Adaptability and Countermeasures of HVDC line protection under the UHVDC system with multiple receiving ends

Zhengguang Chen [1*], Xingguo Wang[1], Shuyang Wang[1] and Hong Cao[1]

[1] China Electric Power Research Institute, Beijing, 100192, China

Abstract. In UHVDC transmission system, the inverter station is located in different geographical locations, and there are two sections of lines in single pole of HVDC system, which brings challenges to the traditional closed line protection. In this paper, firstly, the structural characteristics of series connection mode and the output characteristics of each converter in case of line fault are analysed, and the adaptability of conventional line protection in series multiple receiving ends system is studied. According to the characteristics of UHVDC system with multiple receiving ends in series connection mode, a hierarchical protection strategy is proposed and verified in PSCAD model.

1 Introduction

Line commutated converter based HVDC system has the prominent advantages in large capacity power transmission, and it is still the preferred solution in long-distance bulk power transmission [1-3]. Multi terminal direct current transmission (MTDC) project is a HVDC transmission system composed of three or more converter stations and their DC transmission lines. Up until now, there are several MTDC systems applied Line Commutated Converter technology under operation, Sardinia-Corsica-mainland Italy MTDC system, New England- Hydro Quebec MTDC system, Canada Nelson River four-terminal DC transmission system, Pacific Intertie HVDC, etc.[4-7]. Yunnan-Guizhou interconnected project is the first ± 500kV DC transmission project in China, which is constructed by China Southern Power Grid. To change two-terminal HVDC into three-terminal, the project builds a new Luquan converter station in Yunnan through the construction of DC lines connecting the built Gui-Guang HVDC system. It finally forms a three-terminal UHVDC transmission across Yunnan, Guizhou and Guangdong.

The advantages of UHVDC system with multi-receiving terminal are listed as below: the construction cost is reduced due to less DC line construction; improving the line utilization; reducing the impact of DC blocking on the receiving end grid with sharing one supply resource; each receiving end being able to adjust the power distribution and realize the optimal allocation of sending end resources. On the other hand, when HVDC system is constructed with multiple receiving ends, the line configuration has changed greatly, the closed characteristics of the conventional end-to-end HVDC system have been broken up, the line fault characteristics are different and the original line

protection principle can't be fully applied. Other than that, as a single-terminal protection, it is difficult for traveling wave protection to determine the fault location. In the meantime, there are still risks of wrong or refusal operation for line protection during line faults. Therefore, it is highly necessary to analyse the suitable line protection strategies for multi-receiving ends HVDC system.

This paper analyses the topology of UHVDC system with multiple series receiving ends, and the characteristics of DC line faults. The corresponding simulation model is established in PSCAD. Next, the adaptability of the original DC line protection in new connection mode is analysed, according to the special requirements of this series connection, a novel protection scheme is proposed.

2 The UHVDC system with multiple receiving ends in series connection mode

The series connection mode is shown in figure 1, the sending end of it is constructed as the same as conventional UHVDC system, the high-voltage and low-voltage valve at the receiving ends are connected with DC line, and each of them constitutes a different converter station independently. The DC line fault relevance is fairly high due to the series current. In the series connection mode, each station at receiving end has only one 12-pluse valve, which makes the full use of receiving ends' capacity and reduce the construction cost. Compared to parallel connection mode, series mode has an edge in technical economy. Thus, this paper takes the series connection mode as main research subject.

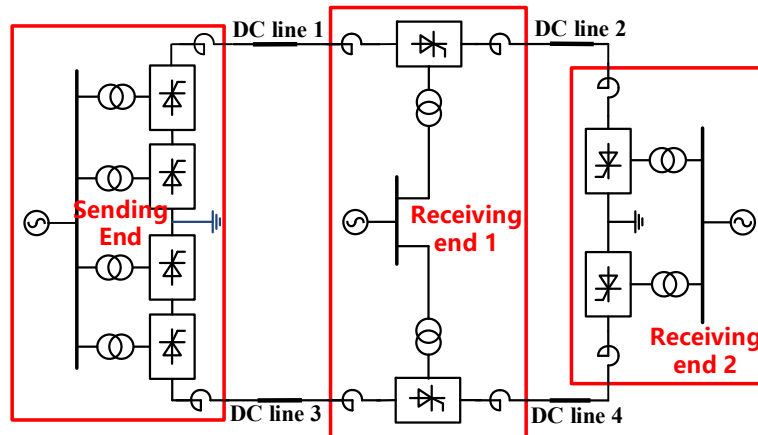*Corresponding author's e-mail: 18121461@bjtu.edu.cn

Figure 1. Multiple receiving ends in series connection mode of UHVDC transmission system

3 The characteristics of DC line fault in series multi-terminal UHVDC system

3.1 The mechanism analysis of DC line fault

The current circuit after the line 1 fault is shown in figure 2, the current at rectifier side is increasing rapidly and the DC voltage reaches 0. Before line protection action, the control system operates in constant current control, raise the firing angle to 90º to decrease the fault current. Because of the one direction conductivity of thyristors, LCC1 and LCC2 will not offer current to fault location. After the interruption of transmission power, the current and voltage of inverter stations will gradually decline to 0, for the easy recover, the controller of inverter station will change its firing angle from 140º to 110º[8-9].
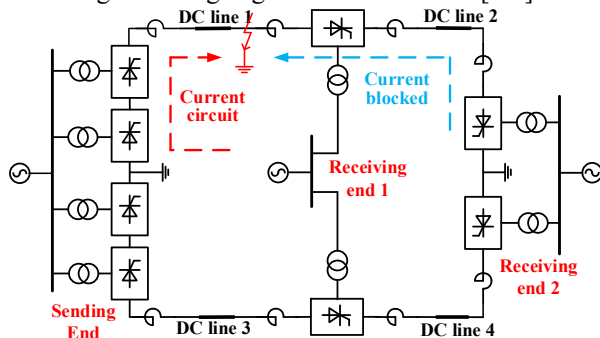

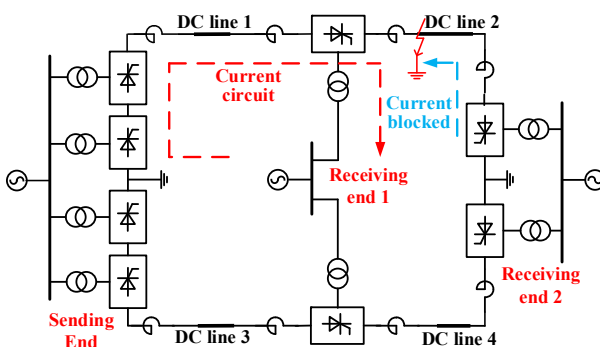**Figure 2.** Current circuit in case of fault in line 1

Figure 3. Current circuit in case of fault in line 2

The current circuit after line 2 fault is shown in figure 3. Different from line 1 fault, in this circumstance rectifier provide shot-circuit current. As a result of discharge of line 1 capacitance to ground, the current measured at LCC1 slightly higher than that of rectifier station, at the same time, current can't across through LCC2. Before the line protection action, rectifier valves will set the firing angle at 90º to decrease the DC current and the firing angle of inverter will change to 110º.

From the above analysis, it can be seen that the rectifier side provides fault current in any case of DC line fault.

3.2 Simulation modeling

According to the basic parameters in Table 1, the simulation model of multi-receiving end UHVDC system in figure 1 is established. The voltage level of the AC system rectifier station connected to is 500kV, and both inverter stations are connected to 500kV AC system.

Table 1. Basic parameters of the simulation model.

Parameters	Values
Rated transmission power/MW	10000
Rated DC voltage/kV	800
Rated DC current/kA	6.25
The length of line 1/km	1618
The length of line 2/km	500

4 The analysis of line protection adaptability

4.1 Traveling wave protection

For long-distance transmission DC lines, line-to-ground fault is the most common one. According to the traveling wave theory, when the line fault occurs, the transient current and voltage traveling wave will propagate to both sides of the fault point almost at the speed of light. Through the derivation of traveling wave on monopole DC transmission line [10-13], it can be seen that the traveling wave of current and voltage in the line can be

represented by the superposition of front traveling wave and backward traveling wave components; however, the actual UHVDC transmission project often adopts the single circuit line mode, and there is a strong coupling between two lines. Through the analysis and decoupling of two wires, the mutually independent common mode wave and differential mode wave can be finally obtained, which are represented by subscripts dif and com respectively. The calculation equations of common mode wave and differential mode wave are as follows:

$$a_{\text{com}}(t) = Z_0 \times i_{\text{com}}(t) - u_{\text{com}}(t) \qquad (1)$$

$$a_{\text{dif}}(t) = Z_0 \times i_{\text{dif}}(t) - u_{\text{dif}}(t) \qquad (2)$$

And the criterion of traveling wave protection is presented:

$$\begin{cases} da_{\text{com}} / dt > (da_{\text{com}} / dt)_{\text{set}} \\ a_{\text{com}} > a_{\text{com\_set}} \\ a_{\text{dif}} > a_{\text{dif\_set}} \end{cases} \qquad (3)$$

It can be seen from equation (3) that there are three characteristic quantities of traveling wave protection, common mode rate of change da_{dif}/dt, common mode wave a_{dif} and differential mode wave a_{com}, in which the polarity of a_{dif} and a_{com} is opposite. The reasonable selection of the three protection criteria can ensure that the system protection will act properly.

4.2 The adaptability analysis of DC line protection

To analyse the adaptability of the main and backup line protection, several grounding faults have been set at the end of line 1, the valve side of smoothing reactor at inverter side and the valve side of smoothing reactor at head end of line 2, as depicted in figure 4. DC line protection will be set to avoid F4, and through the simulation results of F5, the influence of lower line fault on upper line main protection is analysed.
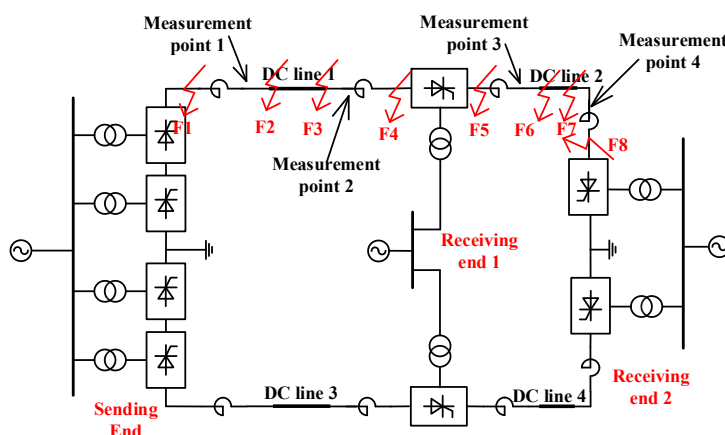

Figure 4. Adaptability analysis of HVDC line protection

According to the traveling wave calculation method, a_{dif}, a_{com} and da_{com}/dt of rectifier side are calculated respectively during metal grounding fault at F3 and F4. For external fault, metal fault at F4 has the largest value of calculated characteristic quantity of traveling wave protection. And for internal fault, F3 metal fault at F3 has the smallest value of calculated characteristic quantity of traveling wave protection. The simulation results are shown in Table 2.

Table 2. Calculation results of traveling wave protection.

Fault	Criterion	Value
F4	$(a_{\text{dif}})_{\text{F4max}}$	518.3
F4	$(a_{\text{com}})_{\text{F4max}}$	338.49
F4	$\left(\dfrac{da_{\text{com}}}{dt}\right)_{F4\max}$	346.7
F3	$(a_{\text{dif}})_{\text{F3min}}$	646.7
F3	$(a_{\text{com}})_{\text{F3min}}$	362.63
F3	$\left(\dfrac{da_{\text{com}}}{dt}\right)_{F3\min}$	528.1

The line protection scheme is set to prevent the most serious external fault, the reliability coefficient is set as 1.2, and the setting value of traveling wave protection is shown below.

The criterion of differential mode variation:

$$(a_{\text{dif}})_{\text{set}} = K_{\text{sen}}(a_{\text{dif}})_{\text{F4max}} = 1.2 * 518.3 = 621.96 \quad (4)$$

The criterion of common mode variation:

$$(a_{\text{com}})_{\text{set}} = K_{\text{rel}}(a_{\text{com}})_{\text{F4max}} = 1.2 * 338.49 = 406.19 \quad (5)$$
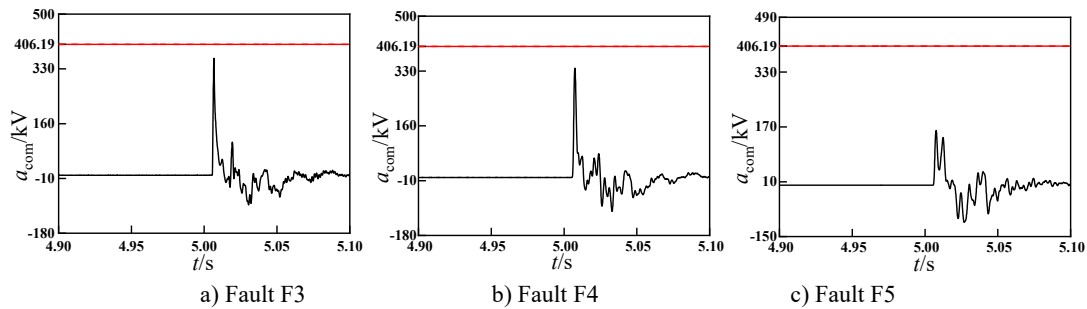
The criterion of common mode changing rate:

$$(da_{com}/dt)_{set} = K_{rel}(da_{com}/dt)_{F4max} = 1.2 * 346.7 = 416.04$$
$$(6)$$

The action characteristics of criterions are drawn in figure 5-7.

a) Fault F3   b) Fault F4   c) Fault F5
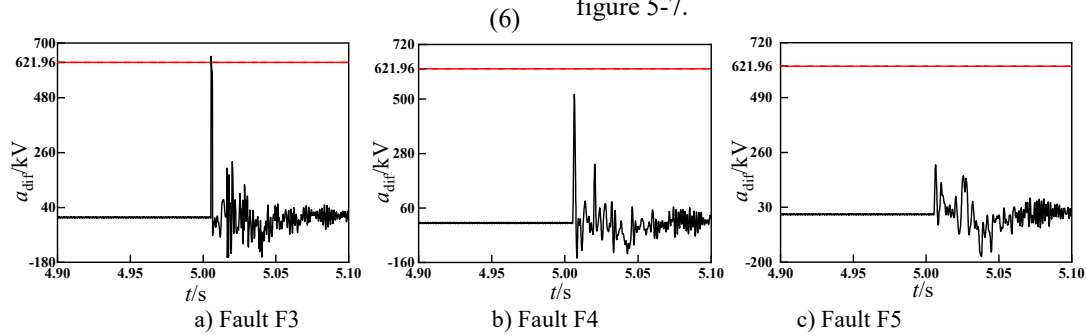
Figure 5. Action characteristics of differential mode variation criterion under different fault points

a) Fault F3   b) Fault F4   c) Fault F5

Figure 6. Action characteristics of common mode variation criterion under different fault points

a) Fault F3   b) Fault F4   c) Fault F5
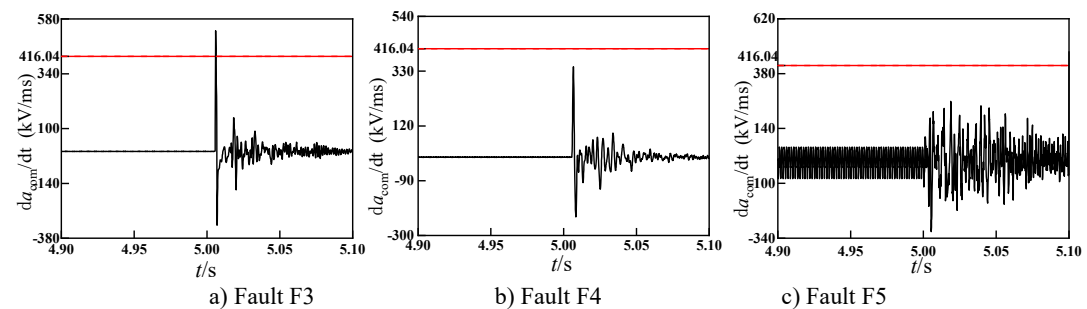
Figure 7. Action characteristics of common mode rate of change criterion under different fault points

It can be seen from the figure above that the traveling wave protection can operate correctly in case of fault in the internal area; it is reliable and does not operate in case of fault in the lower line.

5 Hierarchical protection strategy

The traveling wave line protection is set at line 2 as well. In order to realize the continuous operation of high-end valve under the permanent fault of DC line 2, the positive pole being taken as an example. The disconnector CB1 is configured near the inverter station LCC1, the grounding electrode GND1 is constructed at LCC1 and the isolating switch CB3 is configured to the grounding electrode. In normal operation, CB1 is closed and CB3 is open. The line pattern is shown in figure 8.
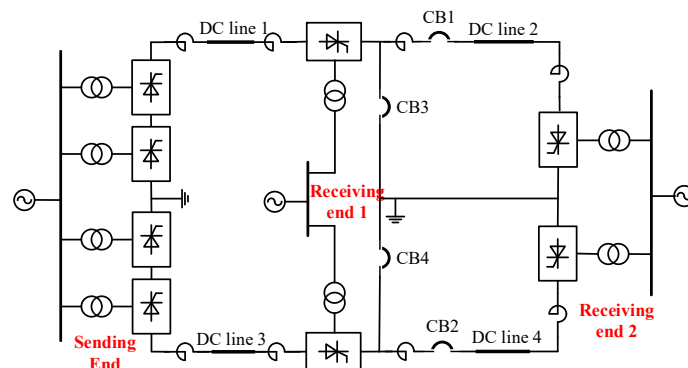
Figure 8. Action characteristics under different fault points

When transient fault occurs at line 2, the inverter station LCC1 sends protection action signal to the rectifier station, and the rectifier station restarts after forced phase shifting. When the permanent fault occurs at line 2, after failed restart, the phase is shifted again. After detecting that the current of line 2 crosses zero, the DC switch CB1 is disconnected and the DC switch CB3 is closed. The fault pole operates at half voltage and the non-fault pole operates at full voltage.

6 Conclusion

This paper studies the line protection strategy suitable for the UHVDC with series receiving ends, and builds the electromagnetic transient simulation model in PSCAD/EMTDC. Next, the adaptability of the current protection is analysed, and the corresponding solutions is carried out. The conclusions are as follows.

1) When the fault occurs at line 2, the rectifier station provides the fault current to the fault location through the high-end inverter valve.

2) At present, traveling wave protection is able to fit in the novel connection mode.

3) A hierarchical protection action strategy is proposed. The protection can act rapidly to isolate the fault in case of line 2 faults and can guarantee half of the power transmission even under permanent line 2 failure.

Acknowledgments

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