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Research on Ampacity and Influencing Factors of High-Voltage Submarine Cables in Deep-Sea Environments

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Keywords: Submarine cable; deep-sea laying; temperature field; ampacity; seawater flow velocity

Abstract: China has a mainland coastline of approximately 18,000 kilometers, with abundant offshore and deep-sea wind energy resources. The technically exploitable capacity reaches 2.78 billion kW. As the core channel for power transmission and grid integration of offshore wind power, the ampacity of submarine cables is a key parameter that characterizes transmission capacity and thermal safety. However, existing ampacity calculation methods still have deficiencies. The analytical methods based on IEC standards lack sufficient accuracy under complex environmental conditions. Moreover, most studies fail to comprehensively consider deep-sea environmental factors (such as seawater flow velocity, seabed temperature distribution, and soil thermal properties), resulting in deviations in ampacity assessment results.To address the above issues, this paper proposes a combined analytical and numerical simulation method for ampacity calculation. First, based on the IEC 60287 standard, an analytical model is established using MATLAB to calculate key parameters. Subsequently, a multi-physics field coupling model is constructed using COMSOL, which comprehensively considers seawater flow and environmental temperature distribution. The temperature field of the cable under deep-sea laying conditions is simulated and analyzed to achieve accurate ampacity evaluation. The results show that considering factors such as seawater flow velocity, soil temperature, and seawater temperature can significantly improve calculation accuracy. This method helps reduce design margins, lower engineering investment and operation & maintenance costs, and provides theoretical support for the safe operation of high-voltage submarine cables.

1. Introduction

China possesses a mainland coastline of approximately 18,000 kilometers and is rich in offshore wind energy resources. The technically exploitable capacity is about 2.78 billion kW, of which deep-sea resources exceed 1.2 billion kW, indicating enormous development potential. Driven by the “dual carbon” targets [1, 2], and to ensure national energy security while reducing the ecological and environmental impact of traditional thermal power generation, China’s energy structure is gradually transitioning from coal-dominated power to a clean energy system primarily based on non-fossil energy sources [3, 4]. As an important component of renewable energy, offshore wind power has developed rapidly in recent years. By the end of 2025, the global cumulative installed capacity of offshore wind power reached approximately 89.2 GW, of which China accounted for about 46.4 GW, representing more than 52% of the global total and ranking first in the world for five consecutive years.

Since offshore wind farms are usually far from land, electricity cannot be transmitted through overhead lines. Submarine cables have thus become the only carrier for power transmission [5, 6]. Submarine cables are not only critical infrastructure for the grid integration of offshore wind power but also directly affect the planning, design, and operational reliability of the entire wind farm. Among them, ampacity, as the core parameter characterizing the cable's transmission capacity, serves as an important basis for ensuring the long-term safe and stable operation of submarine cables.

The ampacity of a submarine cable refers to the maximum current value that the cable can transmit continuously and safely for a long period without exceeding the permissible maximum operating temperature of the insulation material. When the operating current exceeds this limit, it will cause excessive temperature rise in the cable, leading to accelerated aging of the insulation material and even serious faults such as thermal breakdown [7, 8]. Therefore, accurately assessing the ampacity of submarine cables is of great significance for improving the operational safety of the system.

Currently, scholars at home and abroad have conducted extensive research on the ampacity calculation of power cables. The main methods can be divided into two categories: analytical methods based on IEC standards and numerical analysis methods based on physical field coupling. Among them, the equivalent thermal resistance method (e.g., IEC 60287 standard) establishes a steady-state thermal balance model to calculate the thermal resistance and losses of each layer of the cable, enabling rapid engineering-oriented evaluation of ampacity [9]. In contrast, numerical analysis methods (such as the finite element method) can account for complex boundary conditions and multi-physics coupling effects, thereby obtaining temperature field distributions with higher accuracy [10, 11]. However, existing studies have mostly focused on cables with voltage levels of 220 kV and below, while research on higher-voltage submarine cables remains relatively insufficient.

With the continuous advancement of submarine cable manufacturing and laying technologies in China, 500 kV high-voltage submarine cables have been gradually applied in deep-sea power transmission projects. Their ampacity characteristics and thermal stability have increasingly become a research hotspot. At the same time, the deep-sea environment features significant characteristics such as high water pressure, low temperature, and complex ocean currents. Different laying conditions (such as burial depth, soil thermal resistivity, and seawater flow velocity) have a substantial impact on the cable's heat dissipation process. Nevertheless, existing studies still have limitations in environmental factor modeling. For example, insufficient consideration is given to key factors such as deep-sea seawater flow velocity and seabed temperature distribution, which affects the accuracy of ampacity calculations.

In response to the above issues, this paper conducts research on the thermal characteristics and ampacity of high-voltage submarine cables under deep-sea burial conditions. First, an analytical model is established based on the IEC 60287 standard to perform preliminary calculations and parameter analysis of cable ampacity. Second, a multi-physics field coupling model that considers seawater flow and environmental temperature distribution is constructed using numerical simulation methods to accurately solve the cable temperature field. On this basis, the influence patterns of different environmental factors on ampacity are comparatively analyzed. The research results indicate that the proposed method can effectively improve the accuracy of ampacity assessment for submarine cables in deep-sea environments, providing theoretical basis and technical support for the design of high-voltage submarine cables and the planning of offshore wind power projects.

2. Methodology

2.1 Submarine Cable Structure

The object of this study is a high-voltage submarine cable. Its typical structure consists of multiple layers, including the conductor, conductor screen, insulation layer, insulation screen, metal sheath, water-blocking layer, armor layer, and outer sheath. The materials of each layer differ in electrical and thermal conduction properties, collectively determining the overall heat transfer behavior and current-carrying capacity of the cable.

The cable conductor is typically made of copper, offering high electrical conductivity. The insulation layer is primarily composed of cross-linked polyethylene (XLPE), whose thermal stability directly limits the maximum operating temperature of the cable. The metal sheath and armor layer not only provide mechanical protection but also participate in the heat conduction process. The outer sheath serves to prevent corrosion and provide sealing. A schematic diagram of the submarine cable structure is shown in Figure 1, and the relevant parameters of each layer are presented in Table 1. These parameters provide the basic input conditions for subsequent analytical calculations and numerical simulations.

In addition, this paper primarily considers the buried laying method, in which the cable is buried in the seabed soil and forms a coupled heat transfer system with the seawater environment. Different burial depths and the thermophysical properties of the surrounding medium have a significant impact on the cable’s heat dissipation capacity.

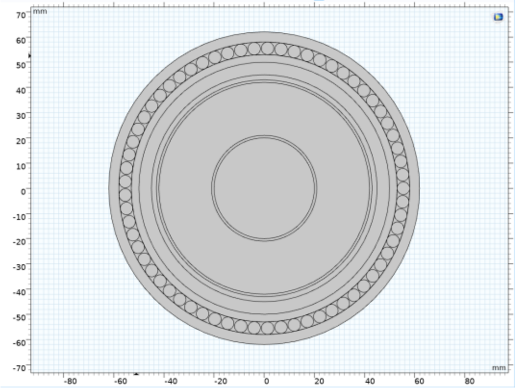

Figure 1. Schematic Diagram of Submarine Cable Structure

Table 1. Structural Parameters of the Submarine Cable

No.	Layer Name	Outer Diameter (mm)
1	Conductor	40
2	Conductor Screen	42
3	Insulation Layer	84
4	Insulation Screen	86
5	Water-Blocking Buffer Layer	90
6	Metal Sheath Layer	100
7	Inner Lining Layer	106
8	Armor Layer	116
9	Outer Serving Layer	124

2.2 IEC-60287 Method

The steady-state thermal circuit model proposed in the IEC 60287 standard is a classical method for calculating the ampacity of power cables. Its basic principle is based on the thermal-electrical analogy, in which the radial heat transfer process of the cable is equivalent to a series of thermal resistance networks. This establishes a steady-state thermal balance relationship between heat generation in the conductor and heat dissipation to the environment.

In this method, the conductor losses of the cable act as the heat source, while the heat conduction processes of each structural layer and the surrounding medium are modeled as different thermal resistances. The conductor temperature rise and ampacity can then be solved accordingly. The basic expression for the cable ampacity is:

$$I=\sqrt{\frac{\Delta\theta_{\mathrm{C}}-W_{\mathrm{d}}\left[0.5T_1+n\left(T_2+T_3+T_4\right)\right]}{RT_1+nR\left(1+\lambda_1\right)T_2+nR\left(1+\lambda_1+\lambda_2\right)\left(T_3+T_4\right)}} \tag{1}$$

where I is the ampacity of the submarine cable; n is the number of cores (taken as 1); $\Delta\theta_{\mathrm{C}}$ is the steady-state temperature difference between the copper conductor temperature and the laying environment temperature; R is the AC resistance of the conductor; W_d is the dielectric loss per unit length per core; λ_1 and λ_2 are the loss factors of the metal sheath and armor losses relative to the total losses, respectively; and T_1, T_2, T_3, and T_4 are the thermal resistances of the insulation layer, equivalent inner lining layer, outer serving layer, and external environment, respectively.

The conductor resistance is temperature-dependent. The DC resistance is given by:

$$R = R_0 \times [1 + \alpha_0 \times (\theta_c - 20)] \tag{2}$$

where R_0 is the DC resistance at 20°C, α_0 is the temperature coefficient of resistance, and θ_c is the conductor temperature.

The AC resistance is expressed as:

$$R_c = R \times (1 + y_s + y_p) \tag{3}$$

where y_s and y_p are the skin effect and proximity effect coefficients, respectively.

Regarding environmental parameters, the external thermal boundary of submarine cables is primarily determined by seawater temperature and seabed soil temperature. This paper selects typical environmental parameters based on different sea area conditions: the deep-sea environmental temperature is usually 4–5 ℃, while the nearshore area is approximately 10–15 ℃. These parameters are used as boundary condition inputs for the analytical model.

2.3 Numerical Simulation Method

To overcome the insufficient accuracy of the IEC analytical method under complex environmental conditions, this paper employs COMSOL Multiphysics to establish a multi-physics field coupling numerical model for detailed analysis of the temperature field and ampacity of submarine cables.

During model construction, the coupling relationships among the electromagnetic field, temperature field, and fluid field are considered, forming a closed-loop calculation system of “electromagnetic heat generation—heat conduction—fluid convective heat dissipation—parameter feedback.” The main governing relationships are as follows:

Coupling relationship between electromagnetic and thermal fields:

$$Q=\sigma\times E^2 \tag{4}$$

Feedback relationship of temperature on electrical conductivity:

$$\sigma(T)=\sigma[1+\alpha(T-T_0)] \tag{5}$$

where Q is the heat source term per unit volume, σ is the electrical conductivity, E is the electric field strength, and α is the temperature coefficient.

In terms of boundary condition settings, the model defines electromagnetic field boundaries, fluid field boundaries, and temperature field boundaries to accurately describe the heat transfer and flow characteristics in the actual seabed environment. The initial temperature is set according to different sea area conditions: 277.15–278.15 K (approximately 4–5 ℃) for deep-sea regions and 283.15–288.15 K (approximately 10–15 ℃) for nearshore regions. In addition, the seawater flow velocity parameter is introduced in the fluid field to simulate the effect of ocean currents on cable heat dissipation.

Through the above multi-physics field coupling model, the temperature distribution characteristics of the cable under different operating currents and environmental conditions can be obtained. The safe ampacity can then be inversely calculated, thereby correcting and supplementing the analytical method.

3. Results and Discussion

3.1 Results of the IEC 60287 Method

Based on the IEC 60287 standard, a MATLAB program was used to solve the thermal circuit model of the submarine cable under buried soil conditions. The thermal resistance distribution of each structural layer and the corresponding heat losses were obtained. On this basis, the ampacity of the cable under steady-state operating conditions was calculated to be 1419.1 A.

The calculation results show that conductor loss is the primary heat source, and the heat generated is transferred outward through the insulation layer, sheath, and surrounding soil to the external environment. There are significant differences in the contribution of each layer's thermal resistance to the total thermal resistance, with the insulation layer and soil thermal resistance dominating and having a decisive influence on the conductor temperature rise. According to the thermal balance relationship, the allowable ampacity of the cable under the rated temperature rise constraint can be further obtained, providing a reference for engineering design.

However, this method is based on the one-dimensional steady-state heat conduction assumption and does not consider the convective heat transfer effect caused by seawater flow or the spatial non-uniformity of environmental temperature distribution. Therefore, its results have certain limitations in complex deep-sea environments.

3.2 Numerical Simulation Results

To further improve calculation accuracy, a numerical simulation analysis of the operating characteristics of the submarine cable was carried out based on the multi-physics field coupling model. The temperature field and flow field distribution characteristics of the cable and its surrounding environment were obtained, as shown in Figures 2 and 3.

From the temperature field distribution, it can be observed that the cable conductor has the highest temperature, reaching the design allowable value (approximately 90 ℃), and the temperature gradually decreases radially outward. This is because the conductor is the main heat source, and heat is transferred outward through the thermal conduction of each layer's material. Differences in the thermal conductivity of different materials lead to a non-uniform temperature gradient. The insulation layer, due to its low thermal conductivity, forms a distinct region of concentrated temperature rise, while the metal sheath and armor layer, with better thermal conductivity, facilitate outward heat transfer.

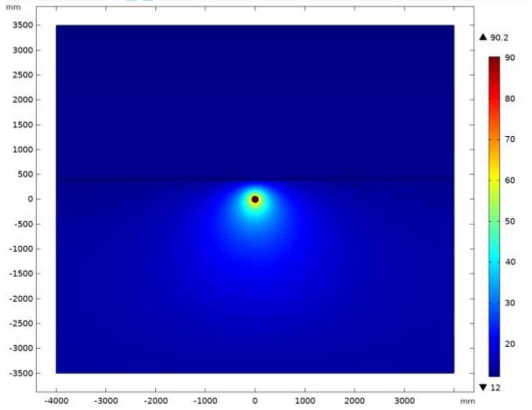

Figure 2. Temperature Field Distribution of the Submarine Cable and Surrounding Environment

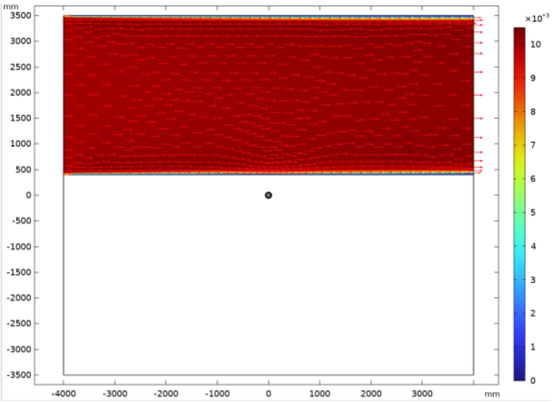

Figure 3. Flow Field Distribution

The flow field distribution results indicate that seawater flow forms a convective heat transfer process around the exterior of the cable, effectively removing heat from the cable surface, thereby reducing the outer sheath temperature and enhancing the overall heat dissipation capacity. Compared with the analytical method, the numerical model explicitly considers the fluid convection effect and can therefore more realistically reflect the heat transfer process under actual marine environmental conditions.

In terms of ampacity calculation, the finite element method yielded a submarine cable ampacity of 1430.0 A, while the IEC analytical method gave 1419.1 A, resulting in a relative error of 0.7%. The main reasons for the error are that the analytical method does not consider the convective heat transfer effect caused by seawater flow and simplifies complex boundary conditions (such as ignoring environmental temperature gradients and nonlinear changes in some thermal resistances), leading to relatively conservative results.

Further analysis was conducted on the influence of environmental factors on ampacity. According to the thermal balance relationship:

$$\theta_c - \theta_0 = (W_c + W_s + W_d) \times R_{total} \tag{6}$$

It can be seen that an increase in ambient temperature will reduce the allowable temperature rise, thereby decreasing the cable’s allowable ampacity. Conversely, an increase in seawater flow velocity enhances convective heat transfer, reduces the equivalent total thermal resistance R_{total}, and thus improves the cable’s current-carrying capacity. When the ambient temperature rises or the flow velocity decreases, the cable’s heat dissipation conditions deteriorate, and the ampacity decreases accordingly. On the contrary, under conditions of lower ambient temperature and higher flow velocity, the cable's heat dissipation capacity is enhanced, and the ampacity increases significantly.

In summary, the numerical simulation method can more comprehensively account for the influence of environmental factors on the thermal behavior of the cable. Its results demonstrate higher accuracy and better engineering applicability compared to the analytical method.

4. Conclusion

This paper addresses the problem of insufficient calculation accuracy for the ampacity of high-voltage submarine cables in deep-sea environments by comprehensively employing the IEC 60287 analytical method and the multi-physics numerical simulation method. An analytical model was solved using MATLAB, and an electromagnetic-thermal-fluid coupling model considering seawater flow and environmental temperature distribution was constructed based on COMSOL. A refined analysis of the cable temperature field and ampacity under deep-sea burial conditions was conducted. The research results show that the proposed method can effectively improve the accuracy of ampacity assessment for cables in complex marine environments. The main conclusions are as follows:

1) Based on the IEC 60287 method, the thermal resistance and heat loss distribution of each structural layer of the cable under deep-sea soil burial conditions were calculated. The results indicate that conductor loss is the primary heat source, and the thermal resistances of the insulation layer and surrounding soil play a dominant role in the overall temperature rise. Under given temperature rise constraints, the steady-state ampacity of the cable can be obtained. However, this method exhibits certain conservatism under complex environmental conditions.

2) The temperature field and flow field distribution characteristics of the cable and its surrounding environment were obtained using the numerical simulation method. The results show that the cable temperature decreases radially outward, with the conductor temperature being the highest and close to the allowable limit. Seawater flow significantly enhances the convective heat transfer capacity on the outer surface of the cable, thereby reducing the overall temperature rise and increasing the ampacity. Compared with the analytical method, the numerical model can more comprehensively reflect the heat transfer mechanism under the multi-factor coupling effect in deep-sea environments.

3) Comparing the calculation results of the two methods, the relative error of the ampacity is controlled within 0.7%, indicating good consistency between the IEC analytical method and the numerical simulation method under certain conditions. The two methods can mutually verify the rationality of the results. The error mainly arises from the analytical method's failure to consider the convective heat transfer effect caused by seawater flow and the spatial non-uniformity of environmental parameters. Therefore, in complex deep-sea environments, the numerical simulation method offers higher calculation accuracy and better engineering applicability.

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