

Research on overvoltage and fault of a UHV AC/DC hybrid system

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Abstract: In view of the overvoltage problem of an ultra-high-voltage DC (UHVDC) AC/DC hybrid system, this study analyses the overvoltage condition under various fault types and gives the identification criterion of the overvoltage form. Firstly, the model of the ± 800 kV UHVDC and 1000 kV UHV AC hybrid system was established in Simulink. The relevant parameters of current and voltage in the hybrid system were simulated and analysed to verify the accuracy and effectiveness of the model. Secondly, the fault simulation of the two system models of AC and DC, respectively, is carried out, and the theoretical analysis of the internal overvoltage caused by the fault is made. Finally, the simulation of the overvoltage condition of the hybrid system under two conditions is carried out, and the waveforms of the important parameters of the AC system and the DC system are obtained. The waveform of each parameter is analysed and the conclusion is obtained. The type of the overvoltage fault of the UHV AC/DC hybrid system is analysed, which provides the basis for fault type judgement.

1 Introduction

With the development of economy and the improvement of people's living standard, the electricity consumption in China's society has been continuously and rapidly increasing. In 2012, the total electricity consumption of the whole society reached 4.96×10^{12} kWh, an increase of 18.9 times that of 1978, with an average annual growth rate of 9.2%. With the increasing role of power grids in the optimisation and deployment of large-scale resources, cross-regional power flows and trans-regional power transactions in China have gradually expanded. In the future, for a long period of time, China's power flow will still show the overall pattern of sending power from the West to the North and sending it to the North [1–3]. The development of ultra-high-voltage (UHV) AC and DC power transmission technology, to meet the future large-scale power base for long-distance, has made large-scale delivery possible.

In the development of UHV AC transmission at the same time, ultra-high-voltage DC (UHVDC) transmission is also gradually affirmed. Due to its large transmission capacity, fast control response, and stability without synchronous operation, DC transmission has obvious advantages in long-distance and high-capacity power transmission, and has become an important part of China's long-distance, high-capacity power transmission and regional networking the way [4, 5].

With the continuous development of UHV transmission technology, the UHV AC/DC hybrid system has become an inevitable trend.

Papers [6–9] only for UHV DC systems or UHV AC system, or system-specific failure of a device overvoltage conditions, but not from the perspective of the AC–DC hybrid system analysis. However, the UHV AC/DC hybrid transmission system is the inevitable trend of future power grid development [10–16]. The

influence of overvoltage on each other cannot be ignored and must be studied.

In this paper, UHV AC/DC hybrid system as the object, the establishment of its electromagnetic transient simulation model, to carry out overvoltage AC–DC system and identification criteria.

2 UHV AC/DC hybrid system modelling

Combined with the existing UHV AC/DC actual project, the model of the ± 800 kV UHVDC and 1000 kV UHV AC hybrid system was established in Simulink, and simulated under various operating conditions.

2.1 UHVDC system model

2.1.1 Extra-high-voltage DC transmission system mathematical model: According to the mathematical model, basic control method, and controllability analysis of the HVDC transmission system, an equivalent circuit of the HVDC transmission system can be obtained according to the steady-state mathematical model of the HVDC converter, as shown in Fig. 1.

Rectifier-side DC voltage:

$$V_{dr} = V_{dor} \cos \alpha - d_{xr} I_d \quad (1)$$

where

$$V_{dor} = \frac{3\sqrt{2}}{\pi} \cdot V_{cr}$$

Inverter-side DC voltage:

$$V_{di} = V_{doi} \cos \beta - d_{xi} I_d \quad (2)$$

where

$$V_{doi} = \frac{3\sqrt{2}}{\pi} \cdot V_{ci}$$

From the rectifier side to the inverter side of the DC current,

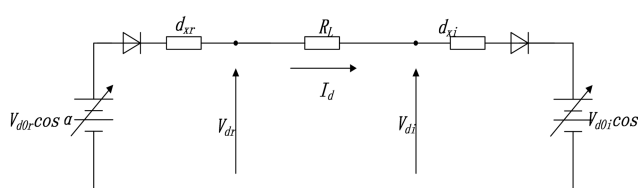


Fig. 1 DC transmission system equivalent circuit

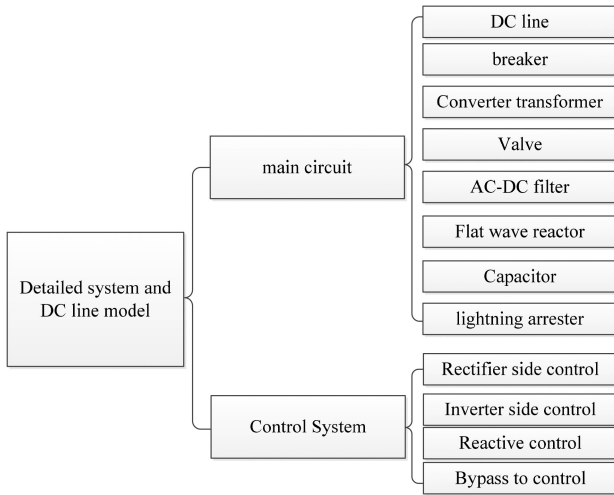


Fig. 2 DC system's overall model framework

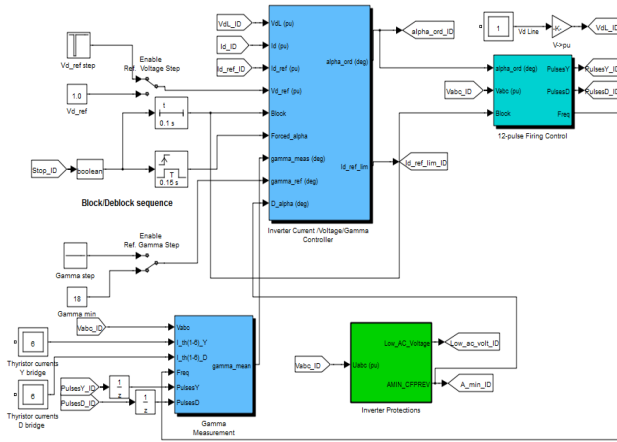


Fig. 3 Inverter-side control system

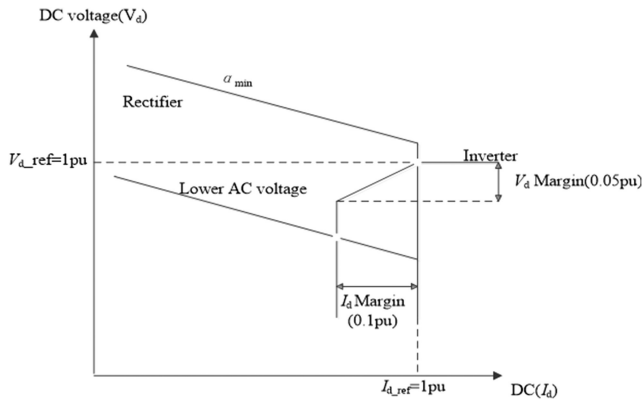


Fig. 4 DC system static volt-ampere characteristics

$$I_d = \frac{V_{d0r} \cos \alpha - V_{d0i} \cos \beta}{d_{xr} + R_1 + d_{xi}} \quad (3)$$

It can be seen from the above three equations that the DC voltage or DC current is determined by four quantities of α , β , V_{d0r} , and V_{d0i} , which are the control quantities of the HVDC transmission system, and no other quantity can be used as a control amount. Therefore, the basic control of DC transmission is to control the above four quantities to meet the various operational requirements of the DC transmission system.

2.1.2 HVDC Simulink model: The UHVDC system modelling, including the main circuit and control system, is based on the ± 800 kV Yun-Guang UHV DC transmission system, which has already been put into operation, and a DC model suitable for

practical engineering is established. The model framework of the DC system is shown in Fig. 2.

The HVDC control system, the hierarchical structure of the HVDC transmission control system, is usually divided into three levels: the first level is called the main control layer (or bipolar control layer), the second level is called the pole control layer, and the third level is called the Valve control level (Figs. 3 and 4):

$$i = 2i_0 \frac{Z_0}{Z_0 + Z} \quad (4)$$

where i_0 is the lightning current, Z_0 is the lightning wave impedance, and Z is the impedance of the struck object.

2.2 UHV AC system model

The UHV AC system in this paper is referenced to the Jindongnan-Jingmen 1000 kV UHVAC transmission system. Firstly, a mathematical model is established to demonstrate the feasibility of UHV AC transmission and its transmission capacity. Then, a 1000 kV UHV AC transmission system model with an equivalent generator network and equivalent end grid is established in Simulink. The transmission line is a 600 kV double-return distributed parameter the overhead line.

The sending AC power grid is designed according to the actual power transmission system. Equipped with 10 600 MW units, the rated voltage of each unit is 22 kV, the power factor is 0.80429, and the total active power is 5300 MW. Genset transformer through two transformers, the voltage rose to 1000 kV, and then by the UHV AC line to the receiving end of the grid, the transmission power of 5000 MW. By the end of the grid by the 1000 kV transformer buck power supply to the load. Related models are shown in Fig. 5.

The system is established through detailed theoretical analysis. Some parameters are referred to the Jindongnan-Jingmen 1000 kV UHVAC system, such as line length and transmission capacity; the other parameters such as generator, transformer, and equivalent power grid are set according to network transmission and distribution requirements for the design, in line with the actual project requirements.

After the extra-high-voltage (EHV) DC system and the UHV AC system are set up, respectively, the two systems are connected by a coupling line to form a UHV AC/DC hybrid system, and the normal operation of the UHV AC/DC hybrid system is simulated to verify the model's accuracy and effectiveness.

2.3 UHV AC/DC hybrid system's normal operation simulation

Taking the DC voltage, DC current, AC voltage, transmission power, and other related parameters of the DC system positive and negative poles, commutation side, and inverter side, respectively, and the voltage, current waveform, and transmission power of the UHV AC 1000 kV bus waveform and other related parameters, the simulation analysis is done to verify the accuracy and validity of the model. The DC voltage and current are expressed in per unit value, the reference value of the DC voltage is 800 kV, and the reference value of the DC current is 3.125 kA.

It can be seen from the simulation results that the AC bus voltages on the rectifier side and the inverter side are all rated values and the waveform is stable, indicating that the filtering effect is very good. Conveying the side of the active power transmission 4850 MW, close to 5000 MW, consider equipment loss lines, in line with the actual project.

In normal operation, the single-phase voltage amplitude of the AC bus at the 1000 kV side is 809.1 kV, which is higher than the voltage amplitude of the sending terminal, slightly lower than the rated value of 816.5 kV, which is acceptable in the project – received by the end of the active power of 4913 MW, in line with requirements (Figs. 6 and 7).

Through analysing the normal operating waveform of the UHVDC AC/DC hybrid system, it can be seen that the hybrid system designed in this paper accords with the actual operating characteristics of the system. All the parameters are in the vicinity

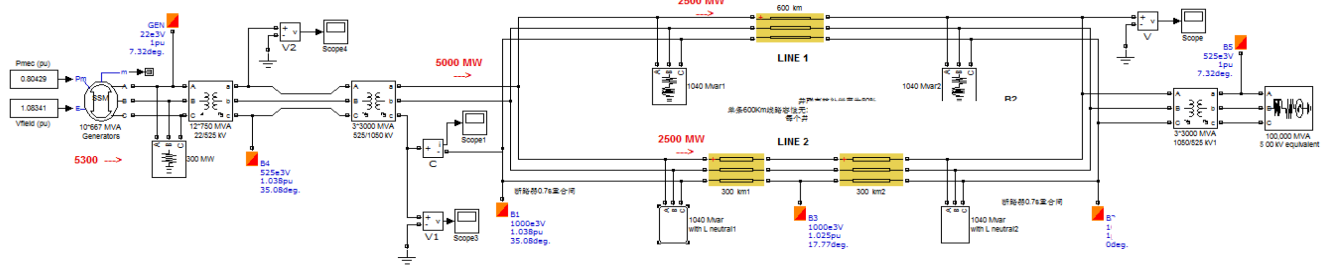


Fig. 5 UHV AC system model diagram

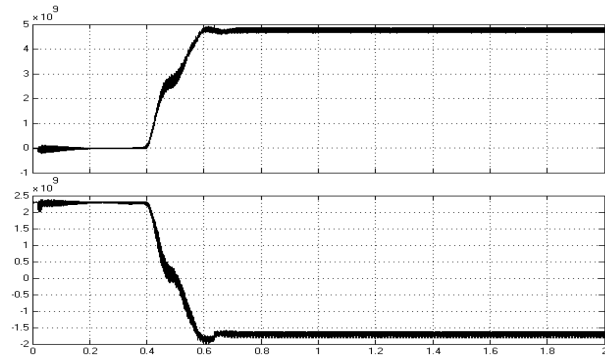


Fig. 6 DC system inverter-side receive power and reactive power

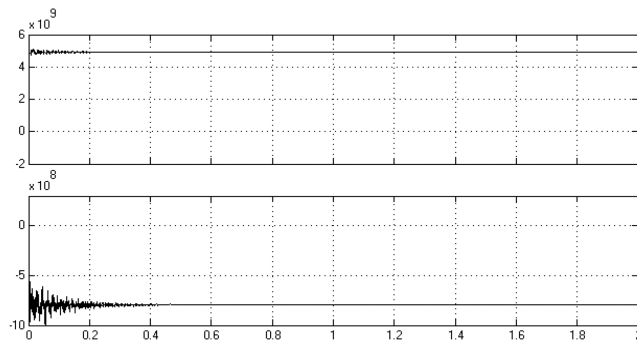


Fig. 7 AC system receiving power and reactive power

of the rated value and meet the engineering requirements, which can be used in subsequent various working conditions of voltage simulation research.

3 Overvoltage simulation of the UHVDC system

In this section, we will simulate the AC/DC hybrid system model built in the previous section and make a theoretical and practical analysis of the DC overvoltage caused by the fault and draw conclusions. A DC system's internal fault is caused by DC internal overvoltage including the converter station's top to ground fault, converter transformer's secondary single-phase ground short-circuit fault, DC line ground fault, DC system emergency shutdown, and the direct connection with the DC system exchange. System failure at the inverter side of the AC load shed is the most typical problem.

In the overvoltage analysis, the simulation of the DC voltage waveform is supplemented by the current waveform and DC system at both ends of the AC voltage waveform, leading to the specific overvoltage situation. In this paper, the inverter station's DC line outlet ground fault has been taken as an example for analysis.

DC system at 0.7 s occurred positive line inverter station outlet short circuit fault, 0.75 s fault was ruled out, the simulation of a total of 2 s. The main voltage and current waveforms are as follows (Figs. 8–10).

Analysis of the overvoltage waveform shows that in the DC system at 0.7 s, at the DC side of the inverter, the DC ground outlet fault occurs. As a result, the rectifier and inverter-side DC positive voltage begins to decay and reaches the 0 level, and then the DC

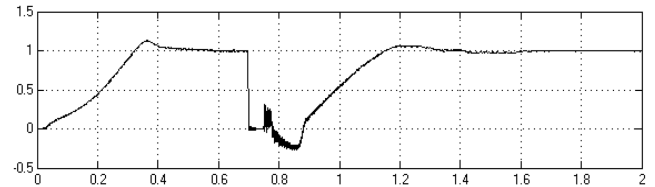


Fig. 8 Positive DC-side DC voltage

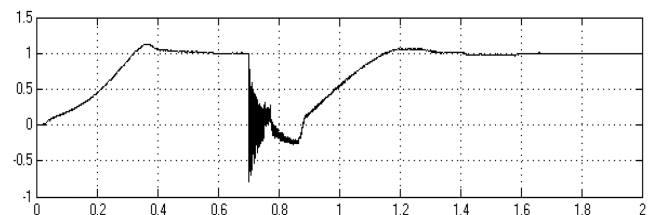


Fig. 9 Positive rectification DC voltage

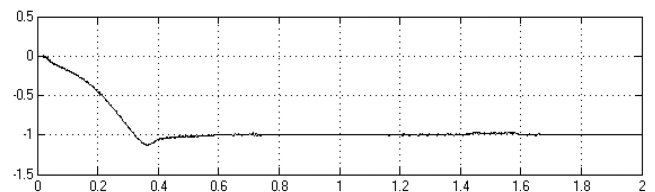


Fig. 10 Inverter negative voltage

line voltage, due to the ground, becomes 0, so there is no DC overvoltage.

The AC bus voltage directly connects with the rectifier and inverter side of the DC line short-circuit fault due to a certain degree of shock, and the short-circuit fault occurs when the DC line voltage drops rapidly because of the existence of converter transformers, so initially in the DC system, at both ends, the AC bus voltage declines temporarily. However, the DC system short-circuit fault affects the DC power transmission, thereby affecting the original AC–DC hybrid system active and reactive power balance; the AC bus voltage rises after a brief decline in an attempt to restore the rated voltage value. As can be seen from Figs. 4 and 5, the negative voltage of the DC system is basically not affected.

At 0.75 s, the DC line short-circuit fault is eliminated, and the electrical structure of the AC/DC hybrid system is restored. However, it takes time to recover the electrical quantities after the fault is rectified, and a certain degree of overvoltage may occur during recovery. From Fig. 4–1 to Figure 4–4, it can be seen that the overvoltage occurred during the AC bus voltage recovery at 0.78 s, the amplitude of the AC overvoltage on the rectifying side reached 700 kV, and the overvoltage on the inverter side was greater. Small, which is related to the structural characteristics of the DC system, the rectifier AC bus voltage received a greater impact. After troubleshooting, the DC positive voltage will also appear overvoltage of 1.05 to 1.1 p.u. during the recovery process, and the overvoltage amplitude of the inverter DC voltage will be higher relative to the rectification side.

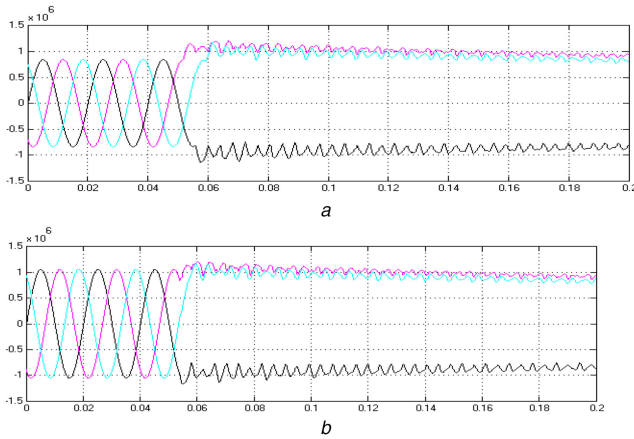


Fig. 11 Off-load dummy line overvoltage simulation waveforms
(a) Line head voltage waveform, (b) The first line voltage waveform

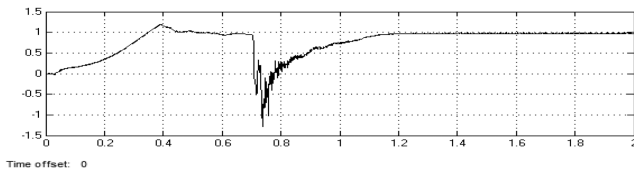


Fig. 12 Positive rectification DC voltage

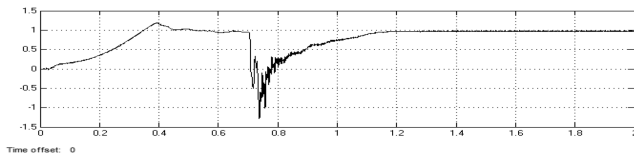


Fig. 13 Negative rectifier DC voltage

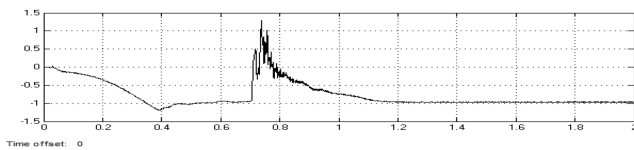


Fig. 14 Negative DC side of the inverter

4 UHV AC system internal overvoltage

Temporary overvoltage includes power overvoltage and resonant overvoltage, temporary overvoltage and system structure, capacity, parameters, operating modes, and the characteristics of a variety of safety devices.

In this paper, sub-gate open circuit overvoltage was taken as an example for simulation analysis.

4.1 Factors that affect the overvoltage of the opening operation

4.1.1 Circuit breaker performance: In order to avoid cutting off the line overvoltage, the most fundamental measure is to improve the circuit breaker arc performance, so as not to rekindle. The use of the modern circuit breaker can prevent or reduce the number of circuit re-ignition, thereby reducing the maximum overvoltage. However, the number of re-ignition is not the only basis for determining the size of the overvoltage. There is also a situation where a re-ignition overvoltage is higher than the re-ignition overvoltage amplitude.

4.1.2 Other occurrences on the bus: When there are other outlets on the bus, it is equivalent to increasing the capacitance. When the electric arc is re-burned, the remnant charge is redistributed rapidly. The initial value of the voltage is changed to be closer to the steady-state value so that the overvoltage is reduced.

4.1.3 Line side with an electromagnetic voltage transformer and other equipment: The remaining charges on the lecturer's line of presence of these devices have an additional release path, reducing the residual voltage on the line, thereby reducing the re-ignition overvoltage.

4.1.4 Neutral grounding method: Neutral point is not effectively grounded in the system, three-phase circuit breaker opening at different times will form an instant Symmetrical circuit, the neutral point will shift, the overvoltage significantly increased; under normal circumstances than the neutral point of the effective ground-line overvoltage over voltage by about 20%. In addition, when the overvoltage is high, corona causes the loss on the line and reduces the open-circuit overvoltage of the no-load line.

4.2 Sub-gate operation overvoltage simulation

Set the simulation time in Simulink at 0.2 s. At 0.05 s, UHV AC transmission line open-load operation occurs. The first and last lines of the voltage waveform are as follows (Fig. 11).

5 UHV AC/DC hybrid system overvoltage

UHV AC transmission is very suitable for high-power, short-distance transmission occasions; it is economically very advantageous. The research shows that the construction of UHV AC transmission as the backbone network replaces the EHV transmission network, which has the advantages of saving line corridor, optimising resource allocation, and reducing transmission loss.

However, HVDC transmission is not limited by the system's stability limit, which has obvious advantages for the interconnection of long-distance and large-area power grids. The use of DC transmission can reduce or avoid a large number of overcurrent flows passing through the inter-area network and can conveniently control the trend size and direction. Whether the UHV AC or UHV DC transmission mode, its characteristics and advantages are obvious, and how to combine the advantages of both to achieve complementary advantages of each other for the UHV AC and DC combined transmission system is the current and ultimate goal of research. Aiming at the possible overvoltage situation of the AC–DC hybrid system, the simulation analysis is carried out in this paper.

This section will simulate the overvoltage conditions of the hybrid system under two conditions to obtain the waveforms of the important parameters of the AC system and the DC system, respectively. DC voltage and current system parameters per unit value, the exchange system parameters using a well-known value, and effective value for characterisation have been considered. The parameters of the waveform analysis, and draw conclusions.

5.1 UHV DC system inverter-side single-converter transformer secondary side two-phase short circuit

First of all, simulate the most serious fault condition of UHVDC converter station and analyse overvoltage generated in this process. The two-phase short-circuit fault is set on the valve side of the Y-bridge converter in the positive inverter station. The simulated short-circuit fault of the DC system occurs at 0.7 s, the fault of 0.75 s is eliminated, and the system simulation is run for 2 s. The fault occurs and the overvoltage occurs more time short, so take the exchange of large changes in the parameters for analysis, the waveform of the main parameters are as follows (Figs. 12–14).

A part of the waveform of the hybrid system is given above. It can be seen that the influence caused by the two-phase ground fault on the converter valve side is relatively large, and both the DC system and the AC system are caused by the large overvoltage.

Through the simulation analysis, the short-circuit fault between the two phases of the converter transformer occurred during 0.7 s in the DC system. The DC voltage on the rectifier side and the inverter side dropped sharply, and the negative overvoltage appeared. The fault was eliminated in 0.75 s. As can be seen from the figure, after the fault occurred on the inverter side of the AC bus high voltage, the AC voltage amplitude rises to 1420 kV. After

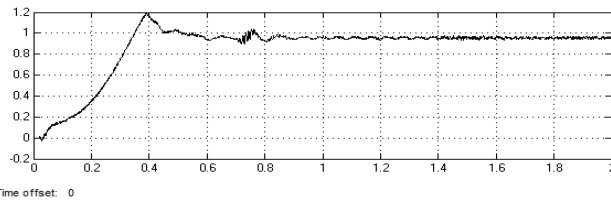


Fig. 15 Positive rectification DC voltage

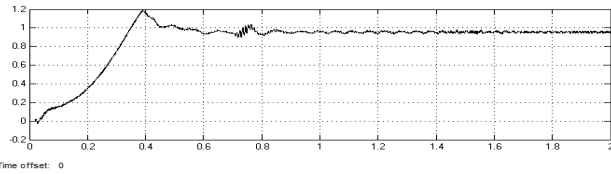


Fig. 16 Positive DC-side DC voltage

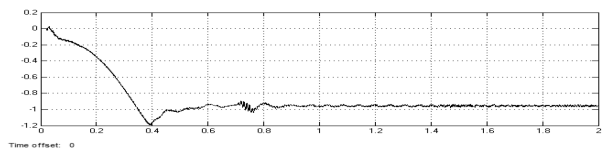


Fig. 17 Negative rectifier DC voltage

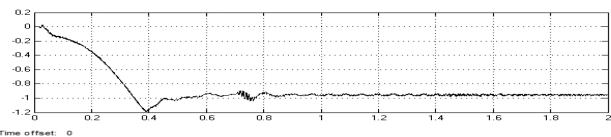


Fig. 18 Negative-side DC voltage

troubleshooting, the voltage waveform oscillates decay and finally reaches the nominal value. After troubleshooting, DC positive and negative voltage recovery, overvoltage in the recovery process, the overvoltage value of 1.16 pu or so. This shows that a fault on the DC system side leads to an overvoltage on the AC side directly connected to the DC system.

In the AC system, the double-circuit AC line also appeared during overvoltage; over the circuit, in a different location, overvoltage levels are different. At the head of the line close to the DC system, the overvoltage condition is the most serious. The voltage single-phase amplitude reaches 1200 kV. However, the overvoltage at the mid-point and the head end of the line, farther away from the DC system, is weakened, their adjustment characteristics are related.

In summary, the DC system due to commutation valve side of the two-phase short-circuit fault caused by commutation failure, reactive power compensation device too late to cut off lead to excess compensation, resulting in overvoltage, and resulting in parallel with the UHV AC system also produced High overvoltage. Table 1 gives the overvoltage amplitude of the main monitoring points in the hybrid system.

5.2 UHV AC system occurs once the line single-phase ground and reclosing

In the AC system, the double-loop circuit is adopted. When the simulation time is 0.7 s, the first phase of the line will be short-circuited to the ground and the line will be protected after the fault. At the time of 0.74 s, the circuit breakers at both ends of the line A will be cut off to cut off the fault. Phase closing start, the fault type is instantaneous fault, the fault is eliminated in 0.75 s, after the protective action 0.7 s that is simulation time 1.44 s single-phase reclosing, the fault has been ruled out, so reclosing success.

AC system in the event of the above-mentioned failure and action AC and DC system parameters of the waveform data analysis is as follows (Figs. 15–18).

Through the simulation analysis, after the single-phase AC ground fault occurred 0.7 s, the phase A voltage was significantly reduced, the voltage of non-fault phase increased, the overvoltage

Table 1 Overvoltage conditions in main monitoring point of the hybrid system when the DC system fails

Measuring point	Normal value /V ^a	The maximum overvoltage value/V ^b
positive rectifier DC voltage	7.92×10^5	1.03×10^6
positive inverter-side DC voltage	7.92×10^5	1.03×10^6
negative rectifier DC voltage	-7.92×10^5	-1.03×10^6
negative polarity DC side of the inverter	-7.92×10^5	-1.03×10^6
positive inverter-side Y transformer side valve voltage	8.20×10^5	1.16×10^6
positive inverter-side transformer D-bridge valve side voltage	6.08×10^5	6.96×10^5
positive rectification-side transformer Y-bridge valve side voltage	7.40×10^5	1.05×10^6
positive rectification-side transformer D-bridge valve side voltage	5.75×10^5	8.90×10^5
rectifier-side AC bus/reactive power compensation device voltage	3.89×10^5	7.25×10^5
inverter-side AC bus/reactive power compensation device voltage	4.35×10^5	1.42×10^6
positive inversion-side Y-bridge valve voltage	2.52×10^5	4.58×10^5
negative inverter-side Y-bridge valve voltage	2.51×10^5	-4.58×10^5
UHV AC transmission line head voltage	7.95×10^5	1.20×10^6
UHV AC transmission line midpoint voltage	8.20×10^5	1.05×10^6
UHV AC transmission line terminal voltage	8.02×10^5	1.15×10^6

^aSingle-phase voltage amplitude during normal operation.

^bSingle-phase voltage maximum during normal operation.

occurred, and the voltage value slightly exceeded the rated value. Phase A appears when the circuit breaker jumps the overvoltage maximum of 1.07 pu. Phase A during the reclosure occurs when the maximum overvoltage amplitude is 1.14 pu.

From DC system inverter-side bus voltage waveform can be seen, AC bus without much change. The inverter side of the positive DC voltage occurs when the fault occurs first, and then it runs smoothly in a certain range, resulting in a certain degree of overvoltage; the overvoltage r.m.s. reaches up to 1.05 pu. During the disconnection of the HVAC system circuit breakers, the DC system is at a lower voltage level of ~ 0.98 pu. From the simulation of the fault, it can be concluded that the reclosing of the AC system line, but with a fault, has little effect on the normal operation of the DC system (Table 2).

6 Conclusion

In this paper, the characteristics of the UHV AC transmission and HVDC transmission systems are summarised. Based on the construction of the mathematical model, the following research work is carried out on the problems of overvoltage fault and commutation failure of AC/DC systems:

(i) Combined with the existing engineering practice of the UHV AC/DC system, the model of the UHV HVDC and UHV AC hybrid transmission systems is established and its operation characteristics are analysed.

Table 2 Overvoltage conditions in main monitoring point of the hybrid system when the AC system fails

Measuring point	Normal value /V ^a	The maximum overvoltage value /V ^b
positive rectifier DC voltage	7.92×10^5	8.64×10^5
positive inverter-side DC voltage	7.92×10^5	8.64×10^5
negative rectifier DC voltage	-7.92×10^5	-8.64×10^5
negative polarity DC side of the inverter	-7.92×10^5	-8.64×10^5
positive inverter-side Y transformer side valve voltage	8.20×10^5	8.55×10^5
positive inverter-side transformer D-bridge valve side voltage	6.08×10^5	6.32×10^5
positive rectification-side transformer Y-bridge valve side voltage	7.40×10^5	7.93×10^6
positive rectification-side transformer D-bridge valve side voltage	5.75×10^5	6.11×10^5
rectifier-side AC bus/reactive power compensation device voltage	3.89×10^5	4.07×10^5
inverter-side AC bus/reactive power compensation device voltage	4.35×10^5	4.41×10^5
positive inversion-side Y-bridge valve voltage	2.52×10^5	2.56×10^5
negative inverter-side Y-bridge valve voltage	2.51×10^5	2.56×10^5
UHV AC transmission line head voltage	7.95×10^5	9.31×10^5
UHV AC transmission line midpoint voltage	8.20×10^5	8.98×10^6
UHV AC transmission line terminal voltage	8.02×10^5	9.22×10^5

^aSingle-phase voltage amplitude during normal operation.

^bSingle-phase voltage maximum during normal operation.

(ii) The internal overvoltages of the UHVDC system and that of the UHV AC system are analysed, respectively. On the basis of the comprehensive analysis of the overvoltage of the UHVDC system

and the overvoltage of the UHV AC system, the interaction relationship between the overvoltage of the UHV AC-DC hybrid system is studied.

(iii) The overvoltage of the UHVDC system and the type of overvoltage of the UHV AC transmission system and its influence on the converter station, HVDC transmission line, substation, and AC transmission line are simulated and analysed, respectively, and corresponding fault identification criteria are proposed for typical faults.

7 References

- [1] Ye, B., Yin, Y., Chen, S.: 'Ultra-high voltage GIS system no-load long-line closing transient ultra-fast transient voltage', *Kunming Univ. Sci. Technol.*, 2013, **38**, (1), pp. 59–64
- [2] Ji, R., Zhou, H., Yi, Q., *et al.*: 'Research on the characteristics of over-voltage during the closing of UHVAC system', *Electr. Power Syst. Prot. Control*, 2011, **39**, (14), pp. 86–93
- [3] Sun, Z., Liang, X., Sun, Y.: 'Simulation of multi-infeed HVDC transmission system based on EMTDC', *Power Syst. Technol.*, 2006, **30**, (S1), pp. 295–298
- [4] Wang, C., Liu, B.: 'Multi-regional DC commutation failure on the sending end of the system', *Netw. Technol.*, 2013, **37**, (4), pp. 1052–1057
- [5] Shao, Y., Tang, Y., Guo, X., *et al.*: 'Flux failure analysis of multi-infeed HVDC system in north China and east China in 2015 UHV planning grid', *Power Syst. Technol.*, 2011, **35**, (10), pp. 9–15
- [6] Wang, X., Yang, Z., Guo, M., *et al.*: 'Study on the influence of UHVDC access on the stability of east China exchange system', *East China Electr. Power*, 2009, **37**, (1), pp. 86–90
- [7] Lin, L., Zhang, Y., Zhong, Q., *et al.*: 'Research on commutation failure in multi-infeed HVDC system', *Power Syst. Technol.*, 2006, **30**, (17), pp. 40–46
- [8] Liu, J., Li, X., Wu, C., *et al.*: 'HVDC system commutation failure of the critical indicators', *Power Syst. Technol.*, 2009, **33**, (8), pp. 8–12
- [9] He, C., Li, X., Jin, X., *et al.*: 'HVDC transmission system commutation failure criterion to determine the standard', *Power Grid Technol.*, 2007, **31**, (1), pp. 20–24
- [10] Ren, K., Li, X., Jin, X., *et al.*: 'Simulation of commutation failure caused by filter switching in inverter station in multi-infeed HVDC transmission system', *Power Syst. Technol.*, 2008, **32**, (12), pp. 17–22
- [11] Huang, J., Zhao, C., Sun, Y.: 'Influence of overvoltage on the transmission capacity of two different HVDC transmission systems', *East China Electr. Power*, 2012, **40**, (10), pp. 1767–1771
- [12] Fu, Y., Shen, Y., Ding, J., *et al.*: 'Overvoltage mechanism and simulation of ± 800 kV UHV DC converter station in chongqing', *Electr. Power Constr.*, 2013, **34**, pp. 48–54
- [13] Xiong, H., Li, M.: ' ± 800 kV UHV DC transmission system over-voltage analysis', *Yunnan Electr. Power Technol.*, 2011, **39**, (4), pp. 36–39
- [14] Wang, D., Deng, X., Zhou, H., *et al.*: ' ± 800 kV Xiluodu - DC transient overvoltage in converter station of west zhejiang DC transmission project', *China South. Power Grid Technol.*, 2012, **6**, (2), pp. 6–13
- [15] Li, X.: '*High voltage DC transmission system*' (Science Press, Beijing, 2010), pp. 122–124
- [16] Ma, Q.: '*Research on electromagnetic transient process caused by switching operation of UHV series compensation devices*' (North China Electric Power University, Beijing, 2013)