Effect of Seawater Immersion on Power Frequency Over Voltage Calculation of AC Three-core Submarine Cable

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Abstract. AC three-core submarine cable is an important carrier to transmit offshore wind power. Limited by the laying conditions, the reactive power compensation is generally carried out at both ends of the submarine cable line. And the armour along the submarine cable is immersed by seawater until the metal sheath, which causes the sheath of the submarine cable line to be grounded everywhere. With the growth of submarine cable lines, power frequency overvoltage becomes more and more serious. In order to effectively limit power frequency overvoltage, it is necessary to study and compare the effect of different reactive power compensation schemes on overvoltage. This paper is based on the research of double loop AC three-core submarine cables. The submergence of seawater is simulated by dividing the submarine cable into sections and grounding the sheath and armour of each section of submarine cable through resistance. On the basis of this model, the changes of line power frequency overvoltage under the conditions of "55" compensation, "28" compensation and three terminal compensation are calculated and compared. Under the scheme of "28" compensation at both ends, the maximum power frequency overvoltage of the line is the lowest. The research results provide a theoretical reference for the reactive power compensation scheme of offshore wind power access system.

1. Introduction

In recent years, a large number of offshore wind power stations have been put into operation. In order to make full use of offshore wind resources, offshore wind power stations are usually located on islands far from land. More and more AC three-core high voltage submarine cables have been put into operation for long distance transmission at sea [1-2]. Power frequency over voltage is an important parameter to be considered in the design of long-distance submarine cable transmission system. The submarine cables are laid on the sea floor. The sea water will be immersed in the armor of the cable until the metal sheath. The inner part of the metal sheath has a layer of semiconductor water-blocking band to block the seawater contact wire core [3-4]. The immersion of seawater makes the armor and metal sheath along the cable short and grounded. Therefore, when calculating power frequency over voltage of submarine cables, the model and calculation results will be different from those of land cables.

At present, scholars focus on single-core cables to study the power frequency over voltage of AC high-voltage submarine cables. Wang Xiaotong and Jue J S calculated the power frequency parameters of 500 kV single-core river-crossing cable and 525 kV submarine cable separately. The influence of sheath grounding mode and line length on power frequency parameters was studied theoretically [5-6]. Zhou Ziqiang and Puharic M simulated the over voltage of single-core submarine cable, and
considered the grounding resistance of the cable at power frequency [7-8]. STEINBRICH K studied the semi-conductive layer of submarine cable. It showed that submarine cable is different from land cable [9]. Guo Faan analyzed the grounding current of three-core cable, calculated the sequence network of three-core cable in different systems, and provided theoretical basis for calculating the power frequency over voltage of three-core cable [10].

In conclusion, there are few studies on power frequency over voltage of AC three-core submarine cable, and most scholars neglect the immersion effect of seawater in submarine cable model. In this paper, a cable calculation model considering seawater immersion is proposed. The variation of power frequency overvoltage of submarine cable and the influence of different reactive power compensation schemes on power frequency overvoltage distribution are studied.

2. Submarine cable line model

Based on a double circuit 220kV submarine cable line, the power frequency over voltage of line is studied by EMTP-ATP model. The basic situation of one circuit is shown in Fig.1. The offshore 35 kV wind turbine A is transformed by boost transformer from 90km long three-core submarine cable and 9km long three-phase single-core land cable to B station. Reactor is installed at both ends of cable line. The reactive power compensation rate is about 70%. The value of each reactor is about 2.2H. The cross section of three-core submarine cable is 3*630mm$^2$. The sheath and armor at both ends of submarine cable line are grounded directly, and the grounding resistance is 1Ω [11-12]. The cross section of single-core cable is 3*630mm$^2$. The sheath of each 1.5km three-phase cable is cross-connected. The two ends of the metal sheath of the land cable are grounded directly, and the grounding resistance is 1Ω.

![Figure 1. Schematic diagram of cable route.](image)

In the model, the submarine cable is divided into several segments. The sheath and armor of each segment are directly connected to ensure the integrity of the whole submarine cable line. In order to simulate seawater immersion into cable armor and sheath, a resistance is set on the sheath and armor connection line between each module to connect to the ground. Each cable sheath and armor is connected with the ground by a resistance, which simulating the seawater immersion into the cable armor and sheath. This resistance is called seawater grounding resistance, and its value represents the resistivity of seawater.

As shown in Fig.1, single-phase grounding faults are set at the first end A, middle B and end C of one circuit respectively. The fault phase is B-phase cable. In the simulation, the fault time is 0.2s, and the three-phase circuit breaker near the fault side breaks 0.1s after the fault [13-15].

3. The effect of seawater immersion

In the model, the submarine cable is divided into several sections, and the sheath and armor between each section are grounded by resistance, which simulates the grounding resistance of seawater. The variation of grounding resistance in seawater simulated seawater with different resistivity. When the seawater immersion is not considered, when the fault occurs at the head, middle and end of the line respectively, the maximum power frequency overvoltage in the line appears at the corresponding fault
position. Among them, the overvoltage reaches 1.32p.u. in case of terminal fault, 1.47p.u. in case of middle part fault and 1.28p.u. in case of head end fault.

Then, the submarine cable is divided into four sections, and seawater grounding resistance is added between each section. In the simulation, the resistance value is set as 5Ω, 10Ω, 20Ω, 40Ω, 80Ω in order to simulate the seawater with different resistivity. The fault is set in the terminal or the head end of cable line. The power frequency overvoltage distribution in the line changes less with the change of resistance. Fig.2 shows the power frequency overvoltage distribution in the line after the terminal failure.

![Figure 2](image-url)

**Figure 2.** Change rule of power frequency overvoltage along the line in case of terminal fault.

When the fault occurs in the middle part of the line, the seawater grounding resistance greatly affects the power frequency overvoltage distribution of the line. Without seawater grounding resistance, the maximum overvoltage in the line reaches 1.47p.u.. After adding 5Ω seawater grounding resistance, the maximum power frequency overvoltage amplitude in the line is reduced to 1.34p.u., which reducing about 8.8%. With the increase of seawater grounding resistance, the maximum power frequency overvoltage amplitude of the line increases continuously. As shown in Fig.3, when the resistance value increases to about 30Ω, the overvoltage amplitude is basically the same as that without seawater resistance. The seawater grounding resistance also affects the magnitude of power frequency overvoltage in the first section of the line. When adding 5Ω resistance, the amplitude of power frequency overvoltage in the first section increases to about 1.25p.u., which increasing about 12.6%. With the increase of resistance, the power frequency overvoltage of the first section decreases gradually.

![Figure 3](image-url)

**Figure 3.** Change rule of power frequency overvoltage along the line in case of intermediate fault.
4. Research on reactive power compensation scheme

Based on the submarine cable model of seawater immersion, the influence of different reactive power compensation schemes on the distribution of power frequency overvoltage is studied. The grounding resistance of seawater is 10Ω. The original pre-set scheme of the line is to install parallel reactors at both ends, each of which is about 80 MVA, and the compensation rate is about 70%. There are two new compensation schemes: one is to change the capacity configuration of high reactance at both ends of the submarine cable with the same compensation degree; the other is to add reactive power compensation station in the middle of the submarine cable with the same compensation degree. The first is called two-terminal compensation. The second scheme is called three-terminal compensation. The results are shown in Table 1. For two-terminal compensation, "55" and "28" are adopted for the capacity configuration proportion of reactance at the head end and the end respectively. The proportion of the capacity of the sending end is 50% and 20% respectively, and the proportion of the capacity of the receiving end is 50% and 80% respectively.

Table 1. Reactive power compensation scheme of submarine cable access system.

| Compensation scheme         | Compensation rate | Sending end | Central section | Receiving end |
|-----------------------------|-------------------|-------------|-----------------|---------------|
| Two-terminal compensation   |                   |             |                 |               |
| "55"                        | 70%               | 80 MVA      | /               | 80 MVA        |
| Two-terminal compensation   |                   |             |                 |               |
| "28"                        | 70%               | 32 MVA      | /               | 128 MVA       |
| Two-terminal compensation   |                   |             |                 |               |
| "55"                        | 60%               | 68.5 MVA    | /               | 68.5 MVA      |
| Two-terminal compensation   |                   |             |                 |               |
| "28"                        | 60%               | 27 MVA      | /               | 110 MVA       |
| Three-terminal compensation |                   |             |                 |               |
| 70%                         | 50 MVA            | 60 MVA      | 50 MVA          |
| Three-terminal compensation |                   |             |                 |               |
| 60%                         | 43 MVA            | 51 MVA      | 43 MVA          |

In the simulation calculation, the fault location is the end of the line and the middle of the submarine cable. In case of fault at the end of the line, the distribution of power frequency overvoltage under different reactive compensation schemes is shown in Fig.4 (a). When the compensation rate is 70%, the power frequency overvoltage multiples at the end of the line are 1.321 p.u., 1.312 p.u., and 1.322 p.u. respectively, under the "55", "28" and three-terminal compensation schemes. Under the three-compensation schemes, the power frequency overvoltage multiples of the middle part of the submarine cable are 1.229 p.u., 1.230 p.u., and 1.222 p.u.. It can be seen that the power frequency overvoltage of the line with "28" reactive compensation layout scheme is the lowest, and the power frequency overvoltage of the line with three-terminal compensation scheme is the largest. For the power frequency overvoltage in the middle part of submarine cable, the three-terminal compensation scheme is the lowest.
Figure 4. Distribution of power frequency overvoltage under different compensation schemes.

When there is a fault in the middle part of the submarine cable, the distribution of power frequency overvoltage under different reactive compensation schemes is shown in Fig.4 (b). When the compensation rate is 70%, the maximum power frequency overvoltage multiples of "55", "28" and three-terminal compensation schemes are 1.394 p.u., 1.404 p.u., and 1.383 p.u. respectively. Under the scheme of "28" reactive power compensation, the power frequency overvoltage of the line is the largest, and under the scheme of three terminal compensation, the power frequency overvoltage of the line is the lowest.

The cost of constructing reactive power compensation station in the middle part of submarine cable is relatively large and the failure rate is lower when the fault occurred in the middle. Therefore, the cost performance of three-terminal compensation is poor. According to the calculation, the scheme of "28" can reduce the maximum power frequency overvoltage to a certain extent. In the design process of submarine cable access system, more capacity reactance can be configured at the receiving end.

5. Conclusion

In this study, the submarine cable is divided into sections and the armor of each section are grounded through resistance to simulate the immersion of sea water. When considering the effect of seawater immersion, the power frequency overvoltage caused by the fault at the head and end of the line changes less, which reducing about 1%. The power frequency overvoltage caused by the fault at the middle part of the line changes larger, which the larger change rate is about 9%.

Based on the model of seawater immersion, the influence of different reactive power compensation schemes on line power frequency overvoltage is calculated. In case of fault at the end of the line, the power frequency overvoltage of the line is the lowest when the "28" reactive compensation layout is adopted. In case of fault at the middle part of the line, the maximum power frequency overvoltage of the line is the lowest when the three-terminal compensation is adopted. In comparison, it is suggested that more high reactance should be given priority to the receiving end when configuring the reactive power compensation device of the submarine cable access system.

References

[1] Ming Z, Ying L U, Jiahao L, et al. Transient Analysis of Lightning Overvoltage of Cable-Overhead Line Transmission System in Offshore Wind Farm[J]. Insulators and Surge Arresters, 2017,(6):44-50.

[2] Zhenbo L, Changwei Z, Jiangjun R. Analysis and calculation of submarine cable-overhead line lightning overvoltage[J]. Electric Power Automation Equipment, 2014,34(10):133-137.

[3] Yin L, Yang X, Yu S, et al. Loss Calculation and Influence on Ampacity of Single-core AC Submarine Cable Under Different Grounding Modes[J]. High Voltage Apparatus, 2018,54(10):56-62.
[4] Jian-Wei L, Bath U O. Research and Simulation of Transient Phenomena of High Voltage AC Submarine Cable Grid Based on ATP-EMTP[J]. North China Electric Power, 2014,(4):20-24,34.
[5] Xiaotong W, Zutao X, Liangeng B, et al. Calculation and Analysis on Power-Frequency Parameters for 500 kV Cable Lines[J]. Power System Technology, 2013,(8):2310-2315.
[6] Jue J S. Performance and operating experience of British Columbia Hydro’s 525 kV AC submarine cable system[C]/CIGRE. Paris, 1994: SC21-201.
[7] Ziqiang Z, Xuezhong L, Shaohua W, et al. Simulation Calculation of Transient Voltages on Insulation and Sheath Along 500kV XLPE Submarine Cable[J]. High Voltage Engineering,2018,44(8):2725-2731.
[8] Puharic M, Wagmann L, Zutobradic S. Overvoltage analysis on submarine cables of atmospheric origin and due to switching operations[C]/ International Conference & Exhibition on Electricity Distribution. 1997.
[9] Steinbrich, K. Influence of semiconducting layers on the attenuation behaviour of single-core power cables[J]. IET Proceedings - Generation Transmission and Distribution, 2005, 152(2):271-276.
[10] Baichao C, Xuanyao L, Jiaxin Y, et al. Reactive power allocation scheme for offshore wind farm considering power frequency overvoltage[J]. Electrical Measurement & Instrumentation, 2018,55(13):78-83.
[11] Wei X U, Minchuan L, Zhiyuan Z, et al. Research on Lightning Overvoltage of 500 kV Submarine Cable Lines[J]. Southern Energy Construction, 2016,3(2):62-66.
[12] Xuan Y, Zheng X, Cheng B, et al. Calculation of transient overvoltage in AC submarine cable system[J]. High Voltage Apparatus, 2014, 50(9):58-65.
[13] Shang-Zhi W U, Li-Ying L, Chencchen L. Calculation Analysis for Big Cross Section High Voltage Cable Over-voltage Protection[J]. Jilin Electric Power, 2013, 41(1):14-17.
[14] Liu X, Wang X, Li Y, et al. Simulating experiment and transient analysis on switching surges in cable collection grid of wind power plant[J]. High Voltage Engineering, 2014, 40(1):61-66.
[15] Sixuan C. Electrical Engineering Foundation[M]. Beijing: China Electric Power Publishing House, 2004.