after the fault has a decisive meaning for the selection of the relay protection scheme and the fault location. Therefore, it is important to deeply study the trend and characteristics of the quantity change of electrical transient variables during the fault. In AC/DC distribution network, the VSC converter station plays an extremely important role as the hub of the AC/DC network. In this paper, the fault response mechanism of the VSC converter station after DC-side single-pole grounding short-circuit fault is deeply studied. The characteristics of the quantity of electrical transient variables are analyzed according to the simulation results obtained on the PSCAD/EMTDC platform, which will be the basis for the selection of relay protection schemes.

Single-pole grounding fault is a common fault type in VSC grid-connected converters. This paper takes the DC-side positive-pole grounding fault of VSC outlet as an example to study the transient process after the fault. The equivalent circuit diagram is shown in figure 2:

Figure 2. Equivalent circuit of DC single pole-to-ground fault and current path

After the fault occurs, the positive capacitor $C_p$ will discharge and form an $RLC$ oscillating circuit with the fault line inductor $L$ and the fault grounding resistance $R_g$ (as indicated by the red dotted line in Figure 1). Since the fault line resistance $R$ is very small, the oscillating process will be closely related to the resistance value of $R_g$. Since the VSC converter station adopts a constant voltage control strategy, the negative capacitor $C_n$ will be charged during the transient process to maintain the DC side voltage as constant as possible.

Now we set the short-circuit current of the fault point is $I_f$, and the short-circuit current of the positive and negative poles on DC side is $I_{scp}$ and $I_{scn}$ respectively. The fault currents of the positive and negative capacitors are $I_{C1}$ and $I_{C2}$ respectively, and the pole-to-pole voltage on DC-side poles is $U_{dcl}$, where the positive voltage is $U_{dcp}$, the negative one is $U_{dcn}$.

After the fault occurs, the positive voltage $U_{dcp}$ is calculated as equation (1):

$$U_{dcp} = I_f \times R_g$$  \hspace{1cm} (1)  

The DC-side pole-to-pole voltage $U_{dcl}$ is calculated as equation (2):
After the fault occurs, because the current limiting device plays a certain role, the fault current will not be infinite. It can be seen from the above equation that the fault voltage \( U_{dcP} \) and the DC voltage \( U_{dcL} \) are related to the resistance value of the grounding resistor \( R_g \). If \( R_g \) is too small, the voltage at the fault point is almost zero, so that the voltage \( U_{dcn} \) will be negative of \( U_{dcL} \), then the system voltage will crash after the fault. If the resistance value of \( R_g \) is large, the DC side voltage will be less affected by the fault, and will gradually recover to the stable operating state after the fault. In this paper, we studied different cases choosing \( R_g \) as 0.01Ω, 1Ω, 5Ω, 10Ω respectively. The simulation analysis is carried out on the PSCAD/EMTDC platform to investigate the affections of different resistance values of the grounding resistor \( R_g \) to the voltage of \( U_{dcL} \), \( U_{dcP} \) and \( U_{dcn} \). The fault is set at 1KM at the exit of the VSC inverter and it occurs at 3s and lasts for 0.5s. The simulation results are as follows from figure 3 to figure 6 respectively:

\[
U_{dcL} = U_{dcP} - U_{dcn} = I_f \times R_g - U_{dcn}
\]  \hspace{1cm} (2)

Other transient variable quantities in the transient process will be analyzed by taking \( R_g = 0.01\Omega \) into account. After the fault occurs, the output power \( P_1 \) of the VSC converter station will fluctuate greatly. Although the power fluctuates around the stable value after the fault disappears, it still has a large impact on the DC side load. The capacitor \( C_P \) will form an \( RLC \) oscillating circuit and discharge, the discharging current \( I_{C1} \) will continue to oscillate. While the negative capacitor will get charged due to the fault current \( I_{C2} \), and the charging current \( I_{C2} \) will gradually increase during the fault. Since the grounding resistance \( R_g \) at the fault is very small, the short-circuit current \( I_f \) at the fault point will be very large, which can reach up to 12.1 KA when the fault occurs. The DC side fault current \( I_{scp} \) and \( I_{scn} \) are also large, so the fault will have a huge impact on the entire system. The simulation results are as follows from figure 7 to figure 10 respectively:
5. Conclusion
According to the simulation results, the trend and characteristics of the transient state after the fault are analyzed. Based on the fault analysis, it is found that when the DC-side positive pole of the VSC converter station has a grounding short-circuit fault, the grounding resistance \( R_g \) at the fault point has a significant effect on the pole-to-pole voltage and the voltage at both positive and negative terminals after the fault. The specific performance is as follows: If the grounding resistance is small, the pole-to-pole voltage and the negative pole voltage will be close to 0, the DC system voltage will collapse. If the grounding resistance is large, the impact of the fault on the system is not obvious. After the fault disappears, the system can still operate in a stable condition. In addition, if we consider the grounding resistance \( R_g \) as 0.01Ω, the remaining transients are analyzed. It is found that a fault current with a large amplitude will appear at the fault point and on the DC side, which will give rise to huge impact on the stable operation of the system, and will seriously affect the safety of the equipment. The output power of the VSC converter will also fluctuate violently, which will seriously affect the load supply on the DC side. In summary, the single-pole grounding fault of the VSC converter will cause a huge impact on the stable operation of the whole system. The corresponding relay protection scheme should be set according to the changing characteristics of the transient state after the fault and
equipped with corresponding protection equipment to ensure the safety, efficiency and stable operation of the system.

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