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Study on ± 500 kV VSC-HVDC Submarine Cable Transmission Bottlenecks Under Different Laying Methods

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Abstract. Since the temperature distribution, electric field distribution and steady-state current-carrying capacity of HVDC (high-voltage direct-current) cables affect each other, the temperature field and electric field should be taken into account when calculating the current-carrying capacity. In addition, in the actual operation of submarine cables, not only their own characteristics but also the impact of the laying conditions on the cable current-carrying capacity should be considered. In this paper, COMSOL Multiphysics is used to calculate the temperature and electric field distribution of ± 500 kV XLPE (cross-linked polyethylene) HVDC submarine cable. By comparing the results of the simulation with the equivalent thermal circuit model, the validity of the heat transfer algorithm applied to engineering practice is verified. And the temperature field models of submarine cables in seawater section, directly buried section and submarine section are established. Through the simulation calculation of the overall model, the effects of soil thermal conductivity and seawater temperature on current-carrying capacity under different laying modes are obtained, and the conclusion that the bottleneck section of the current-carrying capacity of DC submarine cables is directly buried is drawn. The current-carrying capacity analysis method and conclusion of ± 500 kV submarine cable presented in this paper can provide a theoretical basis for HVDC submarine cable transmission.

Keywords. HVDC, XLPE submarine cable, electric-thermal coupling, current-carrying capacity.

1. Introduction

With the advancement of urbanization and the development of renewable energy, HVDC cable plays an increasingly important role in the power system, especially the promotion of VSC-HVDC, which increases the demand for HVDC cable. HVDC cable system is more and more used in long-distance and large-capacity submarine transmission lines due to its small size, light weight, easy maintenance and environment-friendly characteristics[1]. However, there are still some difficulties in its engineering design. Different from AC (alternating current) cables, the temperature distribution, electric field distribution and steady-state current-carrying capacity of HVDC cables affect each other, which are important operating parameters[2]. First, submarine cables are usually

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transported over a long distance, and surround by seawater and soil, where the calculation of temperature field and the determination of the current-carrying capacity are more complicated. Second, the conductivity of XLPE insulation material is a function of temperature and electric field, while the electric field distribution in DC cable insulation is not only determined by the conductivity, but also affected by the cable temperature. Therefore, it is difficult to give accurate results either in simulation calculation or actual measurement.

In recent years, a lot of research has been carried out at domestic and international on the distribution of electric and thermal fields of cables. Chang Liu application of equivalent of thermal conductivity simplifies the structure of the DC cable[3], Yanpeng Hao studied the influence of maximum permissible conductor temperature and temperature difference of insulation layer on steady-state current-carrying capacity of DC cable[4]. Yanhui Wei discussed the influence of current-carrying capacity and laying method of land cable on temperature field distribution of HVDC cable with different insulation thickness[5]. Lin Yang carried out thermal-fluid-structure coupling simulation for DC cables, circulating water and insulation water pipes, and studied the influence of cooling water velocity on the temperature gradient of insulation layer and conductor temperature[6]. S.Baggs calculated the steady-state electric field distribution in XLPE insulation and analyzed the transient process of field intensity change after voltage polarity reversal[7]. C.C.Eddy analyzed the field intensity distribution in XLPE insulation by analytical method, and pointed out that the field intensity in the middle position of coaxial insulation basically did not change with loading, which was approximately equal to the average field intensity of insulation[8]. Huan Zheng studied the field intensity distribution in XLPE insulation under DC superimposed impulse voltage, and pointed out that the maximum field intensity always appeared on the inner surface of insulation[9]. Although the current-carrying capacity and electric-thermal characteristics of cables are more mature, most of the studies only focus on cable characteristics and land environment, without putting cables into actual submarine conditions. Since the laying method and environment of submarine cables are quite different from overland cables, submarine cables should not only consider the maximum permissible temperature of conductor, but also consider the influence of different laying modes on the current-carrying capacity. To solve this problem, the solution domain should be extended to the external area of cables when simulating the thermal field of the cable.Taking the ± 500 kV XLPE HVDC submarine cable as an example, this paper establishes the electric-thermal coupling model of DC submarine cable by using the professional finite element software COMSOL Multiphysics, calculates and analyzes the temperature field of submarine cable under three common laying methods: seawater section, directly buried section and sub-sea section. Finally, the influence of laying methods and environmental factors on the current-carrying capacity of submarine cable is further studied.

2. Cable Structure and Parameters

In this paper, ± 500 kV XLPE HVDC submarine cable is selected, the structure of the cable is shown in figure 1. The radius of the Copper Conductor is 64 mm, the Conductor Screen thickness is 2 mm, the XLPE Insulation layer thickness is 30 mm, the Insulation Shield thickness is 1.5 mm, the Water-blocking Tape thickness is 4 mm, the Lead Sheath thickness is 4.9mm, the HDPE Sheath thickness is 4.6 mm, the Filled Bands thickness is

6 mm, the PE Bedding thickness is 1 mm, the Armor thickness is 6 mm, and Serving layer thickness is 4.5 mm.

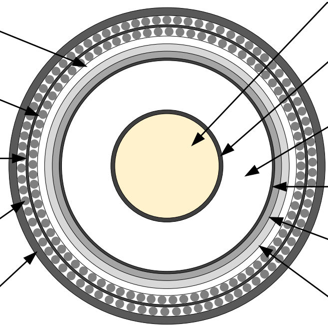

Figure 1. Cross-section of the ± 500 kV XLPE HVDC submarine Cable

The thermal physical properties of cables need to be defined in temperature field simulation studies, and in the electric-thermal coupling, the conductivity changes with the change of temperature and electric field, it needs to be accurately defined by the calculation formula. Main performance parameters are listed in table 1.

Table 1. Electric-thermal physical parameters of cable materials.

Structure	Thermal Conductivity/ (W/(m·K))	Conductivity / (S/m)
Copper Conductor	400	$\sigma_c = \frac{1}{1.72x10^{-8}[1+1.39x10^{-3}(T_c\text{-}20)]}$
Conductor Screen	10	$\sigma_{se} = -\frac{9}{670}T_{se} + \frac{877}{670}$
XLPE Insulation	0.29	$\sigma_i = 0.9x10^{-17}\exp(0.1T_i + 0.3E)$
Insulation Shield	10	$\sigma_{se} = -\frac{9}{670}T_{se} + \frac{877}{670}$
Water-Blocking Tape	0.28	$\sigma_{se} = -\frac{9}{670}T_{se} + \frac{877}{670}$
Lead Sheath	35.3	Not involved in electric field solution
HDPE Sheath	0.46	
Filled Bands	0.22	
PE Bedding	0.46	
Armor	44.5	
Serving	1.25	

σ_c , σ_{se} and σ_i are respectively conductor conductivity, semi-conductive material conductivity and XLPE Insulation conductivity, the units is S/m; T_c , T_{se} and T_i are respectively conductor temperature, semi-conductive material temperature and XLPE insulation temperature, the units is °C; E is the electric field intensity, the units is kV/mm. Due to the metal sheath plays the role of shielding the electric field, the lead sheath and the outside do not participate in the electric field calculation in this paper[10].

3. Fundamental Principle of Current-carrying Capacity

3.1. Equivalent Thermal Circuit Model Method

The cable loop is equivalently considered as a thermal circuit model, and the numerical derivation is carried out based on IEC60287 series formula to study the relationship of submarine cable between the current-carrying capacity and temperature[11]. Since HVDC cable does not have metal sheath loss, insulation loss can be neglected in normal operation, so only conductor loss of DC submarine cable can be calculated. The equivalent thermal circuit model is shown in figure 2.

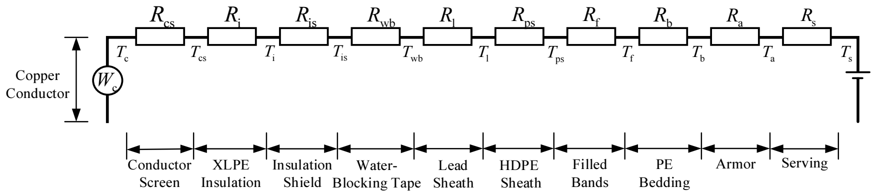

Figure 2. Equivalent thermal circuit model of HVDC submarine cable

In figure 2, W_c is the conductor loss, the unit is W/m. T_{cs}, T_{is}, T_{wb}, T_l, T_{ps}, T_f, T_b, T_a and T_s are respectively the temperature of Conductor Screen, Insulation Shield, Water-Blocking Tape, Lead Sheath, HDPE Sheath, Filled Bands, PE Bedding, Armor and Serving, the units is °C; R_{cs}, R_i, R_{is}, R_{wb}, R_l, R_{ps}, R_f, R_b, R_a and R_s are respectively the thermal resistance of Conductor Screen, XLPE Insulation, Insulation Shield, Water-Blocking Tape, Lead Sheath, HDPE Sheath, Filled Bands, PE Bedding, Armor and Serving, the units is K·m/W, the calculation method is as follows:

$$R_r = \frac{1}{2\pi\lambda_r}\ln\frac{r_{r2}}{r_{r1}} \tag{1}$$

R_r is the thermal resistance of any layer, the unit is K·m/W; λ_r is the thermal conductivity of the layer, the unit is W/(K·m); r_{r1} and r_{r2} are the inner radius and outer radius of the layer, the units are mm.

In a thermal circuit, the temperature difference between the ends of the thermal resistance is equal to the loss multiplied by the thermal resistance, so the difference between the temperature of the conductor and the temperature of the outer surface of the cable is equal to the product of the conductor loss and the total thermal resistance of the cable:

$$T_c - T_s = W_c R_{all} \tag{2}$$

$$R_{all} = R_{cs} + R_i + R_{is} + R_{wb} + R_l + R_{ps} + R_f + R_b + R_a + R_s \tag{3}$$

R_{all} is the total thermal resistance of the cable, the unit is K·m/W.

According to IEC60287 standard[12], the formula of unit length conductor loss W_c is:

$$W_c = I^2 R_{DC} \tag{4}$$

R_{DC} is unit length DC resistance of conductor, the units is Ω/m.

By combining (2), (3) and (4), the calculation formula of DC cable current can be derived as follows:

$$I_{IEC} = \sqrt{\frac{T_M - T_s}{R_M R_{all}}} \tag{5}$$

I_{IEC} is the steady-state current-carrying capacity of the conductor at the highest operating temperature, the unit is A; T_M is the highest operating temperature of the conductor, the units is °C; R_M is unit length DC resistance of conductor when the conductor temperature is T_M, the unit is Ω/m, which can be obtained from the following equation:

$$R_M = R_{20}[1 + \alpha(T_M - 20)] \tag{6}$$

R_{20} is unit length DC resistance of conductor at 20 °C, the unit is Ω/m; α is the Conductor DC Resistance Temperature Coefficient, the units is 1/°C.

3.2. Heat Transfer Methodology

Because the cable is axially symmetrical distribution based on the center line, in order to reduce the calculation amount, this paper uses COMSOL Multiphysics to establish a 2D axisymmetric model (figure 3). Joule heating is generated by applying current to the cable conductor area, and is used as the heat source in the heat transfer process to simulate the effect of current-carrying capacity on the temperature distribution.

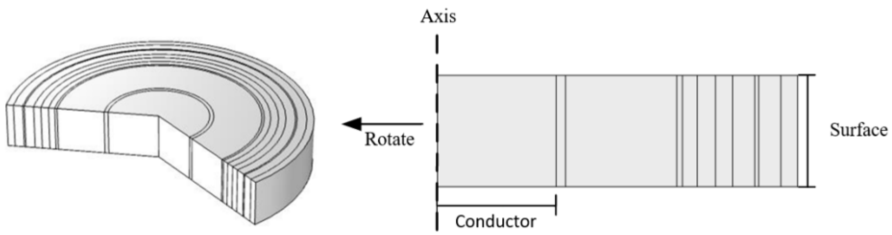

Figure 3. Simulation model of ± 500kV HVDC submarine cable

- Control equation

In COMSOL multiphysics, the temperature field is controlled by the heat transfer equation. Because the cable conductor needs to be loaded with current, the electric field control equation should also be added to study the change of the cable temperature distribution with the current-carrying capacity.

1)The heat transfer control equation is:

$$\rho C_p \cdot \nabla T + \nabla \cdot (-\lambda \nabla T) = Q_e \tag{7}$$

ρ is density, the unit is kg/m^3; C_p is the specific heat capacity, the unit is J/(kg·K); T is temperature, the unit is K; ∇ is the vector differential operator; λ is the thermal conductivity, the unit is W/(K·m); Q_e is the heat of unit length heat source, the unit is W/m^3.

2)The electric field control equation is:

$$\begin{cases} \nabla \cdot J = Q_{\mathrm{j}} \\ J = \sigma E + J_{\mathrm{e}} \\ E = -\nabla U \end{cases} \tag{8}$$

J is the current density vector, the unit is A/m^3; Q_j is the current source, the unit is A/m^3; σ is the electrical conductivity, the unit is S/m; E is the electric field intensity vector, the unit is V/m; J_e is the external injection current density, the unit is A/m^3; U is the electric potential, the unit is V.

3)According to Equations (7) and (8), the electric-thermal coupling equation is:

$$\begin{cases} \rho C_p \cdot \nabla T + \nabla \cdot (-\lambda \nabla T) = Q_e \\ Q_e = J \cdot E \end{cases} \tag{9}$$

- Boundary conditions and meshing

Common heat transfer problems can be summarized into the following three boundary conditions[13].The first type of boundary conditions are known boundary temperatures.

$$\begin{cases} \dfrac{\partial T^2}{\partial x^2} + \dfrac{\partial T^2}{\partial y^2} = 0 \\ T(x,y)|_{\Gamma =} f(x,y)\,|_{\Gamma} \end{cases} \tag{10}$$

The second type of boundary condition is the known boundary normal heat flux.

$$\begin{cases} \dfrac{\partial T^2}{\partial x^2} + \dfrac{\partial T^2}{\partial y^2} = 0 \\ \lambda \dfrac{\partial T}{\partial n}|_{\Gamma} + q = 0 \end{cases} \tag{11}$$

The third type of boundary conditions is the heat transfer coefficient and fluid temperature between fluid and solid are known.

$$\begin{cases} \dfrac{\partial T^2}{\partial x^2} + \dfrac{\partial T^2}{\partial y^2} = 0 \\ -\lambda \dfrac{\partial T}{\partial n}|_{\Gamma} = \beta (T_{\mathrm{r}} - T_{\mathrm{lt}})\,|_{\Gamma} \end{cases} \tag{12}$$

T is the temperature at (x,y), the unit is °C; Γ is the integral boundary; q is heat flux, the unit is A/m^2; β is the heat transfer coefficient, the unit is W/(m^2·K); T_r is the temperature at any point in the temperature field, the unit is °C. T_{lt} is the fluid temperature, the unit is °C.

In this section, the outer surface of the cable is assumed to be the first type of boundary conditions, that the temperature value of the outer surface of the cable is specified, and the analytic domain is meshed by triangular elements.

3.3. Analysis and Comparison of Results

Assuming that the external surface temperature of the cable is 25°C, the current-carrying capacity of each calculation method is calculated respectively when the conductor temperature is from 70°C to 100°C and the step length is 10°C. The calculation results are shown in table 2. The current-carrying capacity calculated by the equivalent heat model and the heat transfer method is compared. The data deviation is analyzed, and the results of the equivalent heat model are similar to those of the heat transfer method, which meet the deviation standard.

Table 2. The amount of capacity carried by each calculation method at different conductor temperatures.

Conductor temperature (°C)	Method of equivalent thermal circuit model (A)	Heat transfer method (A)	Absolute deviation (%)
100	1982	1955	1.3%
90	1871	1841	1.6%
80	1749	1734	1.5%
70	1608	1582	1.6%

Figure 4 shows the cable temperature distribution when the conductor temperature is 90 °C.

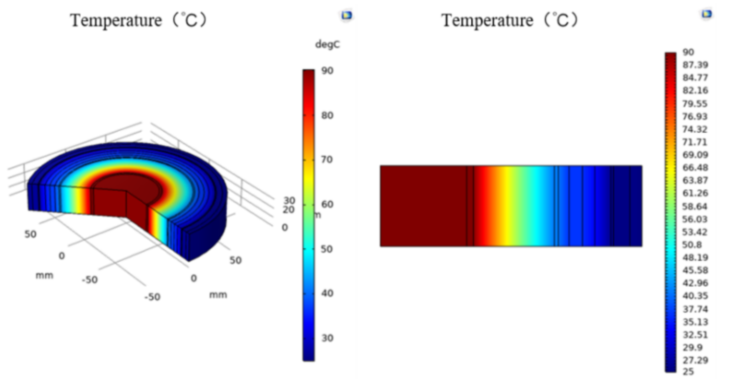

Figure 4. Temperature contours of ± 500kV HVDC submarine cable

4. Factors and Bottlenecks of Current-carrying Capacity

4.1. Effect of Temperature Field

Figure 4 shows that the cable has radial temperature difference. In order to study the influence of radial temperature difference on the current-carrying capacity, the cable temperature field is solved by selecting the current-carrying capacity from 500 to 2000 A and taking 250 A as the step. It can be seen from figure 5 that when the current-carrying capacity increases, the difference between conductor temperature and surface temperature increases. When the capacity reaches a certain limit, the calculation of the current-carrying capacity based on monitoring the surface temperature of the cable will have a large error from the actual allowable operating capacity, which makes it difficult to ensure the safe operation of the cable.

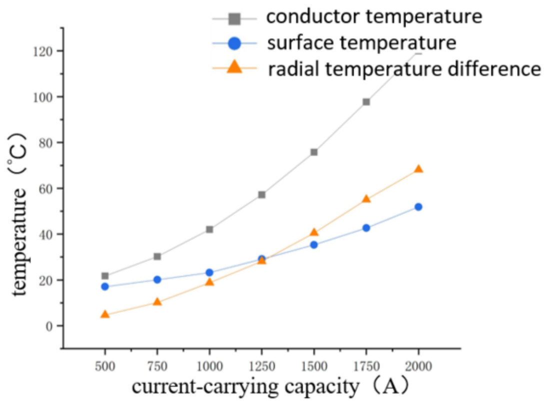

Figure 5. Effect of current-carrying capacity on temperature field

4.2. Effect of Electric Field

Due to the existence of radial temperature difference, the temperature distribution of Insulation is uneven which affects the electric field distribution[14-16]. The electric field of cable is simulated by heat transfer and results are shown in figure 6. The simulation results show that under no-load condition, the maximum field strength in the Insulation is located in the inner side of the layer. With the increase of the current-carrying capacity, the position of the maximum field strength begins to move. When the current-carrying capacity reaches 2200 A, the polarity of the electric field distribution reverses, and the position of the maximum field strength shifts from the inner side the outer side.

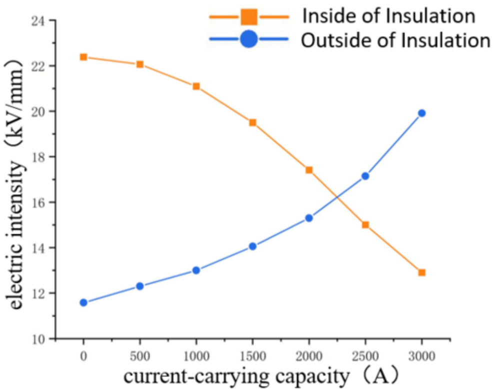

Figure 6. Effect of current-carrying capacity on electric field

4.3. Effect of Laying Methods

In this section, the third type of boundary conditions is used to determine the heat transfer conditions between the cable and the outside region[17].The heat transfer coefficients of seawater and soil are 200 W/(m^{-2}·K) and 8 W/(m^{-2}·K)[18], and the soil temperature is constant at 25 °C.The conditions model of submarine cable laying is shown in figure 7.

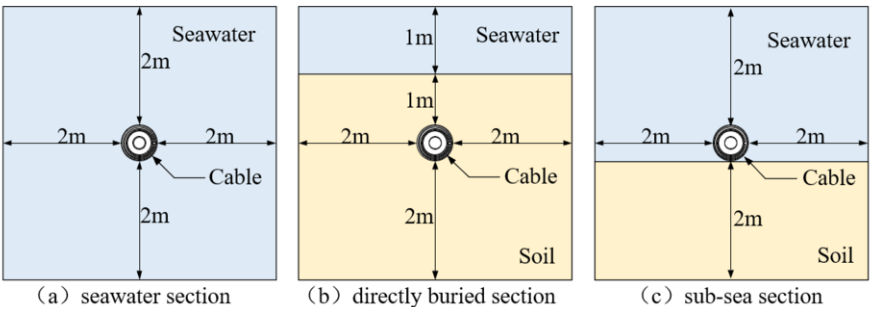

Figure 7. Conditions model of submarine cable laying

- Soil thermal conductivity

Calculate the soil thermal conductivity are 0.8, 1.0, 1.2, 1.4 W/(m·K) the current carrying capacity when the cable reaches the limit temperature[19], The variation of the current-carrying capacity with the thermal conductivity is shown in figure 8. It can be concluded from the results that the cable capacity raises with the increase of soil thermal conductivity. When the cable is laid, the cable current-carrying capacity can be increased by selecting the soil area with appropriate thermal conductivity.

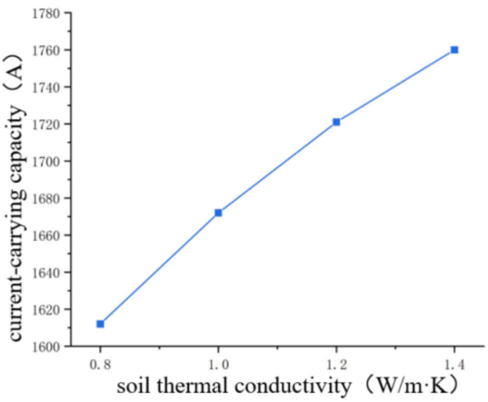

Figure 8. Effect of soil thermal conductivity

- Seawater temperature

When the temperature of the cable conductor reaches 90 °C and the buried depth is 1 m, the seawater temperature is selected from 15°C to 35°C with 5°C as the step to study the variation of the current-carrying capacity with sea water temperature under different laying conditions. The variation trend is shown in figure 9. It can be seen from the results that with the increase of seawater temperature, the current-carrying capacity decreases when the cable reaches the limit temperature. Among them, the seawater section is the most affected by seawater temperature, followed by the sub-sea section, and the directly buried section is negligible.

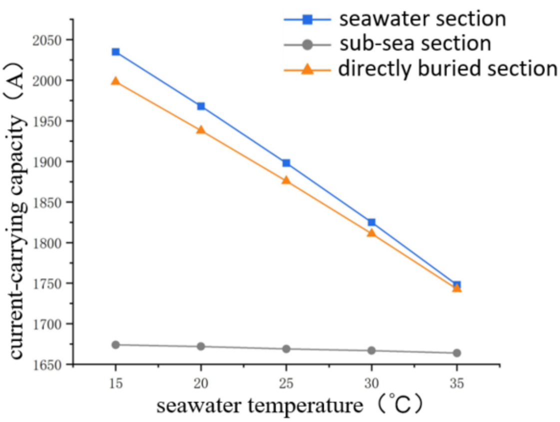

Figure 9. Effect of seawater temperature

- Comparison of laying method

In order to study the effect of the laying method on the current carrying capacity, calculate cable conductor at 70 °C, 80 °C and 90 °C of the current carrying capacity under each mode (figure 10). Except for the laying method, other environmental factors are the same. The sea water temperature is 30 °C, and the soil thermal conductivity coefficient is 1 W/(m·k). It can be seen from figure 8 that under the same conductor temperature, due to the cooling effect of seawater, the current-carrying capacity is close to the sub-sea section, while the directly buried section is slightly lower than that of other methods.

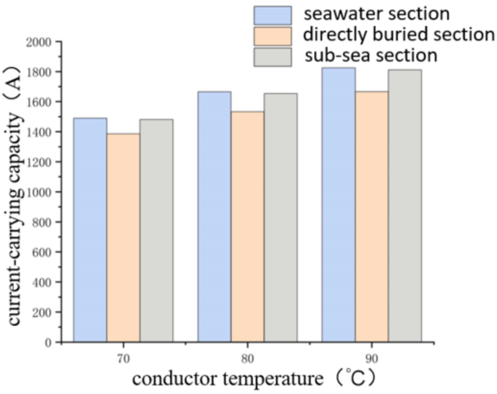

Figure 10. Comparison of capacity in different laying methods

5. Conclusion

For ±500kV flexible HVDC submarine cable, its current-carrying capacity is a very important parameter. This paper takes the ± 500 kV XLPE HVDC submarine cable as the research object, constructs the equivalent thermal circuit and heat transfer model, and studies its current-carrying capacity under different laying methods. The conclusions are as follows:

1) The accuracy of the heat transfer method is verified by comparing the calculation results of the heat transfer method and the thermal circuit model. This method can effectively provide theoretical basis and data support for power grid dispatching operators.

2) The cable has radial temperature difference, so it is difficult to ensure the safe operation of the cable by only monitoring the cable surface.

3) When the carrying-capacity reaches a certain limit, the electric field of the Insulation will have polarity reversal, which is equivalent to applying several times the voltage to the cable instantaneously.

4) The current-carrying capacity of submarine cables is the strongest in the seawater section, and the directly buried section is the bottleneck area that limits the current-carrying capacity. It is necessary to pay attention to the environmental factors and load conditions of the directly buried section of cables.

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