Transient overvoltage characteristics in submarine cables of multi-terminal flexible HVDC transmission system

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Abstract—The overvoltage transient characteristics of submarine cables are one of the key technologies for submarine power transmission. This article takes the submarine cable of Zhoushan Multi-terminal Flexible HVDC Transmission Project as the research object. The MMC-HVDC simulation models at both ends of converter stations are built in PSCAD. The parameters and equivalent models of the flexible HVDC cables are determined, and the submarine DC cable operating overvoltage is calculated by using statistical methods. The simulation results show that the maximum overvoltage of the submarine cable, that is, the maximum overvoltage of the conductor to sheath, the sheath to the armour, and the armour to the ground are 400 kV, 7.27 kV and 0.45 kV respectively. The maximum overvoltage when it occurs faults on grid-side or valve-side appears in the middle of the submarine cable. Maximum overvoltage of HVDC single pole grounding fault appears at the connection point of land cable and submarine cable. The simulation results and the discovery of features in this article provide reference in the design, selection, and testing of submarine power transmission equipment.

1. Introduction

Submarine cables are the critical part of trans-sea power transmission projects, which play an important role in realizing the regional and international power network interconnection. Once the submarine cable has an insulation breakdown due to overvoltage, it will cause power outages for maintenance over several days or even months, and cause significant economic losses. Therefore, the overvoltage transient characteristics of submarine cables are one of the key technologies for submarine power transmission, and its research has an important guiding role in the design, selection, manufacturing, and testing of submarine power transmission equipment.

For the multi-terminal flexible HVDC system, due to its short application history, the current research mainly focused on the basic principles such as Modular Multilevel Converter (MMC) modeling, power modulation strategies, control system designing, start-stop controlling, internal circulation suppression, fault characteristics, and protection configuration. Furthermore, some researchers started from the actual engineering. The Zhoushan multi-terminal flexible DC transmission project [1]-[3] and the Trans Bay Cable project [4],[5] is took as examples to research the insulation coordination of the converter station. Researchers found that the most serious cases of overvoltage in the converter station included single-phase grounding at transformer valve-side, short-circuit of the converter valve, grounding of the valve roof or DC lines. As the connection unit of the flexible HVDC system, the transient overvoltage characteristics of the submarine cable are related to the safe operation, yet there are few relevant literature reports.
This article takes the submarine cable from Dinghai Converter Station to Daishan Converter Station in the Zhoushan Multi-terminal Flexible HVDC Transmission Project as the research object. The statistical method is used to simulate the overvoltage distribution of the MMC flexible HVDC transmission cable, and the transient overvoltage characteristics of the submarine cable is obtained.

2. Simulation Model and Conditions

2.1. Simulation model selections

Zhoushan Multi-Terminal Flexible HVDC Project is a typical model of MMC. The project uses a flexible HVDC submarine cable for interconnecting, and the grid-side of Dinghai and Daishan converter stations is connected to a 220 kV AC system. The DC rated voltage is ±200 kV. The main connection of the DC field adopts a pseudo-bipolar DC connection.

A two-terminal MMC-HVDC simulation model is built in PSCAD as shown in Fig.1. The converter station control and protection include the station controlling and converter controlling. The station controlling determines the control strategy in the station, and the converter controlling generates the trigger pulse of the converter valve basic module. The simulation step is set to 20 μs, and the drawing step is set to 250 μs. The main wiring scheme of the converter station, the main circuit parameters of the flexible HVDC system, the technical parameters of the equipment, and the operating power range refers to the literature [3]. For arrester configuration, parameter selection and modelling methods refer to the literature [4] and [5].

![Fig.1 Two-terminal MMC-HVDC simulation model](image)

The Dinghai-Daishan HVDC cable is 52 km long and is the longest cable segment in the five-terminal network. It includes a 2 km land cable and a 50 km submarine cable, both of which are cross-linked polyethylene DC cables. Among them, the submarine cable model is HVDC-YJQ41-200kV-1x1000mm². Its longitudinal section has 6 layers, including the conductor, insulation I, lead sheath, insulation II, armour, insulation III. The parameters of each layer are shown in Table 1.

| Layers      | Thickness / mm | Resistivity / (Ω·m) | Relative permittivity |
|-------------|----------------|---------------------|-----------------------|
| Conductor   | 0.0191         | 1.75×10⁻⁸           |                       |
| Insulation I| 0.0160         |                     | 2.30                  |
| Lead sheath | 0.0029         | 2.20×10⁻⁷           |                       |
| Insulation II| 0.0110      |                     | 2.25                  |
| Armour      | 0.0060         | 0.55×10⁻⁶           |                       |
| Insulation III| 0.0040     |                     | 2.50                  |

There are three equivalent models of cables in PSCAD: PI model, Bergeron model, and frequency-dependent characteristic model (FDC). Among them, the FDC model considers all frequency-related parameters and can accurately reflect the characteristics of the line in a larger frequency range. It can
be further divided into Frequent Dependent (Mode) Model and Frequent Dependent (Phase) Model. For ideal transposed lines, both models can give sufficiently accurate results. For non-ideal transposed lines, the latter model is more applicable [6]. Because the DC-side line needless to consider the commutation, this article adopts the Frequent Dependent (Phase) Model.

This article takes the insulation level of the submarine cable from Dinghai Converter Station to Daishan Converter Station as the object, and makes the following simplifications:

1. The equipment on the DC-side of the converter station is installed inside, so lightning overvoltage intruding from the DC-side is not considered.
2. Due to the arresters are deployed in the incoming lines, AC busbar, and GIS separately, it can be considered that the lightning overvoltage on the AC-side can be limited, so the lightning overvoltage is not considered.

The statistical method is used to simulate the HVDC submarine cable operating overvoltage. The parameters are set through the Multiple Run component in the PSCAD. In this article, the time of failure is set to be randomly and uniformly distributed within 1.2~1.22s. The Multiple Run component can set the number of sampling calculations. This article is set to 120, and the program will automatically sample and calculate 120 times. After the calculation is completed, the Multiple Run component automatically finds the maximum operating overvoltage of conductor to sheath, sheath to armour, and armour to ground.

2.2. Computing conditions
The Zhoushan multi-terminal flexible DC transmission project is a 5-terminal flexible DC network, in which Daishan Converter Station and Dinghai Converter Station are connected by submarine cables. This article considers the following:

1. The HVDC cable connecting Daishan Converter Station and Dinghai Converter Station is selected as an object due to it is the longest section of the 5-terminal system. Consider the most severe case, namely the outage of submarine cables between Daishan Converter Station and other converter stations.
2. The electric field strength of the HVDC cable insulation layer is proportional to the insulation resistance coefficient and changes exponentially with temperature. When the cable is running at full load, the temperature of the insulation layer close to the conductor is higher, whereas the insulation resistance coefficient is lower and the electric field strength is smaller. In this condition, the fault overvoltage poses the greatest threat to the insulation layer. Hence, the maximum active load of 300 MW and the reactive power of 180 MVA are selected for calculation.
3. 3 types of fault conditions: grounding fault on the grid-side of the converter transformer, grounding fault on the valve-side of the converter transformer, and grounding fault on the DC-side are mainly considered. Under such conditions, the maximum operating overvoltage of the conductor to sheath, sheath to armour, and armour to the ground is calculated. Because the greater the fault resistance, the less severe the fault caused. To strictly consider the grounding resistance, this article assumes that the grounding resistance is 0.01Ω, which is a metallic grounding fault.

The cable connecting Dinghai Converter Station to Daishan Converter Station includes two parts: submarine cable and land cable which are connected by flexible joints. Due to the terminals and connection positions of the cable have a higher failure risk, they are all set as over-voltage observation positions. To calculate operating overvoltage of conductor to sheath, sheath to armour, and armour to ground, a total of 7 calculation points is set up along submarine cable every 10km (as shown in Fig.2), where is, 0 km (Dinghai Station), 2km (land-submarine cable connection point), 12 km, 22 km, 32 km, 42 km, and 52 km (Daishan Station).
3. Simulation Results and Analysis

3.1. Transient overvoltage characteristics of unipolar grounding
DC unipolar grounding faults are generally permanent faults. This type of fault is more serious, which will cause the converter station blocking after it occurs 20 ms. After blocking, the AC system can still form a fault loop through the fault point, the grounding point, and the freewheeling diodes of the three lower bridge arms. Thus, power on the AC circuit breaker after 100 ms due to the fault point can hardly extinguish itself [7]. Assuming that the negative pole of the DC cable is grounded at a single-pole, this situation changes the zero-potential reference point of the valve-side AC system, and the valve-side AC voltage has a DC bias. The fault current forms a loop through the grounding branch, the bridge arm reactor, the DC smoothing reactor, and the fault point. After the fault occurs, the negative pole voltage quickly drops to zero. Due to the existence of the module capacitance between the positive and negative poles of the converter station, the DC voltage between the poles will remain roughly unchanged, resulting in a large overvoltage to the ground and current on the DC pole line of the healthy pole. After the converter valve blocking, the pole line voltage current decreases rapidly. According to the cable continuous operating voltage 202kV, the charge rate is 0.7, the DC reference voltage is calculated as 289kV.

3.2. Transient characteristics of operating overvoltage
In this article, the operation overvoltage simulation of submarine cable is carried out for the asymmetric grounding fault of the outgoing line of AC field, grounding fault of the coupling transformer of the bridge arm reactor, short circuit fault of the bridge arm, AC phase-grounding, AC phase-to-ground and phase-to-phase operating overvoltage, and grounding fault along the DC cable. The simulation results are shown as Fig.3.

(a) Voltage in the cable when occurs the asymmetric grounding of the outgoing line in AC field (kV)

(b) Voltage in the cable when occurs grounding fault of the coupling transformer of the bridge arm reactor (kV)

(c) Voltage in the cable when occurs short circuit fault of bridge arm (kV)
The operating overvoltage simulation is performed at the 7 observation points set up for the submarine cable. The calculation result shows that the highest overvoltage in the middle of the cable is 400kV, which is 1.98p.u (1p.u=202kV), whereas the lowest overvoltage is 398kV, and the standard deviation is 0.6kV. The statistical distribution of the central overvoltage is shown in Fig.4. The maximum overvoltage at the ends of the cable is 395p.u. The DC overvoltage decays with time and decays to the operating voltage within 40ms. The calculated maximum overvoltage of the sheath-armour is 6.69kV. The statistical conductor-to-sheath overvoltage distribution along the line is shown in Fig.5.
The summary simulation result of the operating overvoltage is shown in Table 2. The maximum operating overvoltage of the same polarity as the operating voltage between the conductor to the sheath is 400kV (1.90p.u). The maximum operating overvoltage appears in the middle of the sound pole cable when it occurs the cable terminal head grounding failure.

| Cause of fault                                   | Operating overvoltage in parts of conductor to sheath | sheath to armour | armour to ground |
|-------------------------------------------------|-------------------------------------------------------|------------------|-----------------|
| The asymmetric grounding of outgoing line in AC field | 234 kV                                                 | 5.9 kV           | 0.38 kV         |
| Coupling transformer grounding of the bridge arm reactor | 394 kV                                                 | 7.12 kV          | 0.44 kV         |
| Short circuit of the bridge arm                  | 210 kV                                                 | -                | -               |
| AC phase-to-ground and phase-to-phase operating overvoltage | 383 kV                                                 | 7.27 kV          | 0.45 kV         |
| Grounding fault along the DC cable               | 400 kV                                                 | 6.69 kV          | 0.13 kV         |
| Maximum value                                    | 400 kV                                                 | 7.27 kV          | 0.45 kV         |

4. Conclusion
The MMC-HVDC simulation models at both ends of the Dinghai and Daishan converter stations are built in PSCAD software, the parameters and equivalent models of the flexible HVDC cables are determined, and the DC cable operating overvoltage is simulated using statistical methods. The main conclusions are as follows:

(1) In the case of three-phase grounding faults on the converter transformer grid-side, three-phase grounding faults on the valve-side, and HVDC single pole grounding faults, the overvoltage of the HVDC cable conductor to sheath fault is more serious, which causes the converter valve to be quickly blocked and the commutation. The maximum overvoltage when it occurs faults on grid-side or valve-side appears in the middle of the submarine cable. Maximum overvoltage of HVDC single pole grounding fault appears at the connection point of land cable and submarine cable.

(2) The maximum operating overvoltage of the same polarity as the operating voltage between the conductor to the sheath is 400kV. The maximum operating overvoltage appears in the middle of the sound pole cable. The statistical maximum overvoltage along the cable is distributed in an umbrella shape, with the largest in the middle and decreasing to both sides. The overvoltage of the HVDC cable has the same polarity as the operating voltage. The induction operating overvoltage of sheath to armor in the middle of the cable is the largest, and the maximum overvoltage is 7.27kV.

References
[1] Li, Y., Jiang, W., Yu, S. (2014) System design of Zhoushan multi-terminal VSC-HVDC transmission project. High Voltage Engineering, 40: 2490-2496.
[2] Zhou, H., Shen, Y., Li, M. (2013) Research on insulation coordination for converter stations of Zhoushan multi-terminal VSC-HVDC transmission project. Power System Technology, 37: 879-889.
[3] Deng, X., Wang, D. (2013) Research on transient overvoltage for converter station of Zhoushan multi-terminal VSC-HVDC project. Power System Protection and Control, 41: 111-119.
[4] Zhang, Z., Xu, Z., Xue, Y. (2013) Study of overvoltage protection and insulation coordination for MMC based HVDC. Power System Protection and Control, 41: 58-64.
[5] Huang, J., Zhao, C. (2013) Study on overvoltage and insulation coordination of MMC-HVDC converter station. Journal of North China Electric Power University, 40: 1-6.
[6] Liu, X., Wang, X. (2014) Simulating experiment and transient analysis on switching surges in cable collection grid of wind power plant. High Voltage Engineering, 40: 61-66.
[7] Wang, S., Zhou X., Tang, G. (2011) Modeling of modular multi-level voltage source converter. Proceedings of the CSEE, 31: 1-8.