Electromagnetic Transient Analysis of 500 kV XLPE Submarine Cable Interconnection Project from Zhenhai to Zhoushan

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Abstract. In Zhenhai-Zhoushan transmission project, 500kV XLPE submarine cable lines are used for the first time in the world. Using electromagnetic transient simulation program (EMTP), electromagnetic transient problems in this project are investigated including electrical parameter of submarine cable lines, power frequency overvoltages, secondary-arc currents and recovery voltages during the single-phase reclosing, power frequency resonance overvoltages, induced voltages and induced currents, switching surges and so on. On the basis, the recommended configuration scheme of HV shunt reactors and neutral reactors is proposed. In addition, it is suggested to install closing resistors of 400 ohm on both sides of line breakers in order to restrict switching overvoltages and ensure safe operation of submarine cable lines.

Key words: electromagnetic transient, 500kV, XLPE submarine cable, power frequency overvoltage, secondary-arc current, switching surge, power frequency resonance overvoltage

1. Introduction
The first 500kV transmission cable of the cross-sea interconnection project from Guangdong to Hainan was put into operation in June 2009. It is the first 500kV cross-sea transmission cable in China which is characterized by ultra-high voltage, long distance and large capacity [1-4]. The construction of the second cable started in October 2015. The self-contained oil-filled cable is used in this project. Considering the rapidly growing power load of Archipelago New Area in Zhoushan, it is necessary to build a new 500kV XLPE submarine cable networking channel between Zhenhai and Zhoushan. The submarine cable will be connected once in this period and twice in the future. The interconnection comprises one single submarine cable in this stage, and will comprise two submarine cables in the future. The capacity of one single transmission cable is 1100MW, which is a hybrid of submarine cable and overhead line. In this project, the 500kV cross-linked polyethylene submarine cable is adopted for the first time all over the world. Besides, the world's highest transmission twin tower will also be built for the long span cross of Xihoumen in this project.
Therefore, it is necessary to conduct electromagnetic transient research on the hybrid line, so as to serve the engineering design and construction, and provide a reference for the similar construction projects in the future.

2. System overview and operation mode

The Zhoushan interconnection project will construct the second network channel from Zhoushan to the mainland, and boost the current 220kV line to 500kV for operation, so as to form the network mode of the Zhoushan power grid and the mainland's two 500kV channels. The second network channel is equipped with a submarine cable of about 17km, which is arranged with a single core cable with equal horizontal spacing, and the spacing between the single phases is about 50m. The submarine cable is laid once in the current period and twice in the long term. The section of the cable is 1800mm² and the maximum power flow is 1100MW. The total length of overhead line is 35.5km, of which 4 long span lines are 2*9.5km, and 2*26km are ordinary lines. Except for the approximately 13km line from Jintang island to Zhoushan island and the planned 220kV double-circuits line from Jintang island to Zhoushan as per the four-circuits s of the same tower, the rest of the double-circuits line is set up as per the same tower. The conductor section is 4 * 300mm², which was completed at one time in this period, and its phase sequence is shown in figure 1. The system operation mode takes into account the single loop operation and the double loop operation. The maximum transport capacity of the single loop is considered as 2000MW, and the HV shunt reactor configuration scheme takes into account the 150MVar on each side and 120MVar on each side. The system wiring diagram is shown in figure 2. EMTP power electronics and electromagnetic transient simulation software are used to study the electromagnetic transient of this project.

3. Selection and calculation of cable parameters

The 500kV submarine cable of this project is to adopt the large-section cross-linked polyethylene insulated photoelectric composite submarine power cable. Compared with oil-filled submarine cables, cross-linked submarine cables have the advantages of better mechanical performance, higher operating temperature, larger conveying capacity under the same conductor section, no need for complicated oil-filled system, convenient installation and maintenance, and more environment-friendly, etc., and have become the mainstream direction of future development of submarine cables.

Since the cable armoring is actually in contact with sea water, it can be regarded as a ground conductor, and the armoring can be directly removed when calculating cable parameters. If the metal sheath of the cable is welded together with the armor, the metal sheath of the cable can also be eliminated directly.

According to EMTP calculation, approximate sequence parameters of 500kV submarine cable in the above two cases are shown in table 1. It can be seen that the zero sequence and positive sequence parameters of the cable are basically the same when the sheath and armor are considered as grounding.
The corresponding zero sequence reactance is slightly higher than the positive sequence reactance when only armored ground and the grounding resistance of the terminal station is 4 ohms.

Table 1 The parameters of 500kV single line submarine cable

| computational condition                      | Sequence parameter | resistance(Ω/km) | reactance(Ω/km) | capacitance(μF/km) |
|---------------------------------------------|--------------------|-----------------|-----------------|--------------------|
| Armour ground, sheath ground at both ends   | Zero sequence      | 0.0197          | 0.0811          | 0.1716             |
|                                             | Positive sequence  | 0.0205          | 0.0798          | 0.1716             |
| The armor is grounded, the sheath and the   | Zero sequence      | 0.0205          | 0.0798          | 0.1716             |
| armor are welded together                     | Positive sequence  | 0.0205          | 0.0798          | 0.1716             |

4. Selection Secondary arc currents and recovery voltages under different HV shunt reactor configuration schemes

For the transmission system with single-phase automatic reclosing, when the single-phase grounding fault occurs in the line and the circuit breakers on both sides of the line jump off, due to the coupling effect of phase to phase mutual inductance and phase to phase capacitance, the fault point will flow through a certain value of grounding current. This is the Secondary arc currents, also known as the Secondary arc. After the arc is extinguished, the recovery voltage will appear in the arc gap due to the effect of phase coupling. This increases the difficulty of automatic arc extinguishing at the fault point and may lead to the failure of single-phase automatic reclosing. In the 500kV power transmission project of Zhenhai-Zhoushan, because the submarine cable is partially non-self-restoring insulation, if the cable core and the grounding part of the outer skin discharge, the cable insulation will be damaged, at this time, the single-phase reclosing operation cannot be carried out, and the problem of Secondary arc current need not be considered. However, it is still necessary to consider the Secondary arc currents and recovery voltages in the process of single-phase reclosing for the overhead line connected with submarine cable. It is a conventional limiting measure to install a small resistance with a certain resistance value at the neutral point of HV shunt reactor. It should be noted that the purpose of installing HV shunt reactor neutral reactor is to compensate for the phase capacitance of the line. Since there is no electrostatic coupling between phases in the submarine cable, its phase capacitance is zero, so no compensation is needed. In this project, the overhead line part is relatively short (only 35.5km) and its phase capacitance is small, so it can be considered to directly ground the neutral point with HV shunt reactor of the line. This is different from Guangdong-Hainan 500 kV submarine cable interconnect project [3-4].

When calculating Secondary arc currents and recovery voltages of the line, the situation of different positions (both sides of the overhead lines of Zhenhai-submarine cable and submarine cable-Zhoushan) was taken into account. The results show that there is little difference between the Secondary arc currents and the recovery voltages at different positions. Because the overhead line is un-transposed and the unbalance degree of the line parameters is high, the calculation results of faults in different phases are different to some extent. The curve of Secondary arc currents and recovery voltages (the maximum value in case of failure in different phases or locations) under the two HV shunt reactor configurations with small reactance values is shown in FIG. 3. It can be seen that the recovery voltage of the two groups with 120Mvar in the HV shunt reactor configuration is much lower than that of the two groups with 150Mvar. The minimum of the line potential supply current and recovery voltage occurs at 0 ohm or 100 ohm.
Figure 3 Secondary-arc currents and recovery voltages of overhead lines

Table 2 shows the secondary arc current and recovery voltage when the reactor at the HV shunt reactor neutral point is 0 ohm, 100 ohm and 200 ohm. Considering the complex situation along the line and the existence of certain uncertainty, from the perspective of limiting the line recovery voltage, it is better to adopt two groups of 120Mvar HV shunt reactor configuration schemes. In this scheme, although Secondary arc current and recovery voltage are lower when the small reactance is 100 ohm, the Secondary arc current and recovery voltage when the neutral point is directly grounded (the small reactance is 0 ohm) can meet the requirements of rapid single-phase recalculation [5]. The Secondary arc current of the line is mainly composed of electrostatic coupling component which depends on the phase capacitance of the line. When the neutral point of the line with HV shunt reactor is not equipped with small reactance (that is, the phase capacitance cannot be compensated), the change of HV shunt reactor has little influence on the electrostatic coupling component, and the corresponding Secondary arc current is not different. It can be seen that under the recommended configuration scheme of HV shunt reactor and neutral reactor of the line, the Secondary arc current and recovery voltage of the line can meet the requirements of rapid single-phase reclosing.

Table 2 Secondary-arc currents and recovery voltages of overhead lines

| HV shunt reactor capacity/Mvar | Neutral reactor/Ω | Secondary arc current/A | Recovery voltage/kV | Voltage of Neutral reactor/kV |
|-------------------------------|-------------------|-------------------------|--------------------|-----------------------------|
| 2×150Mvar                    | 2×100             | 8.0                     | 84.7               | 11.2                        |
| 2×200Mvar                    | 2×100             | 8.8                     | 65.6               | 16.0                        |
| 2×100Mvar                    | 2×200             | 17.7                    | 105.6              | 16.0                        |
| 2×120Mvar                    | 2×100             | 8.0                     | 27.5               | 0.0                         |
| 2×200Mvar                    | 2×200             | 5.8                     | 18.3               | 10.4                        |

5. Power frequency resonance overvoltage

For some reason, the EHV transmission line is not in full phase operation, that is, one or two phase circuit breaker is closed, and the other two phases or one phase circuit breaker is not closed at both ends for some reason, forming a non-full phase operation. This may occur in abnormal on-off or single-phase automatic reclosing processes. In the circuit with a high voltage reactor installed, due to the normal phase voltage is added to the relative ground capacitance of the disconnected phase and the high voltage reactor by the phase capacitance between the fault phase and the normal phase, when the parameters are not matched properly, the series resonance circuit may be formed, and a high power frequency resonance overvoltage appears in the disconnected phase.

Table 3 shows the voltage on the disconnected phase of the 500kV line from Zhenhai to Zhoushan under different HV shunt reactor configurations in the non-full-phase operation. It can be seen that when two groups of 150Mvar HV shunt reactor configurations are used, the disconnection phase of the non-full-phase operation is on the high side, which is related to the untransposed part of the overhead line and the high degree of HV shunt reactor compensation. However, when two groups of 120Mvar
HV shunt reactor configurations are used, the disconnecting phase voltage in the non-full-phase operation is lower and there is no power frequency resonance problem.

**Table 3** Power frequency resonance overvoltages of 500kV hybrid transmission lines from Zhenhai to Zhoushan

| HV shunt reactor capacity (Mvar) | off phase voltage (kV) |
|---------------------------------|------------------------|
| / Neutral reactor (Ω)           |                        |
| Zhenhai                         |                        |
| 150/—                           | 150/—                  |
| 120/—                           | 120/—                  |
| Zhoushan                        |                        |
| Disconnect a phase              | 84.3                   |
| Disconnect two phases           | 101.4                  |
| line side                       |                        |
| Busbar side                     | 27.5                   |
| line side                       | 29.3                   |

6. Power frequency overvoltage under different HV shunt reactor configuration schemes

According to literature [6], for the power frequency overvoltage level of the power grid, the side of the circuit breaker substation (bus) shall not exceed 1.30p.u., the side of the circuit breaker line shall not exceed 1.40p.u. In the study of power-frequency over-voltage, load rejection under normal power supply state and single-phase grounding fault at the line end (or receiving end) are taken as the conditions to determine the power-frequency over-voltage of the power grid. The influence factors of power frequency overvoltage under two fault modes are different. The capacitance per unit length of the cable line is much larger than that of the overhead line, so it has a certain influence on the overvoltage of power frequency in the load rejection without fault. The maximum power frequency overvoltage of the line usually occurs in the case of single-phase grounding load rejection. The series impedance per unit length of sea cable line is significantly lower than that of overhead line and the line length is shorter, so the grounding coefficient of hybrid line mainly depends on the overhead line.

The power-frequency overvoltage of the 500kV hybrid line Zhenhai-Zhoushan under different HV shunt reactor configurations is shown in table 4, where the neutral points of the HV shunt reactor line are directly grounded. It can be seen from the results that the overvoltage of power frequency of 500kV Zhenhai-Zhoushan hybrid line does not exceed 1.1p.u., within the allowable range. There is little difference in power frequency overvoltage between the two high reactance configurations.

**Table 4** Power frequency overvoltage of 500kV hybrid transmission lines from Zhenhai to Zhoushan

| Trip side of circuit breaker | HV shunt reactor capacity (Mvar) | load rejection without fault | load rejection with Single phase grounding |
|-----------------------------|---------------------------------|-----------------------------|-------------------------------------------|
|                             | / Mvar                          | Busbar side                 | line side                                 |
| Zhenhai                     | 2×150                           | 0.92                        | 0.93                                      |
|                             | 2×120                           | 0.92                        | 0.93                                      |
| Zhoushan                    | 2×150                           | 0.92                        | 2×120                                     |
|                             | 0.92                            | 0.92                        | 2×120                                     |

7. Induced voltage and induced current

When the double-circuit transmission lines of the same tower runs normally one time and stops operation and maintenance the other time, due to electrostatic and electromagnetic coupling between the circuits, the voltage and current will be induced on the stopped circuit. The induced voltage and current of 500kV hybrid line between Zhenhai and Zhoushan are studied in this paper. The induced voltage and current of the 500kV Zhenhai-Zhoushan hybrid line under different HV shunt reactor schemes are shown in table 5. As a reference, the calculation results without HV shunt reactor are also given. In this study, a certain margin is taken into account, and the maximum line power flow in a single cycle is considered as 2000MW. The bold part of the table is the calculation result after considering the influence of 220kV line. It can be seen that, considering the 120MVar HV shunt reactor configuration scheme, the induced voltage and current flow of this circuit do not exceed the standard of class B switch on average. Therefore, it is suggested that the grounding switches on both sides of the 500kV Zhenhai-Zhoushan hybrid line can be selected according to class B switch standards [7]: electrostatic coupling induced voltage (50kV), electrostatic coupling induced current...
(25A), electromagnetic coupling induced voltage (25kV) and electromagnetic coupling induced current (200A).

Table 5 Induced voltages and Induced currents of 500kV hybrid transmission lines from Zhenhai to Zhoushan

| HV shunt reactor (Mvar) | Electrostatic Coupling | electromagnetic coupling |
|------------------------|------------------------|-------------------------|
|                        | Induced voltage(kV)    | Induced current(A)       | Induced voltage(kV) | Induced current(A) |
| Zhenhai                |                        |                         |                      |                    |
| 150                    | 31.2                   | 3.0                     | 1.9                  | 149.5              |
| Zhoushan               | 40.1                   | 3.2                     | 2.1                  | 148.7              |
| 120                    | 10.3                   | 3.1                     | 1.9                  | 149.5              |
| —                      | 3.1                    | 3.4                     | 1.9                  | 149.5              |

8. Switching surge
According to literature [6], statistics of operating overvoltage (operating overvoltage with a probability of less than 2%) of 500kV overhead line should not exceed 2.0p.u. (1.0p.u. = 550kV × √2/√3). Since the air gap and insulator string on the overhead line are self-restoring insulation, a certain flashover rate (if not more than 1%) is acceptable. However, the insulation of cable line is non-self-restoring insulation, so even such flashover probability is not allowed. Therefore, statistical overvoltage (probability of occurrence less than 2%) is usually taken into account when conducting insulation coordination of overhead line parts. The maximum overvoltage is considered in the insulation coordination of the cable part. The maximum switching overvoltage of the submarine cable part is shown in Table 6, and the statistical switching overvoltage of the overhead line part is shown in Table 7.

The MOA configuration of this project is as follows: MOA with rated voltage of 420kV and 444kV are selected for the bus side and line side respectively, and MOA with rated voltage of 444kV is selected for the connection of cables and overhead lines. The randomness of closing time of circuit breaker is considered when calculating closing operation overvoltage. The circuit breaker closes 300 times randomly, and the highest overvoltage value in each three-phase closing is taken for statistics. The three-phase closing dispersion of circuit breaker shall not be greater than 5ms. The operating bus voltage before switching off is generally 540(550kV); When single-phase reclosing operation, each bus voltage is the corresponding operating voltage of the system.

Table 6 Switching surges of 500kV hybrid transmission lines from Zhenhai to Zhoushan (submarine cable)

| Operation place | Closing resistor(Ω) | Maximum switching overvoltage during closing no load lines(p.u.) | Maximum switching overvoltage during single-phase reclosing(p.u.) |
|-----------------|---------------------|---------------------------------------------------------------|---------------------------------------------------------------|
|                 |                     | Head               | Along the line | Terminal         | Head               | Along the line | Terminal         |
| Zhenhai         | None                | 1.70               | 1.82          | 1.82             | 1.56               | 1.73           | 1.71             |
|                 | 400                 | 1.18               | 1.21          | 1.23             | 1.08               | 1.11           | 1.11             |
| Zhoushan        | None                | 1.82               | 1.86          | 1.84             | 1.73               | 1.78           | 1.78             |
|                 | 400                 | 1.25               | 1.25          | 1.26             | 1.12               | 1.13           | 1.13             |

Table 7 Switching surges of 500kV hybrid transmission lines from Zhenhai to Zhoushan (overhead lines)

| Operation place | Closing resistor(Ω) | Maximum switching overvoltage during closing no load lines(p.u.) | Maximum switching overvoltage during single-phase reclosing(p.u.) |
|-----------------|---------------------|---------------------------------------------------------------|---------------------------------------------------------------|
|                 |                     | Head               | Along the line | Terminal         | Head               | Along the line | Terminal         |
| Zhenhai         | None                | 1.67               | 1.96          | 1.85             | 1.63               | 1.81           | 1.84             |
|                 | 400                 | 1.17               | 1.30          | 1.35             | 1.09               | 1.19           | 1.23             |
Supposing the line circuit breakers at both sides of Zhenhai-Zhoushan transmission lines are not equipped with closing resistors, the overvoltage can merely be controlled by the MOA operation on both sides of the overhead lines and the cables. The following conclusion can be drawn from the calculation results in this situation:

(1) when an open-phase line is closed or there is single-phase reclosing operation at Zhenhai side, the maximum operating overvoltage relative to the cable part and the single-phase reclosure shall be 1.82p.u., and the overvoltage relative to the overhead line part shall be 1.96p.u.

(2) when an open-phase line is closed or there is single-phase reclosing operation at Zhoushan side, the maximum operating overvoltage relative to the cable part and the single-phase reclosure shall be 1.86p.u., and the overvoltage relative to the overhead line part shall be 1.92p.u.

If be pure overhead line, fall in afore-mentioned operation overvoltage level, circuit breaker does not need to install close brake resistance. However, because the insulation of the cable line is non-self-restoring insulation, once the insulation failure occurs, it may bring more serious losses, so its insulation level should be more than the overhead line margin. Considering the high cost of the cable part and the aging insulation problem, in order to ensure the safe operation of the cable line, the operating overvoltage level along the line should be reduced as much as possible. Therefore, it is suggested to install a closing resistor of 400 ohm in both Zhenhai side and Zhoushan side circuit breakers.

9. Conclusion

According to the characteristics of cross-linked polyethylene submarine cable and different HV shunt reactor configuration schemes, this paper studies the electromagnetic transient of Zhoushan networked submarine cable and overhead hybrid line project, which provides a basis for the design and construction of the project, and provides a reference for the construction of similar projects in the future. The results show that:

According to the characteristics of cross-linked polyethylene submarine cable and different HV shunt reactor configuration schemes, this paper studies the electromagnetic transient of Zhoushan interconnection network which consists of submarine cable and overhead line. The research can serve the design and construction of the project, and provides a reference for the similar construction projects in the future. The results show that:

(1) When two groups of 150Mvar HV shunt reactor are adopted, there will be over line voltage when there is a reclosing or open-phase operation. This is related to the untransposed part of overhead line and high degree of compensation for the HV shunt reactor (about 90%). When two groups of 150Mvar HV shunt reactor configurations are adopted (compensation degree of 72%), the power frequency over-voltage, secondary-arc current and recovery voltage, and open-phase voltage are all within reasonable ranges under this configuration. In this study, 2 groups of 120Mvar HV shunt reactor is the recommended configuration scheme, in which the neutral points of HV shunt reactor lines can be directly grounded.

(2) When one line is out of service and the power flow of the other line does not exceed 2000MW, the induced voltage and current of the 500kV Zhenhai-Zhoushan hybrid line will not exceed the standard average of B-classed switch. Therefore, it is suggested that the B-class switches can be selected as the grounding switches on both sides of the line.

(3) Supposing the line circuit breakers at both sides of Zhenhai-Zhoushan transmission lines are not equipped with closing resistors, the overvoltage can merely be controlled by the MOA operation on both sides of the overhead lines and the cables. It is also considered that the insulation of overhead lines and cables cannot be self-restored. So when an open-phase line is closed or there is single-phase reclosing operation at Zhenhai side, although the maximum switching overvoltages of the overhead lines and the cables are below the standard levels, they may still cause great loss in the case of...
insulation failure. In order to ensure the safe operation of the cable line, the operating overvoltage along the line should be reduced as much as possible. Therefore, it is suggested that the circuit breakers at both sides should be equipped with closing resistor.

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