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Simulation Study on Pole-to-Pole Short Circuit Faults of the Hybrid Multi-terminal DC Transmission System

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Abstract. The hybrid multi-terminal direct current (MTDC) system, with the economic superiority of LCCs and technical flexibility of VSCs, is one of the development directions of future DC transmission technology. This paper introduces the development of Hybrid-MTDC transmission projects as well as the related publications especially on fault control strategies. A ring hybrid three-terminal DC transmission system was built on PSCAD/EMTDC to simulate pole-to-pole short-circuit faults at different locations. The fault development process and fault characteristics on DC lines are analysed and summarized, which aims at providing the theoretical basis for the protection principles of hybrid MTDC systems.

1. Introduction

In term of the converter valves used in DC transmission projects, DC systems can be divided into line commutated converter (LCC) based traditional transmission system and fully controlled voltage sourced converter (VSC) based flexible transmission system [1]. The biggest problem of LCC high-voltage direct current (LCC-HVDC) technology is that commutation failure is easy to occur when DC side fails. The existing traditional two-terminal DC systems can be transformed into hybrid MTDC systems by introducing VSC high-voltage direct current (VSC-HVDC) technology with the advantages of no commutation failure, flexible controls and supplying power to passive system. Moreover, MTDC system can supply power to multi-load centers from multi-power areas and effectively solve the problem of centralization of DC landing points. It costs much less than that of using multiple two-terminal DC systems [2]. Therefore, hybrid-MTDC transmission system, effectively combined with the advantages of two kinds of converters, has a promising future in developing DC grids.

The development of hybrid HVDC system depends on the converter technology, especially the flexible technology using full-controlled converters—VSCs or CSCs. The key problem of VSC technology is the isolation between AC and DC system and system recovery from DC line failures. In addition, there is no economical and practical large capacity DC circuit breaker to remove the high DC fault current [3]. Therefore, it is necessary to further analyse and study the control and protection strategies and DC side fault characteristics of the hybrid MTDC system.

In this paper, the pole-to-pole short circuit simulation of ring hybrid MTDC system is mainly studied, and the work will be carried out as followings: part 2 reviews the development process of hybrid MTDC transmission technology and the research results of control and protection strategies. The fault characteristics and fault analysis methods of MTDC system is introduced in part3. In part 4, a ring network hybrid multi-terminal system is built on the PSCAD/EMTDC platform. P-P short circuit faults at different locations of different DC lines are analyzed and fault characteristics are summarized. In section 5 the full text is summarized and the weakness of the study and further research plan is pointed out.

2. Development and Control Strategy Researches of Hybrid MTDC Transmission Technology

The concept of hybrid DC transmission was first proposed by G.Lipphardt in 1993. The three-level Gate-Turn-Off Thyristor (GTO) was used to overcome communication failure at the inverter station [4]. In 1994, [5] proposed that VSC converter station based on GTO valves was used as a branch line to extract energy from the traditional LCC-HVDC transmission system. This hybrid power-tapping system was the earliest hybrid multi-terminal DC system.

Topology is the basic problem of studying hybrid MTDC systems. According to different mixed forms of LCCs, VSCs and CSCs, the hybrid MTDC system can be divided into converter-level and system-level [6]. In this paper, only the system-level hybrid MTDC transmission system, made up of LCC stations and VSC stations and connected by three or more converter stations in parallel, series or mixed connection, is considered. Among them, the parallel connections can be radial, ring or meshed network. Compared with series connection, parallel connection has smaller line loss, larger adjustment range, easier to match insulation, more flexible to expand and less costs. Thus parallel connection is most widely used in MTDC systems.

All the running MTDC transmission projects in the world——five LCC-MTDC systems and two VSC- MTDC systems——are connected in parallel. At present, there is no hybrid MTDC project in operation. In June 2018, China Southern Power Grid Corporation launched the construction of UHV MTDC demonstration project from Udongde to Guangdong and Guangxi (also known as "Kunliulong DC Project"). From Yunnan Kunbei Converter Station in the west to eastern Liubei Converter Station in Guangxi and Longmen Converter Station in Guangdong, the project has a total line length of 1489km; the rated DC voltage is ±800kV and the transmission capacity is 8000MW. It is the first UHV hybrid MTDC transmission project in the world, with a traditional dc station at the sending end and 2 flexible dc stations at the receiving end, which plays an important demonstration role in large-scale power supply delivery, multi-point decentralized access of the receiving ends, saving line corridors, optimizing grid structure and improving the security and stability level of receiving ends.

Researches on hybrid MTDC system now mainly focus on designing fault control and protection strategies to reduce the bad impacts of DC faults while few achievements have been made on the fault process and fault mechanism of DC sides. Control strategies of hybrid DC system was first studied in reference [5,7] and the simulation results show that the proposed control strategy is effective in the steady state and in the case of large disturbance, start-stop control, clearance of DC side faults and AC side faults. A topology of hybrid three-terminal dc transmission system and related control strategies are designed to enhance the reliability of large-scale wind power connected to the grid in [8]. A series-parallel-mixed hybrid MTDC system, composed of five LCC stations and a VSC stations, is established in [9] and the simulation shows this hybrid MTDC system works well in start-up, steady state operation, the failures of DC sides and AC sides. In [10] the AC and DC fault characteristics of a radial three-terminal LCC-MMC hybrid system were studied, and control coordination strategy of converter stations is designed that can improve performance of DC system under AC/DC faults. Most control strategies of hybrid MTDC systems are refer to the research results of conventional multi-terminals and flexible multi-terminals.

Although hybrid MTDC system can use the control and protection strategies of MTDC technology for reference. However, due to the two types of converter components involved in the hybrid HVDC system, it is more complicated in mathematical model, fault analysis, control strategy, protection scheme and so on that makes it different from traditional multi-terminal and flexible multi-terminal systems. So it is necessary to study the hybrid MTDC systems with different topologies and control modes, and design relevant fault control strategies to suppress the development of DC fault current. In addition, researches on hybrid MTDC system now are mostly focused on radial paralleled-DC network [11], while there are few researches done on fault characteristics for ring or meshes parallel MTDC

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systems. Therefore, this paper will preliminarily explore and study the fault mechanism of hybrid MTDC system with ring network.

3. Fault Characteristics and Analysis Methods of the MTDC system

Fault characteristic analysis is the basis of researching relay protection technology of MTDC transmission system. DC side line fault is one of the most serious faults in MTDC transmission system, usually including pole-to-ground short circuit fault, pole-to-pole (P-P) short circuit fault and broken line fault. Among them, the P-P fault is regard as the most serious fault. When P-P fault occurs in DC lines, whether in LCC-MTDC systems or VSC-MTDC systems, the AC systems at both sides of DC line is similar to three-phase short-circuit fault, which seriously affects safe operation of the systems. Besides, the transient current on AC side contains a large DC component, which easily leads to saturation of converter transformer [12]. The transient process of DC fault current has obvious nonlinear characteristics, lacking fundamental frequency components, including multiple attenuation components and abundant harmonic components.

For the LCC-HVDC transmission system, considering the long overhead line, the fault transient traveling wave process is mainly discussed. Because the damping of DC system is far less than that of an AC system, fault current rises extremely fast and reaches a large over-current level within a few milliseconds when the DC system fails. Moreover the fault process is also affected by fault type, transition resistance, fault location, control mode. The fault process in the traditional two-terminal DC system can be divided into initial traveling wave stage, transient stage and fault steady state stage according to the control response time. The traditional two-terminal system can eliminate DC fault by controlling trigger angle. For the LCC-MTDC transmission system, the operation characteristics of the connected AC systems can be improved by DC power modulation, and the communication failure can be effectively avoided by reasonably designing the current balance controller and the composite control strategy.

For the two-level VSC-HVDC transmission system, IGBT will be blocked rapidly when the short circuit fault occurs between the poles of DC lines, and the converter can be equivalent to an uncontrollable rectifier. According to the fault characteristics of current and voltage variations, the process of P-P short circuit fault can be divided into three stages: DC capacitor discharge stage, diode natural commutation stage and diode full conducted stage [13].The capacitor on the DC side discharges rapidly, and the DC current reaches its peak within few milliseconds. When the capacitor voltage drops to zero, the current flowing through the diodes is more than ten times of the rated current, which is the most serious stage of P-P fault. After the DC voltage is lower than the AC voltage, the AC grids at two ends begin to feed current to the fault point. DC line fault current fast reaches a high peak and likely causes temporary overcurrent on AC sides. In addition, VSC-HVDC systems cannot clear faults by adjusting trigger angle. Similar to the two-terminal systems, the capacitor will discharge rapidly when the P-P fault occurs in MTDC systems.

The fault analysis methods of DC system mainly include time domain method and frequency domain method. Since HVDC transmission systems are made up of a large number of primary components, such as linear elements like inductances and capacitances, power electronic devices with discrete switching characteristics, and transmission lines with frequency-varying distribution parameters, time domain simulation is the most important method for fault analysis in HVDC systems [14]. The time-domain simulation for line faults on digital electromagnetic transient simulation tools such as PSCAD and RTDS can accurately reflect the commutation process, the control systems' responses and the frequency dependent characteristics of actual line parameters, etc. In this paper, time domain simulation method is used to analyse the P-P fault process and fault mechanism in a ring hybrid MTDC system.

4. Pole-to-Pole Short-Circuit Fault Simulation and Analysis in the Ring Hybrid MTDC System

A pseudo-bipolar hybrid three-terminal ring HVDC transmission system is built on PSCAD/EMTP platform. Converter station 1 is LCC rectifier station with constant DC current control mode;

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Converter station 2 and 3 are VSC inverters. Converter station 2 is equipped with constant DC voltage control and reactive power control, while the control strategies of converter station 3 are constant active power and constant reactive power. The rated DC voltage is ±200kV; the rated active power is 800WM. Frequency Dependent (Phase) model is used in all DC lines of 900 km. The line fault occurs at 2s and lasts for 0.5s. Faults occurring on DC Line 1, Line 2 and Line 3 are respectively called f_1, f_2 and f_3, as shown in Figure 1.

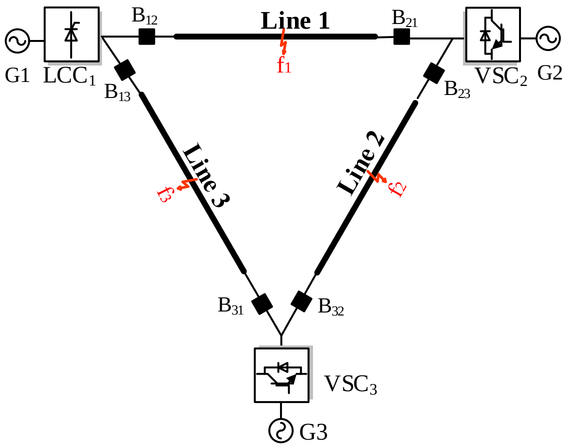

Figure 1. Schematic diagram of DC line faults in a ring-type hybrid MTDC transmission system

Firstly, the fault characteristics of P-P short circuits at different locations on the same line are studied.

(1) When the fault f_1 occurs on DC Line1 between LCC1 and VSC2, in order to compare fault features at different locations, the fault points are respectively set at 1%, 50% and 99% of the total length of Line1, namely 9km, 450km and 891km away from LCC1 station. The DC current waves of the lines close to LCC1, VSC2 and VSC3 stations are respectively compared in Figure 2 when f_1 fails at different positions on Line 1.

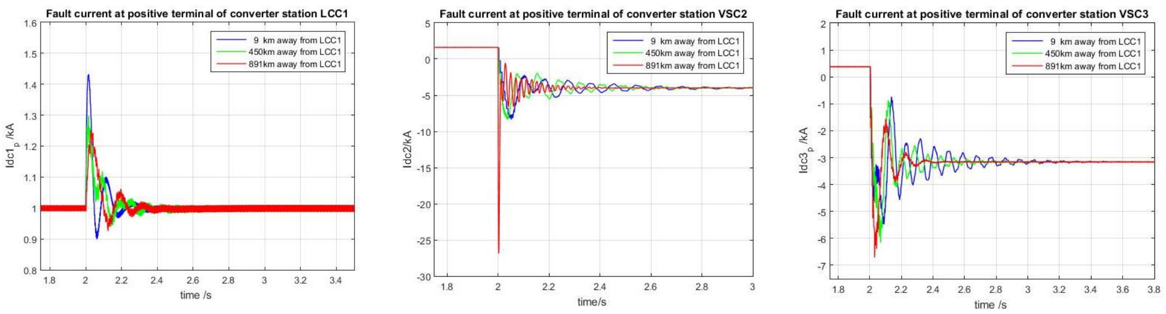

Figure 2. Fault current waveforms at the outlet of converter stations when f_1 occurs

Simulation shows that the current at the DC outlet of LCC1 can be restored to the original level after 0.5s when the fault occurs in the DC line between LCC1 and VSC2. The fault transient process at the outlet of LCC1 of the converter station is a second-order underdamped oscillation. The closer the fault location is to LCC1, the higher the peak current will be. However, due to the limitation of constant current, the peak current is no more than 1.45 times of the rated value. The DC voltage between the poles of lines close to LCC1 is quickly reduced to about 100kV. It can be seen that the constant current control strategy is effective in protecting the station LCC1. For VSC2 station, it is easily to find that the fault transient current is related to the fault location. The closer the fault location is to the VSC2, the more obviously the shunt capacitor discharge is on the DC side. The fault current rises and even reaches more than ten times of the rated current in a very short time while the DC voltage drops and oscillates to fault steady state quickly. Although the lines directly connected to

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VSC3 station are all sound lines, the changes of current and voltage at the outlet of the converter station show an obvious second-order over-damped oscillation process due to the influence of adjacent line fault.

(2) When the P-P fault f_2 occurs on the DC lines between two VSC stations, fault locations are as similar as to f_1 in (1). Figure 3 shows the DC currents of the lines nearby stations LCC1, VSC2 and VSC3.

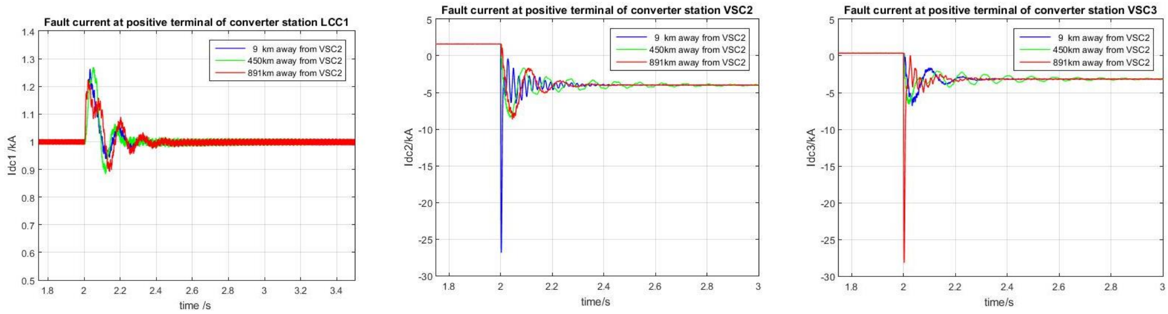

Figure 3. Fault current waveforms at the outlet of converter stations when f_2 occurs

When the P-P occurs on the lines near the VSC stations, the capacitor discharges obviously and thus make AC systems, internal freewheel diodes and DC lines undergo overcurrent. The current limiting device should be chose to avoid the overcurrent, such as fault current limiting reactors (SFLCs). When the fault place is at the middle of the line, the current and voltage traveling waves will attenuate and their amplitudes decrease. And it takes relatively long time to oscillate to reach the fault steady state.

Secondly, the waveforms of P-P faults at the same location on different lines are compared and analyzed. The fault current waveforms at 1% and 99% of the total length of the three lines, namely at 9km and 891km, are compared in Figure 4.

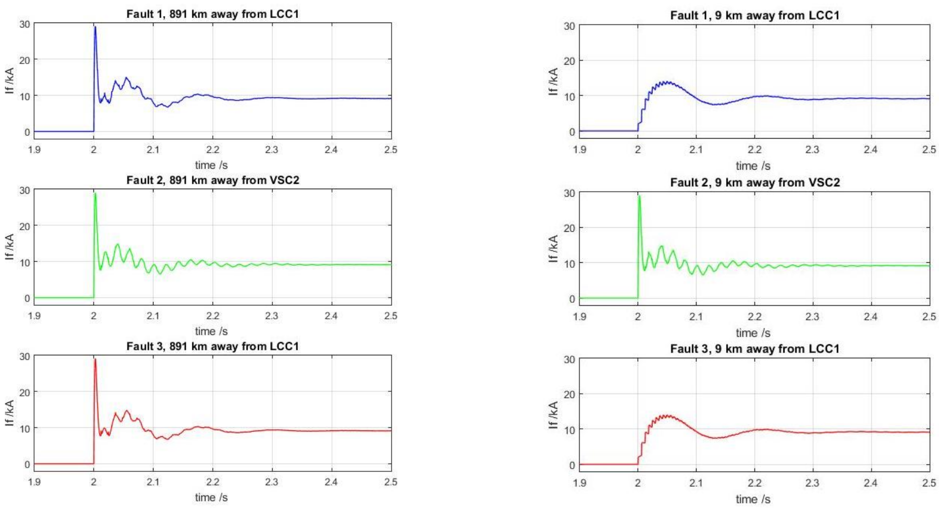

Figure 4: Current waveforms of P-P faults at the same location of different lines

By comparing the fault current waveforms at the same position on the DC Lines between LCC-VSC and VSC-VSC, we can find that the closer the fault location is to LCC1, the smoother the transient waveforms of DC fault current will be and the more quickly they will transit to the fault steady-state process. While the fault occurs near the VSC converter station, the peak value of the fault current is extremely large, and it takes a relatively long time (about 0.3s) for the oscillation process to reach the fault steady state.

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In a word, the fault current waveform is affected by the large DC capacitors of VSC stations——the closer the fault place is to VSC stations, the larger the peak current will be. Besides, as the result of constant current control, the closer the fault point is to LCC stations, the more gently the current waveform will oscillate to the fault steady state. Therefore, the fault current of P-P short circuit at different positions is affected by two types of converter stations, and the fault features are coupled with each other at different time scales.

5. Summary

A ring three-terminal hybrid DC transmission system is built in this paper. The basic control mode in converter station is designed and the fault simulation proves the control strategy can effectively suppress short-circuit current on lines connected to LCC stations. The features of P-P faults on DC lines are studied by simulating DC line faults at different locations in the network. The shortcomings of the above research are that the fault process is only qualitatively described by time domain simulation and the control mode of the simulation is not perfect. Besides, there is no mathematical modelling process. The next step is to establish a mathematical model of the hybrid MTDC system to quantitatively describe the fault process as well as to further improve the control strategies of the simulation to accurately reflect the fault process.

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