Research Progress in Aging State Assessment of High-Voltage XLPE Power Cables Insulation

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Abstract. The insulation aging status of high-voltage cross-linked polyethylene (XLPE) power cables is crucial for ensuring power supply reliability. Therefore, research on methods for detecting and evaluating the insulation aging status of high-voltage cables holds significant importance. Both domestic and international studies have yielded relevant research outcomes in this field. This paper summarizes the commonly used offline and online methods for detecting and evaluating the insulation status of high-voltage cables.Offline detection methods offer high accuracy but are not suitable for extensive sampling of in-service cables. On the other hand, online monitoring methods face numerous environmental interference factors that can affect monitoring results, resulting in certain limitations to the detection process. Furthermore, there is a lack of widely accepted evaluation standards and systems for assessing the insulation aging status of cables.In addition to summarizing the existing methods, this paper identifies the challenges in the current comprehensive evaluation methods for cable insulation aging status and suggests directions for future research that can enhance the evaluation of cable insulation aging.

Keywords: High-voltage cables; Cross-linked polyethylene; Insulation aging; Online monitoring; Offline detection; Status evaluation.

1 Introduction

The reliable operation of high-voltage cross-linked polyethylene (XLPE) power cables directly affects the safety and stability of the power system. However, during the energized operation, cables are subjected to aging factors such as electrical, thermal, chemical, and mechanical influences, causing the insulation of the cables to deteriorate over time, and potentially leading to insulation breakdown accidents[1]. In the event of an insulation breakdown accident, power cables need to be de-energized for maintenance. This can inconvenience consumers and even result in significant economic losses[2-3]. To enhance the reliability of XLPE power cable operation, research can be conducted to modify XLPE insulation cable materials. Additionally, it is essential to perform condition monitoring of cables already in operation[4-5].

Currently, there is no highly effective preventative testing method for high-voltage power cables. Once an insulation breakdown incident occurs, locating defects and faults in

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underground, long-distance power cables requires substantial human resources, equipment, and financial investments. Such incidents can disrupt residents' normal lives and impact business operations[6]. Therefore, it is of great importance to research scientifically effective testing methods and propose a method for assessing the insulation condition of in-service cables, providing a rational basis for cable operation and maintenance planning, which is essential for improving the reliability of the power system.

2 Cable insulation aging offline detection method

2.1Electrical performance indicators

The development of medium voltage XLPE cable insulation testing technology is relatively mature. However, due to the manufacturing process and cable structure of medium-voltage cables and high-voltage cables in consistent with the working environment, diagnostic methods for medium voltage cable insulation performance it cannot be fully deduced to high voltage cables. For example, in medium voltage cables, one of the common causes of aging is water tree aging, and for high-pressure for cables, the problem of insulation aging caused by water trees is not prominent. Therefore, methods such as the dielectric loss method that have a strong correlation with the aging condition of water trees. This method is not applicable to the detection of high-voltage cables. At present, high-voltage power commonly used offline detection methods for cable insulation aging status include: insulation resistance measurement method, partial discharge method and breakdown test method.

2.2Non-electrical performance indicators

In addition to the above common electrical performance testing methods, domestic and foreign researchers have also developed some non-electrical methods for cable insulation aging diagnosis gas performance index detection method[7].

(1)Mechanical property testing method

Tensile testing is one of the commonly used methods for assessing the mechanical properties of materials, and it is used to evaluate the tensile performance of XLPE insulation materials. The tensile properties of XLPE insulation materials are influenced by various factors, including the polarity of molecules, molecular weight, cross-linking, crystallinity, and the development of defects within the insulation material. During the thermal oxidative aging of XLPE materials, reactions such as thermal cleavage and thermal oxidative cleavage can cause the breakage of polymer chains and damage to the overall cross-linking network. Additionally, oxidation reactions can result in the local re-crosslinking of small molecules within the insulation material. As a result, thermal aging leads to a decrease in both the tensile strength and elongation at break of XLPE.

Furthermore, microvoids, impurities, and protrusions in the semiconductive shielding layer inside XLPE cable insulation can act as stress concentration points, further reducing the tensile strength and elongation at break of the cable insulation. Tensile testing can determine these important mechanical properties, such as tensile strength and elongation at break.

According to Fig 1, it can be observed that the tensile strength and elongation at break of cable insulation materials decrease as the cable's thermal aging time increases. This indicates that the tensile properties of XLPE cable insulation gradually decrease during thermal aging, likely due to the breakage of polymer chains, re-crosslinking, and the development of defects caused by the thermal aging process.

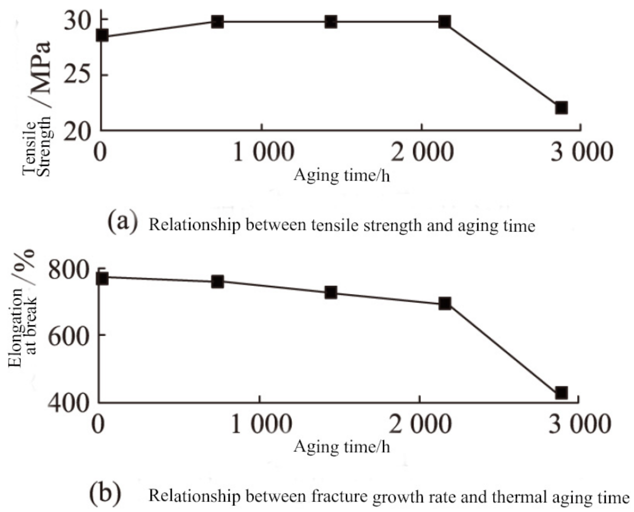

Fig. 1. The relationship between tensile test results and cable thermal aging time

3 Online monitoring method for cable insulation aging

3.1Partial discharge online monitoring method

The Local discharge phenomena can be detected not only offline but also online. Since there is currently a lack of more effective online monitoring methods for high-voltage cables, research institutions such as IEC, IEEE, and CIGRE, as well as numerous scholars, consider local discharge monitoring to be the most effective method for assessing the insulation condition of XLPE cable[8].

During the process of local discharge, various types of electrical and non-electrical signals are generated. Electrical signals include electromagnetic waves and pulse currents, while non-electrical signals include sound, light, and heat, among others . There are different techniques used to measure these signals. For measuring electromagnetic wave signals, the local discharge measurement techniques include ultra-high frequency sensor method (UHF). This method has strong interference resistance but experiences rapid signal attenuation. To measure pulse current signals, techniques like high-frequency current sensor method (HFCT), capacitor coupling sensor method (CC), and metal coupling sensor method (MFC) are employed. These methods are widely used, have high sensitivity, and can detect the charge generated by local discharge. However, they are susceptible to electromagnetic interference. To measure sound wave signals, the acoustic emission sensor method (AE) is used. This method is not affected by electrical signal interference but experiences rapid signal attenuation and has lower sensitivity. Online monitoring methods for local discharge are intended for entire in-service cables, and the illustration of the connection of various local discharge sensors to the cable is shown in Fig 2.

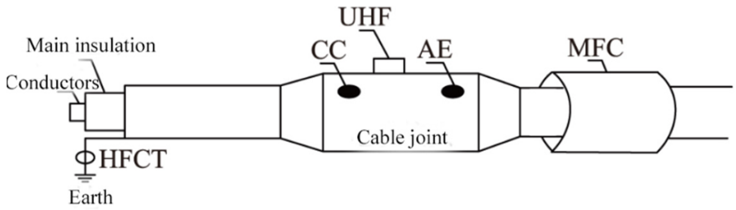

Fig. 2. Schematic diagram of each type of sensors for PD tests in cable

The research prospects for online partial discharge monitoring methods are promising. However, in the field operation of cable insulation, the signals of partial discharges are weak, and there is substantial electromagnetic interference. Additionally, they are affected by factors such as sensor sensitivity and signal attenuation. As a result, there are challenges in extracting and identifying partial discharge signals[9].

3.2Actual running cable performance test

(1)Broadband dielectric impedance spectral testing

The above method is used to test the interloss spectrum of the actual operating cable samples with different operational years, and to obtain the results as shown in Figure 3. As can be seen from Figure 3, with the increase of cable operation years, the dielectric loss factor of XLPE cable insulation gradually increases, and the trend in the low frequency region below 1Hz is more obvious. The relationship between the dielectric loss value of different XLPE cables at 0.05 Hz and their operating life is shown in Figure 4.

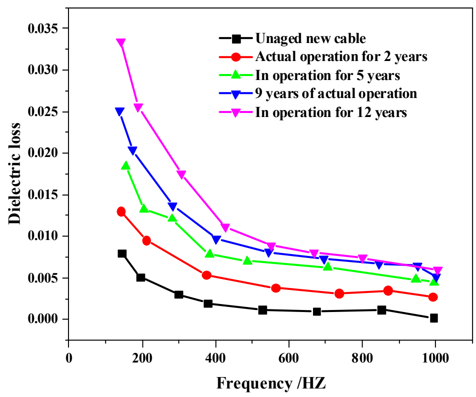

Fig 3. Comparison of dielectric loss frequency spectrum of XLPE cable slice samples of different years

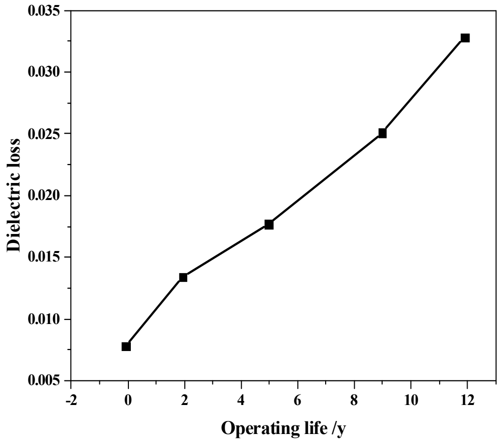

Fig4. 0.05HzThe dielectric loss value of XLPE cable samples for different years is measured below

As can be seen from the figure, the more serious the aging degree of the cable is, the greater the dielectric loss value in the low frequency area is. The broadband intermediate loss spectrum of XLPE cable insulation (especially in the low frequency area) is obviously related to its operating life. The results are in good agreement with testing the artificial accelerated aging XLPE samples.

(2)Differential scanning calorimetry test

Oxidation induction period (OIT) is an index to evaluate the oxidation resistance of materials, which can be used to reflect the antioxidant properties of materials. OIT test was conducted on XLPE cable insulation samples of different years, and the results are shown in Figure 5.

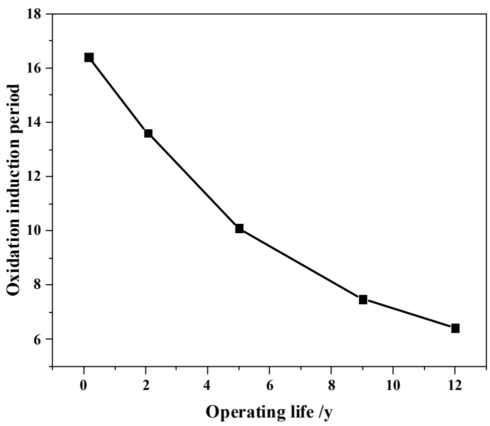

Fig5. Oxidation induction period of XLPE cable slice specimens at different years

The test results show that the oxidation induction period of the unaged new cable is the largest. With the increase of the cable running years, the oxidation induction period of the insulation gradually decreases. The smaller the oxidation induction period is, the weaker the antioxidant capacity of the cable insulation is, indicating that the more serious the aging degree is. Crosslinked polyethylene material is a kind of polymer, under the combined action of heat and oxygen, chemical degradation and produce free radicals, free radicals as catalyst chain reaction, cause crosslinked macromolecules, oxidative degradation, thus reduces the thermal stability of insulation materials and antioxidant capacity, lead to oxidation induction period. Therefore, there is a correlation between the aging degree of XLPE cable insulation and the oxidative induction period, with the increase of running years, the more serious the thermal degradation of XLPE insulation, the smaller the oxidative induction period. The oxidative induction period method can be used to qualitatively assess the thermal aging of running XLPE cables. The disadvantage of oxidation induction period method is that its test is sensitive to experimental parameters and requires the sample itself.

4 Research Prospects on Evaluation of Aging Condition of High-voltage Cable Insulation

Summarizing the high-voltage XLPE cable insulation performance testing methods discussed earlier, as shown in Table 1. From Table 1, it can be observed that offline testing methods for cable insulation performance offer high accuracy and can reflect some aging characteristics of the cable. However, they are not suitable for extensive sampling tests on cables in service. On the other hand, online monitoring is subject to numerous on-site interference factors, which can affect the monitoring results. Moreover, current online monitoring methods are primarily used to detect local defects or faults in cable insulation, and are not suitable for assessing the overall aging condition of cable insulation.

Table 1. Insulation testing methods of high-voltage cable

Item	Method	Applicability
Electrical Offline Monitoring	Insulation Resistance Measurement	Can reflect the overall aging of the cable
	Partial Discharge Measurement	Used to detect local insulation defects in cables
	Breakdown Field Strength Measurement	Can reflect the degree of dielectric performance aging
Non-electrical Offline Monitoring	Tensile Test	Reflects the degree of mechanical performance aging
	DSC	Indicates the degree of thermal oxidation aging
	TGA	Reflects the degree of thermal degradation
	FTIR	Indicates the degree of thermal oxidation aging
Online Monitoring	Partial Discharge	Used to detect local insulation defects in cables
	Sheath Current Monitoring	Used for external insulation fault

	monitoring of cables
Temperature Monitoring	Reflects localized temperature variations in the cable

The establishment of cable insulation aging evaluation models based on these performance indicators faces several challenges. Firstly, the factors influencing cable insulation aging are numerous, and the mechanisms involved are complex, making it difficult to derive precise evaluation models based on physical or chemical processes. Secondly, when utilizing big data technology for cable aging analysis, there is often a lack of sufficient data to support extensive big data analytics.In light of the above analysis, the paper suggests that the evaluation of cable insulation aging can be enhanced in the following ways:

(1) Establishing an initial cable insulation aging evaluation model based on historical operational data and online monitoring indicators. Utilizing information such as the operational lifespan of high-voltage cables, historical load data, installation methods, environmental conditions (temperature, humidity, chemical exposure), past failures, inherent defects, and online monitoring indicators, a cable insulation aging preliminary evaluation model can be created using the linear weighted comprehensive evaluation method. This model enables the initial classification of cable aging states based on real-time operational information, allowing for selective sampling and testing of cables with higher aging levels, thus avoiding the need to test all cables.

(2) Creating a precise cable insulation aging evaluation model based on the analysis of offline experimental data. This model employs methods such as insulation resistance, breakdown field strength, mechanical performance testing, thermal analysis, and infrared spectroscopy to evaluate the electrical and physicochemical performance indicators of cable insulation. Using the fuzzy comprehensive evaluation approach, this model offers a more accurate assessment of cables with higher initial aging levels from the preliminary evaluation. This allows for the formulation of appropriate retirement or maintenance decisions to ensure the safe and stable operation of the cable network.

(3) Establishing a database management system for cable insulation aging states. Building upon the "online initial evaluation" and "offline precise evaluation" models, this system manages historical operational, online monitoring, and experimental testing data, recording the conclusions of cable insulation aging assessments. By gradually accumulating data related to cable aging analysis, and as the dataset reaches a significant size, it can be used to adjust the design of evaluation indicators and weights in both the preliminary and precise evaluation models. This data-driven approach enhances the accuracy of the evaluation models[10].

5 Conclusion

This With the continuous advancement in research on high-voltage cross-linked cable insulation materials, offline detection methods for cable insulation aging have become increasingly rich and sophisticated. When establishing precise aging assessment models, it is possible to enhance the accuracy of insulation aging assessment models by studying the correlation between various detection indicators and cable insulation aging through data analysis methods. This involves selecting the most representative aging characteristics from multiple detection indicators. The advancement of big data technology provides a new approach for the evaluation of cable insulation aging status. However, there is currently a lack of sufficient data support. Building a database management system for cable insulation aging status, collecting operational data, and establishing a comprehensive database can offer valuable decision support for cable insulation aging analysis, lifespan assessment, and the overall lifecycle management of cables once completed.

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