Temperature Analysis Based on Multi-Coupling Field and Ampacity Optimization Calculation of Shore Power Cable Considering Tide Effect

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ABSTRACT
Shore power system that powers berthing ships is gradually becoming widely used worldwide because it helps reduce air and noise pollution. However, due to the bad environment of the port, the influence of the port tide on the temperature distribution and the ampacity of the shore power cable connecting the ship and shore can’t be ignored. Therefore, in this paper, a thermal field calculation model of shore power cable based on electromagnetic-thermal-flow coupling field is presented, in which the impact of tide has been considered. And the validity of the coupling model is verified by thermal circuit method based on IEC(International Electrotechnical Commission) 60287 standard. Then, the influence of cable immersion depth, water velocity and temperature, wind speed and air temperature on the temperature distribution of shore power cable was analyzed based on the multi-field coupling model. Finally, the ampacity of shore power cable in different environments is calculated by the combined Newton iterative and numerical simulation method. The results indicate that the conductor temperature firstly decreases and then increases with the immersion depth. And when the immersion depth is small, the wind speed dominates the temperature of the conductor. While the water flow speed plays a leading role in the conductor temperature when the immersion depth is deeper. In addition, the relationship between ambient temperature and capacity of shore power cable is approximately linear.

INDEX TERMS
Shore power cable, temperature calculation, ampacity calculation, multi-field coupling model, tidal effect, finite element simulation, iteration.

I. INTRODUCTION
According to the International Maritime Organization, the marine industry emits about 1.1 billion tons of carbon dioxide and about 16 million tons of sulfur dioxide each year, which is twice and 200 times the world’s automobile emissions. However, Shore power system will reduce more than 90% of the toxic Sox, NOx and particulate matter emitted by ships during their berthing [1]. Therefore, in order to solve air pollution problem caused by berthing ships to coastal and riverside cities, it has become more and more common for ships to shut down ship generators to use the alternative maritime power (AMP) while in port [2].

Since the release of the international standard “Part I of Facilities in port: General Requirements for High-Voltage Shore Power Systems (IEC / ISO / IEEE80005-1) in 2012, it indicates that the development of shore power supply technology has come into scale. As an important power equipment of alternative maritime power, its working environment is different from ordinary direct buried and tunnel laying cables. The port environment of shore power cable is very bad. There are some special working conditions, such as being submerged by water or being directly exposed to the sun with the rise and fall of tide. It is easy to cause the overheat of shore power cable and accelerate the aging of cable and limit the ampacity of shore power cable. The performance of shore power cables directly affects the reliability of power distribution grid power supply, and even endangers
the safe operation of ships. Therefore, it is necessary to study the real-time calculation method of the current carrying capacity of shore power cables under the influence of tide.

At present, the research on shore power cable mainly focuses on the material selection and type design of shore power cable, but there is almost no research about temperature and ampacity calculation of shore power cable. For example, Reference [4] designed a new type of intelligent control high-voltage shore power cable that integrates power transmission and intelligent control functions. In reference [5], a shore power cable with abrasion resistance and long-term water submerged electrical performance is developed. And reference [6] developed a bend-resistant and flame-resistant shore power cable. For the temperature and ampacity calculation method of shore power cable, we can learn from the land and submarine cable temperature and ampacity calculation research methods. Obtaining cable temperature includes experimental measurement, thermal analysis method based on IEC standard, and numerical calculation method based on finite difference method, boundary element and finite element method. Reference [7] detailed the calculation of the cable temperature distribution based on the thermal circuit model. Based on the transient thermal path of the cable, the insulation layering method is used to calculate the conductor temperature in reference [8]. It is found that the more stratification, the smaller the error of temperature calculation. In reference [9], the influence of soil moisture transfer and closed air layer on the thermal path analysis model is investigated in detail, and a method combining real-time environmental monitoring and multi-physical field numerical simulation is proposed. In addition, Sedaghat and de Leon studied the steady-state temperature field of cables laid in air, and improved relevant IEC standards [10]. Meng et al. [11] combined a numerical method with a temperature measurement experiment and proposed a dynamic temperature prediction method of cable conductor.

The IEC analytical method cannot fully consider the coupling relationship between the physical fields of the cable and the cable laying mode, which affects the accuracy of the temperature calculation of cables and makes the cable ampacity calculation too conservative. Due to its good adaptability to the complex and irregular area, the finite element numerical method can accurately simulate the laying environment and consider the coupling effect of multiple fields, which has attracted many scholars’ attention. The calculation of cable temperature mainly includes the electromagnetic-thermal coupling and the thermal-flow coupling. Many scholars [12]–[15] have studied the electromagnetic thermal flow coupling model of the cable to calculate the flow field and temperature field distribution of the cable accurately. The purpose of calculating the cable temperature is to accurately calculate the ampacity of the cable. The purpose of cable temperature analysis is to calculate the cable ampacity. The cable ampacity calculation includes the analytical algorithm of establishing the thermal path model based on IEC standard and the numerical method of deducing the ampacity by calculating the temperature field.

The optimization methods of cable real-time ampacity calculation include dichotomy, chord section method and Newton iteration method, among which Newton iteration method is more accurate than chord section method and faster than dichotomy.

At present, there are few researches on the temperature and ampacity calculation of shore power cables. Based on the research results of temperature and ampacity calculation of land cables, this paper proposes a method for calculating the ampacity by combining numerical simulation and Newton iteration method. Not only the calculation results are more accurate, but also the influence of external environmental effect on the ampacity of the cable can be more conveniently considered. However, as the use environment of shore power cable is affected by tide, the calculation of temperature field of shore power cable involves physical processes such as eddy current, heat transfer, convection, etc. Thus, studying the temperature field numerical simulation of shore power cables based on electromagnetic-thermal-current coupling with tide influence considered is of great significance for the accurate calculation of the ampacity.

In this paper, an electromagnetic-thermal-current multi-field coupled temperature field calculation model for a 8.7 / 10 kV three-core shore power cable in Chongqing Foeryan Port is established, and further consideration of tidal effects is conducted. Furthermore, considering the influence of tide, the effects of cable immersion depth, water flow velocity and temperature, wind speed and air temperature on the temperature distribution of shore power cable are studied. Then based on the simulation results of cable temperature field, the real-time ampacity of shore power cable is calculated by the coupling simulation and Newton’s method.

II. MATHMATICAL AND FEM MODELLING

The installation environment of shore power cables is complicated. As the tide rises and falls, sometimes the shore power cables are directly exposed to the air environment, and sometimes they are immersed in water. Figure 1 shows the laying of shore power cables. Therefore, an electromagnetic-thermal-flow multi-field coupling model for shore power cables is established with this complicated

![FIGURE 1. Laying of shore power cable.](image-url)
laying environment considered, and the ampacity of shore power cable is calculated.

The 3D model of shore power cable laying is shown in Figure 2. The model includes four parts: air, shore power cable, concrete and water. Figure 2(a) shows the cable is exposed to the air, and Figure 2(b) shows that the cable can be partially or completely immersed in water by changing the value of \( h \). When the shore power cable is immersed in water, \( h \) indicates the immersion depth. It is difficult for finite element method to calculate the air and water area in infinite space. It is generally believed that the temperature in the space 2 m away from the heat source is not affected by the heat source. Therefore, the space 2 m away from the cable in the air area and water area is selected in this model.

**FIGURE 2.** 3D model of shore power cable laying.

A triaxial shore cable was used in the cable simulation, and the cable type is XEV22 - 8.7/10 - 3 \( \times \) 120 mm\(^2\). Figure 3 shows the simplified two-dimensional cross-sectional structure of shore cable. From inside to the outside, they are conductor, conductor shield, insulation layer, insulation shield, metal shield, filler, inner sheath, aluminum sheath, and outer sheath respectively.

**FIGURE 3.** Simplified two-dimensional cross-sectional structure of shore cable. 1 Conductor (CO); 2 Conductor shield (CS); 3 Insulator layer (IN); 4 Insulator shield (IS); 5 Metal shield (MS); 6 Filler (FI); 7 Inner sheath (INS); 8 Aluminum sheath (AS); 9 Outer sheath (OS).

Compared with ordinary cables, the insulation materials and outer sheath materials used in shore power cables are different. For shore power cables, the conductor and metal shielding layer are copper, and the conductor shield and insulation shield are semi-conductive materials. The specific material and geometric parameters of the cable are shown in Table 1.

**TABLE 1.** Material and geometric parameters of the cable.

| Structure                  | Material  | Size          |
|----------------------------|-----------|---------------|
| conductor                  | copper    | \( R_{so}=7.95 \text{mm} \) |
| conductor shield           | semiconductor | Thickness=1mm |
| insulation layer           | EPDM/LDPE | Thickness=4.75mm |
| insulation shield          | semiconductor | Thickness=8.08mm |
| metal shield               | copper    | Thickness=0.75mm |
| inner sheath               | PVC       | \( R_{ins}=35.9 \text{mm} \) |
| aluminum sheath            | aluminum  | \( R_{as}=36.9 \text{mm} \) |
| outer sheath               | TPU       | \( R_{os}=40.6 \text{mm} \) |

**A. ELECTROMAGNETIC-THERMAL-FLOW COUPLING MODEL**

The heat of the cable comes from the heat generated by the conductor current and the heat generated by the dielectric loss. In order to simplify the calculation and ensure the scientific nature and validity of the electromagnetic field calculation model, the following issues are assumed: [16]

1) The influence of space charge and displacement current is ignored for power frequency current.

2) The length of the cable is infinite compared with the cross section, so it can be regarded as a two-dimensional plane without considering the cable bending.

3) The conductor and shell materials are isotropic linear media, the relative permeability is constant, and the conductivity is only a function of temperature.

4) Regardless of the imbalance of the three-phase current, a current of 350 A with a phase angle difference of 120° is applied to each cable conductor.

Based on the Maxwell equations, the vector magnetic potential \( \mathbf{A} \) and the scalar potential \( \varphi \) are introduced to solve the model electromagnetic field distribution. The vector magnetic potential \( \mathbf{A} \) control equation is as follows [17]:

\[
\nabla \times ( \nabla \times \mathbf{A} ) = \nabla ( \nabla \cdot \mathbf{A} ) = \nabla^2 \mathbf{A} = \mu ( J + \frac{\partial \mathbf{D}}{\partial t} ) \tag{1} \n\]

\[
\nabla^2 \varphi + \frac{\partial}{\partial t} ( \nabla \cdot \mathbf{A} ) = -\frac{\rho}{\varepsilon} \tag{2} \n\]

where \( \mathbf{A} \) is magnetic vector potential; \( J \) is the known source current density; \( \mu \) and \( \sigma \) are magnetic permeability and conductivity of the material respectively; \( \varepsilon \) is the dielectric constant; \( \varphi \) and \( \rho \) are scalar potential and charge density respectively. Introducing the Lorentz normal form, equations (1) and (2) can be changed to equation (4) and (5).

\[
\nabla \cdot \mathbf{A} + \mu \varepsilon \frac{\partial \varphi}{\partial t} = 0 \tag{3} \n\]

\[
\nabla^2 \mathbf{A} - \mu \varepsilon \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu J \tag{4} \n\]

\[
\nabla^2 \varphi - \mu \varepsilon \frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon} \tag{5} \n\]

After the vector magnetic potential \( \mathbf{A} \) and the scalar potential \( \varphi \) are obtained, the electric field \( \mathbf{E} \) and the magnetic
field $B$ can be obtained by the following formula:

$$E = -\frac{\partial A}{\partial t} - \nabla \varphi$$  \hspace{1cm} (6)$$ $B = \nabla \times A$  \hspace{1cm} (7)$$

The material sources of the shore power cable are the heat loss $q_1$ from conductor, metal shield and aluminum sheath, and dielectric loss $q_2$ of insulating layer. The control equation of temperature field [18] is as follows:

$$C_p \rho \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} \right) = \lambda \nabla^2 T + q_v$$  \hspace{1cm} (8)$$

where $\rho$ is the material density; $C_p$ is the specific heat capacity; $T$ is temperature; $\lambda$ is the thermal conductivity while assume that the thermal conductivity of each material is isotropic; and $q_v$ is the heat generated by unit volume. In steady-state calculation, the partial derivative of temperature to time on the left side of the equation is equal to zero, and $q_v = q_1 + q_2$.

$$q_1 = \frac{1}{2} \int_V \mathbf{J} \cdot \mathbf{J}^* dV$$  \hspace{1cm} (9)$$ $$q_2 = \frac{1}{2} \int_V \mathbf{R} \cdot [\mathbf{E} \cdot \mathbf{J}^*] dV$$  \hspace{1cm} (10)$$

where $\mathbf{J}^*$ is the conjugate current density; and $J_d$ is the displacement current density.

Since the electrical conductivity of the cable conductor changes with temperature, the cable loss power will also be affected by temperature. Therefore, in order to accurately calculate the loss power, the electromagnetic field and temperature field need to be coupled in both directions. The two-way coupling of electromagnetic and temperature fields is essentially an iterative calculation of conductivity. The resistivity of metallic materials generally changes linearly with temperature, and the relationship between conductivity and temperature can be illustrated as equation (11) [13].

$$\sigma(T) = \frac{\sigma_{ref}}{1 + \beta(T - T_{ref})}$$  \hspace{1cm} (11)$$

where $\sigma_{ref}$ is the conductivity at the reference temperature of $T_{ref}$; $T$ is the temperature; $\beta$ is the conductivity temperature coefficient, 0.00395 for copper and 0.00403 for aluminum.

The continuous water flow is governed by the unsteady incompressible flow equations [19].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right)$$  \hspace{1cm} (12)$$

The fluid flow is described by k-ε turbulence model, as shown in following.

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + G_k - \rho \varepsilon$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right)$$  \hspace{1cm} (13)$$

where $G_k$ is the turbulence energy contributed by average viscous gradient; $C_1k$ and $C_2\varepsilon$ are the coefficient, respectively. $\sigma_k$, $\sigma_\varepsilon$ are the parameters correspond to turbulence energy $k$ and dissipation rate $\varepsilon$, and $C_{\mu}$ is the body force. The parameter values are shown in TABLE 2.

**TABLE 2. Value of constants in k-ε model.**

|     | $C_{1k}$ | $C_{2\varepsilon}$ | $\sigma_k$ | $\sigma_\varepsilon$ | $C_{\mu}$ |
|-----|----------|---------------------|------------|----------------------|----------|
| $C_{1k}$ | 1.44     | 1.92                | 1.0        | 1.03                 | 0.09     |

**B. BOUNDARY CONDITIONS AND MESHING**

Apply a current with the amplitude of 350 A and the phase difference of 120° to the cable conductor. Each cable conductor is high potential. 10kV voltage with a phase difference of 120° is applied, and the metal shield and aluminum sheath are grounded.

$$\varphi|_{CO} = 10 \text{ kV} \quad I|_{CO} = 350 \text{ A}$$  \hspace{1cm} (14)$$ $$\varphi|_{MS} = \varphi|_{LS} = 10 \text{ kV}$$  \hspace{1cm} (15)$$

The magnetic vector $A$ attenuates rapidly in the outer space of the cable conductor, and its value is about 0 at 1 m from the cable surface. Therefore, the magnetic insulation boundary condition is set at the outer boundary of air and water far away from the cable:

$$A|_{\text{out}} = 0$$  \hspace{1cm} (16)$$

The detailed boundaries of flow and temperature field for the coupling fields are given in FIGURE 2(a) and TABLE 3.

**TABLE 3. The boundaries of flow and temperature field.**

| Type | Boundaries                     |
|------|--------------------------------|
| $\Gamma_1$ | Inlet ($V_s=2\text{m/s}$); $T=20^\circ\text{C}$ |
| $\Gamma_2$ | Inlet($\nu_s=0.5\text{m/s}$); $T=20^\circ\text{C}$ |
| $\Gamma_3$ | Outlet (p=0)                  |
| $\Gamma_4$ | Wall; $T=20^\circ\text{C}$    |
| $\Gamma_5$ | Wall; $T=20^\circ\text{C}$    |

Due to the viscosity of the fluid and the resistance of the wall to the fluid, a thin layer of fluid is formed near the wall surface, and the velocity of the fluid drops rapidly to zero in this flow boundary layer. Therefore, the fluid velocity is 0 at the front, back, upper, and lower boundaries of the water area, the concrete wall and the outer surface of the cable, and that means the boundary is set as no slip boundary condition.

$$V|_{\text{wall}} = 0$$  \hspace{1cm} (17)$$
III. CALCULATION RESULTS AND ANALYSIS

A. ANALYSIS OF TEMPERATURE DISTRIBUTION RULE AND INFLUENCE FACTORS OF CABLE CONDUCTOR

Figure 4 shows the temperature of shore power cable with cable immersed in water or not, in condition of the air velocity is 2 m/s and the water velocity is 0.5 m/s. When not submerged, the maximum temperature of the cable conductor laid in the air is 64.8 °C, and the maximum temperature of the main insulation is 63.3 °C. However, when submerged in water, the maximum temperature of the cable conductor is 57.1 °C, and the maximum temperature of the main insulation is 55.7 °C. The average temperature of a submerged cable is 7.65 °C lower than the cable temperature laid in air.

**FIGURE 4.** Temperature distribution for the cable laid in air and water.

Figure 5 shows the velocity distribution of cable when not submerged. It can be seen that the air velocity above and on the right side of the cable is relatively high, and the vortex is formed on the right side (leeward side) of the cable, while the boundary velocity near the cable and concrete is reduced.

**FIGURE 5.** Velocity distribution.

Due to the special working condition that the shore power cable is submerged or not during the tide rising and falling, the immersion depth of cable, velocity of water flow, water temperature, wind speed and air temperature all have different degrees of effects on the temperature of the shore power cable conductor. Aiming at the two conditions of the shore power cable laid in the air and water due to the tide effect, the variation law of the temperature of the shore power cable conductor under different environmental factors was studied. Among them, only the influence of wind speed and air temperature is considered when laid in air, and only the influence of water flow speed and temperature is considered when laid in water.

The change law of cable conductor temperature with wind speed and water flow speed when laid in air and water is shown in Figure 6. The temperature of cable conductor in water laying condition is 8.75 °C lower than that in air laying condition, when the water and the air are both considered static. And when the flow speed of air and water becomes 5 m/s, that difference value turns to 5.29 °C. It means that the greater the water speed or wind speed, the smaller the temperature difference between air laid and water laid cable conductors.

**FIGURE 6.** Variation curve of cable conductor temperature with wind speed and water flow speed.

If the water partially submerged the cable, that is, h is smaller than the outer diameter of the shore power cable, 81.2mm, the change rule of the conductor temperature with the depth of water immersion under different water velocities is shown in Fig. 7. It can be found seen the conductor temperature decreases first and then increases with the increase of immersion depth. The temperature is the lowest when the water immersion depth is 40-50mm. This is because when the water immersion depth is small, the surface area of the cable exposed in the air is large, and the effect of water flow on the heat dissipation of the cable is not obvious, which is greatly affected by the wind speed.

The depth of immersion in water continues to increase, but the surface area of the cable exposed in the air decreases. At this time, the water flow starts to play a leading role, so the temperature of the cable conductor begins to decline. As the immersion depth further increases, the effect of water flow on the temperature of the cable is gradually stabilized. At this time, the surface area of the cable exposed in the air becomes smaller and smaller, the heat dissipation effect of
FIGURE 7. Cable conductor temperature varies with the immersion depth of water.

the air velocity decreases, and the temperature starts to rise again.

B. VALIDATION OF METHOD

In this paper, the thermal path method in IEC 60287 standard is used to verify the temperature simulation results. And Figure 8 shows the equivalent thermal path model of triaxial shore cable. Where $Q_C$ is the loss power per unit length of single-phase conductor, which equals to $I^2R$; $Q_d$ is the loss power per unit length of insulating layer and inner and outer shielding layer; $\lambda_1$ is the ratio of metal shielding loss to total loss of the cable conductor; $\lambda_2$ is the ratio of aluminum sheath loss to total loss of the cable conductor; $R_1$ is the thermal resistance of insulating layer and inner and outer shielding layer; $R_2$ is the thermal resistance of filling layer and inner sheath; $R_3$ is the thermal resistance of outer sheath resistance; $R_4$ is the environmental thermal resistance.

From the equivalent model of thermal circuit, the temperature rise of conductor above ambient temperature can be derived as:

$$
\Delta T = (I^2R + 0.5Q_d)R_1 + [I^2R(1 + \lambda_1) + Q_d]nR_2 \\
+ [I^2R(1 + \lambda_1 + \lambda_2) + Q_d]n(R_3 + R_4) \quad (18)
$$

where $I$ is the conductor current; $R$ is the resistance per unit length of conductor; $n$ is the number of cable conductors, in this condition the cable is a triaxial cable, so $n$ equals to 3.

The calculation results of the circuit model and the simulation model of the temperature variation of the cable conductor under different loads are compared, as shown in Figure 9. And the maximum temperature error calculated by the two methods is 4 °C.

IV. REAL-TIME AMPACITY CALCULATION OF SHORE POWER CABLE AND INFLUENCING FACTORS

A. METHOD OF CABLE AMPACITY REAL-TIME CALCULATION

The conductor temperature of the port shore power cable is affected by the tide, and also the cable ampacity. In general, the load current at the cable insulation maximum temperature of 90 °C is the cable ampacity. In this paper, objective optimization method is used to calculate the real-time cable ampacity. Combining with the coupling simulation and iterative method, the variation law of the current carrying capacity of the shore power cable is calculated in order to consider the influence of the ambient temperature, the wind speed and the flow speed simultaneously. The calculation flow is shown in Figure 10.

Since the temperature is a quadratic function of the load current, this paper uses the Newton’s method to calculate the cable ampacity. It is assumed that the relationship between the maximum temperature of the cable insulation and the current is:

$$
T(I) = aI^2 + f(e_1, e_2, e_3, \cdots, e_5) \quad (19)
$$

where $a$ is the current term parameter; $f(e_1, e_2, e_3, e_4, e_5)$ is the constant term, indicating the influence of environmental factors on the cable temperature, whose value is determined by the environmental temperature, wind speed, water flow speed, water temperature, and the cable immersion depth $h$, and expressed by variables $e_1, \ldots, e_5$ respectively.

The schematic diagram calculated by Newton’s iterative method is shown in Figure 11. The value which corresponding to the intersection point $P_0$ of straight-line $T = 90$ °C
and curve $T(I)$, equals to $I_0$, the shore power cable ampacity. Specific steps of calculation are as follows:

1) The environmental data monitored in real time is substituted into the constant term $f(e_1, e_2, e_3, e_4, e_5)$ in equation (18).

2) Give the initial value $I_1$ of any current close to the ampacity, and $T(I_1)$ is calculated. If $T(I_1)$ meets the accuracy requirements of equation (19), then $I_1$ will be considered as the ampacity $I_0$, otherwise, following step will be taken:

$$|90 - T_1| \leq \varepsilon \quad (20)$$

where $\varepsilon$ is the accuracy value.

3) Obtain the derivative $T'(I_1)$ and tangent equation of temperature at $I_1$

$$g(I) = T'(I_1)I + T(I_1) - T'(I_1)I_1 \quad (21)$$

where $T_1$ can be obtained from equation (18).

4) Let $g(I) = 90$, find $I$, and record it as $I_2$, then substitute $I_2$ into equation (18), find out temperature $T(I_2)$, and record it as $T_2$. If $T_2$ meets equation (19), then $I_2$ is the cable ampacity, otherwise use the following iterative equation to repeat steps 2 to 4 until the ampacity meets the accuracy requirements.

$$f^{(n+1)} = \frac{T'(I^{(n)})I^{(n)} - T(I^{(n)}) + 90}{T'(I^{(n)})} \quad (22)$$

B. CABLE AMPACITY CALCULATION WITH TIDAL EFFECT CONSIDERED

The cable will not be immersed in the water during the ebb tide, and its temperature is mainly affected by air velocity and ambient temperature. When the ambient temperature is $20 \, ^\circ C$, the variation characteristic of cable ampacity change with wind speed is shown in Figure 12. It can be found that with the increase of wind speed from $0.5 \, m/s$ to $5.0 \, m/s$, the cable ampacity increases from $397.93 \, A$ to $425.6 \, A$. However, as the wind speed increases, the change rate of cable ampacity per unit wind speed decreases from $12.39 \, A$ to $1.29 \, A$. It shows that with the increase of wind speed, the influence of wind speed on the increase of current carrying capacity of shore power cables decreases.

When the wind speed is of $2 \, m/s$, the variation characteristic of cable carrying capacity varying with the ambient temperature is shown in Figure 13. It can be seen from the figure that the shore power cable ampacity decreases with the increase of ambient temperature, which is approximately linear, that is, the average cable ampacity decreases by $14.24 \, A$ every $5 \, ^\circ C$ increase of ambient temperature.

During high tide, some shore power cables will be immersed in water. The temperature distribution of shore power cables is affected by the water flow speed, water temperature and the depth of cable immersion. When the immersion depth is $0.1m$ and the water temperature is $20 \, ^\circ C$, the variation of the current carrying capacity of the cable with the water flow speed is shown in Figure 14. The ampacity of the shore power cable is $432.7 \, A$ when the water current is close to stationary. When the flow velocity is less than $0.1 \, m / s$, the ampacity of the shore power cable increases rapidly; however, when the water flow velocity is greater
than 0.5 m/s, the ampacity hardly changes with the water flow velocity. This is because when the water flow speed is greater than 0.5 m/s, the maximum temperature change of the shore power cable insulation is within 0.1 °C per unit speed increase. when the water speed is greater than 0.5 m/s, the current carrying capacity of the shore power cable does not change with the water speed.

When the shore power cable is immersed in water and the flow velocity is 0.5 m/s, the influence rule of the flow temperature on the carrying capacity of the shore power cable is shown in Figure 15. It can be found that the change rule of cable current carrying capacity affected by ambient temperature is the same when immersed in water and not immersed in water. However, when comparing with cable not immersed in water, the carrying capacity of the cable immersed in water decreases by 16.13 A on average in ambient temperature of 0 ~ 40 °C, which is 1.89 A larger than that of the cable that is not immersed. Further analysis, the current carrying capacity of the cable is 436.63 A when the water speed is 0.5 m/s. Assuming that the current carrying capacity of the cable is 436.63 A when it is not immersed in water, the required wind speed is 24.53 m/s. The ratio of the wind speed to the water flow speed is 49.1, which shows that the water speed is better than the wind speed in increasing the cable ampacity.

From the analysis of the variation of the conductor temperature with the immersion depth in Fig. 7, it can be seen that there is an optimal immersion depth at different wind speeds to make the cable conductor temperature the lowest, which means the cable current carrying capacity is the largest at this time. Figure 16 shows the influence rule of cable ampacity at different depth of water immersion when the wind speed is 2 m/s. It can be seen that when the depth of water immersion $h$ is 44.17 mm, the maximum cable ampacity is 459.85 A. The maximum carrying capacity of other wind speeds can also be calculated in the same way.

The change rule of convective heat exchange coefficient under different water speed and air speed has been studied, as shown in Figure 17. It can be found that as the wind speed increases, the convective heat exchange coefficient increases slowly, and as the flow velocity increases, the convective heat exchange coefficient starts to increase rapidly, and then basically remains unchanged. In general, the convective heat exchange coefficient increases with the increase of speed, indicating the heat dissipation effect of the cable is better and the cable ampacity is higher, which is also consistent with the influence of wind speed and flow velocity on the cable.
ampacity analyzed previously. Further analysis is made on the variation law of the cable ampacity with different convective heat exchange coefficients. As shown in Figure 18, the cable ampacity increases linearly with the convective heat exchange coefficient.

V. CONCLUSION

In this paper, the temperature variation law of shore power cable conductor under the influence of port tide is studied based on the electromagnetic-heat-flow multi-field coupling model, and the validity of the coupling model is verified by thermal circuit model. Furthermore, the method of coupling cable simulation combined with Newton iteration is used to calculate the current carrying capacity of the cable, so as to consider the influence of different environments including the depth of immersion, ambient temperature, wind speed and velocity on the current carrying capacity of shore power cables. And the following conclusions are obtained:

1) When the cable is completely immersed in water, the conductor temperature of the cable is 8.75 °C lower than that when the cable is not immersed, and the effect of water speed on cable ampacity is better than that of wind speed when the cable is immersed in water. Therefore, it is recommended to use strong cooling to increase the current carrying capacity of shore power cables in high temperature areas in summer.

2) The conductor temperature decreases firstly and then increases with the immersion depth. When the immersion depth is small, the wind speed plays a leading role, and the water flow plays a dominant role as the immersion depth increases. When the wind speed is 2 m / s, the immersion depth is 44.17mm when the cable ampacity is the largest.

3) The relationship between ambient temperature and cable ampacity is approximately linear. When laid in air, the cable ampacity decreases about 14.24 A on average for every 5 °C increase in ambient temperature. However, when laid in water, the cable ampacity decreases about 16.13 A on average for every 5 °C increase in ambient temperature. 4) When the wind speed is more than 5 m / s, the increase of unit wind speed has little effect on the current carrying capacity of shore power cable. However, when the flow velocity is greater than 0.3m/s, the increase of unit flow velocity has no obvious effect on the current carrying capacity of shore power cable.

5) The convective heat exchange coefficient between the cable and the fluid increases with the increase of wind speed and flow velocity. In addition, the shore cable ampacity increases linearly with the convective heat exchange coefficient.

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