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Simulation of Partial Discharges Detection of High Voltage Cables

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ملخص

تُعد التفريغات الجزئية ظاهرة حرجة يمكن أن تؤثر بشكل كبير على موثوقية وعمر أنظمة العزل للجهد العالي، وخاصة في كابلات البولي إيثيلين المتشابك، تقدم هذه الأطروحة دراسة تفصيلية لسلوك التفريغات الجزئية داخل فراغات العزل، مع التركيز على تأثير موقع وحجم الفراغ على نشاط التفريغ. تم تطوير نموذج مكافئ موثوق به لمحاكاة التفريغات الجزئية تحت ظروف مختلفة، حيث تم حساب المعاملات الكهربائية استنادًا إلى الخصائص الهندسية للفراغات.

كلمات مفتاحية: التفريغ الجزئي، الفراغات، كابل XLPE، العوازل، الجهد العالي.

Abstract

Partial discharge (PD) is a critical phenomenon that can significantly compromise the reliability and lifespan of high-voltage insulation systems, particularly in cross-linked polyethylene (XLPE) cables. This thesis presents a detailed investigation into PD behavior within insulation voids, with a focus on how void location and size affect discharge activity. A reliable equivalent circuit model was developed to simulate PD under various conditions, with electrical parameters derived from the geometric properties of the voids.

Keywords: Partial Discharge, Voids, XLPE Cable, Insulators, High Voltage.

RÉSUMÉ

La décharge partielle (DP) est un phénomène critique qui peut fortement compromettre la fiabilité et la durée de vie des systèmes d'isolation à haute tension, en particulier dans les câbles en polyéthylène réticulé (XLPE). Ce mémoire présente une étude approfondie du comportement des DP dans des vides d'isolation, en mettant l'accent sur l'effet de la position et de la taille du vide sur l'activité de décharge. Un modèle de circuit équivalent fiable a été développé pour simuler les DP dans diverses conditions, avec des paramètres électriques dérivés des propriétés géométriques des vides.

Mots-clés : Décharge partielle, Cavités, Câble XLPE, Isolants, Haute tension.

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First and foremost, praises and thanks to Allah Almighty for giving me the opportunity and guidance to achieve my goals and to be successful

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Amar TALEB BAHMED

Dedication

I dedicate this modest work.

To the one who planted the seeds of ambition in my heart, nurtured me with endless love, and stood by me through every step To my beloved mother, a symbol of sacrifice and unconditional support

To my dear father Abdelaziz, who always supported me and helped me face difficulties.

To all my family

To all my friends

And to all those dear to me

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List of Abbreviations

AC	Alternating Current
ANSI	American National Standards Institute
CD	Coupling Device
DC	Direct Current
EHV	Extra High Voltage
EPDM	Ethylene Propylene Diene Monomer
EVA	Ethylene Vinyl Acetate
FEA	Finite Element Analysis
HDPE	High-Density Polyethylene
HV	High-Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
LV	Low Voltage
MI	Measuring Instrument
MRI	Magnetic Resonance Imaging
MV	Medium Voltage
PD	Partial Discharge
POE	Polyolefin Elastomers
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
RIV	Radio Interference Voltage
SiR	Silicone Rubber
TLM	Transmission-Line Matrix
UHV	Ultra-High Voltage
XLPE	Cross-Linked Polyethylene

General Introduction

High-voltage equipment constitutes a fundamental component of modern electric power systems, as it enables the efficient transmission and distribution of electrical energy over long distances. The reliability and safe operation of high-voltage installations largely depend on the effectiveness of their insulation systems, which are designed to withstand severe electrical, thermal, mechanical, and environmental stresses throughout their service life. Despite significant advances in insulation materials and manufacturing techniques, insulation systems remain vulnerable to degradation caused by aging, material inhomogeneities, voids, impurities, and sustained high electric field stress. One of the most critical problems affecting high-voltage insulation is the occurrence of partial discharges (PD). Partial discharges are localized electrical breakdowns that take place within the insulation or along its surface without completely bridging the electrodes. Although PD events involve relatively low energy, their repetitive nature leads to progressive deterioration of the insulating material, accelerating aging processes and increasing the risk of insulation failure. If left undetected, partial discharges can ultimately result in sudden and catastrophic breakdown of high-voltage equipment. A comprehensive understanding of the mechanisms, sources, and characteristics of partial discharges is therefore essential in the field of high-voltage engineering. In this context, PD detection and measurement techniques have become indispensable tools for insulation condition assessment, fault diagnosis, and predictive maintenance of high-voltage systems. These techniques allow early identification of insulation defects, thereby enhancing system reliability and reducing unexpected outages.

This thesis focuses on the study of partial discharge phenomena in high-voltage insulation systems, addressing their physical origins, classification, impact on insulation integrity, and modern methods of detection and analysis.

. The structure is as follows:

Chapter 1: Introduction : Provides an overview of the research problem, objectives, and significance of the study.

Chapter 2: high voltage and PD: Reviews existing research on partial discharge, high voltage insulators, and current detection and simulation methods.

Chapter 3: Methodology: Details the simulation models and experimental procedures used to analyze partial discharge behavior.Summarizes the key findings, highlights the contributions of the study, and suggests directions for future research

Chapter I General Framework of the Study

I.1. Introduction

High-voltage insulation systems play a critical role in ensuring the reliability and safety of power equipment systems continue to grow in complexity and scale, the need to understand subtle electrical phenomena that may compromise insulation integrity becomes increasingly important. Among these phenomena, partial discharges (PD) stand out as early indicators of insulation degradation.

PD typically occurs within voids or imperfections in the insulation material and can, if left undetected, lead to significant equipment damage and operational downtime.

This chapter provides a comprehensive overview of the research context, outlines the main motivations behind the study, and introduces the core problem being addressed. It also presents the research objectives and questions, delineates the scope and limitations of the study, and offers a roadmap of the dissertation's structure. This foundational chapter is essential for understanding the rationale and direction of the research work.

I.2. Background and motivation

High voltage insulators are essential components in power systems, serving as barriers that prevent unwanted current flow between conductors and grounded structures. By isolating electrical connections and supporting heavy transmission lines, these insulators ensure the safety, efficiency, and reliability of electricity delivery across vast distances. Their robust design allows them to withstand high voltages, resist environmental pollutants, and bear significant mechanical loads, making them indispensable for the stable and economical operation of modern power grids [1] [2].

One of the primary threats to the integrity of high voltage insulation is partial discharge (PD), a phenomenon that occurs when localized electrical discharges partially bridge the insulation between conductors. PD is widely recognized as a leading cause of long-term degradation and eventual failure of insulation materials, as it can create conductive channels, generate localized heat, and chemically alter the insulation, ultimately compromising its dielectric strength [3] [4].

Detecting PD in real-world conditions is challenging due to external noise and varying environmental factors, which can mask or distort discharge signals. As a result, there is a growing need for advanced simulation tools that allow researchers and engineers to study PD phenomena without the expense and complexity of large-scale physical experiments. These simulations provide valuable insights into insulation behavior under different conditions, supporting the development of more reliable and cost-effective power systems.

I.3. Problem statement

Current partial discharge (PD) detection methods face significant challenges in terms of accuracy and sensitivity, which hampers the reliable identification and assessment of insulation defects in high voltage equipment. Many existing techniques, such as acoustic and electrical detection, are susceptible to background noise and external interferences, leading to false positives or missed PD events. As a result, the effectiveness of these methods in real-world conditions is often limited, making it difficult to ensure the long-term reliability of power system insulation [5] [6].

Additionally, there is a notable lack of comprehensive simulation models that can accurately capture the complex behavior of PD within insulators. While some finite element analysis (FEA) and transmission-line matrix (TLM) models have been developed to study PD phenomena in controlled laboratory settings, their application to real-world scenarios especially those involving complex geometries and environmental conditions remains insufficient. This gap in simulation capability restricts researchers' and engineers' ability to predict insulation performance, optimize designs, and develop more robust detection and mitigation strategies [7].

I.4. Research objectives

The primary objectives of this research are centered on advancing the understanding and detection of partial discharge (PD) phenomena in high voltage insulators. The first goal is to develop a simulation model specifically tailored to capture PD activity within these insulators. Such a model will enable detailed analysis of PD characteristics, including parameters like magnitude, frequency, and location, which are critical for assessing insulation health and predicting potential failures.

Subsequent objectives involve validating the developed simulation model by comparing its outputs with experimental results or data available in the literature, ensuring its reliability and practical relevance. Finally, leveraging insights gained from simulation, the research aims to propose optimized detection techniques that enhance the accuracy and efficiency of PD identification in real-world applications. This systematic approach not only addresses current limitations in PD detection but also contributes to the design of more robust and reliable high voltage insulation systems [8].

I.5. Research questions

Understanding how accurately partial discharge (PD) behavior can be modeled using simulation tools is fundamental to improving the reliability of high voltage insulation systems. Simulation models allow researchers to replicate complex PD phenomena under controlled conditions, offering valuable insights that are often difficult or expensive to obtain experimentally. The accuracy of these models depends on how well they represent the physical, electrical, and environmental factors influencing PD activity. By validating simulation results against experimental data, researchers can refine their models, increasing confidence in their predictions and enabling more effective insulation design and maintenance strategies.

Identifying the key parameters that affect PD detection in insulators is another crucial aspect of this research. Factors such as material properties, insulator geometry, applied voltage, and environmental conditions all play significant roles in the initiation and propagation of PD events. By systematically analyzing these parameters through simulation, it becomes possible to determine which variables have the greatest impact on PD detection sensitivity and reliability. Insights gained from these simulations can then be used to enhance PD detection systems, making them more accurate and robust in real-world applications. Ultimately, leveraging simulation-based knowledge supports the development of advanced monitoring technologies that contribute to safer and more efficient power transmission networks.

I.6. Scope and limitations

This study focuses on the simulation and analysis of partial discharge (PD) behavior in cross-linked polyethylene (XLPE) insulated cables using a modified capacitive model. The model incorporates real-world parameters and configurations, such as varying void locations within the insulation and the inclusion of key components like the coupling capacitor, high voltage measuring capacitor, and an RLC-based detector circuit. These elements are modeled in MATLAB Simulink to replicate standard experimental setups and ensure accurate representation of PD phenomena. The analysis covers the impact of void positioning on electrical characteristics such as capacitance and resistance, and includes the use of a correction factor (**Kr**) to adjust for non-uniform electric fields in ellipsoidal voids.

However, the study is subject to certain limitations. The simulation assumes ideal conditions and uniform material properties, which may not fully capture the complexities of real-life cable environments such as temperature variations, moisture ingress, or mechanical stresses. Additionally, only a single void is considered at a time, whereas in practice, multiple voids with irregular geometries and distributions may exist. The model also assumes a fixed operating frequency of 50 Hz and a specific applied voltage, limiting its generalizability to other voltage levels or frequencies. Despite these constraints, the approach provides a reliable and insightful foundation for understanding PD behavior in XLPE cables under controlled conditions.

I.7. Dissertation Structure

This dissertation is organized into several chapters, each addressing a key aspect of the research on partial discharge phenomena in high voltage insulators. The structure is as follows:

Chapter 1: Introduction

Provides an overview of the research problem, objectives, and significance of the study.

Chapter 2: high voltage and PD

Reviews existing research on partial discharge, high voltage insulators, and current detection and simulation methods.

Chapter 3: Methodology

Details the simulation models and experimental procedures used to analyze partial discharge behavior.

Summarizes the key findings, highlights the contributions of the study, and suggests directions for future research.

I.8. Conclusion

High voltage insulators play a critical role in ensuring the safe and reliable transmission of electrical power by preventing undesired current flow and supporting transmission lines under challenging environmental conditions. However, their performance and longevity are often threatened by partial discharge (PD), a localized electrical phenomenon that gradually degrades insulation materials and may lead to catastrophic failures. Accurate detection and analysis of PD are therefore essential for maintaining the integrity of power systems and preventing costly outages.

This research emphasizes the importance of developing robust simulation models to better understand PD behavior in cross-linked polyethylene (XLPE) insulated cables. By focusing on these materials and employing advanced simulation techniques, the study addresses current limitations in experimental PD detection methods, which are often affected by noise and environmental factors. The validated simulation models provide valuable insights into the parameters influencing PD initiation and propagation, enabling the design of improved detection strategies. While the scope of the research is primarily simulation-based with some experimental validation, the findings contribute significantly to advancing PD analysis and monitoring technologies. Ultimately, this work supports the development of more reliable, efficient, and cost-effective insulation systems, enhancing the safety and stability of modern power grids.

Chapter II

High voltage And PD

II.1. Introduction

Modern power systems rely heavily on high-voltage equipment for energy transmission and voltage conversion; hence it is essential to enhance this equipment's reliable and healthy functioning.

The capacity level of equipment has been gradually increased as it has grown more mature. However, the harsh working environment, high operating load, and prolonged operation can easily cause insulation aging and material deterioration, among other triggering factors, leading to varying degrees of high-voltage equipment failures. These events not only put the equipment in danger of failing, but they also interfere with the city's regular operations and result in financial losses [9].

II.2. High voltage

High voltage generally refers to an electrical potential large enough to cause harm to living organisms or damage to electrical systems and equipment. The specific threshold for what constitutes "high voltage" can vary depending on context and regulations, but here are some general guidelines.

II.2.1. voltage range

The voltage range for high voltage (HV) applications can vary widely depending on the specific use case. Here is a general classification of voltage ranges according to ANSI C84.1 [10]

Table 1 Range voltage according to ANSI C84.1 [10]

	Range	Applications
Low Voltage (LV)	**up to 1,000 volts (1 kV)**	Commonly used in residential, commercial, and light industrial applications.
Medium Voltage (MV)	**1 kV ~ 100 kV**	Used in local power distribution, industrial plants, and large commercial buildings.
High Voltage (HV)	**100 kV ~ 230 kV**	Used for regional power distribution, long-distance power transmission.

Extra High Voltage (EHV)	**230 kV ~ 1000 kV**	Used for long-distance, high-capacity power transmission in national grids.
Ultra-High Voltage (UHV)	**Typically, above 1000 kV**	Used for very long-distance, very high-capacity power transmission, often in large countries.

In practical terms, high voltage is often used in power transmission, industrial applications, and specialized equipment

II.2.2. High voltage uses

1) **Power Transmission and Distribution:**

High voltage is used to transmit electrical power over long distances from power plants to substations near populated areas. Higher voltages reduce energy losses that occur due to resistance in the conductors. There are two main voltage transmission types: High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC), and they are used for efficient power transmission over long distances and underwater cables. HVDC is particularly advantageous for very long distances and interconnecting different grid systems.

2) **Electric Traction Systems:**

High voltage is used in railway electrification systems to power electric locomotives and trains.

3) **Industrial Applications:**

Industries use high voltage for various processes like arc welding, electrostatic precipitators for pollution control, and large-scale manufacturing equipment.

4) **Medical Equipment:**

High voltage is used in medical equipment such as X-ray machines and MRI scanners.

5) **Scientific Research:**

High voltage is used in particle accelerators, fusion research, and other scientific experiments that require strong electric fields.

II.2.3. High voltage transmission network

High voltage transmission network is an essential part of the electrical supply system, it is responsible for transporting electricity over long distances from power plants to substations before it is distributed to homes, businesses, and industries.

At the start of the electricity supply industry, there was a significant conflict between advocates of alternating current (AC) and direct current (DC) for electricity distribution. Ultimately, AC emerged victorious and has since dominated nearly all domestic, industrial, and commercial electricity supplies.

As electricity supply systems grew in size, AC systems faced several significant challenges. Increasing the voltage (and thereby capacity) and extending the range of undersea cables proved difficult. Additionally, transporting large quantities of electricity from remote hydroelectric projects to load centers became increasingly problematic for AC systems. For very large transmission schemes, high voltage direct current (HVDC) was recognized as more efficient and capable than AC systems. The advantages of DC transmission for such applications were acknowledged as early as the 1920s, but development was hindered by the lack of suitable technology for converting AC to DC and vice versa.

In the late 1920s, the mercury arc rectifier emerged as a potential converter technology, but it wasn't until 1954 that this technology matured enough for commercial use. This breakthrough led to several successful projects. Concurrently, a new technology, the silicon semiconductor thyristor, emerged as a viable option for HVDC system valves. The thyristor valve was first used in HVDC applications in 1970, largely overcoming the limitations of HVDC.

Today, HVDC technology is mature and rapidly advancing in voltage, power capacity, and transmission line length. This progress coincides with growing pressure to improve electricity supply system efficiency due to greenhouse gas concerns. Additionally, the development of large hydroelectric schemes is critical for reducing reliance on fossil fuel power generation, which contributes significantly to global greenhouse gas emissions [11].

II.2.4. Power infrastructure

Two major processes are required to supply the generated electricity to the demand site: transmission and distribution. The transmission and distribution processes of electricity are summarized in (Figure II-1). First, when electricity is generated from various types of power plants, it is delivered at a high voltage of 154–756 kV through transmission lines to the substation. In other words, the electricity ‘transmission’ process involves delivering generated electricity near key demand sites. Then, the substation transforms the voltage of delivered electricity to 22.9 kV for distribution lines, and the voltage of electricity is again transformed to 220 V in pole transformers to be provided to end-use points. This process is called the electricity ‘distribution’ process [12].

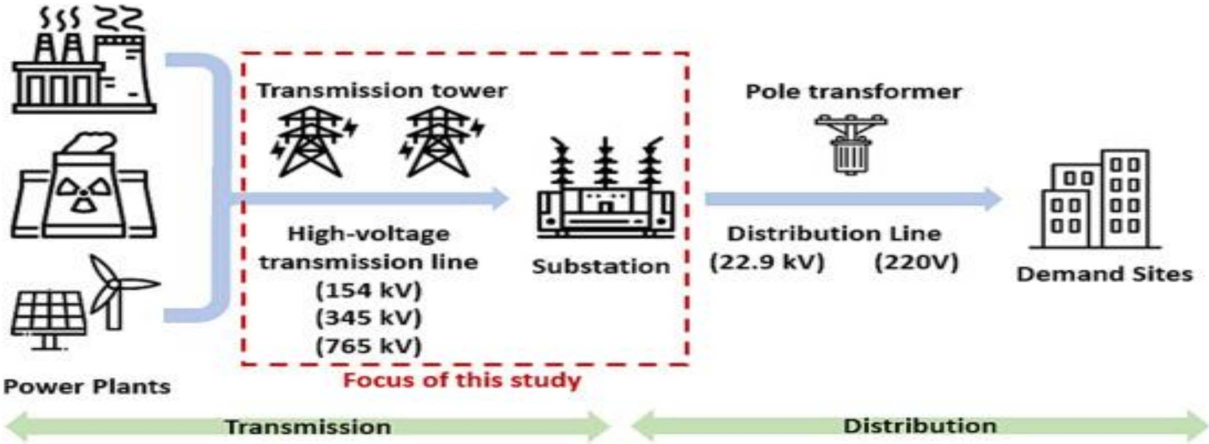


Figure II-1 Process of electricity transmission and distribution

High voltage (HV) equipment refers to a range of specialized electrical equipment designed to operate at voltages above 1,000 volts AC or 1,500 volts DC. This equipment is essential for the safe and reliable transmission and distribution of electrical power in high-voltage power systems.

Some key types of HV equipment include Cables and Conductors, Transformers, Insulators

II.3. Insulators

In overhead transmission systems, insulators are essential for providing insulation between each phase and the grounded crossarm, preventing current leakage to the ground and supporting the line conductors. Therefore, insulators must have high electrical insulation resistance, a high mechanical strength-to-weight ratio, high thermal conductivity, easy moldability, and low maintenance costs [13].

Insulators are primarily classified based on their material composition. Over 90% of insulators used in electricity transmission are made from glass, porcelain, or polymers. Glass and porcelain insulators have been widely utilized worldwide for over a century. However, in the past 20 years, composite insulators have gained significant popularity in the market due to their unique properties. Each material offers specific advantages and disadvantages [14].

II.3.1. Glass Insulators

Glass insulators are produced by heating glass to very high temperatures. To enhance their strength, they also include small amounts of lime and quartz. Despite these additives, there is still a risk of surface leakage current. In polluted environments, dust and other contaminants can significantly reduce their dielectric strength, potentially causing flashover.

Due to the crystalline properties of glass, faults in these insulators can be easily detected as any cracks are visible. They have a very low thermal expansion coefficient, so normal temperature variations do not significantly affect their performance. These insulators offer electrical resistance ranging from 500 to 1000 kV per centimeter. However, the crystalline nature of glass can be a disadvantage if a strong and heavy object impacts the surface, potentially causing the entire insulator to become brittle and fail completely [14].

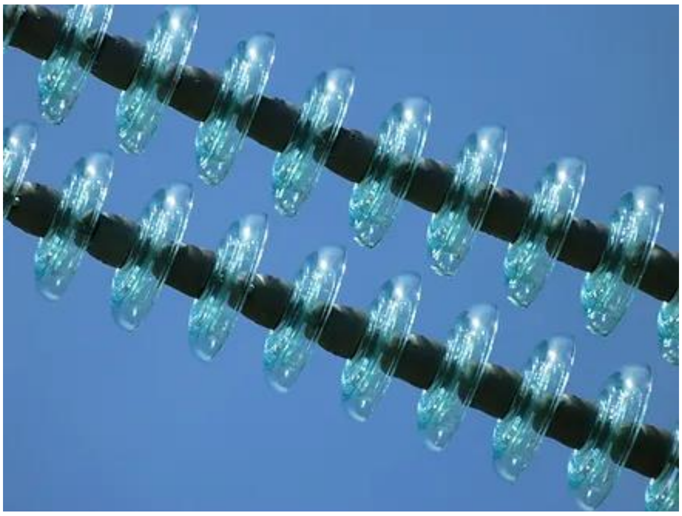


Figure II-2 Glass insulator [14]

II.3.2. Porcelain Insulators

Porcelain insulators are the most commonly used insulators in high voltage lines. They are made from porcelain, produced by heating kaolinite materials or a mixture of clay, quartz, aluminum silicate, and feldspar at very high temperatures. Since porcelain is porous, its surface is glazed with a specialized coating to prevent the accumulation of contaminants such as moisture and dust, which can degrade insulation strength. However, despite this coating, flashovers can still occur in polluted areas. Additionally, porcelain insulators are excellent at repelling water, making them highly effective during thunderstorms and rain, as they help prevent power interruptions due to current leakage. They are ideal for transmission lines with medium voltage levels and offer electrical resistance of about 250+ kV per centimeter. Another important characteristic is that, unlike glass insulators, porcelain insulators can be designed and molded into various shapes to suit different applications and voltage levels of transmission lines [14].

Figure II-3 Porcelain insulator [14]

II.3.3. Polymer/Composite insulators

Polymeric insulators, introduced in the 1960s, emerged as an attractive alternative to ceramic insulators for electric utilities and equipment manufacturers. Due to their chemical formulation, polymeric materials facilitate the creation of complex designs and easier fabrication. Key advantages of polymeric insulators include their lightweight nature, compact line design, and reduced risk of consecutive failures. Additionally, their low surface energy ensures that the surface hydrophobicity remains intact even in wet conditions. The lightweight nature of polymeric insulators positively impacts the economic design of towers, enabling the upgrade of transmission voltage without significant changes to the dimensions of the supporting towers [13].

Figure II-4 composite or polymer insulator [14]

The commonly used polymeric materials for high-voltage outdoor insulators are silicone rubber (SiR), ethylene propylene diene monomer (EPDM), epoxy resins and ethylene vinyl acetate (EVA). These materials are used to manufacture sheds which offer required creepage distance, while the mechanical strength is provided by the fiberglass rod. Some other polymeric materials such as polytetrafluoroethylene (PTFE), polyolefin elastomers (POE) and high-density polyethylene (HDPE) find their applications at a low voltage level both in outdoor and indoor environments [13].

II.4. Cable

II.4.1. Insulated cable

Figure II-5 insulated cable

An insulated cable is an electrical cable whose conductive core is surrounded by a layer of insulating material. Insulation protects conductors from damage and prevents electrical energy from escaping from the cable.

ZMS offers insulated cables made from different materials such as PE, the XLPEs, PVC or caoutchouc. Depending on the application, you can choose cables with different insulation materials.

XlPE insulated cable

Features: XLPE is an insulating material highly resistant to heat and voltage, which keeps drivers in safety even when the electric load is high.

Application : XLPE cables are used in particular in power electrical installations, like high voltage cables and underground cables. They are also commonly used in electrical distribution networks and in electrical buildings of buildings.

II.4.2. High voltage cable

Figure II-6 high voltage cable

A high voltage cable is a type of cable used to carry electricity at high voltages (generally greater than 35 kV) over long distances. The very high voltage cable for a voltage greater than 110KV.

They are usually made from insulating materials such as rubber, polyvinyl chloride or thermoplastic sheath, and can be buried underground or installed on electricity pylons.

High voltage cables are used to transport electricity from power plants to distribution power networks, where they are transferred at lower voltages to power buildings and electrical appliances.

Features : An underground high voltage cable is a type of cable used to transport electricity at high voltages in densely populated areas or where it is desired to minimize the visual impact on the environment. It is buried underground to protect drivers from outside weather conditions and avoid visual disruption.

Application : High voltage cables buried are used to transport electricity over short distances in densely populated areas, such as cities and urban centers, where air cables are not desirable due to their visual impact.

They are also used to connect power plants to distribution networks to supply local buildings and electrical equipment. These cables can also be used to connect remote electrical systems to improve the reliability and safety of the electrical network.

II.5. Partial Discharges

According to the IEC 60270 standard Partial discharge (PD) is defined as "a localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor". Partial discharges are generally a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. They typically appear as pulses having a duration of much less than 1 µs [15].

In general, partial discharges can be categorized into four types based on their discharge phenomena: internal discharges, surface discharges, corona discharges, and electrical treeing [16].

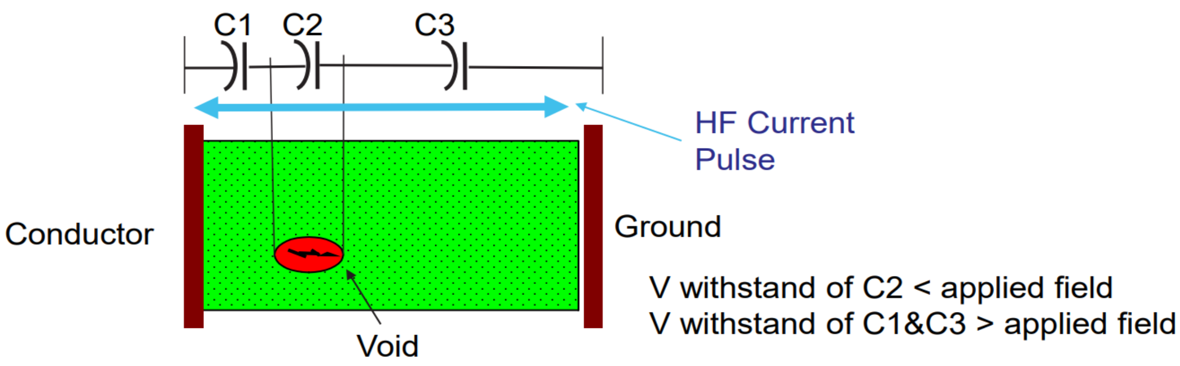


Figure II-7 Scheme of electrical model of defects present inside a dielectric

II.5.1. Causes of partial discharges

The causes of partial discharges are multifaceted and can be categorized into several key factors:

II.5.1.1. Environmental Factors

High humidity and moisture can significantly weaken insulation materials, enhancing conditions favorable for partial discharge (PD) by amplifying localized stressors like water trees, which form within insulation due to electrical stress and moisture. Additionally, extreme temperature fluctuations can cause thermal expansion and contraction in insulation materials, leading to mechanical stresses that may initiate PD. Moreover, contaminants on insulator surfaces can create conductive paths that facilitate surface discharges, especially in outdoor environments where pollution tends to accumulate [17] [18].

II.5.1.2. Mechanical and Structural Factors

The presence of voids (gas pockets) within solid insulation materials, often resulting from manufacturing defects or deterioration over time, is a common cause of partial discharge (PD) as these voids can lead to localized electrical breakdown when subjected to high voltage. Additionally, mechanical damage to cables from external factors, such as improper installation or physical impact, can compromise insulation integrity, increasing the risk of PD. Insulation aging, characterized by chemical and physical changes over time, also reduces dielectric strength, making materials more susceptible to PD, a process further accelerated by thermal, mechanical, and electrical stresses [17] [18].

II.5.1.3. Electrical Factors

High voltage levels can exceed the dielectric strength of insulation, particularly in areas with existing weaknesses, leading to the initiation of partial discharge (PD), which often begins as a minor discharge but can intensify over time. Additionally, electrical surges and transients caused by switching operations, lightning strikes, or other disturbances can temporarily elevate voltage levels, triggering PD activity and potentially causing further degradation of the insulation if not addressed [17] [18].

II.5.2. Effects of partial discharges

Partial discharge (PD) initiates a cycle of damage within insulation materials, where the localized energy from PD events causes thermal, electrical, and chemical degradation, leading to a reduction in dielectric strength. Over time, this degradation can result in the formation of conductive channels, known as "treeing," which further compromises insulation integrity. Additionally, the high-energy particles generated during PD can cause oxidative degradation, altering the molecular structure of the insulation material and reducing its mechanical integrity and dielectric strength. This chemical breakdown may also increase the electrical conductivity of the surrounding material, further accelerating the degradation process [3].

Continuous partial discharge (PD) activity progressively weakens insulation, increasing the risk of complete electrical breakdown, which can result in catastrophic failures such as outages, equipment damage, and, in severe cases, electrical fires or explosions. PD-induced insulation failure often leads to unplanned outages, disrupting operations and causing significant economic losses. In fact, it is estimated that over 80% of substation failures are linked to PD activity [19].

As insulation degrades, the efficiency of electrical systems diminishes, leading to increased power losses due to higher leakage currents and resistive heating along damaged insulation, which can further exacerbate thermal degradation. Additionally, PD can necessitate more frequent maintenance and inspections, raising operational costs [3] [19].

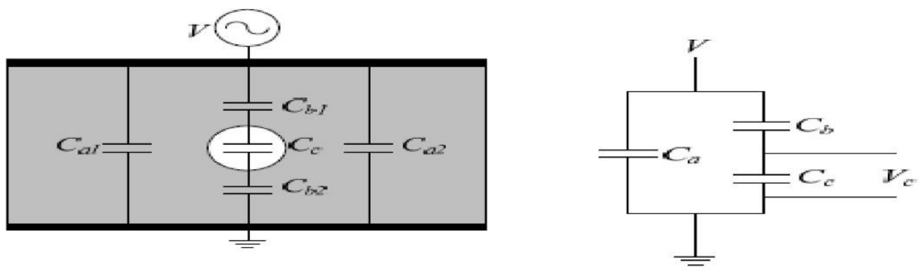
II.5.3. Strategies for Preventing Partial Discharges

To prevent partial discharges, it is crucial to start with proper design and material selection. High-quality insulation materials with excellent electrical and mechanical properties should be used, and designs must avoid sharp edges, voids, or air gaps that could create conditions conducive to PD. Additionally, rigorous quality control during manufacturing and comprehensive testing of components before deployment can help identify and rectify potential issues early on.

Ongoing maintenance and monitoring are vital to preventing partial discharges throughout the equipment's lifespan. Regular monitoring using techniques like acoustic emission, ultrasonic detection, or electrical PD detection helps in early detection of PD. Environmental control, such as maintaining low humidity and cleaning surfaces to remove contaminants, also plays a significant role in reducing the risk of PD. Proper installation practices and regular inspections further contribute to minimizing the likelihood of partial discharges, ensuring the longevity and safety of high-voltage systems [20].

II.5.4. Electrical model of partial discharges

The capacitance model, often referred to as Whitehead's three-capacitance circuit model or the a-b-c model, was introduced by Whitehead to represent the behavior of cavities within insulation materials.



(a) (b)

Figure II-8 The equivalent circuit model with three capacitors (a) Full model, (b) Simplified model

C_{a1} and C_{a2} in Figure II-6(a) represent the capacitance of the remaining insulator parallel to C_{b1} and C_{b2}. Whereas C_{b1} and C_{b2} replicate the insulator capacitance that is in series with the cavity, C_c in both Figure II-6(a) and (b) is the capacitance's cavity and V is the voltage applied to the circuit. Figure II-6(b) demonstrates the simplified model of three capacitance equivalent circuit. C_a is the correspondent capacitance in parallel of capacitances C_{a1} and C_{a2} while C_b is the correspondent capacitance in series of capacitances C_{b1} and C_{b2} and V_c is the potential crosses the cavity.

Before an existence of PD, voltage across cavity (V_c) is equal to

$$V_c = \frac{C_b}{C_b + C_c} V \tag{I.1}$$

Figure I-6(b) illustrates that, during PD, the magnitudes of the apparent charges (q_{app}) and real charges (q_{real}) are calculated using equation (I.2) and equation (I.3) individually.

$$q_{app} = C_b \Delta V \tag{I.2}$$

$$q_{real} = \left(C_c + \frac{C_a C_b}{C_a + C_b}\right) \Delta V \tag{I.3}$$

Where ΔV denotes the voltage depletion across the cavity due to discharge. The simplicity and typicality of this model is used to represent the transient happening during an occurrence of discharge, suchlike the apparent charge magnitude and PD current. Nevertheless, the limitation of this model is the surface of the cavity, which is constantly employed as an equipotential surface, which is not often practical for real life application especially with the accumulation of surface charge along the cavity wall being ignored.

Overall, this model is suitable for explaining the occurrence of PDs for academic means as well as a deterministic model. For the a-b-c model to be transformed into a contingent model, the model must be linked with an analytical approach [21].

II.5.5. Measurement Units Partial discharges

PD are measured using various units that reflect the nature of the electrical phenomena involved. The most common measurement units for partial discharges include:

- **Picocoulombs (pC)**: This is the most widely used unit for measuring the magnitude of partial discharges. One picocoulomb is equal to 10^{-12} coulombs, and it represents the charge associated with the discharge event. This unit is preferred because it allows for the detection of very small discharge events that can indicate insulation degradation.

- **Millivolts (mV)**: PD activity can also be measured in millivolts, particularly when assessing the voltage signals generated by the discharges. This measurement is often used in conjunction with specific testing setups that capture the electrical signals produced during PD events.
- **Radio Interference Voltage (RIV)**: This unit, typically measured in microvolts (μV), is used to quantify the radio frequency emissions generated by partial discharges. RIV measurements are particularly relevant in the context of transformers and surge arrestors.
- **Decibels (dB)**: While not a direct measure of charge or voltage, dB is used to express the power ratio of PD signals relative to a reference level. For example, dBmW refers to decibels relative to 1 milliwatt, allowing for a logarithmic representation of PD signal strength [22].

II.5.6. Test circuits

IEC 60270 – High-voltage test techniques – Partial discharge measurements is a general standard that defines the broad lines of PD measurement in electrical apparatus. It is applicable for electrical measurements of PD using alternating voltages up to 400 Hz and direct voltage. The standard defines several parameters such as the test circuit, measured quantities, calibration requirements and guidance on test procedures.

II.5.6.1. Test circuit for alternating voltages

Several test circuits can be used for PD measurements according to IEC 60270. The standard provides five examples of accepted test circuits. However, they can all be summarized into one schematic which is illustrated in Figure II-7.

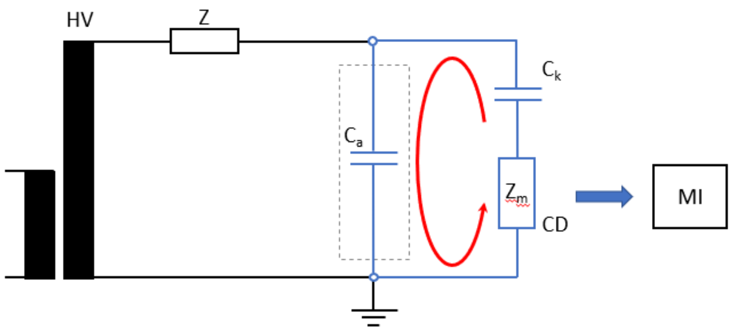


Figure II-9 PD measurement circuit according to IEC60270

where,

HV high-voltage supply

Z high-voltage filter (optional)

C_a test object

C_k coupling capacitor

Z_m measuring impedance

CD coupling device

MI PD measuring instrument

In theory, an optimal sensitivity is achieved when $C_k >> C_a$. However, this condition is not convenient for most applications. This is mainly due to the additional load that would need to be supplied by the high-voltage source. IEC 60270 thus recommend using a value of C_k of 1nF or higher.

Every component in the test circuit must exhibit a sufficiently low level of background noise. This background noise is referred to as signals detected during the PD measurement, which do not originate from the test object. In some cases, a high-voltage (HV) filter can help to attenuate unwanted signals circulating from the HV supply. In addition, the filter also prevents PD pulses from circulating through the HV transformer and thus increases the sensitivity of the test circuit.

Some variations of the test circuit of Figure II-7 can also be used. For example, the test object and the coupling capacitor can be exchanged so that the measuring impedance is series connected with the test object. Another accepted test circuit is the use of a bushing capacitance C_1 to replace the coupling capacitor. The coupling device is therefore connected to the bushing tap.

The coupling device is usually a four-terminal network that is often referred to as quadrupole. It converts to PD current pulse into an output voltage. Additionally, it often includes fast overvoltage protection and some filtering features that separate the test voltage to allow for synchronization [15].

II.5.6.2. Test circuit for direct voltage

The test circuit used during tests using direct voltage is very similar to the test circuit used for alternating voltage (Figure II-7). However, the coupling capacitor cannot be used to obtain the voltage information. If a voltage reference is needed, an additional DC voltage divider is required.

The measured quantities and evaluation criteria are also different than the ones used under alternating voltage. There is no polarity reversal in the voltage waveform. Thus, the discharge pulse repetition rate will be highly dependent on the insulation relaxation characteristics [15].

II.6. Conclusion

The performance and longevity of high voltage equipment critically depend on the integrity of its insulation systems. This chapter has shown that partial discharges, often caused by voids, contamination, or gas bubbles, are early indicators of insulation deterioration. Although each discharge may seem minor, their cumulative effect can significantly damage the insulation, eventually leading to complete failure. Understanding the mechanisms, causes, and effects of partial discharge is therefore essential. Effective detection and monitoring not only help prevent unexpected equipment breakdowns but also support proactive maintenance strategies that enhance the reliability and safety of high voltage systems.

Chapter III

Methodology

III.1. Introduction

This chapter presents the methodology used to simulate partial discharge (PD) activity within high-voltage cables insulated with cross-linked polyethylene (XLPE). The focus is on developing an equivalent electrical model that replicates the behavior of voids within the insulation, using electrical elements such as capacitors and resistors to represent the physical structure. Particular attention is given to the position of the void relative to the conductor. MATLAB Simulink was utilized as the simulation platform to build and execute the model, replicating realistic operating conditions of a high-voltage cable under PD stress. The methodology also includes detailed calculations of electrical parameters such as capacitance and resistance, based on the physical and geometric characteristics of the insulation and void. This chapter provides an in-depth explanation of the modeling approach and serves as the foundation for analyzing and interpreting the results in subsequent chapters.

III.2. Modeling Of Partial Discharge in Voids

One of the most effective and suitable approaches to study and comprehend the nature, activities, impact, and influence of partial discharges (PD) on insulating materials is through the development of accurate and precise models. For PD analysis and interpretation, researchers like Brunt (1991) and Neimeyer (1995) have developed physical models. The simplest electrical representation of defects within insulation, known as the classical capacitance model, was introduced by Gemant and Philippoff in 1932 shown in (Figure III-1) [23]. However, to date, limited progress has been made in establishing a generalized and theoretical framework to describe the stochastic nature of PD phenomena. Computer simulation programs and models for PD remain scarce in research, and integrated models, such as the one explored in this study, have not been fully realized by previous researchers due to the complexity of the PD process. Heitz (1999) pointed out that there is often a significant disconnect between highly sophisticated measurement tools and the considerable challenges in interpreting the resulting PD data. Recent advancements were made by Hoof and Patsch (1998), who developed a model applicable to various defect types. However, Wu (2004) later criticized this model, arguing that conventional approaches like these assume purely deterministic

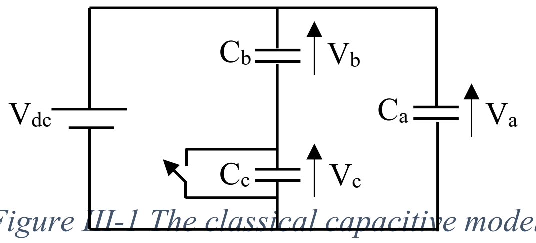


Figure III-1 The classical capacitive model discharge behaviors and are inadequate for scenarios where the inherent stochastic nature of PD generation is significant [24].

The model used in the study shown in (Figure III-2) is also a modification of the capacitive model, the model used takes remnant charges into account, these are the charges believed to be dissipated due to former PD activities in the void as suggested by Y. Z. Arief et al in [25].

This model is presented in (Figure III-2). The void and the insulations are represented by capacitors and resistors. The value of these capacitors and resistors were later determined through calculations.

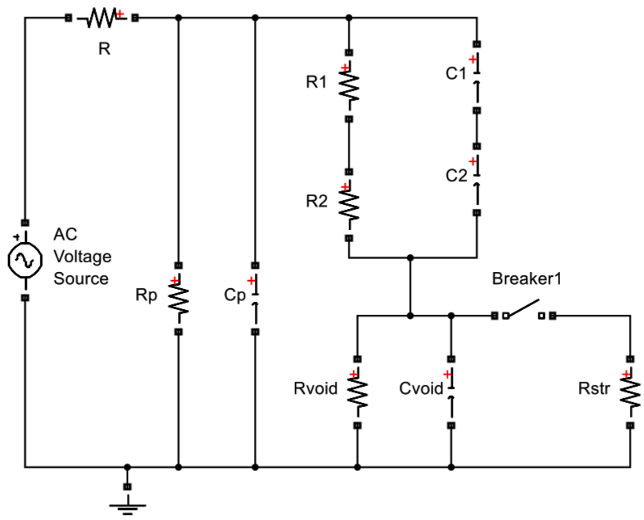


Figure III-2 The void model

Where Cp represent the insulation of the cable at other point apart from where the void is located, Rp is that insulation related resistance, C1 and C2 are the insulations around void, they are in series with the void while R1 and R2 are their corresponding resistances, C_{void} is the capacitance associated with the void while R_{void} is the associated void resistance and R_{str} signifies the void discharge.

III.3. Construction of XLPE cable

The construction of the XLPE cable is illustrated in Figure III-3. In this study, a copper conductor is considered, which is encased by a semiconductor screen. Surrounding this screen is the XLPE insulation, followed by a layer of semiconductor tape and a final outer sheath. The outer sheath is typically composed of polyethylene or PVC plastic.

Since XLPE cables do not require oil, they are environmentally friendly and demand less maintenance. Additionally, their single-core design enhances flexibility, making them easier to install.

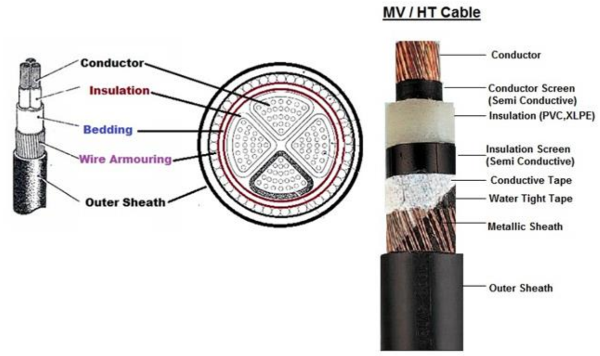


Figure III-3 XLPE cable construction.

The cross sectional 2D diagram of XLPE cable construction including void is shown in (Figure III-4). The parameters like radius and distances are represented in the diagram.

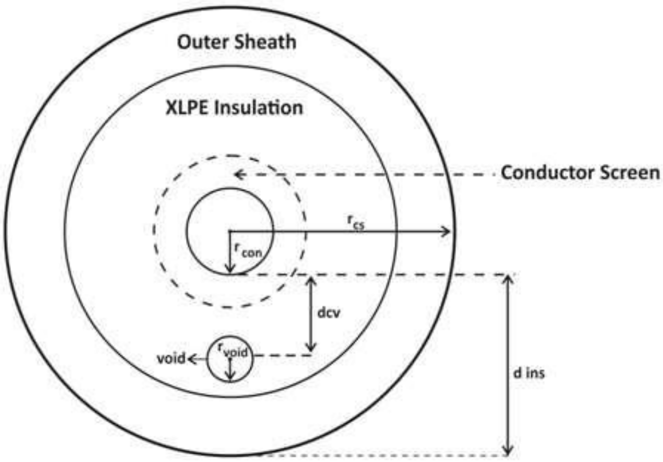


Figure III-4 cross sectional 2D diagram of XLPE cable with void.

r_{con} - Radius of the conductor or core

r_{void} - Radius of the void

r_{cs} - Radius of Cable

d_{ins} - Distance between conductor and outer sheath

d_{cv} - Distance between conductor and center of void

The void is assumed to be located within the insulation layer of the cable, and parameters were computed for various potential positions of the void. The positions considered are:

1. Near the conductor but distant from the outer sheath.
2. Between the conductor and the outer sheath.
3. Near the outer sheath but distant from the conductor.

Initially, the parameters related to the void's location are determined using data from the XLPE cable datasheet. The electrical properties are then calculated in accordance with the method proposed in [26] ensuring accurate implementation of the void partial discharge (PD) simulation in MATLAB.

Following the analysis of the void parameters, the electrical characteristics of both the void and the insulation—such as capacitances and resistances—are evaluated using the approaches described in [25] [24] and [27]. The calculations are conducted for the different void positions within the insulation using the following equations gotten from carefully examining the cross-sectional area of a XLPE cable.

III.4. Parameter Calculation

The parameters like radius and distances are represented in the diagram. The parameters of 110 kV XLPE cable are referred to from Estralin [28].

The specification data for 110kV XLPE insulator is given by.

r_{con} - 9 mm Radius of the conductor or core

r_{void} - 1 mm Radius of the void

r_{cs} - 32 mm Radius of Cable

dins - 23 mm Distance between conductor and outer sheath

$\varepsilon 0$ - 8.854 e-12 F/M

εr - 4

σins - 7e-17 mho/m

As per the Gauss's law (Nayfeh and Brussel, 1985) the potential difference between shells of any two concentric cylinders with radius R and r is given by.

$$V_{R-r} = \frac{q}{2\pi\varepsilon 0\varepsilon r}\ln\left({}^{R}/_{r}\right) \quad \text{(III.1)}$$

Where q is the charge of conductor in coulombs per meter length. The value of capacitance between the concentric cylinders of insulator can be derived as

$$C_{R-r} = \frac{2\pi\varepsilon 0\varepsilon r}{\ln\left({}^{R}/_{r}\right)} \quad \text{(III.2)}$$

From the above equation the capacitance value of the regions C_{s1} (from core outer surface to void) and C_{s2} (from void to outer sheath) can be derived as

$$C_{s1} = \frac{\varepsilon 0\varepsilon r\ lv\ tv}{\ln\left(\frac{r_{con} + d_{cv} - \frac{r_{void}}{2}}{r_{con}}\right)(r_{con} + d_{cv})} \quad \text{(III.4)}$$

$$C_{s2} = \frac{\varepsilon 0\varepsilon r\ lv\ tv}{\ln\left(\frac{r_{con} + d_{ins}}{r_{con} + d_{cv} + \frac{r_{void}}{2}}\right)(r_{con} + d_{cv})} \quad \text{(III.4)}$$

Thus, capacitance in series with the void can be found from equation.

$$C_{seri} = \frac{C_{s1}C_{s2}}{C_{s1} + C_{s2}} \quad \text{(III.5)}$$

Neglecting tv with respect to the length of the cable L (consider it as 1 m) the parallel capacitance C_{parl} is given by the following equation.

$$C_{parl} = \frac{2\pi\varepsilon 0\varepsilon r\ L}{\ln\frac{r_{con} + d_{ins}}{r_{con}}} \quad \text{(III.6)}$$

The void capacitance can be found by substituting relative permittivity as 1, since it is filled with air the $\varepsilon r = 1$. Cvoid is given by.

$$C_{void} = \frac{\varepsilon 0\ lv\ tv}{\ln\left(\frac{r_{con} + d_{cv} + \frac{r_{void}}{2}}{r_{con} + d_{cv} - \frac{r_{void}}{2}}\right)(r_{con} + d_{cv})} \quad \text{(III.7)}$$

Similarly, the insulation resistance values of void, series and parallel are given by the relation between insulation conductivity and insulation region. Like capacitance, resistances in two regions Rs1 and Rs2 are.

$$R_{s1} = \frac{1}{\sigma ins}\frac{r_{con} + d_{cv}}{l_c t_c}\ln\left(\frac{r_{con} + d_{cv} - \frac{r_{void}}{2}}{r_{con}}\right) \quad \text{(III.8)}$$

$$R_{s2} = \frac{1}{\sigma ins}\frac{r_{con}+d_{cv}}{l_c t_c}\ln\left(\frac{r_{con}+d_{ins}}{r_{con}+d_{cv}+\frac{r_{void}}{2}}\right) \quad \text{(III.9)}$$

$$R_{seri} = R_{s1} + R_{s2} \quad \text{(III.10)}$$

Similar to capacitance value, the parallel and void resistances are given by.

$$R_{parl} = \frac{1}{2\pi\sigma ins}\ln\left(\frac{r_{con}+d_{ins}}{r_{con}}\right) \quad \text{(III.11)}$$

$$R_{void} = \frac{1}{\sigma ins}\frac{r_{con}+d_{cv}}{l_c t_c}\ln\left(\frac{r_{con}+d_{cv}+\frac{r_{void}}{2}}{r_{con}+d_{cv}-\frac{r_{void}}{2}}\right) \quad \text{(III.12)}$$

As proposed by Stratton in [29], **Kr** is a dimensionless correction factor that accounts for the amplification of the electric field within an ellipsoidal void relative to that in the surrounding insulating material. The presence of a void disrupts the uniformity of the electric field, introducing irregularities that must be considered during analysis. This correction factor is therefore essential for adjusting the calculated results to accurately reflect the effect of the void on the local electric field distribution.

$Kr = \frac{2\varepsilon r}{1+2\varepsilon r}$ then

Corrected C_{void} = C_{void} . εr / Kr

Corrected C_{seri} = C_{seri} . Kr

Corrected R_{seri} = R_{seri} / Kr

The capacitance and resistance values are calculated for various void distances and sizes are tabulated in Table 2 and Table 3.

Table 2 Parameter values for different void distances

Calculated C and R values	Void Distance from Core (dcv)		
	d_{cv} = 0.25 X dins	d_{cv} = 0.5 X dins	d_{cv} = 0.8 X dins
R_{void} (Ω)	1.429 X 10^{16}	1.428 X 10^{16}	1.428 X 10^{16}
R_{seri} (Ω)	1.9 X 10^{17}	2.67 X 10^{17}	3.621 X 10^{17}
R_{paral} (Ω)	2.88 X 10^{15}	2.88 X 10^{15}	2.88 X 10^{15}
C_{void} (F)	2.66 X 10^{-13}	2.65 X 10^{-13}	2.65 X 10^{-13}

C_{seri} (F)	2.6467 X 10^{-12}	1.8834 X 10^{-12}	1.13 X 10^{-12}
C_{paral} (F)	1.754 X 10^{-10}	1.754 X 10^{-10}	1.754 X 10^{-10}

Table 3 Parameter values for different void sizes

Calculated C and R values	Void sizes		
	6mm	4mm	2mm
R_{void} (Ω)	1.329 X 10^{16}	4.428 X 10^{16}	6.828 X 10^{16}
R_{seri} (Ω)	1.7 X 10^{17}	1.7 X 10^{17}	1.7 X 10^{17}
R_{paral} (Ω)	2.55 X 10^{15}	2.55 X 10^{15}	2.55 X 10^{15}
C_{void} (F)	4.66 X 10^{-13}	3.65 X 10^{-13}	1.12 X 10^{-13}
C_{seri} (F)	2.5367 X 10^{-12}	2.5367 X 10^{-12}	2.5347 X 10^{-12}
C_{paral} (F)	1.854 X 10^{-10}	1.854 X 10^{-10}	1.854 X 10^{-10}

III.5. Simulink Model

The simulation model, illustrated in Figure 3.4, is a modified version of the conventional capacitive model. In this configuration, C_{scor} represents the capacitance of the insulation surrounding the void and is connected in series with the void. This component is adjusted using the correction factor Kr. The corresponding resistance of the surrounding insulation is denoted as R_{scor}. The void itself is characterized by its own capacitance, C_{void}, and resistance, R_{void}.

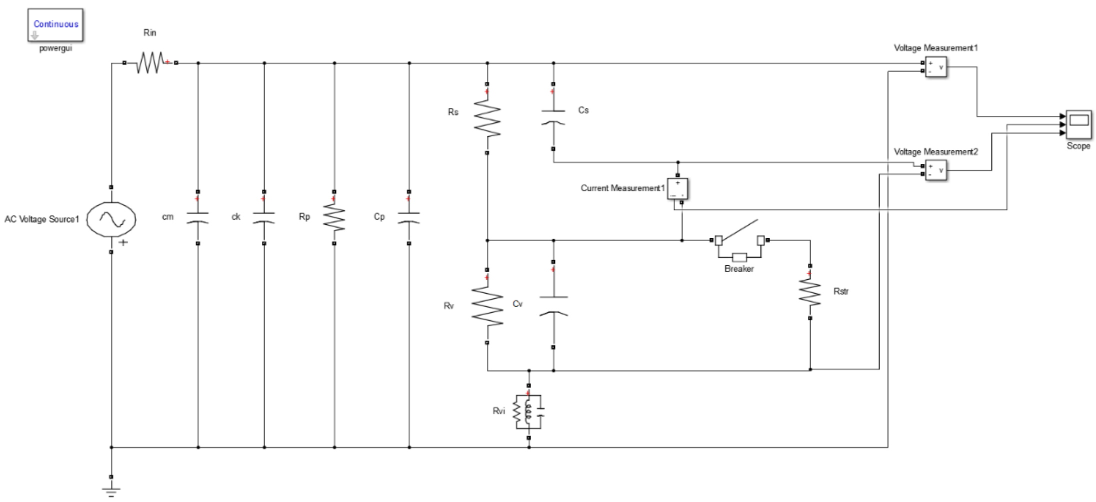


Figure III-5 Model configuration in MATLAB Simulink

The breaker is switched once to initiate the discharge at an applied voltage of 110 kV with a frequency of 50 Hz. The resulting partial discharge (PD) current, PD voltage, and the applied voltage waveform are then observed using an oscilloscope. The model, shown in Figure III-5, was developed in MATLAB Simulink.

To closely replicate a real-life experimental setup and ensure accurate simulation of the discharge behavior, the model includes a coupling capacitor ($\mathbf{C_k}$), a high voltage measuring capacitor ($\mathbf{C_m}$), and a detector device ($\mathbf{R_{vi}}$) modeled as an RLC parallel circuit. These components are essential for a standard PD testing setup.

The values used in the simulation are:

- **Cm** = 100 pF
- **Ck** = 1000 µF
- $\mathbf{R_{vi}}$ **(RLC Branch):**
    - Resistance (**R**) = 50 Ω
    - Inductance (**L**) = 0.63 mH
    - Capacitance (**C**) = 0.47 µF

The oscilloscope displays the waveforms of the applied voltage, PD voltage, and PD current to enable effective analysis and comparison.

III.6. Results and Discussion

III.6.1. Introduction

This chapter presents the simulation results related to the partial discharge phenomenon in a high-voltage XLPE cable, along with an analysis of the influence of both the void location and its size on the resulting discharge current. The obtained results are discussed and compared with theoretical expectations and previous studies to extract the engineering implications associated with insulation performance and reliability.

III.6.2. Results for different void distances

The simulation was run for 0.07 sec, with an applied voltage of 110 kV, frequency of 50Hz while ode23tb (stiff/TR-BDF2) solver with a variable step-size and non-adaptive algorithm configuration in MATLAB Simulink.

The resulting simulations for the different void locations are shown below. The locations considered are 5.75 mm (0.25Xdins), 11.5 mm (0.5Xdins) and 18.4 mm 0.8Xdins) distances from the conductor.

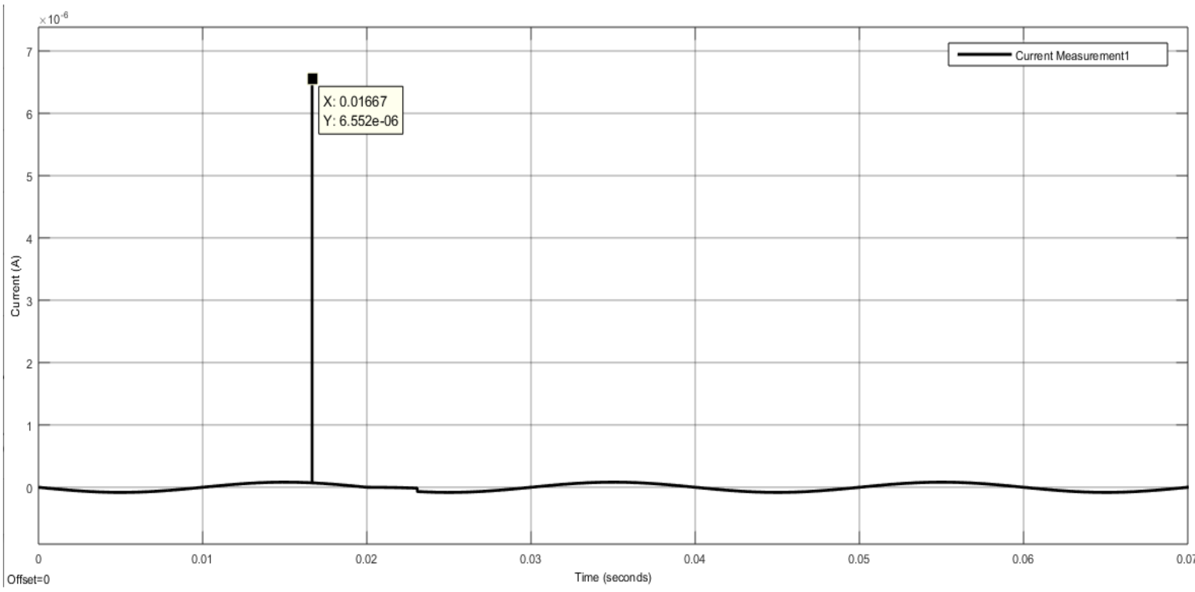


Figure III-6 PD Current result for 5.75mm void distance location

Figure III-6 illustrates a partial discharge pulse with a peak of approximately 6.55 µA at 0.0167 s, in the case where the gap is located 5.75 mm from the conductor, followed by a gradual decay due to energy dissipation within the dielectric.

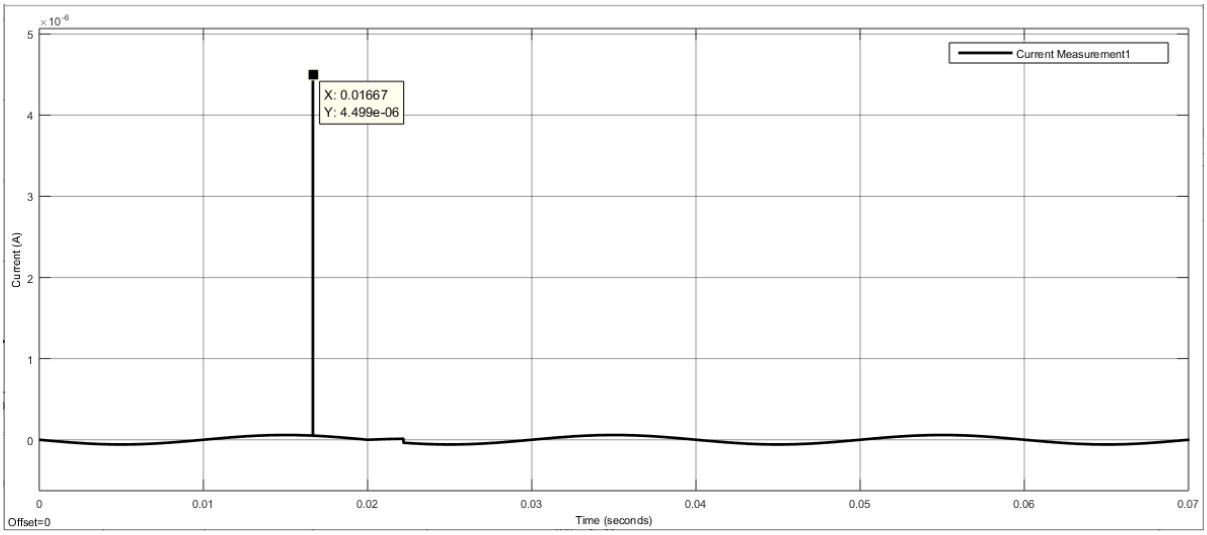


Figure III-7 PD Current result for 11.5mm void distance location

The results showed a decrease in the current value to about 4.49 µA at a gap position of 11.5 mm, indicating a weaker field in this region compared to the first case.

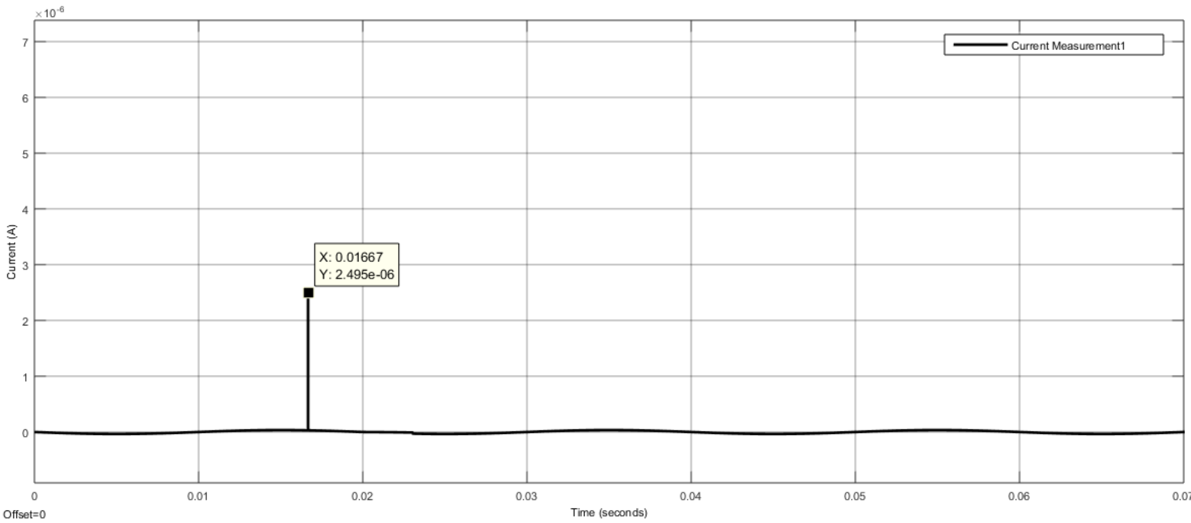


Figure III-8 PD Current result for 18.4mm void distance location

As shown in the figure, a clear reduction in the discharge pulse to 2.49 µA at 18.4 mm is observed, highlighting the weakening of the electric field as the gap distance from the conductor increases.

Table 3 PD current of each void distances from the conductor

PD Current (A)	Void distance from conductor (mm)
$6.552x10^{-6}$	5.75
$4.499x10^{-6}$	11.5
$2.495x10^{-6}$	18.4

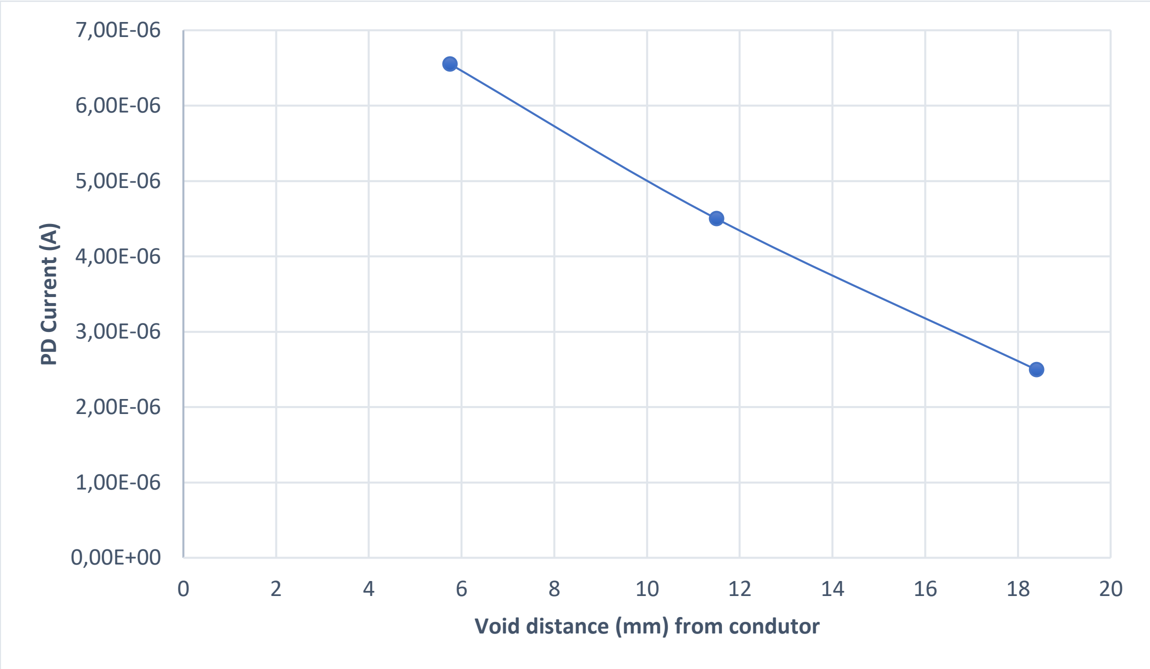


Figure III-9 Plot of PD Current with respect to void distance from conductor

The simulation carried out on the insulation of an XLPE cable confirmed that partial discharge (PD) activity under void conditions can be effectively analyzed using an equivalent PD model. The model was tested with void positions located at 25%, 50%, and 80% of the total insulation thickness (d_{ins}). As illustrated in Figure III-9, the simulation results for each void location differ significantly, aligning well with the anticipated behavior.

To isolate the effect of void position, the same applied voltage was maintained across all three cases. When the void was positioned 5.75 mm from the conductor (25% d_{ins}), the PD current amplitude reached 6.552×10^{-6} A. At a distance of 11.5 mm (50% d_{ins}), the amplitude decreased to 4.499×10^{-6} A, and further dropped to 2.495×10^{-6} A when the void was 18.4 mm away (80% d_{ins}).

These results clearly indicate that PD current amplitude decreases as the void moves farther from the conductor. Therefore, it can be concluded that PD behavior is inversely related to the distance of the void from the conductor, the closer the void is to the conductor, the higher the resulting PD amplitude.

III.6.3. Results for different void sizes(5.75mm)

The simulation was run for 0.07 sec, with an applied voltage of 110 kV, frequency of 50Hz while ode23tb (stiff/TR-BDF2) solver with a variable step-size and non-adaptive algorithm configuration in MATLAB Simulink.

The resulting simulations for the different void sizes are shown below. The sizes considered are 6 mm , 4 mm and 2mm .

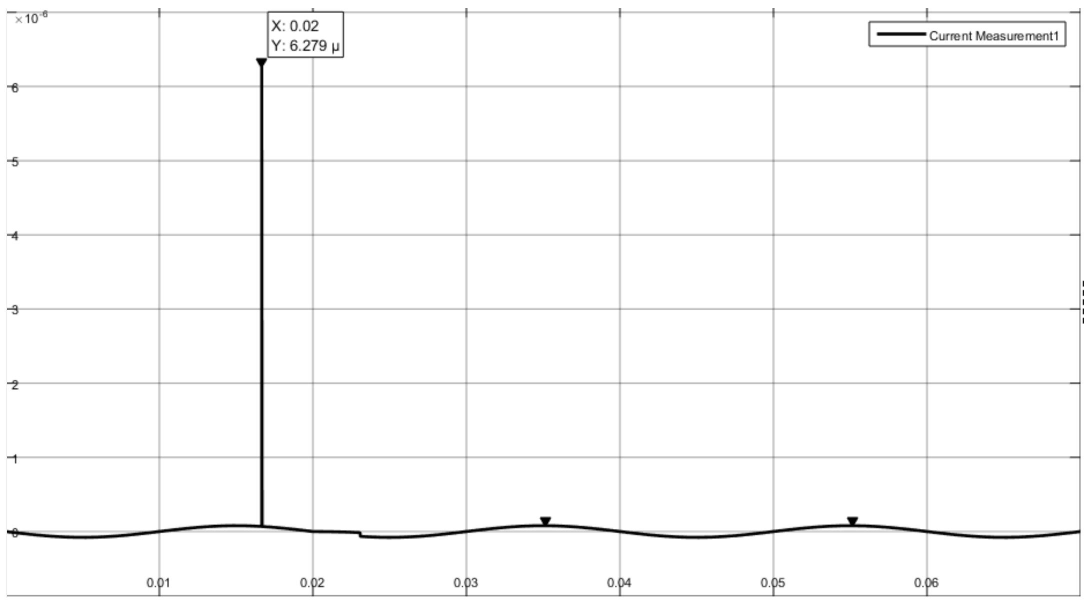


Figure III-10 PD Current result for 6 mm void sizes

Figure III-10 represents the partial discharge current when adopting an air gap of 6 mm inside the insulator. The curve shows the appearance of a strong discharge pulse with a peak of approximately 6.279 µA at a time around 0.02 seconds, which is the highest value among the set of gap sizes. This reflects the ability of the larger gap to store a greater amount of charges before breakdown, resulting in a discharge with higher energy when it occurs.

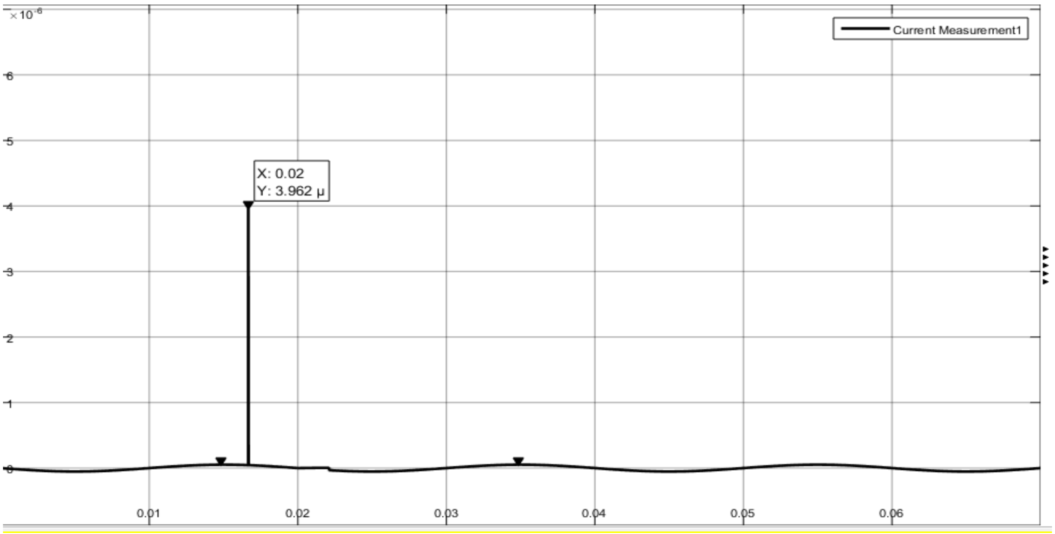


Figure III-11 PD Current result for 4 mm void sizes

Figure III-11 illustrates the discharge behavior at a gap size of 4 mm. From the graph, the maximum current reaches about 3.962 µA at a time close to 0.02 seconds, which is noticeably lower compared to the 6 mm gap size. This reduction is attributed to the smaller gap limiting the available space for charge accumulation, thereby producing a discharge with lower energy.

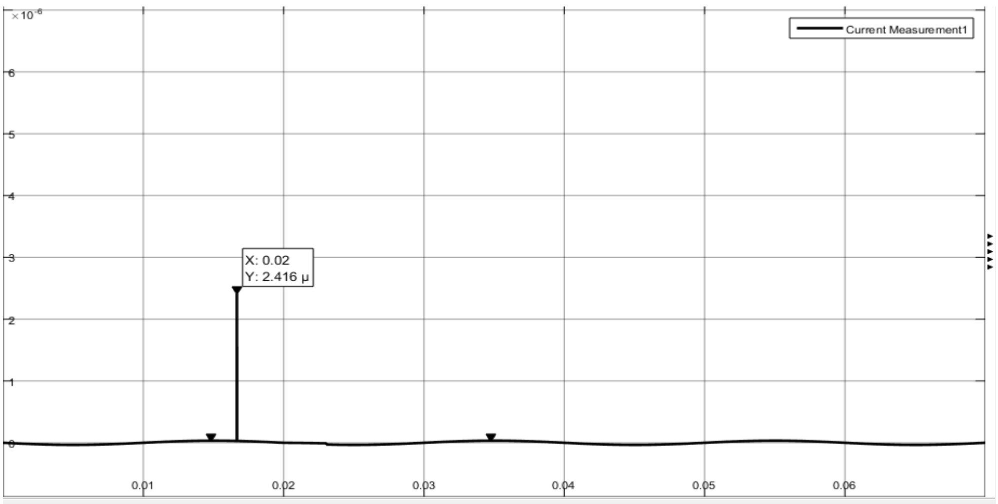


Figure III-12 PD Current result for 2 mm void sizes

Figure III-12 represents the case of a small gap with a size of 2 mm. The discharge peak reached approximately 2.416 µA at around 0.02 seconds, which is the smallest value among the three cases. As the gap size decreases, the number of electrons stored inside the gap is reduced, resulting in a relatively weaker discharge compared to the previous two cases.

Table 4 PD current of each void sizes

PD Current (A)	Void sizes (mm)
$6.279x10^{-6}$	6
$3.962x10^{-6}$	4
$2.416x10^{-6}$	2

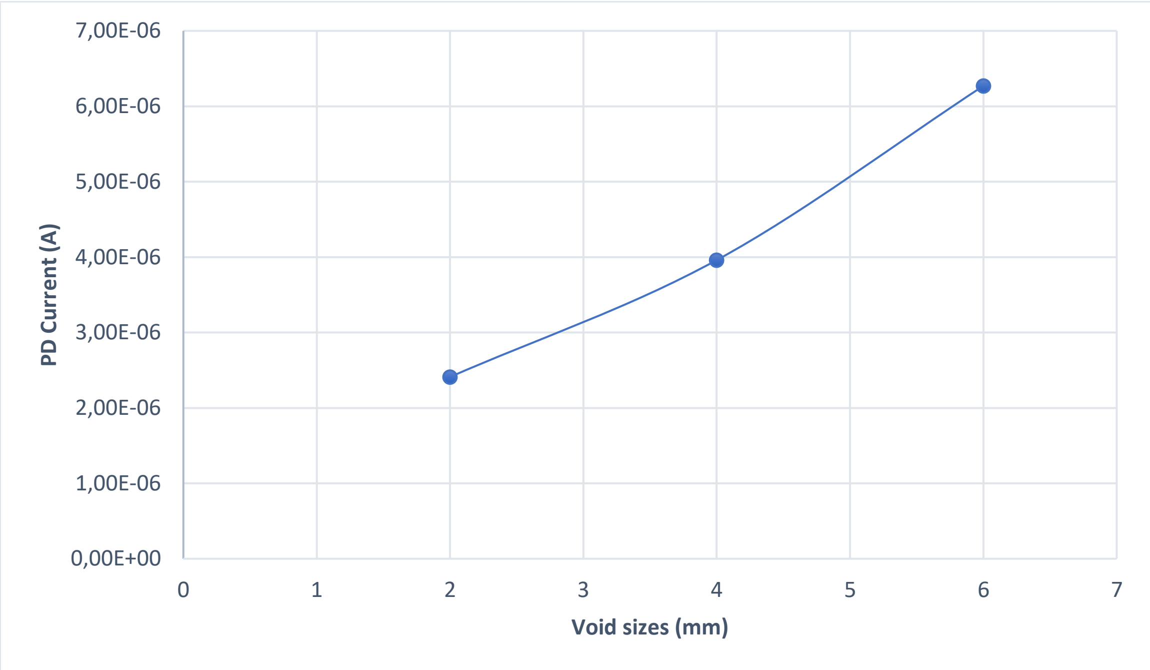


Figure III-13 Plot of PD Current with respect to void sizes

III.6.3.1. Results for different void (11.5mm)

The simulation was run for 0.07 sec, with an applied voltage of 110 kV, frequency of 50Hz while ode23tb (stiff/TR-BDF2) solver with a variable step-size and non-adaptive algorithm configuration in MATLAB Simulink.

The resulting simulations for the different void sizes are shown below. The sizes considered are 6 mm , 4 mm and 2mm .

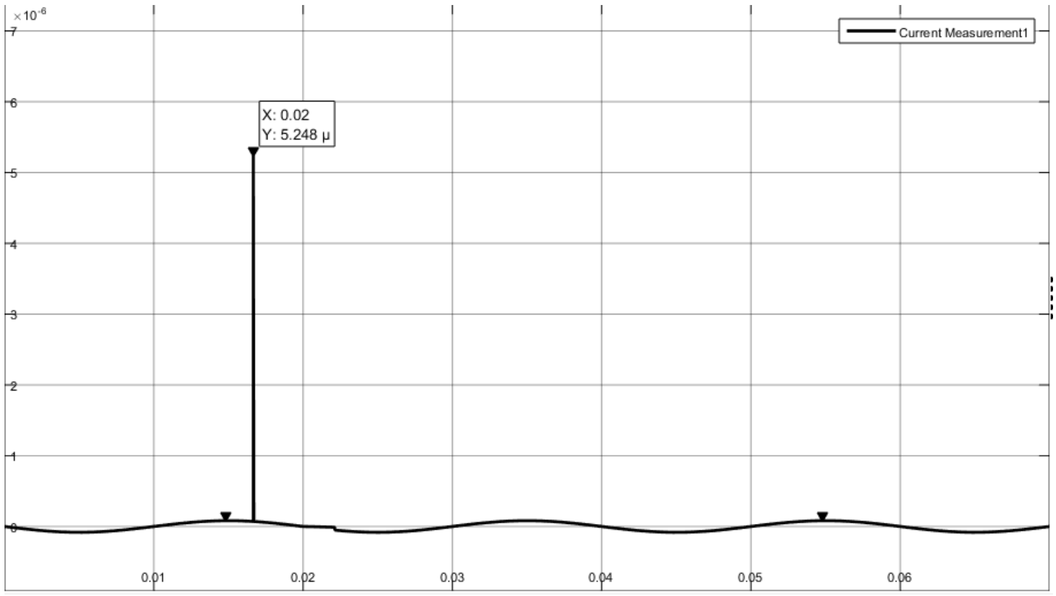


Figure III-10 PD Current result for 6 mm void sizes

Figure III-10 represents the partial discharge current when adopting an air gap of 6 mm inside the insulator. The curve shows the appearance of a strong discharge pulse with a peak of approximately 5.248 µA at a time around 0.02 seconds, which is the highest value among the set of gap sizes. This reflects the ability of the larger gap to store a greater amount of charges before breakdown, resulting in a discharge with higher energy when it occurs.

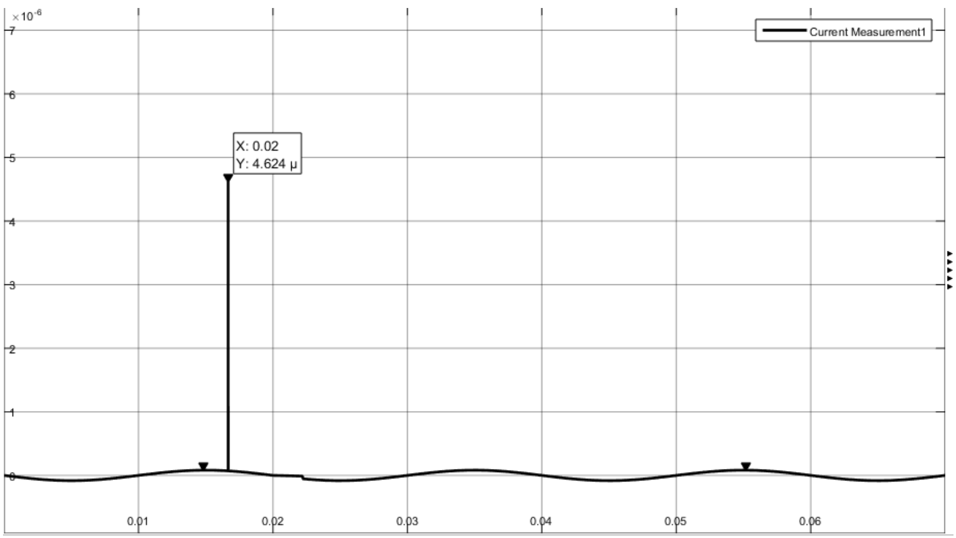


Figure III-11 PD Current result for 4 mm void sizes

Figure III-11 illustrates the discharge behavior at a gap size of 4 mm. From the graph, the maximum current reaches about 4.624 µA at a time close to 0.02 seconds, which is noticeably lower compared to the 6 mm gap size. This reduction is attributed to the smaller gap limiting the available space for charge accumulation, thereby producing a discharge with lower energy.

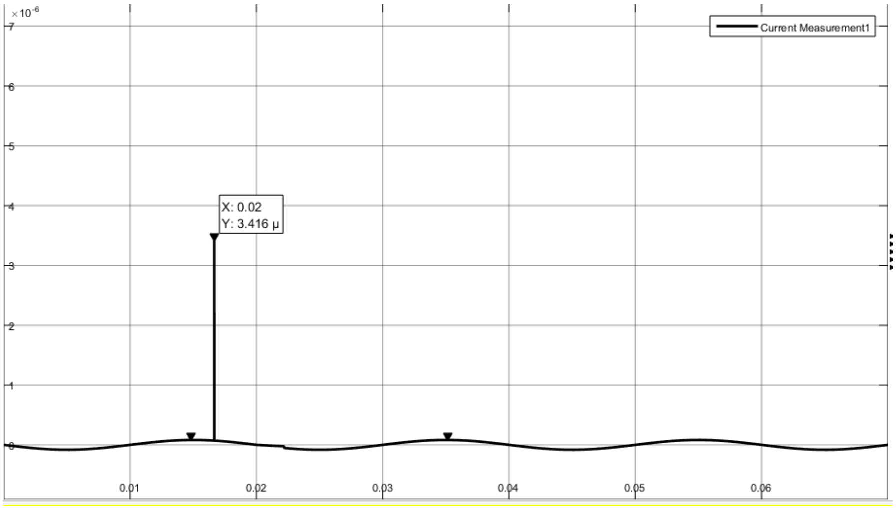


Figure III-12 PD Current result for 2 mm void sizes

Figure III-12 represents the case of a small gap with a size of 2 mm. The discharge peak reached approximately 3.416 μA at around 0.02 seconds, which is the smallest value among the three cases. As the gap size decreases, the number of electrons stored inside the gap is reduced, resulting in a relatively weaker discharge compared to the previous two cases.

Table 5 PD current of each void sizes

PD Current (A)	Void sizes (mm)
5.248×10^{-6}	6
4.624×10^{-6}	4
3.416×10^{-6}	2

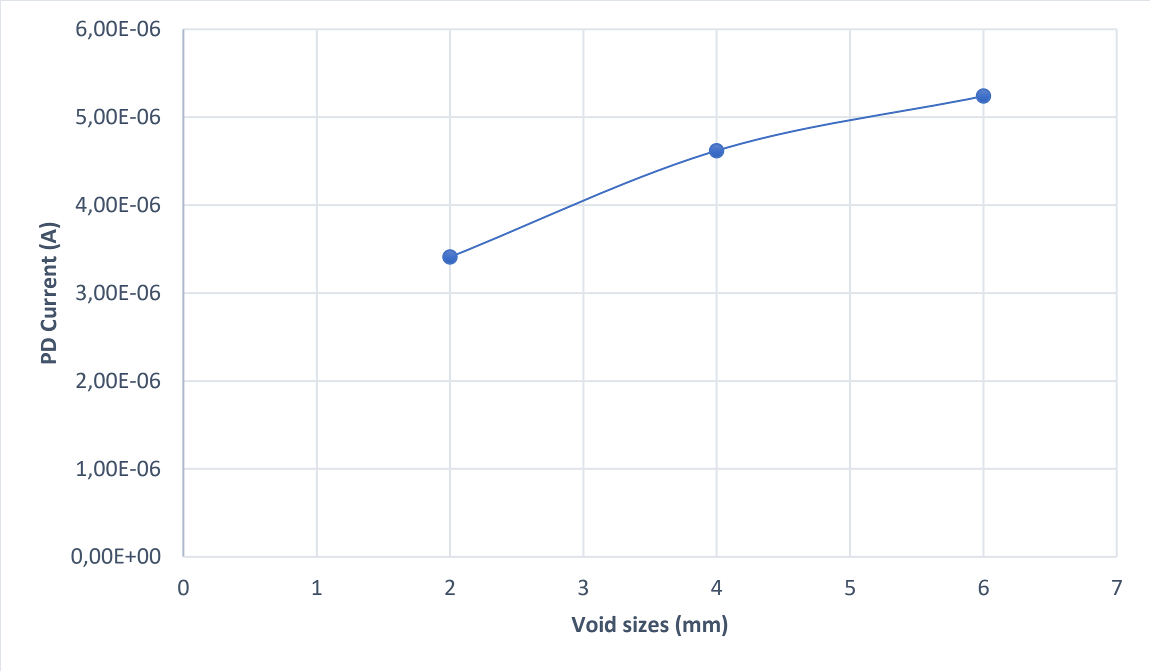


Figure III-13 Plot of PD Current with respect to void sizes

III.6.3.2. Results for different void sizes(18.4mm)

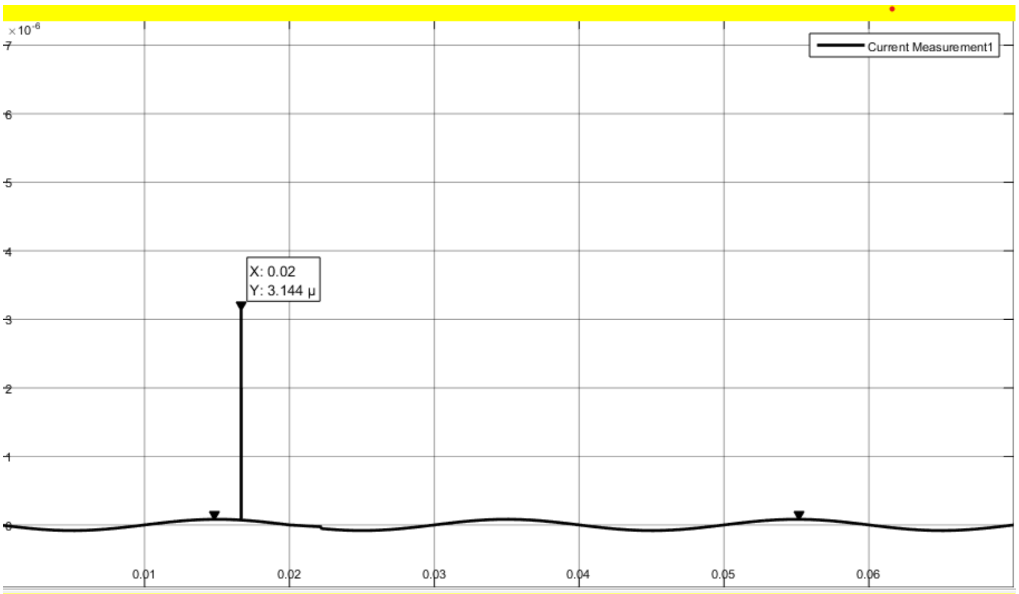


Figure III-10 PD Current result for 6 mm void sizes

Figure III-10 represents the partial discharge current when adopting an air gap of 6 mm inside the insulator. The curve shows the appearance of a strong discharge pulse with a peak of approximately 3.144 µA at a time around 0.02 seconds, which is the highest value among the set of gap sizes. This reflects the ability of the larger gap to store a greater amount of charges before breakdown, resulting in a discharge with higher energy when it occurs.

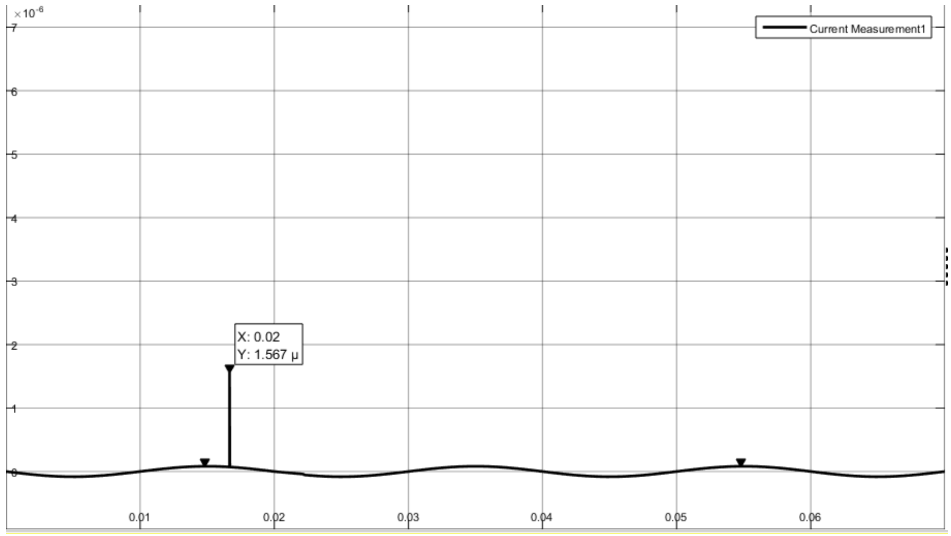


Figure III-11 PD Current result for 4 mm void sizes

Figure III-11 illustrates the discharge behavior at a gap size of 4 mm. From the graph, the maximum current reaches about 1.567 µA at a time close to 0.02 seconds, which is noticeably lower compared to the 6 mm gap size. This reduction is attributed to the smaller gap limiting the available space for charge accumulation, thereby producing a discharge with lower energy.

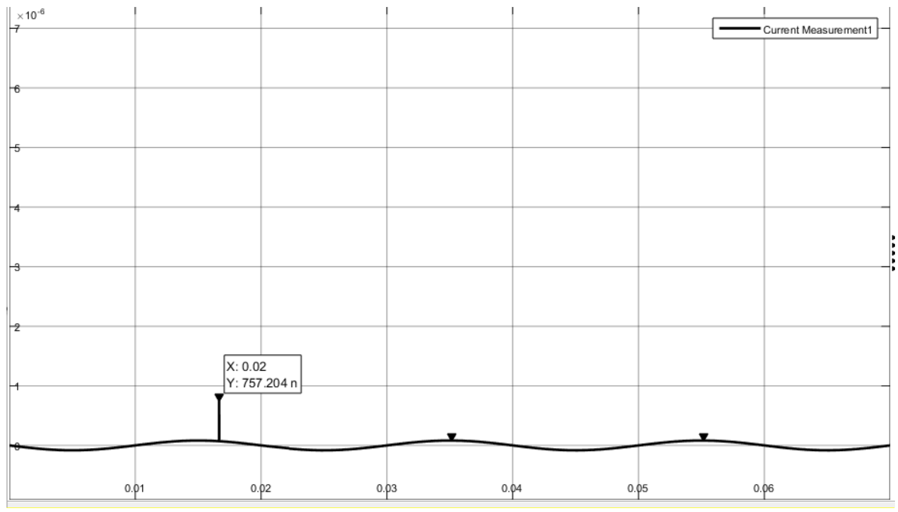


Figure III-12 PD Current result for 2 mm void sizes

Figure III-12 represents the case of a small gap with a size of 2 mm. The discharge peak reached approximately 0.757 µA at around 0.02 seconds, which is the smallest value among the three cases. As the gap size decreases, the number of electrons stored inside the gap is reduced, resulting in a relatively weaker discharge compared to the previous two cases.

Table 6 PD current of each void sizes

PD Current (A)	Void sizes (mm)
3.144×10^{-6}	6
1.567×10^{-6}	4
0.757×10^{-6}	2

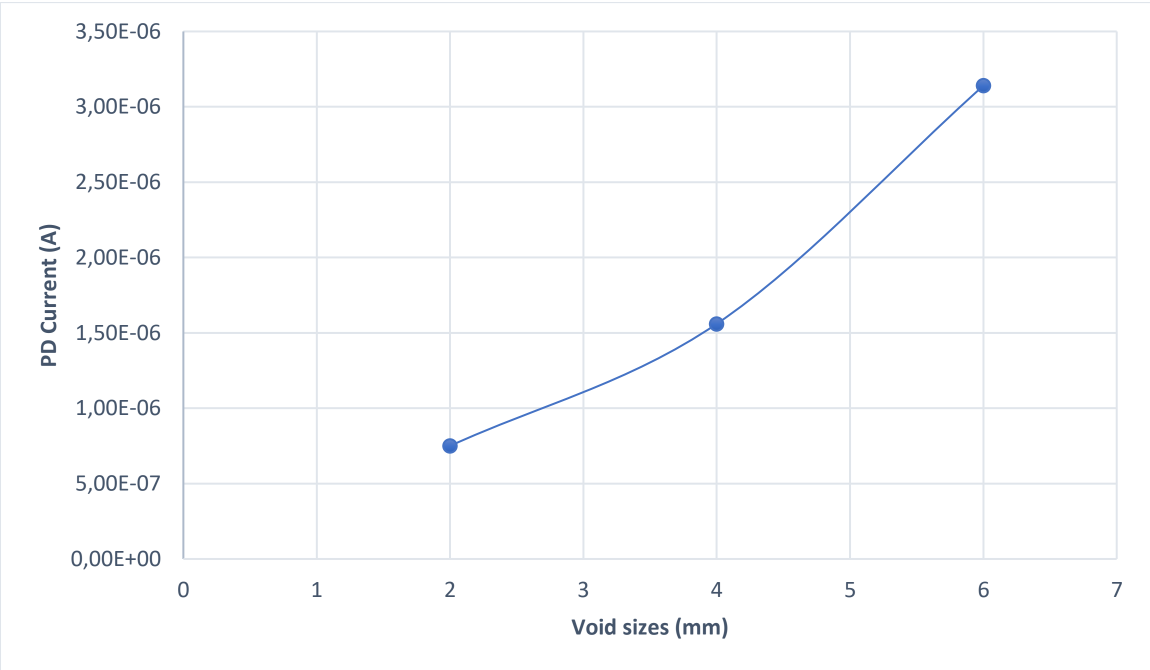


Figure III-13 Plot of PD Current with respect to void sizes

The simulation carried out on the insulation of an XLPE cable confirmed that partial discharge (PD) activity under void conditions can be effectively analyzed using an equivalent PD model. The model was tested with void sizes at 6mm, 4mm, and 2mm of the total . As illustrated in Figure III-13, the simulation results for each void sizes differ significantly, aligning well with the anticipated behavior.

To isolate the effect of void sizes, the same applied voltage was maintained across all three cases. When the void was sizes 6 mm , the PD current amplitude reached 6.279×10^{-6} A. At a sizes of 4 mm , the amplitude decreased to 3.962×10^{-6} A, and further dropped to 2.416×10^{-6} A when the void was 2 mm

III.7. Conclusion

In this chapter, an equivalent electrical model was developed to simulate partial discharge (PD)behavior within insulation materials using MATLAB Simulink. The model represented a void embedded in XLPE insulation and incorporated key parameters such as void location relative to the conductor.

Simulation results clearly demonstrated that the position of the void significantly influences PD current amplitude, with higher discharge activity observed when the void is located closer to the conductor. This trend aligns with physical expectations and confirms the validity of the proposed model.

The methodology enabled a precise analysis of the relationship between void geometry and electrical response, providing a reliable tool for understanding PD behavior. This foundation can be used to enhance insulation design and improve monitoring strategies in high-voltage systems.

General conclusion

Partial discharges (PD) are among the most critical electrical phenomena that directly impact the analyzing their behavior is a fundamental step toward improving the reliability and sustainability of modern electrical networks.In this thesis, an equivalent circuit model was developed to simulate partial discharge activity within XLPE cables, with a particular focus on how the position of the void inside the insulation affects the discharge characteristics.The simulation results clearly demonstrated that the location of the void significantly influences the PD current amplitude. Specifically, voids located closer to the conductor lead to higher discharge intensities, which implies a greater risk of insulation breakdown in such cases. This highlights the importance of considering void position when designing or assessing the condition of high-voltage insulation systems.

The use of MATLAB Simulink provided an efficient and safe means to study PD behavior without the need for costly or hazardous field experiments. The simulation approach also generated valuable data that can be leveraged to enhance early fault detection technologies and improve insulation reliability.

It is hoped that this study contributes to the advancement of research and development in predictive maintenance and the optimization of insulation design. Further research is recommended to develop more complex models that incorporate multiple environmental factors, such as humidity, temperature, and the presence of multiple voids within the insulation structure.

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الجمهورية الجزائرية الديمقراطية الشعبية
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جامعة غرداية
كلية العلوم والتكنولوجيا

قسم : الآلية و الكهروميكانيك

غرداية في : 03./03./2025

شعبة : الكترو ميكانيك
تخصص: صيانة صناعية

شهادة ترخيص بالتصحيح والايداع:

انا الاستاذ(ة) بوشلغم فاطمة

بصفتي المشرف المسؤول عن تصحيح مذكرة تخرج (ليسانس/ماستر/دكتورا) المعنونة بـ:
Simulation of partial discharges detection of High Voltage Cable

من انجاز الطالب (الطلبة):
الطالب أحمد عمار

التي نوقشت/قييمت بتاريخ : 12/06/2025

اشهد ان الطالب/الطلبة قد قام /قاموا بالتعديلات والتصحيحات المطلوبة من طرف لجنة المناقشة وقد تم التحقق من ذلك من طرفنا
وقد استوفت جميع الشروط المطلوبة .

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