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Maintenance Practices of High-Voltage Cross-Linked Polyethylene (XLPE) Cable Buffer Layers

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Abstract. As urbanization accelerates globally, the demand for electricity continues to rise, especially within high-voltage power transmission systems. Cross-linked polyethylene (XLPE) cables have become crucial due to their exceptional insulation properties and mechanical characteristics. However, the buffer layers of XLPE cables may undergo aging and faults caused by various factors, including electrical aging, thermal aging, chemical impacts, and improper design. This paper synthesizes existing literature to provide an in-depth analysis of the material properties, aging mechanisms, fault causes, design principles, and maintenance practices related to XLPE cable buffer layers. Through finite element method (FEM) simulations, it evaluates the electric field distribution across XLPE cables under different operating voltages and the contact state between the buffer layer and the metal sheath. Additionally, this study explores the recyclability and environmental impact of XLPE materials, as well as how improvements in material properties and detection technologies can enhance cable reliability and safety. The findings offer comprehensive theoretical and practical guidance to the power industry, aiding in optimizing cable design, improving system reliability, and reducing failure rates, while also suggesting future research directions.

Keywords: Cross-linked Polyethylene (XLPE) Cables; Buffer Layer Aging; Fault Mechanisms; Electric Field Distribution Simulation; Material Properties; Maintenance Practices; Sustainability; Power Transmission Systems.

1. Introduction

Due to their excellent electrical properties, cross-linked polyethylene (XLPE) cables are widely used as transmission equipment in power systems. In high-voltage XLPE cable structures, the buffer layer facilitates a good electrical connection between the insulation shield and the aluminum sheath while providing water-blocking capabilities, playing a crucial role in the cable's electrical and insulation performance. However, defects in the buffer layer often appear within XLPE cables (Liu, Fifield, & Bowler, 2021), damaging the insulation. As the extent of insulation damage deepens, it may eventually lead to cable breakdown incidents, severely impacting the safe and stable operation of the power system. In recent years, multiple incidents of cable breakdowns due to buffer layer ablation defects have been reported. However, current research lacks a unified understanding of the mechanisms behind these defects (Zhu et al., 2019). By establishing a mathematical model for axial surface ablation of high-voltage cables, it is suggested that the separation of the metal sheath from the insulation shield is a primary cause of ablation. Mainstream research, through finite element simulation analysis, identifies buffer layer conductivity and air gaps as major factors influencing ablation (Zhao et al., 2020). By establishing a partial discharge model of the cable body, it is found that air gaps between the insulation shield and the aluminum sheath are significant causes of ablation. Factors such as water ingress and moisture absorption by the cable, large gaps between the aluminum sheath and insulation shield, or loss of semiconductor properties in the water-blocking tape contribute to ablation issues (Zhang et al., 2020). The non-conductive nature of the buffer layer material and prolonged water exposure of the buffer tape are primary reasons for ablation (Liu, Fifield, & Bowler, 2016). Since there is no definitive conclusion on the defect mechanisms of the buffer layer and no effective detection methods currently available, undetected defective cables pose a hidden danger to the safe and stable operation of the cable system (Harsha & Joyce, 2013). This literature review aims to comprehensively examine and analyze the key factors influencing the performance of high-voltage XLPE cable buffer layers, covering material properties, fault mechanisms, and maintenance practices (Tanaka et al., 2014). Firstly, we will conduct an in-depth analysis of the materials used in buffer layers, including their physical, chemical, and electrical characteristics, to reveal how these properties affect the long-term performance of the buffer layer. Secondly, the systematic study will outline various causes of buffer layer faults, such as material aging, environmental impacts, and improper design, and explore how these faults affect the overall performance and lifespan of the cables (Zhang et al., 2020). Additionally, this review will cover simulation and experimental studies, establishing simulation models to replicate the contact state between the buffer layer and the metal sheath under different operating conditions, and verifying the accuracy and reliability of the simulation results through experiments (Harsha & Joyce, 2013). These studies will provide scientific evidence for cable design, helping engineers optimize material selection and structural design, while also offering theoretical support for quality control and maintenance strategy formulation in cable production (Zhang et al., 2020). Furthermore, the review will assess existing buffer layer defect detection technologies and propose new methods to enhance detection accuracy and efficiency. Through these new approaches (Tanaka et al., 2014), the study will explore how to achieve early diagnosis and preventive maintenance of buffer layer defects, aiming to reduce the likelihood of failures and extend the service life of cables. In summary, the significance of this study lies in providing the academic community with a comprehensive perspective on XLPE cable buffer layer research and offering practical guidance and recommendations to practitioners in the power industry (Tanaka et al., 2014). By improving buffer layer material properties and detection technologies, economic losses and social impacts caused by cable failures can be significantly reduced. This study also provides policy suggestions and industry guidance, contributing to the stable operation and sustainable development of power systems (Zhang et al., 2020).

2. Review framework

In analyzing the performance of cross-linked polyethylene (XLPE) as a cable buffer layer material, it is imperative to adopt a comprehensive theoretical framework that integrates concepts from materials science, electrical engineering, mechanics, thermodynamics, chemical stability, and environmental impact assessment (Shao et al., 2018). This interdisciplinary approach facilitates a thorough understanding of the material's properties and its performance in practical applications, thereby guiding the design and optimization of cables. From a materials science perspective, the relationship between polymer structure and performance is fundamental. The physical and chemical structure of XLPE directly impacts its thermal stability, electrical properties, and mechanical strength. Cross-linking density, as a critical parameter, not only determines the thermal and chemical stability of the material but also affects its mechanical properties, such as tensile strength and toughness (Liu, Fifield, & Bowler, 2019). Additionally, understanding the mechanisms of aging and degradation of the material over long-term applications, especially under conditions of high temperature, high voltage, and humidity, is crucial for predicting its lifespan and reliability (Harsha & Joyce, 2013). In the field of electrical insulation, analyzing electrical performance based on dielectric theory, such as resistivity and dielectric strength, helps assess XLPE's performance under high voltage conditions. Partial discharge theory further explains potential electrical breakdown and discharge phenomena at high electric field strengths, which is essential for cable design, particularly concerning the contact issues between the buffer layer and the metal sheath (Liu, Fifield, & Bowler, 2019).

Mechanics theory involves stress-strain analysis to understand the material's behavior under various mechanical loads, including tensile, compressive, and torsional stresses that may occur during cable installation and operation. The application of fatigue and fracture mechanics focuses on the material's degradation and eventual failure under repeated loading conditions (Nikvar-Hassani et al., 2024). Thermodynamics and thermal behavior theories reveal how the material responds to temperature changes, especially thermal expansion behavior and the impact of thermal cycling on material performance. Thermal stability studies not only consider the material's ability to maintain its physical state under continuous high temperatures but also its performance changes during thermal aging. Chemical stability and corrosion theories explore XLPE's resistance to environmental factors, including chemical corrosion resistance and behavior in specific chemical environments. This provides a basis for predicting the material's suitability and stability in complex environments. Lastly, environmental impact assessment theories, such as life cycle analysis (LCA), offer methods to evaluate the environmental impact of the material throughout its production to disposal. This helps formulate more environmentally friendly material selection and disposal strategies while considering economic and social benefits (Nikvar-Hassani et al., 2024). Integrating these theoretical frameworks not only deepens our understanding of XLPE material performance but also provides scientific guidance for its application in power systems. From material selection and cable design to the formulation of maintenance strategies, each stage can benefit from theoretical support and practical guidance, ensuring the stability and reliability of cable systems (Leguenza, Robert, & Giacometti, 2004). XLPE widely used as insulation material in high-voltage and ultra-high-voltage cables, owes its superior comprehensive performance to its unique chemical structure and physical properties. This study systematically explores the performance and challenges of XLPE in cable buffer layer applications, drawing from theoretical frameworks in materials science, electrical engineering, mechanics, thermodynamics, chemical stability, and environmental impact.

From a materials science perspective, XLPEis polyethylene that has been cross-linked through chemical or physical methods. This cross-linking alters the linear structure of its molecular chains, forming a three-dimensional network structure, thereby significantly enhancing the material's melting point and thermal stability. The establishment of a cross-linked network reduces the mobility of chain segments and enhances the material's chemical resistance. However, it may also introduce non-uniformities in cross-linking density, which can lead to localized performance degradation, affecting the material's long-term stability and reliability. In terms of electrical performance, XLPE is an ideal choice for cable insulation due to its high resistivity and excellent dielectric strength. Its low dielectric constant and loss factor help reduce energy loss during electrical transmission, thereby improving transmission efficiency. However, under prolonged high voltage, XLPE may experience partial discharge phenomena, especially in the presence of microscopic defects or impurities in the material (Liu, Miyazaki, Hirai, & Ohki, 2020). These discharge phenomena can accelerate the aging process of the material and increase the risk of failures. XLPE demonstrates good mechanical strength and toughness, which are crucial for cables to withstand mechanical stresses during installation and operation. Additionally, its low coefficient of thermal expansion helps maintain the geometric stability of cables amid temperature fluctuations. XLPE's thermal resistance enables it to effectively withstand mechanical stresses induced by temperature changes, reducing material damage caused by thermal stress under cyclic thermal conditions (Freitas & Bonse, 2019). XLPE exhibits strong resistance to most chemicals and common solvents, but its performance may be adversely affected in specific chemical environments such as strong acids or bases (Liu, Miyazaki, Hirai, & Ohki, 2020). Moreover, prolonged exposure to ultraviolet light or high oxygen environments can lead to photo-oxidative aging, thereby impacting its physical properties. The production, use, and recycling processes of XLPE have a relatively low environmental impact, making it an environmentally friendly material choice. Nevertheless, further research and improvement in XLPE recycling technologies are essential to enhance resource recycling efficiency and reduce environmental burdens (Liu, Miyazaki, Hirai, & Ohki, 2020).

3. The Impact of XLPE Material Properties on Cable Buffer Layer Performance

Cross-linked polyethylene (XLPE) is a widely used material in the power industry, playing a crucial role particularly in the manufacture of high-voltage and ultra-high-voltage cables due to its superior comprehensive performance. The physical properties of XLPE are exemplified by its significant thermal resistance, allowing it to maintain stable operation under extreme climatic conditions, ranging from -90°C to +250°C. This ensures the reliability of cables in various environmental conditions.

Furthermore, the high tensile strength and impact resistance of XLPE enable the cable to maintain structural integrity under physical stress. These physical properties are achieved through the cross-linked structure formed during production, which not only provides excellent thermal stability but also enhances the material's mechanical strength (Freitas & Bonse, 2019).

Chemically, XLPE exhibits high resistance to most oils, chemical solvents, and acids and bases, ensuring stable performance even in potentially corrosive environments. XLPE's anti-aging characteristics are equally impressive, with strong resistance to UV and ozone degradation, helping to extend the cable's lifespan and reduce the need for long-term maintenance and associated costs. Electrically, XLPE's high insulation strength allows for high-voltage isolation with relatively thin layers of material, which is crucial for improving the compactness and cost-effectiveness of cables (Freitas & Bonse, 2019). Additionally, XLPE's low dielectric constant and small dielectric loss ensure minimal energy loss during electrical transmission, thereby improving transmission efficiency. Most importantly, XLPE's excellent resistance to partial discharge significantly reduces the risk of insulation failures during long-term operation, which is critical for enhancing the stability and reliability of the entire power system (Freitas & Bonse, 2019). Due to its outstanding physical, chemical, and electrical properties, XLPE is widely recognized as an ideal material for high-voltage cable insulation, including the protection of buffer layers. This section explores the direct relationship between the inherent characteristics of XLPE and the performance of cable buffer layers, especially in the context of preventing cable failures.

XLPE exhibits excellent thermal stability, attributed to its cross-linking through physical or chemical methods, enhancing its ability to withstand extreme temperatures without significant degradation. However, prolonged exposure to high temperatures can accelerate thermal aging, affecting the buffer layer's effectiveness by reducing its elasticity and ability to absorb mechanical stress. This reduction in mechanical buffering capability increases the likelihood of mechanical failures within the cable structure (Meneghini et al., 2015). From an electrical perspective, the high resistivity and excellent dielectric strength of XLPE are crucial for maintaining the insulation integrity of high-voltage cables. Mismatched electrical properties between XLPE insulation and its buffer layer can lead to uneven electric field distribution, potentially causing electrical discharge and insulation puncture in areas of high field strength, especially if the buffer layer has defects or weak points introduced during manufacturing or installation (Meneghini et al., 2015).

XLPE's mechanical strength also plays a vital role in the functionality of the buffer layer. Its ability to resist physical impacts and pressure ensures the cable is protected from external mechanical forces. However, poor material quality or improper processing that impairs the buffer layer's mechanical properties can lead to physical damage, often a precursor to more severe electrical failures. Chemically, XLPE's resistance to most corrosive substances allows it to perform reliably in various environmental conditions. However, in specific chemical environments, particularly those with high acidity or alkalinity, the buffer layer material may degrade over time (Selvin et al., 2024). This degradation can compromise the structural integrity of the buffer layer and diminish its effectiveness as a protective barrier. The phenomenon of water trees, a form of degradation occurring in polyethylene materials in humid environments, poses a significant reliability concern (Selvin et al., 2024). Water trees can gradually reduce electrical insulation performance, eventually leading to cable failure (Lv et al., 2015). Therefore, the design of buffer layers must incorporate materials or additives that inhibit water tree growth to maintain long-term reliability. Thermal expansion behavior is another key aspect of XLPE performance. Its low coefficient of thermal expansion helps minimize mechanical stress induced by temperature fluctuations. Ensuring the thermal expansion compatibility of the buffer layer with XLPE insulation is crucial for avoiding additional stress from thermal cycling, which can lead to mechanical failures (Lv et al., 2015). The potential for oxidative aging in XLPE, particularly under high temperature and oxygen conditions, is an area requiring in-depth study. Detailed research into the aging mechanisms of buffer layer materials is necessary to predict and mitigate aging processes, ensuring the long-term stability and reliability of both the buffer layer and the entire cable system (Lv et al., 2015).

4. Fault Mechanisms and Design and Maintenance Practices of High-Voltage XLPE Cable Buffer Layers

An in-depth analysis of the performance and potential risks of XLPE in practical applications is crucial for ensuring the stability and safety of power systems. This study aims to systematically investigate the various potential hazards associated with the use of XLPE in high-voltage cables by applying multiple theoretical frameworks, including materials science, electrical engineering, mechanics, thermodynamics, and chemical stability. High-voltage XLPE cables, especially those in service for over five years and with voltage ratings exceeding 110kV, frequently experience buffer layer breakdown failures, attracting significant attention. Failure analysis indicates that buffer layer defects are associated with several factors, including the decreased contact performance between the copper wire braid and the aluminum sheath (Muhr et al., 2004). This issue often arises from an insufficient number of copper wires, which are unable to withstand the capacitive current generated during cable operation, leading to localized temperature increases and accelerated exudation of water-blocking powder. Consequently, the contact resistance between the insulation shield and the outer sheath increases, potentially causing cable failures. Moreover, the improper selection of optical fiber materials is another critical factor contributing to cable failures, particularly when the cable becomes damp. The presence of optical fibers can accelerate the formation of white powder, increasing the contact resistance between the aluminum sheath and the buffer layer and potentially causing discharge (Muhr et al., 2004).

The application of X-ray inspection methods provides a new means of detecting internal defects in buffer layers, allowing for the direct observation of significant gaps between the aluminum sheath and the insulation shield in faulty cables. The formation of white powder is a notable feature of buffer layer breakdown failures (Andjelkovic & Rajakovic, 2001). Experimental analysis of its formation process and physicochemical properties reveals that moisture is a necessary condition for white powder formation, and the presence of electric fields and mechanical stress accelerates its generation (Liu et al., 2022). The white powder, possessing insulating properties, increases the resistance between the insulation shield and the aluminum sheath in faulty cables. Upon exposure to moisture, the water-blocking powder undergoes electrochemical reactions with air and the aluminum sheath, forming white powder with resistance reaching megaohm levels, further demonstrating its negative impact on cable insulation performance (Liu et al., 2022). Experimental validation and simulation calculations are crucial for verifying the causes of failures. Through electric field simulation models, the effect of copper wire diameter on electric field distribution was studied, revealing that when the copper wire diameter is smaller than the thickness of the braid, localized discharge phenomena are likely to occur (De Steiger, Lorimer, & Graves, 2018). A three-dimensional finite element simulation model of the cable was established to investigate the impact of air layer gaps, water-blocking tape resistivity, and overvoltage amplitude on the electric field intensity of the buffer layer. The results indicate that the highest field intensity within the buffer layer is related to the air gap and is significantly affected by the resistivity of the water-blocking tape. These research findings provide deep insights into the mechanisms of buffer layer defects, offering theoretical support for fault diagnosis and important guidance for cable design, manufacturing, and operational maintenance (De Steiger, Lorimer, & Graves, 2018).

From a materials science perspective, the cross-linked network structure of XLPE is crucial to its performance. However, non-uniformity in the cross-linking process can lead to the formation of microscopic defects such as voids and microcracks within the material. Under high voltage, these defects may become initiation points for partial discharges, triggering electrical tree growth and material aging, ultimately leading to cable breakdown. Furthermore, catalysts and additives introduced during the production of XLPE may cause chemical aging during long-term operation, affecting the material's stability and lifespan (Andjelkovic & Rajakovic, 2001). In terms of electrical properties, the dielectric strength and resistivity of XLPE are key parameters for its use as an insulation material. However, mismatched electrical properties of the buffer layer material or performance degradation due to environmental factors can create areas of high local electric field strength within the cable, increasing the risk of breakdown. Particularly in humid environments, XLPE may undergo water treeing, a phenomenon where increased conductivity and decreased insulation performance caused by moisture lead to cable failures. Mechanical and thermodynamic behaviors are also significant factors influencing XLPE cable performance. The low thermal expansion coefficient of XLPE helps maintain the dimensional stability of cables during temperature fluctuations. However, if the thermal expansion coefficients of the buffer layer and other cable components are mismatched, thermal stress may develop during temperature cycling, leading to material fatigue and performance degradation. Additionally, long-term thermal stress accelerates the thermal aging process of XLPE, impacting the cable's long-term operational performance (Andjelkovic & Rajakovic, 2001).

Chemically, XLPE exhibits good resistance to most chemicals, but its chemical structure can be compromised in specific environments, such as strong acids, bases, or organic solvents, leading to degradation of its physical properties. Environmental stress cracking is another potential issue for XLPE in specific environments, especially in the presence of organic solvents, which can cause material failure. Environmental factors also significantly impact XLPE. When used outdoors, XLPE may be exposed to ultraviolet light, oxygen, and humidity, which can accelerate aging through photo-oxidation and oxidation mechanisms. Extreme temperatures and high humidity can also expedite the deterioration of XLPE's performance, affecting cable reliability.

In high-voltage XLPE cables, the formation mechanisms of buffer layer defects are primarily influenced by two key factors: the volume resistivity of the material and the air gap between the aluminum sheath and the buffer layer. First, the volume resistivity of the buffer layer material plays a crucial role in the electrical stability of the cable. An abnormally high volume resistivity in the buffer layer can lead to unstable electrical connections between the insulation shield and the metal sheath, causing the insulation shield to be in a floating potential state. As the cable voltage increases, so does the floating potential, potentially causing partial discharges and buffer layer ablation. Studies using equivalent circuit diagrams of discharge points have revealed the relationship between increased potential difference and breakdown phenomena. Comparative studies also show that the maximum electric field strength at contact points in faulty cables is significantly higher than normal, further confirming the impact of volume resistivity on partial discharge. Therefore, maintaining the stability of the buffer layer's volume resistivity is vital for ensuring the cable's long-term stable operation. Second, the air gap between the aluminum sheath and the buffer layer is another important factor affecting the electrical performance of the cable. Air gaps may arise from various factors during cable production, installation, or operation, such as gaps at overlaps, repeated bending of the installation route, and differences in thermal expansion coefficients. The presence of air gaps reduces the electrical and thermal conductivity of the cable. Simulation experiments have found that the tightness of the connection between the aluminum sheath and the insulation shield directly affects the resistance and initial discharge voltage at both ends. Simulation analysis also shows that poor contact forms a potential difference, leading to high electric field strength in the air gap. To study the impact of air gaps on cable performance, some studies have modeled the relationship between the maximum electric field strength within the buffer layer and the size of the air gap, finding a negative correlation between them. Additionally, simulation results indicate that even with increased resistivity, ensuring a tight connection between the buffer layer and the aluminum sheath can effectively prevent air discharge phenomena. In summary, although XLPE possesses many excellent physical, chemical, and electrical properties, a deep understanding of its material characteristics, strict control over the production process, and quality assurance are crucial for ensuring the safety and reliability of cable systems. Future research will focus on developing more advanced and precise material characterization techniques, improving cable design and manufacturing processes, and enhancing the accuracy and efficiency of fault detection and diagnosis. These measures can effectively manage and mitigate potential hazards in XLPE cables, enhancing their performance and lifespan in high-voltage power transmission. Additionally, research will explore the recyclability and environmental impact of XLPE to promote sustainable development in the power industry.

5. Design and Maintenance Principles and Best Practices for XLPE Cable Insulation Material

In high-voltage power transmission systems, cross-linked polyethylene (XLPE) is widely utilized for cable insulation due to its exceptional mechanical properties and insulation characteristics. However, in practical operation, XLPE is subject to electrical aging, thermal aging, and combined electro-thermal aging (Liu et al., 2018). These aging mechanisms lead to a decline in material performance and a reduction in service life. Consequently, studying the aging characteristics, assessing the lifespan, and formulating control strategies for XLPE are of paramount importance. This paper summarizes the key design and maintenance principles and experiences for XLPE cable insulation material, and discusses their application in practical cases (Liu et al., 2018).

First and foremost, understanding and controlling the aging and lifespan of XLPE materials is crucial for ensuring the long-term stable operation of cables. Aging characteristic analysis reveals that XLPE undergoes changes in its microstructure and chemical composition under prolonged exposure to electric fields and heat (Sakellariou et al., 2013). These changes are evaluated using various aging models to predict the material's service life. Lifespan assessment and control strategies include accelerated life testing and the application of theoretical models, such as the Arrhenius equation, to predict the lifespan of XLPE under different aging temperatures, thereby providing a scientific basis for cable maintenance and replacement (Walker et al., 2020). In terms of detection technology, techniques for monitoring the insulation state of XLPE cables, such as partial discharge monitoring, sheath current monitoring, and temperature monitoring, are crucial for promptly identifying defect points and assessing the degree of insulation degradation. The dielectric response method, as a non-destructive testing technique, evaluates the insulation state of XLPE by analyzing its dielectric properties, offering an effective means of detection (Miyazaki, Hirai, & Ohki, 2020). In practical cases, 0.1 Hz ultra-low-frequency detection technology is employed, categorizing test results into normal, attention, and abnormal levels according to IEEE Std 400, significantly enhancing cable safety. Professor Chen Junwu's research team at Huazhong University of Science and Technology has established a numerical model correlating dielectric loss detection and cable water treeing through ultra-low-frequency detection of abnormal cable slices. This provides new technical means for the aging diagnosis of XLPE cables. Furthermore, the failure mechanisms of XLPE cables are closely related to maintenance practices (Shamsaei, Aghayan, & Kazemi, 2017). Cable failures are primarily caused by external force damage, manufacturing quality of cable accessories, quality of cable laying and installation, and manufacturing quality of the cable body, with failures of cable accessories accounting for over half (Kemari et al., 2020). Consequently, power companies typically conduct withstand voltage tests and partial discharge tests on newly constructed or repaired XLPE cable lines, incorporating partial discharge detection into routine inspection tasks (Miyazaki, Hirai, & Ohki, 2020). XLPE cable detection technologies mainly include withstand voltage tests, routine state evaluations, and partial discharge detection, with partial discharge detection being the primary method for cable testing in field operations. Methods such as electromagnetic coupling, ultrasonic (AE), and ultra-high frequency (UHF) can effectively detect and locate partial discharges within cables, providing a basis for fault diagnosis. Future research will focus on developing more advanced material characterization techniques, improving cable design and manufacturing processes, and enhancing the accuracy and efficiency of fault detection and diagnosis (Shamsaei, Aghayan, & Kazemi, 2017). Additionally, the recyclability and environmental impact of XLPE will become key areas of research to promote the sustainable development of the power industry. By gaining a deeper understanding of the aging mechanisms of XLPE, implementing effective aging performance control measures, and developing new detection technologies, the reliability and safety of XLPE cables can be significantly improved, ensuring the stable operation of power systems (Shamsaei, Aghayan, & Kazemi, 2017).

6. Design and Maintenance Practices for Electric Field Distribution Simulation of High-Voltage XLPE Cable

In the realm of high-voltage power transmission, XLPE cables are extensively utilized for their superior insulation properties. However, ensuring their long-term stable operation necessitates a reliable assessment of their insulation performance and the risk of partial discharge (Liu et al., 2018). This study aims to analyze the electric field distribution in XLPE cables under different operating voltages using finite element method (FEM) simulations. The core objective of the experimental design is to evaluate the reliability of the cable's insulation performance and the risk of partial discharge (Miyazaki, Hirai, & Ohki, 2020). To achieve this, we employed simulation software such as COMSOL Multiphysics or ANSYS Maxwell, in conjunction with data analysis tools like MATLAB or Python, for simulation and post-processing analysis. In our simulation model, we meticulously defined the geometric parameters of the cable, including conductor diameter, insulation thickness, sheath diameter, and outer diameter. We also specified the material properties for the XLPE insulation layer and the aluminum sheath, such as resistivity, relative permittivity, and conductivity (Miyazaki, Hirai, & Ohki, 2020).

The simulation settings considered a working voltage of 110 kV with a static electric field type and set boundary conditions of internal conductor potential and external grounding. Through geometric model construction, material property settings, mesh division, solver configuration, and simulation execution, we obtained data on electric field intensity and potential distribution (Musa et al., 2023). Data analysis revealed areas of electric field concentration, providing a basis for assessing the risk of partial discharge. Expected results indicate that electric field distribution simulations can clearly delineate the insulation performance of cables under high voltage operation, particularly at the interface between the insulation shield and buffer layers (Mecheri et al., 2000). These detailed simulation steps and parameter settings are anticipated to guide the design and utilization of cables, reducing the risk of partial discharge and enhancing the reliability and safety of the cables. Furthermore, the simulation study encompasses aging simulations, partial discharge (PD) simulations, water treeing and electrical treeing simulations, material modification simulations, fault diagnosis and prediction, evaluations of environmental and operational conditions, recyclability, and environmental impact studies, as well as the development of novel XLPE materials (Mecheri et al., 2000). These investigations not only deepen our understanding of XLPE cable performance but also provide scientific foundations for improving cable design, optimizing material selection, and enhancing cable operation and maintenance practices (Musa et al., 2023). As simulation technology continues to advance, future research will focus more on multi-scale, multi-physics, and multi-phase coupled simulations, providing more precise and detailed predictions for the future development of XLPE cables (Musa et al., 2023).

7. Discussion and Conclusion

In contemporary power transmission and distribution systems, high-voltage XLPE cables play a pivotal role due to their exceptional insulation properties and mechanical characteristics (Mouchache et al., 2020). This paper undertakes a comprehensive review of existing literature to thoroughly explore the material properties, failure mechanisms, design principles, and maintenance practices of XLPE cable buffer layers, aiming to provide extensive theoretical and practical guidance for the power industry (Tanaka et al., 2015). From a materials science perspective, the cross-linking density, thermal stability, and electrical properties of XLPE are crucial factors determining its cable performance (Zehil & Assaad, 2019). The high dielectric strength and resistivity of cross-linked polyethylene offer outstanding insulation protection in high-voltage applications, while its mechanical strength and chemical stability ensure reliability and durability under harsh environmental conditions (Thomas et al., 2019). However, potential failures such as partial discharges and breakdowns during actual operation highlight the risks associated with electrical performance mismatches (Tanaka et al., 2015). Therefore, investigating the tolerance of XLPE under high voltage and high-temperature conditions is essential for ensuring the long-term stability of power systems

(Kurihara et al., 2011). In the field of electrical engineering, this paper emphasizes the importance of the electrical connection between the buffer layer and the metal sheath, and how optimizing this design can mitigate the risk of partial discharges (Harsha & Joyce, 2013). Research on partial discharge simulation and water treeing phenomena reveals the aging mechanisms of XLPE cables in humid environments, which is crucial for enhancing cable lifespan and reliability. Mechanical and thermodynamic properties are two additional key factors in the design of XLPE cables (Tanaka et al., 2015). The mechanical strength of the cable is directly related to its durability and tensile resistance during installation and operation, while controlling the coefficient of thermal expansion helps reduce stress concentration and potential damage due to temperature fluctuations (Thomas et al., 2019). Consequently, cable design must holistically consider these physical properties to maintain stable performance under varying operational conditions (Miyazaki, Hirai, & Ohki, 2020).

The paper also discusses the chemical stability of XLPE cables in aggressive environments, particularly under exposure to strong acids, bases, or organic solvents. Moreover, the impact of water treeing and electro-thermal aging on XLPE cable performance is a focal point (Miyazaki, Hirai, & Ohki, 2020). Environmental factors such as UV radiation, oxygen, and humidity also contribute to the aging and performance degradation of XLPE cables, underscoring the importance of environmental adaptability in cable design and material selection (Kurihara et al., 2011). Lastly, the paper addresses sustainability issues, including the recyclability of XLPE cables and their environmental impact (Mouchache et al., 2020). With the growing global awareness of environmental protection, developing eco-friendly and recyclable XLPE cable materials has become a significant topic in the power industry. In summary, an in-depth study of XLPE cable buffer layers is crucial for optimizing cable design, enhancing system reliability, and reducing failure rates. Future research and practice should focus on the following areas:

1. Improvement of Material Properties: Enhancing the thermal stability and mechanical performance of XLPE through novel additives, nanocomposites, and advanced cross-linking technologies (Li et al., 2022).
2. Optimization of Manufacturing Processes: Employing precise manufacturing techniques to control cross-linking density and minimize material defects, thereby improving cable consistency and reliability.
3. Advancement in Fault Detection Technologies: Developing more sophisticated detection technologies, such as AI-based diagnostic tools and multi-physics coupled simulation techniques, to increase the accuracy and efficiency of fault detection (Ali et al., 2021).
4. Research on Environmental Adaptability: Investigating the aging mechanisms of XLPE cables under various environmental conditions and modifying materials to improve their adaptability.
5. Sustainable Development: Exploring recycling and reutilization technologies for XLPE to reduce environmental impact and promote green development in the power industry (Ali et al., 2021).

Through these efforts, XLPE cables can meet future power system demands for high-performance, high-reliability, and environmentally friendly insulation materials, providing a solid foundation for the safe and stable operation of power systems.

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