Discussion on the Improvement of Current Carrying Capacity of AC 500kV Submarine Cable

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Abstract: A three-dimensional electro-thermal coupling physical and mathematical model of the submarine cable landing section together with the cable trench was established to analyze the effect of the current-carrying capacity improvement scheme of the 500kV submarine cable. The effects of three types of submarine cable landing section current carrying capacity improvement schemes were analyzed and compared. The research results show that the flow rate of the medium around the cable in the cable trench (fluid medium), thermal conductivity, temperature of the cooling medium and the arrangement of the submarine cable affect the current carrying capacity. The fluid medium in the cable trench that is forced to flow along the radial direction of the cable can fully exert the heat absorption effect of the cooling system in the cable trench. The greater the thermal conductivity of the medium around the submarine cable, the Joule heat generated in the submarine cable conductor dissipates more quickly, reducing the temperature rise of the cable conductor, which is beneficial to increasing the current carrying capacity of the submarine cable. The research results have guiding significance for the selection and engineering design of submarine cables.

1. Introduction
In recent years, China's submarine cable technology and applications have developed rapidly. The demand for submarine cables has doubled every year and the voltage level has reached 500kV. The heat dissipation conditions of the submarine cable after landing are far less than the seabed. The soil in the landing section has poor thermal conductivity. The loss of armor and metal sheath is greater than that of the submarine cable. The allowable current capacity of the landing cable is generally only 60%~70% of the submarine section. Therefore, the submarine cable is subject to the current-carrying capacity bottleneck of the landing section, and the long-term operation is lower than the current carrying capacity of the cable conductor. On the other hand, increasing the cross-sectional area of the submarine cable conductor to improve the actual current carrying capacity will greatly increase the line investment cost of the submarine cable [1-4].

Reducing the loss of the submarine cable landing segment and improving the heat dissipation conditions of the landing segment are two key factors to eliminate the current-carrying capacity bottleneck of the landing section, and the long-term operation is lower than the current carrying capacity of the cable conductor. On the other hand, increasing the cross-sectional area of the submarine cable conductor to improve the actual current carrying capacity will greatly increase the line investment cost of the submarine cable [1-4].

In the literature [5-9], the method of stripping metal armor was adopted to reduce the power loss of the submarine cables of different voltage levels. The submarine cable landing section in the literature [8-10] used non-magnetic (copper or aluminum) armor, non-magnetic wire (copper or aluminum) and steel wire mixed armor structure, lead armor in series with resistance, and
lead-and-socket interconnection to reduce the loss of metal armor. These methods improved the
current carrying capacity of submarine cables from the perspective of reducing the loss of the
submarine cable landing segment. In the literature [2,10-14], the cooling characteristics of the
submarine cable landing section were improved by laying cooling water pipes in the cable trenches,
backfilling special soils, and filling the cable trenches with water.

The way of destroying the submarine cable structure will increase the possibility of damage to the
rest of the cable. The submarine cable with hidden dangers reduces reliability of the cable line. And
the above researches are mainly on some measures to improve the current carrying capacity of
submarine cables of 220kV and below. This paper is based on a 500kV submarine cable project and is
designed for single-phase copper armor XLPE submarine cable. Through the method of finite element
electro-thermal coupled field simulation calculation, measures such as the current carrying capacity of
the submarine cable landing section under the conditions of cold water pipe cooling, backfilling
special soil and cable trench filling with water are studied. The advantages and disadvantages of
different measures are compared, providing reference for sea cable selection and engineering
construction design.

2. Schemes of submarine cable current carrying capacity improvement
The cable trench layout of the landing section submarine cable is shown in figure 1. Three options for
increasing the current carrying capacity of the submarine cable are as follows.

![Figure 1. Schematic diagram of the relative position of the submarine cable and cable trench in the landing section](image1)

2.1. Forced cooling.
The cable trench is filled with air, and the cooling water pipe is arranged in parallel with the landing
cable. The air in the cable trench is forced to flow radially in the cable. The cooling water pipe is not
in contact with the submarine cable. The heat generated in the cable conductor is transmitted to the
cable surface through the layers of the cable. Some of the heat is absorbed by the cooling water
through air conduction and radiation, the remaining heat is conducted to the cable trench wall through
the air and then dispersed through the earth soil.

2.2. Backfill special soil.
The change of current carrying capacity of the submarine cable is considered when there is no cold
water pipe in the cable trench filled with the soil. The heat generated in the cable conductor is
conducted to the cooling water pipe and the cable trench wall via the backfill soil.

2.3. Cable trench filled with seawater.
The cable trench is filled with seawater, without cold water pipe. The seawater runs radially. The heat
generated in the cable conductor is absorbed by the cable trench wall through the convection and
conduction of seawater.

In the above three schemes, the heat absorbed by the cable trench cover is also radiated to the
atmosphere by radiation, convection and conduction; meanwhile, the upper surface of the cable trench
cover and the ground surface also receive radiant energy from the sun.

3. Calculation model of submarine cable and cable trench

3.1. Structure and model parameters

In figure 1, the cable trench has a top width of 3.5 m, a bottom width of 1 m, and a depth of 3 m. The submarine cable is a 500 kV single-phase copper armor XLPE submarine cable. The cable cross section is shown in figure 2. The cable structural parameters and the thermal conductivity of the materials used in this paper are shown in Table 1.

| Serial number | Material                        | Nominal outer diameter, mm | Thermal conductivity, W/(m·K) |
|---------------|---------------------------------|----------------------------|-------------------------------|
| 1             | Water blocking copper           | 50.2                       | 380                           |
| 2             | Conductor shield                | 55.4                       | 0.28                          |
| 3             | XLPE insulation                 | 118.4                      | 0.286                         |
| 4             | Insulating shield               | 121.4                      | 0.28                          |
| 5             | Buffer water barrier            | 125.4                      | 0.167                         |
| 6             | Alloy lead sleeve               | 134.0                      | 33                            |
| 7             | Asphalt + HDPE sheath           | 143.0                      | 0.4                           |
| 8             | Filling unit                    | 155.0                      | 0.5                           |
| 9             | Light unit                      | 155.0                      | 0.5                           |
| 10            | Armor cushion                   | 158.0                      | 0.22                          |
| 11            | Copper wire armor               | 170.0                      | 380                           |
| 12            | Outer layer                     | 178.0                      | 0.22                          |
| /             | Water                           | /                          | 0.6                           |
| /             | Aluminum water pipe             | /                          | 236                           |
| /             | Concrete                        | /                          | 1.74                          |
| /             | Soil                            | /                          | 0.6                           |
| /             | Air                             | /                          | 0.02                          |

3.2. Mathematical model of electrical-thermal coupled field

The governing equation for the current field of the cable conductor is

$$\nabla^2(\sigma(-\nabla V)) + j\omega D + J_e = Q_{j,v} \tag{1}\n$$

Where $\sigma$ is the electrical conductivity of the cable conductor, S/m; $V$ is the potential on the conductor, V; $\omega$ is the angular frequency, rad/s; $D$ is the electric displacement field, C/m²; $J_e$ is the external current density, A/m²; $Q_{j,v}$ is the volumetric electric density, W/m³.

The control equation of general heat conduction in the solid and fluid domains is

$$\rho C_p (\partial T / \partial t + \mathbf{u} \cdot \nabla T) + \nabla \cdot (-\lambda \nabla T) = Q_e \tag{2}\n$$

Where, $\rho$ is the density, kg/m³; $C_p$ is the specific heat capacity, J/(kg·K); $T$ is the temperature, K; $\lambda$ is the thermal conductivity, W/(m·K); $\mathbf{u}$ is the fluid velocity vector, m/s; $Q_e$ is a unit volume heat source, W/m³. In this paper, the submarine cable is armoured with copper wire. The additional loss on the metal armour can be neglected. The Joule heat generated by the current flowing through the cable conductor is the total internal heat source. That is $Q_e = Q_{j,v}$.

There are two radiation pairs in the calculation model. One of the radiation system is among the outer surface of the cable inside the cable trench, the outer surface of the cooling water pipe and the
inner walls of the cable trench, when the cable trench is filled with air; the other is among the ground surface, the upper surface of the cable trench cover and the atmosphere [18]. The governing equation of the radiation relationship is

\[ J = \varepsilon_{b} \varepsilon_{b}(T) + \rho_{d}(G_{m}(J) + F_{amb}e_{b}(T_{amb}) + G_{ext}) \]  

(3)

Where, \( J \) is the surface irradiance, W/m²; \( \varepsilon \) is the surface radiance; \( e_{b} \) is the blackbody radiation power, W/m²; \( T \) is the temperature, K; \( \rho_{d} \) is the radiation direction; \( G_{ext} \) is external radiation, W/m²; \( G_{m} \) radiates to each other, W/m²; \( F_{amb} \) is the environmental angle coefficient; \( T_{amb} \) is the ambient temperature, K.

Among them, the black body radiation power can be expressed as

\[ e_{b}(T) = n^{2}\delta T^{4} \]  

(4)

Where, \( n \) is the refractive index of the transparent medium; \( \delta \) is the blackbody radiation constant, which is \( 5.67 \times 10^{-8} \) W/(m²K⁴).

3.3 Calculating boundary conditions

The calculation model in this paper is a finite length section of the submarine cable and the cable trench in the axial direction to reduce the calculation amount. The two end faces of the model section are electric-thermal insulated.

A closed field is obtained by scaling up the cable trenches other than the cover by 5 times. It is considered that the temperature of the soil outside the closed domain no longer changes, as shown in figure 3.

**Figure 3.** Schematic diagram of the electro-thermal coupling calculation domain

The boundaries of the closed computation domain are divided into three categories, the temperature of the first type boundary is known, the heat flux density of the second type boundary is known, and the temperature and heat transfer coefficient of the third type boundary and the fluid medium are known. The boundary conditions are as follows:

The first type of boundary condition is:

\[ T|_{\Gamma} = T_{w} = f(x, y, t) \]  

(5)

The second type of boundary condition is:

\[-k(\partial T / \partial n)|_{\Gamma} = q = g(x, y, t) \]  

(6)

The third type of boundary condition is:

\[-k(\partial T / \partial n)|_{\Gamma} = \alpha(T - T_{f}) \]  

(7)

Where, \( \Gamma \) is the boundary; \( T_{w} \) is the boundary wall temperature, K; \( f(x, y, t) \) is a known temperature function, K; \( q \) is the heat flux density or \( g(x, y, t) \) is a known heat flux density function, W/m²; \( T_{f} \) is the temperature of the known fluid medium, K; \( \alpha \) is the heat transfer coefficient, W/(m²·K).

In this paper, the cable conductor is applied with a voltage of 303.12 kV, the designed current is 1411 A, and the highest ambient temperature in summer is 35 °C on the location of the project. The
initial temperature of all objects in the cable trench is 30 °C, and the normal irradiance of the midday solar is 484 W/m², the wind speed is 4.5m/s, and the relative humidity of the environment is 80%.

4. Simulation analysis of submarine cable current carrying capacity improvement schemes

4.1. Forced cooling of the submarine cable landing section

The influence of air convection, cooling temperature, arrangement and cooling water on the current carrying capacity of the cable are analysed, when the cold water pipe is used for cooling in the cable trench.

4.1.1. Effect of air flow and cooling water temperature. In the axial direction of the cable trench, the Joule heat generated by the current flowing through the copper conductor is the same. The heat in the cable conductor mainly flows along the radial direction of the cable. It is therefore envisaged that the air in the cable trench will have a certain flow rate in the radial direction of the cable. The effect of air at different flow rates in the cable trench on the current carrying capacity of the submarine cable is shown in figure 4.

The radial flow of air in the cable trench facilitates the heat dissipation of the submarine cable, so the submarine cable allows for a larger current carrying capacity. When the radial flow rate of the air is 0.1m/s, with or without cooling water pipes, the current carrying capacity of the submarine cables is increased by 3.05% or 5.97%, respectively. The radial flowing air fully exerts the cooling effect.

The influence of the submarine cable current is weak at different cooling temperatures, as shown in figure 5, when the air in the cable trench does not flow.

Although the cooling current of the cooling water is indeed improved, the lifting degree is very weak. The cold water temperature is reduced from 20 °C to 0 °C, but the current carrying capacity is only increased from 0.21% to 0.62%, which is extremely uneconomical for the input-output ratio in practical applications.

4.1.2. Arrangement of submarine cable when forced water cooling. The increase in current capacity of submarine cable is shown in figure 6 and figure 7, when the distance between the submarine cable and the cooling water pipe is adjusted, and the radius of the cooling water pipe is thickened to increase the amount of cooling water.

The current carrying capacity of the submarine cable is increased from 0.3% to 0.75%, when the distance between the cooling water pipe and the submarine cable is reduced from 0.24m to 0.12m. The current carrying capacity increases from 0.35% to 1.78%, when the inner diameter of the cooling water pipe increases from 0.035m to 0.11m. It can be seen that reducing the distance between the cooling water pipe and the submarine cable and increasing the amount of cooling water can effectively increase the current carrying capacity of the submarine cable.
The flow of air in the cable trench is obviously beneficial to the heat dissipation of the submarine cable. Under this condition, the cooling system can exert a certain heat dissipation effect.

4.2. Backfilling soil

The influence of the thermal conductivity of the soil, the temperature of the cooling water, and the arrangement of the cooling water pipes of the submarine cable on the current carrying capacity are analysed, when the cable trench is filled with the soil.

4.2.1. Backfilling soil and cooling temperature. The soil is backfilled in the cable trench and cooled by a cooling water pipe. The effects of different cooling temperatures and soil thermal conductivity on the current carrying capacity of the submarine cable are shown in figure 8.

The current carrying capacity of the submarine cable increased by 2.79% without the cooling system, when soil is backfilled in the cable trench. Under the action of the cooling water pipe, the current carrying capacity increases from 2.83% to 4.98%, when the cooling water temperature is reduced from 20°C to 0°C.

The thermal conductivity of the soil is increased from 0.6 W/(m·K) to 1.279 W/(m·K) to improve the thermal conduction of the backfill soil. The current carrying capacity of the submarine cable is increased by 4.78%, when the cooling water temperature is 10°C.

4.2.2. Arrangement of submarine cable when backfilling soil. The distance between the submarine cable and the cooling water pipe is adjusted, the radius of the cooling water pipe is thickened to...
increase the cooling water volume, when the cable trench is filled with soil. The lifting effect of the ampacity of the sea cable is shown in figure 9 and figure 10.

The current carrying capacity of the submarine cable is increased from 2.69% to 5.21%, when the distance between the cooling water pipe and the submarine cable is reduced from 0.24m to 0.12m. The current carrying capacity increases from 3.44% to 6.47%, when the inner diameter of the cooling water pipe increases from 0.035m to 0.11m.

It can be seen that the backfilling soil has obvious effect on the current carrying capacity of the submarine cable in the cable trench, and the cooling system can fully exert the cooling and heat dissipation effect on the submarine cable.

4.3. Simulation of water-filled cable trench

The cable trench is filled with seawater, which flows in the radial direction of the submarine cable. The effect of the flow rate of the seawater in the cable trench on the current carrying capacity of the submarine cable is shown in figure 11.

The promotion of the current carrying capacity of the submarine cable is very obvious, when the cable trench is filled with water. It is even better than the backfilling soil in the cable trench. The flow rate of water in the trench has a significant influence on the heat dissipation of the submarine cable. The current carrying capacity of the submarine cable is increased by 3.4%, when the water flow speed is not considered. Considering a small water flow rate, for example, 0.001 m/s, the current carrying capacity of the submarine cable can be increased by 6.84%. The current carrying capacity of the submarine cable can be increased by 7.84%, when the water flow speed is increased to 1 m/s. The water-filled cable trench has a significant saturation trend on the promotion of the current capacity of the submarine cable.

5. Comparison of the effects of current carrying capacity improvement measures

5.1. Inductive analysis

The greater the flow rate of the fluid medium in the cable trench, the higher the heat transfer efficiency between the objects, which plays a key role in the increase of the current capacity of the submarine cable. Both of the two kinds of fluids in the cable trench, air and seawater, considerably promote the current carrying capacity of 500 kV single-phase copper wire armoured XLPE submarine cable at a certain radial flow rate, although the thermal conductivity of the two is very different. The difference is that the seawater in the cable trench increases the current capacity of the submarine cable by about 7% at a radial flow rate of 0.001 m/s, and the air in the cable trench gains an equivalent improvement requires a radial flow rate of 1 m/s, which is shown in figure 4 and 11.

The thermal conductivity of the medium around the submarine cable directly affects the heat dissipation capacity of the cable trench. The greater the thermal conductivity of the dielectric, the
Joule heat generated in the cable conductor dissipates more quickly, reducing heat accumulation, and inhibiting the cable conductor temperature from rising too fast. The backfill soil in the cable trench has the highest thermal conductivity, followed by seawater, and the thermal conductivity of the air is the worst. Therefore, the order of improvement of the current carrying capacity of the stationary fluid (air or seawater) and backfilled soil on the submarine cable is just the opposite of the above relationship, as shown in figure 4, 8, and 11. Improving the thermal conductivity of the medium around the submarine cable can significantly improve the current carrying capacity of the submarine cable.

Different medium in the cable trench and different layout of the submarine cable bring different changes of current carrying capacity. The farther the distance between the submarine cable and the surrounding cable trench wall, or the larger the proportion of air in a certain range around the submarine cable, the more unfavourable the heat dissipation of the submarine cable.

When there is a cooling water pipe in the cable trench, the closer the distance between the cooling water pipe and the submarine cable, and the larger the cooling water volume, the more favourable the heat dissipation of the submarine cable, the greater the current carrying capacity of the submarine cable, as shown in figure 6, 7, 9 and 10.

5.2. Comparison

It is calculated that the current carrying capacity of the submarine cable can be increased by 11.2% when forced water cooling, by 6.54% when the soil is backfilled, and by 8.03% when seawater is filled, when all factors are considered to be optimal.

From the perspective of achievable, forced cooling scheme has the greatest effect on improving ampacity of submarine cable, followed by water-filled cable trench, the effect of backfilling special soils is generally. In actual engineering applications, a certain length of cable, it is difficult to achieve radial forced flow of the fluid medium over the full length. The method of backfilling special soil causes the submarine cable to be buried deeply in the soil (the submarine cable trench is 3m deep), which is not conducive to engineering protection, operation and maintenance. Therefore, it is an engineering and technical advantage to fill the cable trench with seawater to improve the current carrying capacity of the submarine cable.

6. Conclusion

The finite element electro-thermal coupling simulation calculation of 500 kV single-phase copper wire armoured XLPE submarine cable and its pre-excavated cable trench model was carried out. The effects of different submarine cable current-carrying schemes were compared, and factors affecting the current carrying capacity of the submarine cable, such as the fluid flow rate of cable trench medium, temperature, thermal conductivity of the medium, and layout of the submarine cable was analysed.

(1) Forcing the radial flow of air in the cable trench, backfilling the cable trench with high thermal conductivity soil, and filling the cable trench with seawater can effectively improve the current carrying capacity of the submarine cable, each has its own advantages and disadvantages.

(2) The greater the flow velocity of the fluid medium in the cable trench, the higher the heat transfer efficiency between the objects, which is beneficial to the heat dissipation of the cable. The cooling system can fully exert its heat dissipation effect when the air in the cable trench flows.

(3) The thermal conductivity of the medium around the submarine cable directly affects the heat dissipation capacity of the cable trench. The greater the thermal conductivity of the dielectric, the Joule heat generated in the cable conductor dissipates faster, reducing heat accumulation, and inhibiting the cable conductor temperature from rising too fast. It is conducive to increasing the current carrying capacity of the submarine cable.

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