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REAL-TIME MONITORING METHOD OF INSULATION STATUS OF PHOTOELECTRIC COMPOSITE SUBMARINE CABLE BASED ON THERMOELECTRIC COUPLING

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Abstract. The existing approach for monitoring the insulation state of photoelectric composite submarine cables primarily relies on detecting the current of the cable protection layer. However, this conventional method suffers from limited monitoring accuracy due to the absence of parameter identification processing for the cable. As a result, there is a need to improve the monitoring methodology by incorporating robust parameter identification techniques to enhance the accuracy of insulation state evaluation. In this regard, a real-time monitoring method based on thermoelectric coupling is proposed to monitor the insulation status of the photoelectric composite submarine cable. By constructing an equivalent composite circuit model and a thermodynamic function, a thermoelectric coupling model is constructed and used to identify the parameters of the submarine cable; by extracting the frequency extremes in the spectral values of the submarine cable current signal, an equivalent insulation characteristic function is constructed to realize the determination of the insulation state. The proposed method is verified for the insulation state monitoring effect in the experiment. The experimental results show that when the proposed method is used to monitor the insulation state of the photoelectric composite submarine cable, the calculated partial discharge quantity has a small error, and the monitoring accuracy is high.

Key words: thermoelectric coupling model; equivalent circuit; photoelectric composite submarine cable; insulation condition monitoring;

1. Introduction. there are three main methods for monitoring the insulation state of photoelectric composite submarine cable: partial discharge monitoring method, insulation protection layer monitoring method and cable temperature monitoring method. Among them, the partial discharge monitoring method is mainly through the sensing equipment of the discharge signal issued by the photoelectric composite submarine cable to collect and combined with filtering algorithms for the discharge signal discrete processing to achieve signal denoising based on identifying the frequency peak in the discharge signal curve, determine the number of partial discharge of the photoelectric composite submarine cable in the sampling period [1]. At the same time, combined with the change of frequency amplitude of the discharge signal, it can also be roughly inferred from the discharge signal issued by the specific node coordinates. The insulation protection layer monitoring method is mainly through the power outage state of the protection layer in the photoelectric composite submarine cable residual current value detection. The construction of the equivalent current model will be compared with the normal form of the current if the present error is large, it means that at this moment, the photoelectric composite submarine cable insulation aging situation needs to repair and replace the treatment [15]. The cable temperature monitoring method is mainly through the infrared imaging method to capture the heat of the unit length of the photoelectric composite submarine cable and the formation of infrared images through the cable in the abnormal temperature fluctuations node to determine the cable insulation aging state. The above three methods can be achieved to a certain extent to monitor the insulation status of the photoelectric composite submarine cable, but there are certain limitations. First, the temperature monitoring method can be applied to a small range, only to the middle part of the cable, for the cable joints, and the temperature of the connection with other electrical equipment can not achieve more accurate monitoring. This research focuses on finding strong photoelectric composite submarine cable insulation material and studying its efficiency.

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The insulation layer protection monitoring method needs to be carried out under the scene of power failure, which is not conducive to the regular work of the photoelectric composite submarine cable and quickly affects production efficiency. This method can only determine whether the insulation aging situation, the specific breakdown of the insulation state can not be accurately identified, and can not get the particular insulation node coordinates, so it is also not conducive to the maintenance of photoelectric composite submarine cable [14]. The partial discharge monitoring method not only can identify the different states of insulation but also can get the specific partial discharge node coordinates by combining the fluctuation of the discharge amount to achieve the identification of the insulation point location, which has a more excellent monitoring effect. Therefore, this paper combines the conventional partial discharge monitoring method through the optimization of the traditional process and the introduction of the thermoelectric coupling model to identify the parameters of the photoelectric composite submarine cable. For the interference of the conventional way in terms of noise, a filtering algorithm is used to discretize the noise of the discharge signal and improve the processing effect of the discharge signal [17]. The major research challenge is as follows:

1. Submarine cables must be designed to accommodate high transmission capacities to meet the growing demand for data and communication services across continents and undersea regions.
2. Submarine cables are vulnerable to physical damage caused by fishing activities, anchoring, natural disasters, and geological hazards such as earthquakes and landslides. Designing adequate protection measures, such as armoring, shielding, and burial, is essential to safeguard the cables against these potential risks.
3. Submarine cables can span hundreds or even thousands of kilometers across various terrains, including deep ocean trenches and shallow coastal areas. Designing cables that can withstand the stresses and strains associated with installation, deployment, and maintenance in diverse environments is crucial.
4. Submarine cables face signal degradation due to attenuation, dispersion, and noise. Design considerations include minimizing signal loss, optimizing signal integrity, and employing repeaters and amplifiers to maintain signal quality over long distances.
5. Submarine cable installations can impact marine ecosystems and habitats. Mitigating environmental impacts through careful route selection, installation techniques, and adherence to environmental regulations is an important aspect of cable design.
6. Submarine cables are critical infrastructure for global communication networks. Ensuring high reliability and redundancy is crucial to minimize downtime and service disruptions. Designing robust cable systems with redundant paths, fault detection and localization capabilities, and quick restoration mechanisms is essential.
7. Accessing and repairing submarine cables in deep-sea environments pose significant logistical and technical challenges. Designing cables that facilitate efficient maintenance and repair processes, including remotely operated vehicles (ROVs) and repair ships, is essential to minimize downtime and service disruptions.
8. Submarine cable projects involve substantial manufacturing, installation, and maintenance investments. Balancing the cost with performance, lifespan, and other requirements is a key challenge in designing economically viable submarine cable systems.

The main contribution of the research is performing real-time monitoring of thermo electric coupling of the submarine cable with insulating solid advantage.

2. Photoelectric composite submarine cable parameter identification based on thermoelectric coupling model.

The photoelectric composite submarine cable is affected by different electromagnetic fields in the working state, so it has more complex physical characteristics. To accurately capture the insulation state of the photoelectric composite submarine cable, it is necessary to construct its temperature function first. In this regard, this paper combines the thermoelectric coupling model to identify the parameters of the photoelectric composite submarine cable. It provides help for the subsequent online monitoring of the insulation state [2]. Therefore, when monitoring the insulation state of photoelectric composite submarine cable, not only the circuit state can be monitored, but also the heat change can be observed by the temperature function, which is combined with the equivalent circuit model and thermodynamic model to build the thermoelectric coupling model shown in Figure 2.1 [7].

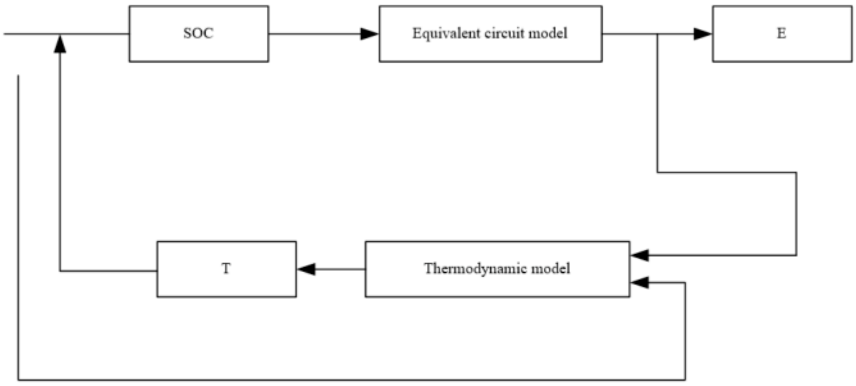

Fig. 2.1: Thermoelectric coupling framework

The optical composite submarine cable will generate and transfer heat in the working state, and in the insulated state, the heat will also appear transient, so combined with the law of conservation of energy, this paper describes the heat transfer process of the optical composite submarine cable as follows [16].

$$\rho_i C_i \frac{\sigma T}{t} = \nabla \cdot (\lambda_i \nabla T) + q \tag{2.1}$$

In the above equation, the heat gain of a submarine cable in the insulated state is equal to the product of the rate of heat production of the wire inside the line and the combined heat generated when the submarine cable wire interacts with the outside world. Where,ρ_i represents the density of the submarine cable wires,C_i represents the specific heat capacity of the insulation,T represents the average temperature of the wires,q represents the thermal conductivity of the whole line,λ_i represents the rate of heat generation of the submarine cable, andσ represents the number of the submarine cable wires. For the above thermoelectric coupling model, the conventional CFD simulation software can be used to solve and analyze it. Still, because the software cannot effectively identify the multi-parameter mathematical model, it takes a long time to analyze using the software, which quickly affects the subsequent monitoring efficiency [9]. There are two ways to optimize the model: one is to change the order of the model and reduce the demand of the model, thus reducing the analysis time of the software; the other is to decompose the transient conditions of the model and divide it into different stages, which are input into CFD software for solving and analyzing. Since the second method is more complicated to implement, this paper chooses the first method to reduce the order of the thermoelectric coupling model to achieve effective non-capture of the operating state of the photoelectric composite submarine cable [10]. The literature shows that this method has the same data processing effect as the CFD model, and it takes less time to complete the simulation analysis of the thermoelectric coupling model in a limited time, which can improve the subsequent insulation state monitoring efficiency. The parameters to be identified and their corresponding mathematical expressions are shown below in the equivalent circuit model of the photoelectric composite submarine cable.

In order to improve the accuracy of the parameter identification of the equivalent circuit model, this paper chooses to combine the least squares method to estimate the parameters in the above table and then combine them with the actual observations to achieve the online identification of the parameters [11]. Since the parameters of the equivalent circuit model need to be reformatted for each set of data when using the conventional method, which may affect the efficiency of the model, this paper adopts a recursive method to process them, and the specific processing formula is shown below.

$$\begin{cases} \theta(k) = \theta(k-1) + K(k)[y(k) - \varphi(k)] \\ K(k) = P(k)\varphi(k) \\ P(k) = [1 - K(k)\varphi(k)]P(k-1) \end{cases} \tag{2.2}$$

Table 2.1: Equivalent circuit model identification parameters

Model parameters	Expressions
Open circuit voltage	R_o
Open circuit current	R_e
SOC	R_d
Submarine cable resistance	C_e
Submarine cable capacitance	C_d

Table 3.1: Optical composite submarine cable insulation state division results

Insulation status	Relative dielectric constant
intact	2.46
Slightly aged	2.57
Moderate ageing	2.63
Severe ageing	2.69
Damaged insulation	2.78

Where,$\theta(k)$ represents the predicted value of the least squares method for the parameters of the equivalent circuit model,$y(k)$ represents the actual observed value of the model,$\varphi(k)$ represents the output and input values of the equivalent circuit,$\varphi^T(k)$ represents the circuit data format conversion matrix,$K(k)$ represents the recursive gain parameters, and$P(k)$ represents the root mean square error matrix of the recursive results [13]. The above principle is applied to the thermoelectric coupling model constructed in this paper, assuming that the input value is the internal equivalent current flow value of the photoelectric composite submarine cable, representing the output value, and the frequency domain value of the model can be obtained by discretizing its transformation, and the specific formula is shown below.

$$y(k) = \alpha y(k-1) + \beta y(k-2) \tag{2.3}$$

The above equation can be used to identify the parameters of the equivalent circuit model, and the actual model parameters can be predicted by combining the recursive results with the actual observed values.

As can be seen from the above figure, the model parameter identification first requires initialization of the parameters, including the data sampling period of the photoelectric composite submarine cable, the open-circuit voltage of the cable, and the state of charge [8]. Then, the kth moment observation data, including voltage data and current data, are obtained through the sensor, and the equivalent parameters are estimated in real-time. The open-circuit voltage of the optical composite cable at time k is calculated by the correspondence between the open-circuit voltage and the equivalent parameters. Then the recursive least squares method is enabled to perform recursive operations on the parameters of the model and calculate the expression parameters to obtain the online identification results at [6]. Through the above steps, the thermoelectric coupling model of the photoelectric composite submarine cable can be constructed, and the recursive least squares method can be used to identify the parameters of the model and provide data for the subsequent online identification of the insulation state of the submarine cable [18].

3. Optical composite submarine cable insulation eigen function extreme frequency extraction.

To effectively monitor the insulation state of the photoelectric composite submarine cable, this paper takes the common AC submarine cable in the power system as an example and divides the relative dielectric constant under its insulation state, by using the relative dielectric constant under different values to judge the insulation state of the submarine cable, the specific division results are shown in Table 3.1 [5].

Through the above division results can be seen when the relative dielectric constant of the photoelectric composite submarine cable is 2.78, which means that at this moment the submarine cable appears insulation

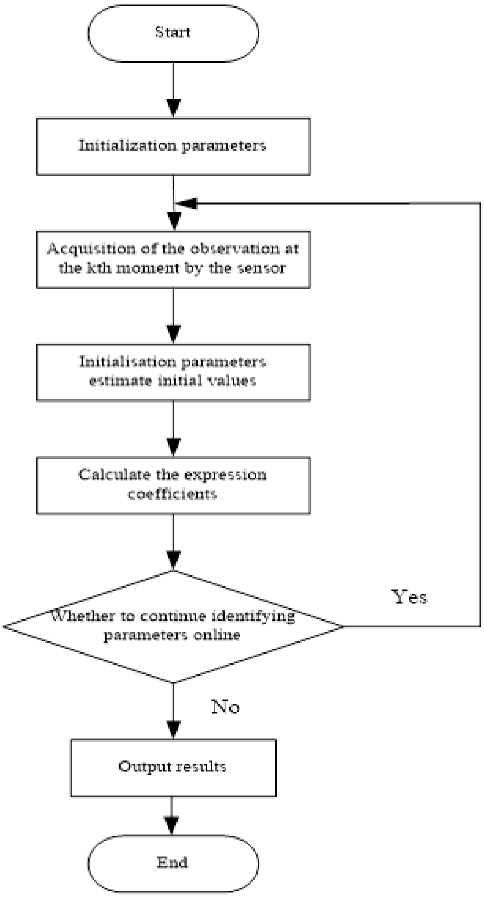

Fig. 2.2: Flow chart of parameter identification

damage situation. In this regard, this paper analyzes the variable parameters of the submarine cable to explore the influence of different variable parameters on the sensitive frequency of the cable, the specific analysis results are shown in Figure 3.1 [3].

Through the study of the relevant literature, it is known that the length change of the cable is negatively correlated with its sensitive frequency, while the radius of the cable core and the thickness of the insulation wrapping layer are positively correlated with the sensitive frequency of the cable. For an installed photoelectric composite submarine cable, its sensitive frequency variation interval is a definite fixed value, which can be solved by calculating the maximum and minimum values of the frequency variation curve. [4]. In this paper, we choose to extract the frequency of the extreme value of the insulation characteristic function, combined with the least squares method, to analyze the variable parameters of the submarine cable, the specific implementation process is as follows.

In order to optimize the above process, this paper extracts the insulation spectrum by combining the high-frequency excitation generated outside the photoelectric composite submarine cable, by measuring the current flowing in the core inside the cable, by using the output value of the equivalent circuit model as the ground current, and by using the least squares method. According to the equivalent insulation function constructed above, this paper combines the cable parameters of the photoelectric composite submarine cable and inputs the parameters into the equivalent insulation function to obtain the reference values of the extreme frequency of the photoelectric composite submarine cable under different aging states, and the specific reference values are shown in Table 3.2.

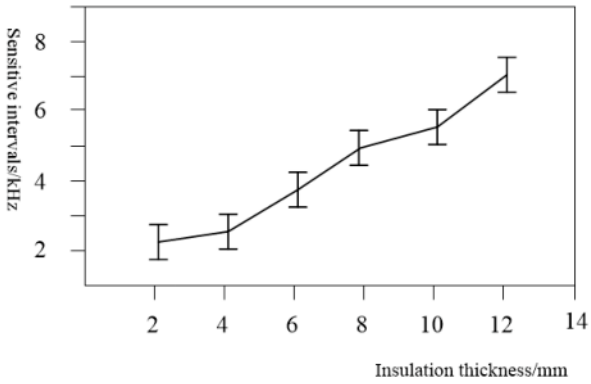

Fig. 3.1: Variable parameters on submarine cable sensitive frequency

Table 3.2: Reference values of extreme frequencies under different aging conditions

Insulation status	Relative dielectric constant
intact	7.05
Slightly aged	7.35
Moderate ageing	7.21
Severe ageing	7.16
Damaged insulation	6.75

According to the principle of equivalent insulation function, photoelectric composite submarine cable in different units of the length of the grounding resistance will not have an impact on the polar frequency, so this paper will be set to the value of the resistance of the core of the photoelectric composite submarine cable to 0, you can get for the polar frequency has a real impact on the equivalent insulation function, the specific function expression is shown below.

$$G_{in} = \lim G_0 = \left| \frac{y(z_c + z_s)}{{z_c}^2 + {z_s}^2} \right| \tag{3.1}$$

The above equivalent insulation function is consistent with the actual insulation state frequency extrema, so the actual insulation frequency extrema can be obtained by solving the above equivalent insulation function extrema [12].

4. Optical composite submarine cable insulation state identification. Optical composite submarine cable in the insulation state due to local aging and damage part of the resistance capacity is missing, so there will be a partial discharge situation, by capturing the partial discharge frequency, you can effectively determine the current insulation state of the optical composite submarine cable. This paper combines the above constructed insulation function and insulation frequency extremes to achieve effective monitoring of the insulation state by using the local discharge signal identification of the photoelectric composite submarine cable as the main means [19]. In general, the current pulse sensor can be used to detect the discharge signal generated by the local wear of the photoelectric composite submarine cable, but the local discharge signal detected by this method usually contains a complex signal including the external environment, the signal noise is large, so first need to remove the noise of the local discharge signal to obtain a pure discharge signal, in order to achieve the effective insulation state of the photoelectric composite submarine cable Identification.

Firstly, the current sensor is used to collect the discharge signal from the current flowing inside the photoelectric composite submarine cable; then the signal conditioning circuit is used to process the collected discharge

Table 5.1: Optical composite submarine cable parameters

Parameter type	Voltage Rating			
	10kV	35kV	110kV	220kv
Wire core radius	8.2	5.5	8.6	8.9
Insulation thickness	4.5	10.5	12	16.5
Cable length	0-2000			

signal, amplify the signal wave value, and use the denoising algorithm to discretize the collected signal to obtain the denoised signal. If the result shows that the extreme value of the discharge exceeds the set threshold, it means that the cable is aging and wearing insulation, and an alarm is issued to remind the staff to replace the insulated cable as soon as possible.

Through the above steps, the effective identification and early warning of the insulation state of the photoelectric composite submarine cable can be completed. Combined with the thermoelectric coupling model and the extreme frequency extraction of the insulation function constructed in this paper, the design of the real-time monitoring method of the insulation state of the photoelectric composite submarine cable based on thermoelectric coupling is now completed.

5. Experiment and analysis.

5.1. Experimental preparation. In order to prove that this paper proposes a real-time monitoring method based on the thermoelectric coupling of photoelectric composite submarine cable insulation state in the actual monitoring effect than the conventional photoelectric composite submarine cable insulation state real-time monitoring method, after the theoretical part of the design is completed, the experimental part is constructed to test the actual monitoring effect of this paper's method. In order to ensure the experimental effect, two conventional photoelectric composite submarine cable insulation state real-time monitoring methods are selected for comparison, namely, the photoelectric composite submarine cable insulation state real-time monitoring method based on electrical characteristics analysis, and the photoelectric composite submarine cable insulation state real-time monitoring method based on power disturbance.

The experimental object selected for this experiment is an offshore electrical engineering photoelectric composite submarine cable combination, the cable combination for different voltage levels has corresponding cable changeable parameters, and specific parameters configuration as shown in Table 5.1.

The above parameters of photoelectric composite submarine cable are used as input values, combined with MATLAB simulation software to construct a mathematical model of the submarine cable, and simulate different insulation states of the photoelectric composite submarine cable. Three methods are used to monitor the mathematical model in real-time and to compare the accuracy of the methods by comparing the error between the partial discharge amount and the actual amount under different methods.

5.2. Analysis of test results. The comparison standard selected for this experiment is the monitoring accuracy of the monitoring method, The specific measurement index is the error between the calculated partial discharge amount about the actual value under different methods, the smaller the error represents the higher the monitoring accuracy of the method, the more accurate monitoring of the insulation state of the photoelectric composite submarine cable, the specific experimental results are shown below.

The above experimental results show that the errors between the calculated partial discharge amount and the actual value under different partial discharge nodes and different methods are different. By observing the change curve of the partial discharge error, it is obvious that the partial discharge amount calculated by the method in this paper is closer to the actual value, while the error of the partial discharge amount under the conventional method is higher. Thus, it can be proved that the insulation condition monitoring method proposed in this paper has better monitoring accuracy.

6. Conclusion. This research paper addresses the issue of low accuracy in insulation state monitoring of conventional photoelectric composite submarine cables. By incorporating the thermoelectric coupling model and

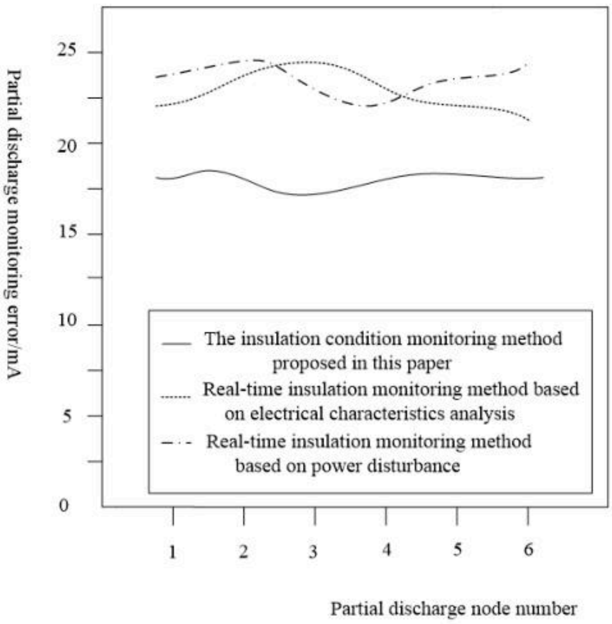

Fig. 5.1: Comparison of local discharge monitoring errors

analyzing the thermodynamic and power transmission processes, the proposed approach effectively adjusts the insulation state function using error tolerance. This adjustment leads to calculated partial discharge quantities that closely align with actual results. By determining the magnitude and location of the partial discharge, the insulation state of the photoelectric composite submarine cable can be accurately identified and monitored.

However, it is important to acknowledge the limitations of this study. The research primarily relies on mathematical modeling and simulation. In particular, future work should concentrate on investigating the signal's anti-interference capabilities to enhance the analysis of partial discharge signals. This research direction will contribute to improving the practical effectiveness of analyzing partial discharge signals and provide valuable assistance in maintaining photoelectric composite submarine cables. By addressing these limitations and conducting more extensive experimental validations, the proposed method can be refined and applied effectively in real-world submarine cable monitoring systems.

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