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Title:

A COMPREHENSIVE STUDY ON PARTIAL DISCHARGE MEASUREMENTS AND DIAGNOSTICS

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Author’s Declaration of Originality

We hereby certify that we are the sole authors of this thesis. All the materials used, references to the literature, and the work of others have been appropriately cited. This thesis has not been presented for examination anywhere else.

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30-06-2024

Dedication

This thesis is dedicated to the pillars of strength and inspiration in our lives.

To our families: Your endless love and unwavering encouragement have been the bedrock upon which we have built our dreams. Your belief in our potential has propelled us to surpass every challenge and reach for the stars.

To our advisors and professors: Your wisdom, guidance, and invaluable insights have not only shaped our academic journey but have also broadened our intellectual horizons. Your mentorship has been the compass directing us towards excellence.

To our friends: Your steadfast support, understanding, and camaraderie have infused our journey with joy and resilience. Through every high and low, your presence has made this path more enriching and unforgettable. Special thanks to the one and only Nadjib, also the prime Djilali, the calmest Sohaib, the toughest Charif, the craziest Azizes (both of them), and the loveliest Nihad for being there every step of the way.

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in our abilities and their continuous encouragement have been instrumental in our success.
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We are truly grateful for the blessings and opportunities provided to us, and we pray that this thesis may contribute to the advancement and betterment of the field of power engineering.

Abstract

This study aims to explore the applicability and benefits of partial discharge (PD) testing for high voltage equipment, particularly in the context of Algeria, where such practices are not yet widely implemented. The scope of this research encompasses various high voltage equipment used in the energy sector.

To achieve a thorough examination, we utilized multiple detection methods, including electromagnetic, optical, acoustic, and chemical techniques. Each method was assessed for its effectiveness in identifying and analyzing partial discharge occurrences.

Our findings indicate that partial discharge testing provides a more comprehensive understanding of insulation integrity compared to traditional methods such as high-pot and high voltage tests. Additionally, PD testing showed excellent compatibility with other insulation assessments like tan delta tests. Through detailed interpretation of PD patterns and comparative analysis, we demonstrated the superior diagnostic capabilities of PD testing.

These results suggest that adopting partial discharge testing in Algeria could significantly enhance the reliability and safety of high voltage equipment, contributing to improved maintenance practices and longer equipment lifespan.

List of Abbreviations and Terms

A/D	Analog-to-Digital
AC	Alternating Current
AE	Acoustic Emission
Ca, Cb, Cc	Equivalent Capacitances
CC	Coupling Capacitor
DCS	Direct Coupling System
DC	Direct Current
DGA	Dissolved Gas Analysis
EA	EA Technology (name of a company)
EM	Electromagnetic
flo	Lower Cutoff Frequency
GIL	Gas-Insulated Lines
GRTE	Groupe Réseau de Transport d'Électricité
HFCT	High-Frequency Current Transformer
HiPot	High Potential
HV	High Voltage
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
kV	Kilovolt
MVA	Mega Volt-Amps
MHz	Megahertz
MV	Medium Voltage
PD	Partial Discharge
PDEV	Partial Discharge Extinction Voltage
PDIV	Partial Discharge Inception Voltage
pC	PicoCoulombs
PRPD	Phase-Resolved Partial Discharge
Ra, Rb, Rc	Equivalent Resistances
RLC	Resistor-Inductor-Capacitor
SNR	Signal-to-Noise Ratio
tan()	Dissipation/Power Factor
TDR	Time Domain Reflectometry
TEV	Transient Earth Voltage
UHF	Ultra High Frequency

Vi	Inception Voltage
Ve	Extinction Voltage
Vc	Voltage across Cc
VHF	Very High Frequency
VLF	Very Low Frequency
Zm	Measuring Impedance

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General Introduction

Partial discharge (PD) is a critical and fascinating phenomenon in electrical engineering, particularly in high-voltage equipment insulation systems. These localized dielectric breakdowns occur within the insulation or on its surface when the electric field strength exceeds a certain threshold. Understanding and managing PD is essential for ensuring the reliability and longevity of electrical power systems. If left unchecked, PD can lead to severe insulation deterioration, ultimately causing catastrophic equipment failures.

The journey to understanding partial discharge began with the advent of high-voltage technology in the early twentieth century. In the 1930s, researchers conducted loss angle measurements, setting the stage for further innovations. A pivotal moment came in the 1960s when Frederik Hendrik Kreuger introduced modern PD testing through charge-based measurement techniques. This breakthrough quickly led to the establishment of an international standard (IEC 60270), solidifying PD measurement's importance in both research and industrial applications. As microelectronics and computing technologies progressed, novel methods such as phase-resolved PD measurement became standard practice. Concurrently, significant strides were made in developing advanced PD detection techniques like the acoustic and UHF methods, enabling more precise and reliable field tests.

This graduation project delves into the theories, measurement techniques, and practical applications associated with partial discharge in high-voltage systems. It covers the factors influencing PD initiation, various types of partial discharges, and the physical effects that arise from these phenomena. Furthermore, the project examines state-of-the-art methods for PD measurement, including electromagnetic, optical, acoustic, and chemical byproduct detection techniques.

Dielectric insulations in high-voltage equipment must withstand the adverse effects of PD caused by inhomogeneous field configurations or dielectric materials. Continuous PD stress can progressively damage insulation, leading to power outages and equipment failures. Therefore, detecting, identifying, and localizing PDs are crucial for assessing the dielectric insulation performance of electrical power equipment. PD measurement plays a vital role in quality assurance during high-voltage tests, ensuring that the equipment operates reliably and efficiently, with PD levels within acceptable standards.

This project also includes a comparative analysis between partial discharge testing and other insulation testing methods. The comparison highlights the advantages and limitations of each approach, providing a well-rounded perspective on insulation testing. Additionally, an in-depth analysis of PD data offers insights into the interpretation of measurement

results and their implications for high-voltage equipment maintenance and reliability. Notably, the techniques and methods explored in this project are not yet widely used in Algeria. By focusing on these advanced PD measurement and analysis techniques, this project aims to introduce and advocate for their implementation within the Algerian context, enhancing the reliability and safety of the country's high-voltage electrical systems.
This introduction sets the stage for a detailed examination of partial discharge theory and measurement, highlighting the significance of PD management in ensuring the safety, efficiency, and reliability of electrical power systems. The following chapters systematically cover the theoretical and practical aspects of PD, aiming to equip readers with an in-depth understanding of this critical subject in electrical engineering.
By exploring both historical and modern perspectives, this project provides a holistic view of partial discharge, demonstrating how past innovations continue to influence present and future advancements in high-voltage technology.

Chapter 1 Partial Discharge Theory

1.1 Overview

Partial discharges (PDs) are localized electrical discharges that only partially bridge the insulation between conductors. They generally occur due to local electrical stress concentration within the insulation or on its surface and manifest as pulses lasting much less than 1 s. PDs are initiated when the local electrical field strength (Eloc) exceeds the dielectric strength (Ed) of the insulation material, coupled with the presence of free charge carriers, primarily electrons, which initiate ionization processes [1, 2, 3, 4].

1.2 Factors Influencing PD Initiation

1.2.1 Electrical Field Strength:

The local electrical field strength (Eloc) of the insulating material must be greater than the dielectric strength (Ed) in order for a partial discharge to occur. This relationship emphasizes how crucial it is to keep the electric field in high-voltage equipment uniform and controlled in order to avoid localized field increases that can cause partial discharges. The geometry of the electrodes and the surrounding material can affect the local electric field strength equation [4, 5, 6, 7].

$$Eloc > Ed \tag{1.1}$$

1.2.2 Paschen's Law:

A framework for comprehending how the breakdown voltage changes with pressure and gap distance in a particular gas is provided by Paschen's Law. Paschen's Law states that the breakdown voltage (Vb) is a function of the gap distance (d) and the product of pressure (p). The law is stated as follows:

$$V_b = \frac{B.p.d}{\ln(A.p.d) - \ln(\ln(1 + \frac{1}{\gamma}))} \tag{1.2}$$

Where γ is the secondary ionization coefficient and the constants A and B are dependent on the kind of gas. According to Paschen's Law, the breakdown voltage drops as pressure drops until a minimal value is reached, at which point it rises once more. Understanding gas discharges under various pressure circumstances, especially in environments where pressure conditions, particularly depends on this behavior [1, 2, 8, 9].

1.2.3 Presence of Charge Carriers:

The beginning of partial discharges requires the existence of free charge carriers, such as ions and electrons. The ionization activities that take place within the insulating material are caused by these charge carriers. These carriers obtain enough energy to ionize gas molecules or other insulating components when the nearby electric field is high enough, causing an avalanche effect that may lead to a partial release. Important elements in the beginning process are these charge carriers' mobility and availability [1, 2, 3, 10, 11].

1.2.4 Townsend's Criteria:

The circumstances for the beginning of an electrical breakdown are described by Townsend's first ionization coefficient (α) and second ionization coefficient (γ). The following formula provides Townsend's breakdown criterion: Where d is the gap distance. According to this criterion, if the ionization created by an electron in the gap can continue, a discharge will happen. In essence, the criterion takes into consideration the interaction between ionization processes and the electric field to forecast the threshold circumstances under which a partial discharge will begin [1, 2, 12].

1.2.5 Material Properties:

Partial discharge start is also significantly influenced by the material characteristics of the insulation. The local electric field distribution and the chance of a partial discharge can be greatly influenced by the dielectric qualities, such as permittivity and conductivity, and the existence of impurities or flaws like voids or cavities. Partial discharges are more likely to occur in localized areas of high electric field strength caused by flaws in the insulating material, such as vacancies, fractures, or contaminants. The age, operating circumstances, and manufacturing method of the insulation material all have an impact on the type and distribution of these flaws [1, 2, 3, 13].

1.2.6 Streamer Theory:

Streamer theory provides insights into the formation of streamers, which are filamentary discharges that occur when a high voltage pulse creates a conductive path through the gas. Streamers are characterized by their rapid propagation and high ionization density. According to streamer theory, primary electrons, accelerated by the electric field, ionize gas molecules to form an avalanche. This avalanche can transition into a streamer if the local electric field and ionization processes are sufficient to sustain it. Streamers are critical in the context of partial discharges because they represent a more advanced stage of ionization that can lead to more severe insulation damage [1, 2, 14].

1.3 Types of PDs

Partial discharge are divided to thee main types.

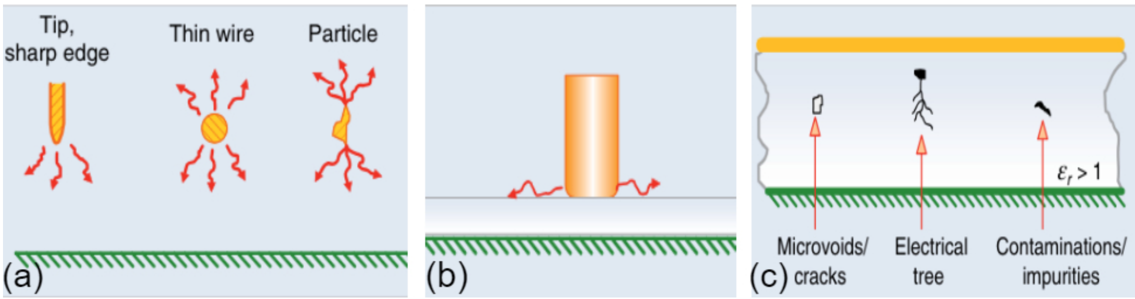

Figure 1. *PD types: (a) External (b) Gliding (c) Internal.*

1.3.1 External Discharges

External discharges happen outside the insulation, usually on sharp edges, points, or surfaces of solid insulation. The field efficiency factor can affect these common gas discharges. Corona discharges, which occur on the surface of conductors, are an example of external PD that is distinguished by light emission, mechanical and chemical processes, and acoustic events. The geometry of the electrodes and the type of the gas in which the discharge occurs both influence the discharge's behaviour[1, 2, 3, 14].

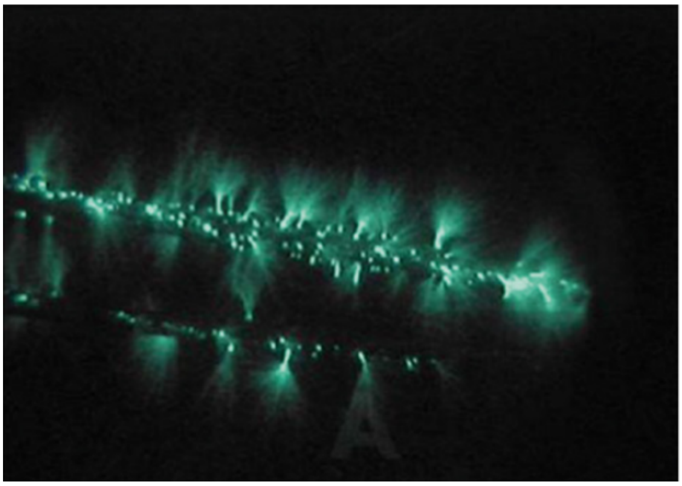

Figure 2. *Corona discharges.*

Tip with Negative Polarity:

Leads to the formation of a dipole field with repetitive Trichel pulses, characterized by low magnitude and high repetition rate [1, 2, 14].

Tip with Positive Polarity:

Results in more disruptive discharges with a higher inception voltage, influenced by the divergent electric field near the tip [1, 2, 14].

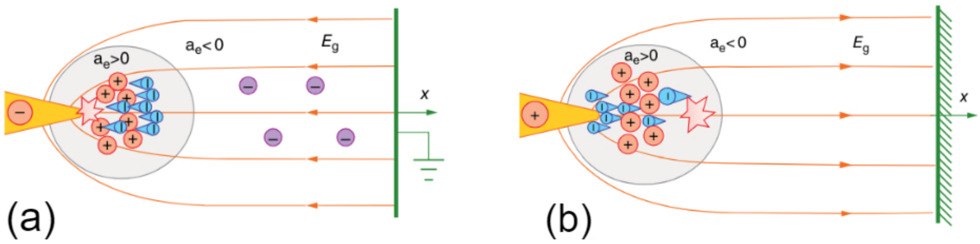

Figure 3. *Charge behavior and electric field distribution after ionization process: (a) negative tip polarity, (b) positive tip polarity.*

1.3.2 Internal Discharges

Internal discharges are caused by flaws in the insulation such as vacancies, cavities, or contaminants. The ionization processes in these discharges are complicated due to their interaction with the surrounding dielectric material. Internal PDs can cause considerable harm to insulation materials if not discovered and controlled correctly. Discharges in liquid insulation frequently result in streamer discharges in micro-bubbles or gas-filled cavities, whereas discharges in solid insulation occur in voids or impurities, potentially generating treeing structures that can lead to failure [1, 2, 3, 15].

Discharges in Liquid Insulation:

When a discharge is initiated in liquids, it often leads to a gas discharge occurring in microbubbles or gas-filled cavities caused by vaporisation and local overheating. If the electrical field within such a gas-filled space is high enough for further ionization, a streamer discharge is formed. These discharges are accompanied by transient currents (bursts) and emitted light signals. Shock waves are generated, and the streamer moves towards its counter electrode, stopping when the local electric field becomes insufficient for further movement. Streamer characteristics depend on the rise time, polarity of the applied voltage, pressure, temperature, chemical structure, and physical properties of the liquid. In mineral oil, a common insulating liquid, partial discharges can lead to the formation of gas bubbles due to local overheating. These bubbles can then initiate further discharges as leader discharge if the local electric field is high enough [1, 2, 3, 15].

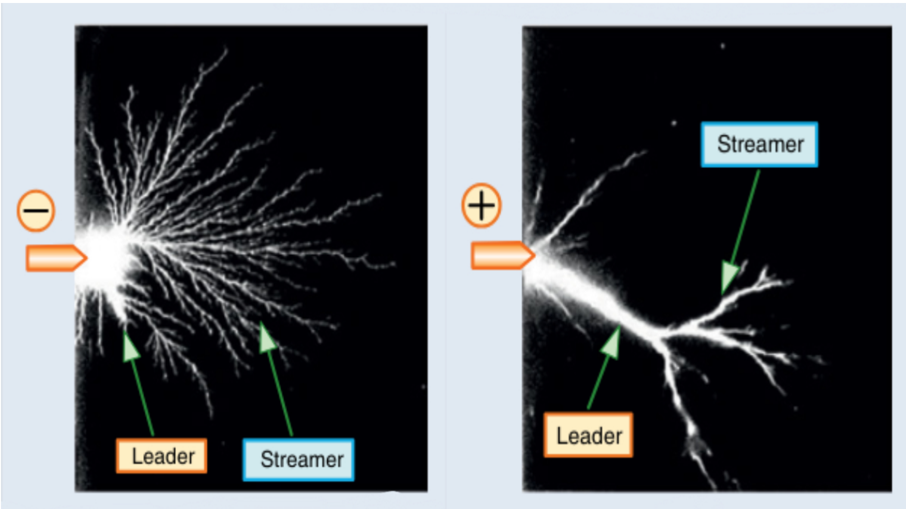

Figure 4. *Discharges in mineral oil at different tip polarity.*

Discharges in Solid Insulation:

Partial discharges in solid dielectrics can occur in voids or other impurities where the intrinsic field strength is surpassed at lower voltage values than the total insulation gap voltage. Cracks or cavities filled with lower-molecular components formed during insulation manufacturing, as well as air-filled cavities created by chemical reactions, are examples of typical defects. Tree-like structures in polymeric materials can arise as a result of water inclusions, embrittlement, or molecular chain breakdown. Under electrical stress, local increases in electric field values can cause tree discharges, potentially resulting in insulation failure. Water treeing in XLPE (cross-linked polyethylene) cables occurs when microvoids filled with water form elongated structures under the influence of an electric field, eventually leading to insulation breakdown [1, 2, 3, 15].

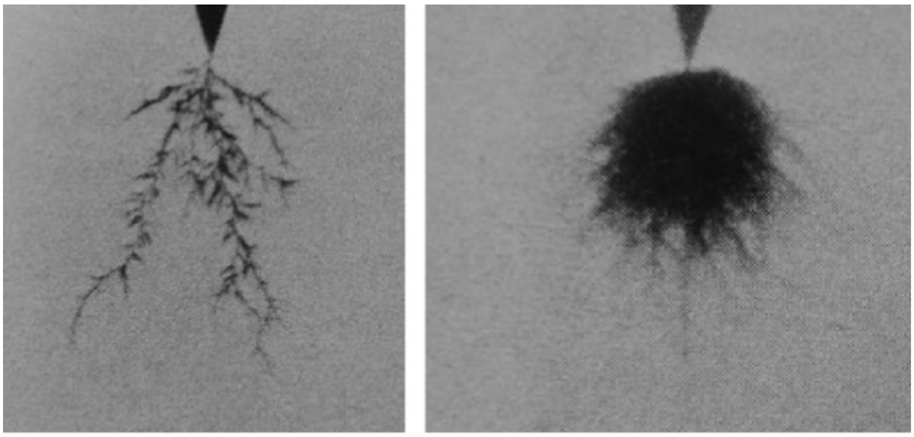

Figure 5. *Typical types of treeing structure in polymeric insulation.*

1.3.3 Gliding Discharges

These happen at the interfaces where several dielectric materials meet, like insulator surfaces in gases or pressboard barriers in liquids. Driven by the strength of the electrical field, these discharges "glide" across the surface; they are distinguished by their mobility along the surface and the high tangential component of the electric field. Gliding discharges usually happen at outdoor and indoor insulators, in transformer sites, bushings, and cable terminations [1, 2, 3, 16].

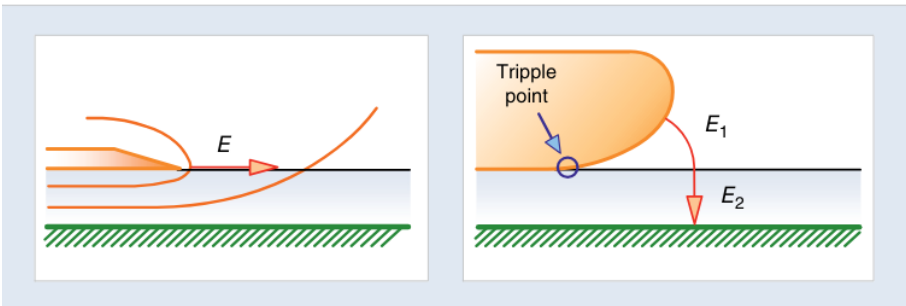

Figure 6. *Typical field configuration for occurrence of gliding discharges.*

1.4 PD Quantities

Partial discharges are quantified by several key parameters:

1.4.1 Discharge Magnitude (q):

The amount of charge transported in a PD event, which is commonly expressed in picocoulombs (pC), denotes the discharge's severity. For instance, PD magnitudes in many high-voltage systems might vary from a few nanocoulombs to a few picocoulombs. In some power cables, a discharge magnitude of 50 pC can be deemed safe; higher magnitudes could be a sign of possible insulation breakage [1, 2, 3, 7].

1.4.2 Partial Discharge Inception Voltage (PDIV):

The minimum voltage at which PDs begin to occur, crucial for determining insulation strength. For instance, in transformer insulation, the PDIV might be in the range of 20-30 kV, depending on the insulation material and the operational conditions. This parameter helps in identifying the voltage levels at which the insulation material starts to degrade [1, 2, 3, 7].

1.4.3 Partial Discharge Extinction Voltage (PDEV):

The voltage at which PDs extinguish, used to assess the resilience of insulation under varying electrical stress. For example, a PDEV value lower than the PDIV indicates that once initiated, PDs continue to occur even at reduced voltages, highlighting areas of concern within the insulation system [1, 2, 3, 7].

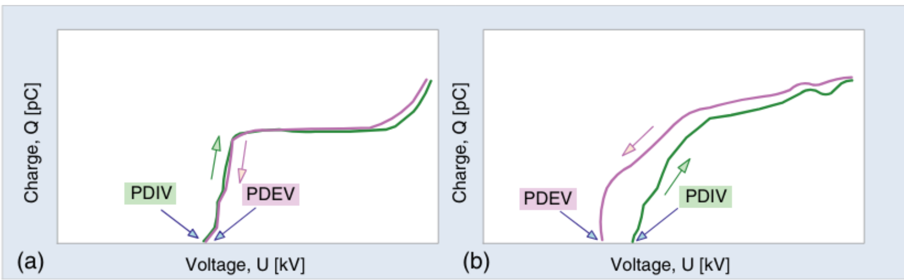

Figure 7. *Charge pulse oscillograms for simple PD arrangements at AC conditions and PDIV/PDEV values (schematically) in which insulation is (a) ambient air and (b) liquid or solid.*

1.4.4 Discharge Frequency (n):

The frequency of PD events per unit of time; greater frequencies correspond to more severe breakdown of the insulation. For example, a high discharge frequency in a high-voltage cable may indicate serious insulation degradation and the need for repair or replacement

[1, 2, 3, 7].

1.4.5 Apparent Charge (Q):

This makes it easier to compare PD activity across many systems by transferring the charge that would be involved in a single discharge if the PD event happened. In PD measurements, apparent charge is frequently employed to offer a consistent means of comparing discharge magnitudes. For instance, an apparent charge of 500 pC may be a sign of serious insulation problems in a power transformer, which would call for additional research and possibly even intervention [1, 2, 3, 7].

1.5 Modeling of PD Behavior

1.5.1 Network-Based Models

Network-based models represent the insulation system and its defects as a network of electrical components, such as resistors, capacitors, and inductors. These models are used to simulate the electrical characteristics of partial discharges (PDs) and their interaction with the external circuit. By using simplified electrical analogs to represent complex interactions within an insulation system, network-based models provide valuable insights into the mechanisms and effects of PDs. The primary purpose of these models is to analyze the electrical response of the insulation system to applied voltages and to understand the initiation and propagation of PDs [17, 18, 19, 20, 21].

Equivalent Circuit Model for AC Conditions:

Many models have been created and then changed based on variables like the conductance of the intact insulation and the void caused by shunts in order to approximate the behavior of genuine solid insulation with gaseous cavities and to assess the partial discharge (PD) charge transfer. With its three characteristic capacitances, the ABC model is the most widely used network-based PD model. Figure 8 shows the circuit that is comparable to it [20, 22].
In this model, Ca represents the equivalent capacitance of the test object, while Cb1 and Cb2 simulate the equivalent capacitances of the healthy solid dielectric between the gaseous cavity and the electrodes of the test object. The gaseous cavity itself is represented by the equivalent capacitance Cc , and the spark-gap is represented by an electronic switching device.

Regarding the initiation of a PD event, it is assumed that the cavity capacitance Cc is fully

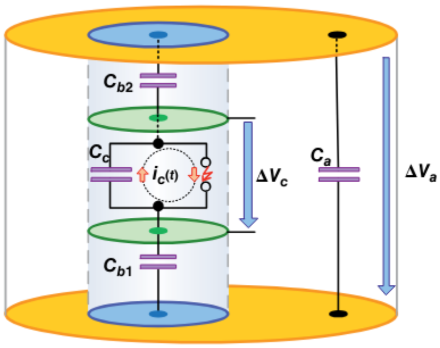

Figure 8. *Network-based PD model for AC Conditions.*

discharged via the parallel-connected spark gap. This results in the transient voltage across Cc dropping from the inception voltage Vi to a residual (extinction) voltage Ve, leading to a voltage drop Vc across Cc.

Equivalent Circuit Model for DC Conditions

Since quality testing for HVDC equipment is becoming more and more important, the modeling created has been verified for use in direct voltage circumstances. Permittivity has less of an impact on the potential distribution between electrodes under DC conditions than do the volume and surface conductance of the insulating material. Thus, the network-based model presented in Figure 8 has been updated to represent cavity discharges under direct voltage, as seen in Figure 9. Resistances Ra, Rb, and Rc bridge the equivalent capacitances Ca, Cb, and Cc in this updated model to replicate the resistive potential distribution. The PD pulses' repetition rate and inception voltage are both impacted by this resistive distribution. However, it is sufficient to take into account simply the capacitive parts in order to examine very fast PD transients. Therefore, the ideas that were previously presented are still relevant without limitation [20, 23, 24, 6, 25].

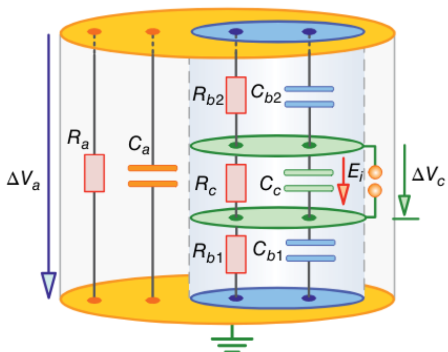

Figure 9. *Network-based PD model for DC Conditions.*

1.5.2 Field-based models

Partial discharge (PD) field-based models concentrate on the ionization and physical processes that take place inside the insulating material. These models take into account the distribution of the electric field and the motion of charge carriers to mimic the behavior of PDs. Understanding PD activity under various electrical stress situations, such as alternating current (AC) or direct current (DC) voltage, is made easier by these models. The beginning of ionization processes, the creation of an electrical dipole, and the dissipation of the electrical dipole are crucial elements in field-based models. Ionization is started during the inception phase by the production of free charge carriers. The movement of these charge carriers causes an electrical dipole to form during the setup phase. The dissipation phase culminates in the dipole's decrease and the discharge's termination [17, 26, 27, 28, 7, 29].

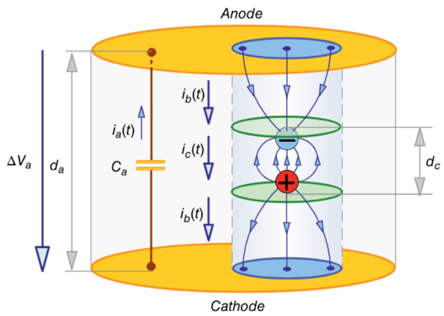

Figure 10. Field-based PD model.

1.6 Physical effects based on partial discharges

Partial discharges cover several physical effects based on the discharge process, with varying intensity depending on the insulation material and location. An overview of these effects is shown in Figure 11:

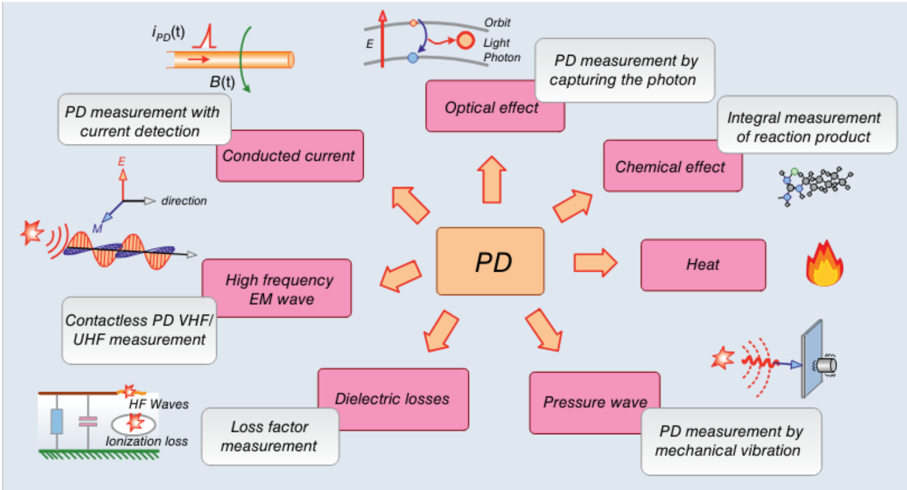

Figure 11. *Physical effects based on partial discharges.*

- Conducted Currents: After an internal discharge, a rebalancing of charges between the capacitances leads to a high-frequency current, measurable in the affected network branches. This is typically measured using a well-defined measurement circuit.
- High-Frequency EM Waves: The high-frequency content of discharge currents results in EM waves that can be detected by inductive, capacitive sensors, or UHF antennas.
- Dielectric Losses: PDs cause power losses within the fault area, leading to localized heating. These losses are measurable by loss factor measurement systems, such as Schering Bridges, evaluating parameters like permittivity and loss factor $\tan\delta$

- Pressure Waves: Discharges generate micropressure waves, leading to material vibration and erosion, detectable by ultrasonic sensors or microphones.
- Heat Losses: Localized temperature increases (hot spots) affect material behavior and PD resistivity. However, measuring small PD events using temperature systems like infrared cameras is uncommon.
- Chemical Effects: Energy from PDs can induce chemical reactions, detectable by analyzing reaction products (e.g., O3 content, fault gases like H2, C2H2 in insulating oils).
- Optical Effects: Photons emitted during the discharge process can be measured using photon multipliers and other optical measuring systems.

Chapter 2 Measurement of Partial Discharges

2.1 Introduction

Assessing partial discharges (PD) is a crucial component in assessing the functionality and state of high-voltage insulating systems. Precise identification and assessment of PDs can guarantee the dependability of electrical apparatus and assist in spotting possible malfunctions. Over time, PDs can do a great deal of harm, which can result in equipment failure, insulation deterioration, and a loss of dielectric strength. Advanced signal processing techniques and a variety of electrical, acoustic, and optical PD measurement methods are covered in this chapter. Maintaining the integrity and lifespan of high-voltage systems requires an understanding of the impacts of PDs and the application of efficient measurement techniques.

2.2 Signal Properties

The shape, size, and frequency of the partial discharge (PD) signal—which is produced by the discharge current within insulation—are all impacted by a number of variables as it travels into the ultimate assessment [1, 4].

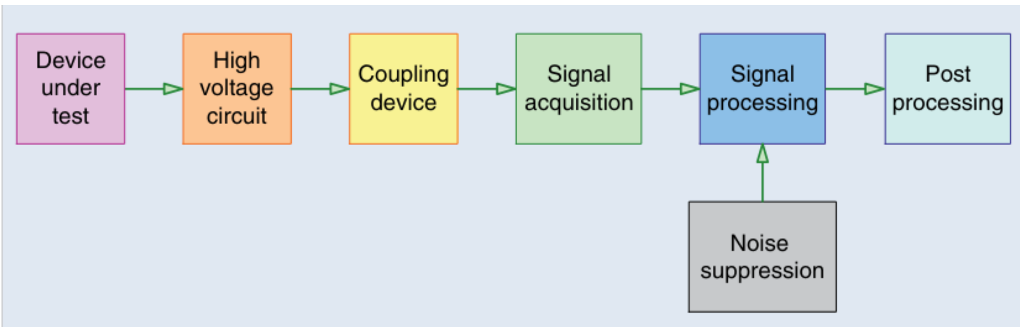

Figure 12. *Signal path for measurement of partial discharges (schematically).*

2.2.1 Device Under Test

The internal signal path to the "output" of the tested object significantly impacts signal properties, varying with device type:

- Concentrated (compact) volume/size: Examples include switchgear, transformers, and machines.

- Extended (elongated) volume/size: Examples include cables, gas-insulated lines (GIL), and overhead lines.

These paths may cause signal deformation, reflections, or resonances, requiring analysis of potential paths for PD signals.

2.2.2 High Voltage Circuit

Measurable PD signals are influenced by the high-voltage test circuit's kind and size.

Type of High-Voltage Supply:

- AC: Sinusoidal wave shapes are standard, but harmonics can affect PD behavior.
- DC: Often includes a small AC component (ripple), influencing PD activity.
- Impulse voltage.

Size of Test Circuit:

- Characterized by inductance of connection leads and parasitic capacitance to Earth or other potentials.

2.2.3 Coupling Method

The Partial Discharge (PD) signal is indeed affected by both the coupling method (whether capacitive or inductive) and the installation location of the coupling devices. Here's a more detailed look at how these factors influence the PD signal:

Capacitive Coupling with Measuring Impedance

The measuring impedance (Zm) in a high-voltage test circuit can be positioned in three principal locations:

- Coupling Capacitor Branch: When Z_m is in series with the coupling capacitor, it transfers high-frequency PD current signals to the measuring device. The advantage of this setup is that Z_m remains unaffected if the test object fails, making it ideal for test objects that cannot be disconnected from the ground, such as rotating machines. However, the disadvantage is that this setup has lower measuring sensitivity compared to placing Z_m in the test object branch.
- Test Object Branch: When Z_m is in series with the test object, it transfers high-

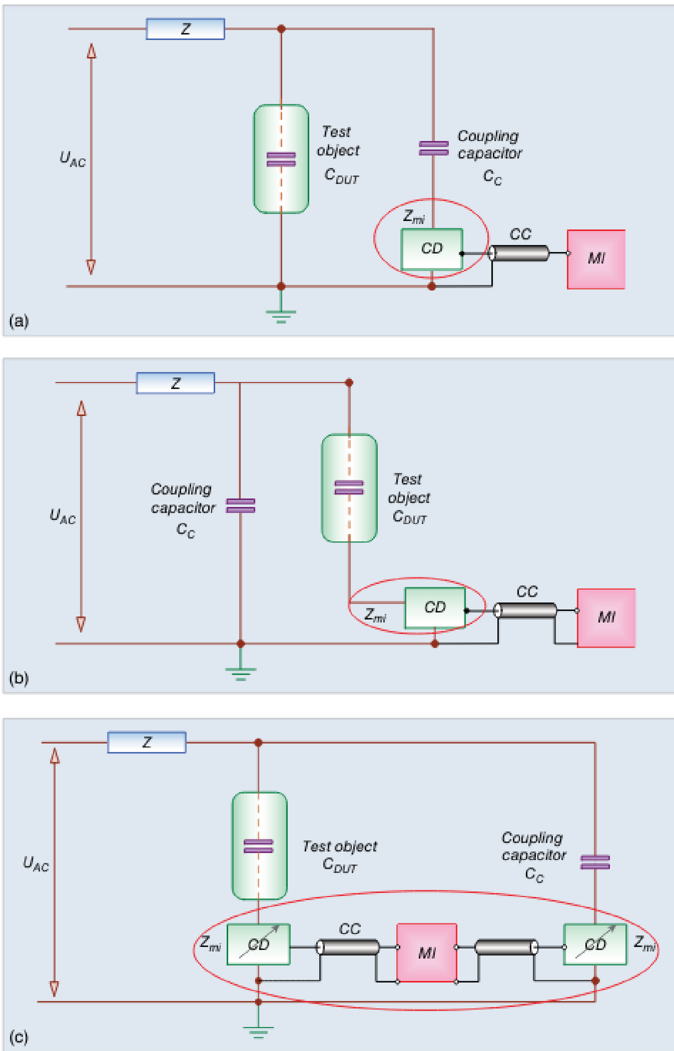

Figure 13. Possible positions of measuring impedance in the high-voltage test circuit: (a) in the coupling capacitor branch; (b) in series with the test object; (c) in both branches using a bridge impedance and appropriate bridge measuring methods.

frequency PD current signals directly to the measuring device. The advantage of this setup is higher measuring sensitivity. However, the disadvantage is the risk of damage to Z_m and the measuring device if the test object fails. Additionally, if Z_m is placed on the high-voltage side, data transfer requires optical systems.

- Both Branches(Bridge Impedance): When Z_m is in both the test object and coupling capacitor branches, or using a special bridge impedance, it offers higher sensitivity due to differential probe gain and common mode rejection. This setup also allows for polarity discrimination of PD pulses. However, the disadvantage is the potential damage to Z_m if the test object fails, and the setup is more complex and expensive.

Inductive Coupling with High-Frequency Current Transformer

All possible HFCT sensor positions for inductive coupling of PD current signals are:

- Pos.1: In series with impedance Z bridging the high-voltage source. Offline, Z is a coupling capacitor or cable; online, it is the substation impedance network. This setup protects smaller HFCT sensors, as they only handle currents through Z.
- Pos.2: Connected to the grounded cable screen. This is the most convenient, sensitive, and safe position, often the only viable one in service. The sensor must handle high reactive currents and, during online tests, additional currents from neighboring phases.
- Pos.3: Encloses the lower part of the sealing end or the cable sheath near the sealing end. This position captures PD signals superimposed with high operating currents, with the cable screen current canceled out if conducted twice through the sensor.
- Pos.4: Mounted on high-voltage potential, similar to Pos.3 but requires optoelectronic transfer of PD signals to a low potential measuring system.
- Pos.5: Encloses both conductor and screen, where currents compensate each other, leading to low sensitivity for measurements.

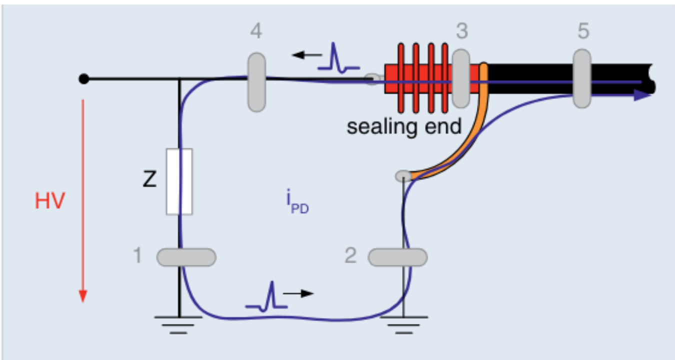

Figure 14. *Possible positions of HFCT sensors in a PD test circuit.*

2.2.4 Signal Processing

Three forms of signal processing exist for partial discharge (PD) signals obtained from high-voltage circuits: complete analog, semi-digital, and full digital processing.

Full Analog Processing

The PD signal is first processed through an analog band-pass filter intended for integration behavior in complete analog processing, after which it is either amplified or muted depending on its strength. A peak detector—typically an analog sample-hold circuit—processes the filtered signal, and the result is shown on a needle instrument. Resistive potentiometers or needle instruments are used for calibration in charge units (pC). This approach is straightforward and simple to fix, but it is not synchronized with the voltage signal, cannot handle large amounts of data, and needs distinct analog filters for different cutoff frequencies.

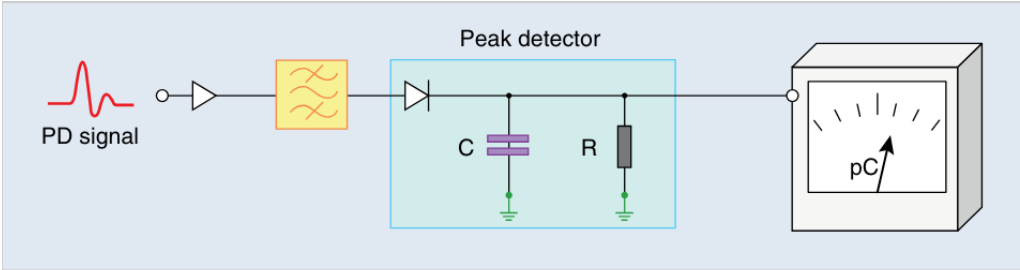

Figure 15. *Full analogue PD processing (schematically).*

Semi-Digital Processing

After the high-frequency PD signal has been processed by analog band-pass filters, amplifiers, and attenuators, it is digitalized in semi-digital processing. PC-based software subsequently processes this digitized signal and has the option of digitizing the AC test voltage. This technique enables the creation of PRPD patterns, synchronization with the test voltage, identification and storage of each filtered pulse, and integration with remote controllers or operational systems. The analog circuit, however, fixes the filter settings, and altering the cutoff frequencies necessitates using new filters and remote control switches, which has the disadvantage of not capturing every raw pulse.

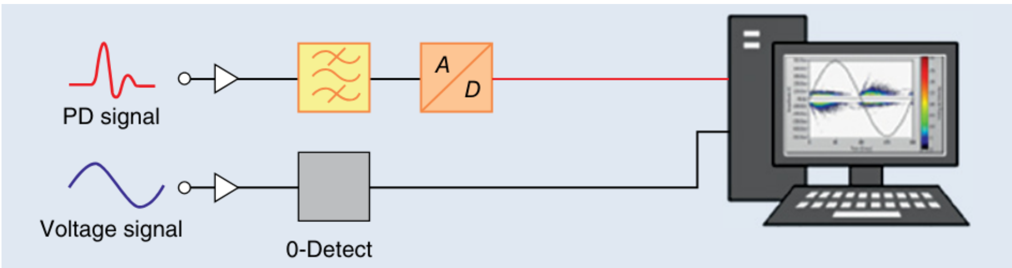

Figure 16. *Semi digital PD processing (schematically).*

Full Digital Processing:

In order to properly digitize PD pulses, full digital processing uses sophisticated ADCs and DSPs, necessitating a sample rate of at least 10ˆ 7 samples. Attenuators and amplifiers modify the PD signal to match the dynamic range of the ADC input, while a high-pass filter eliminates power-frequency components. After the signal has been digitalized, it is either streamed to a PC for additional processing or filtered using DSP and assessed using peak detection. This technique synchronizes with the test voltage, allows for adjustable filtering, supports multichannel measurement, recognizes and stores every original PD pulse, and facilitates PRPD pattern evaluation and PD fault detection. The primary constraints include the higher cost and complexity in comparison to analog systems, as well as the requirement for sophisticated systems and post-processing capabilities.

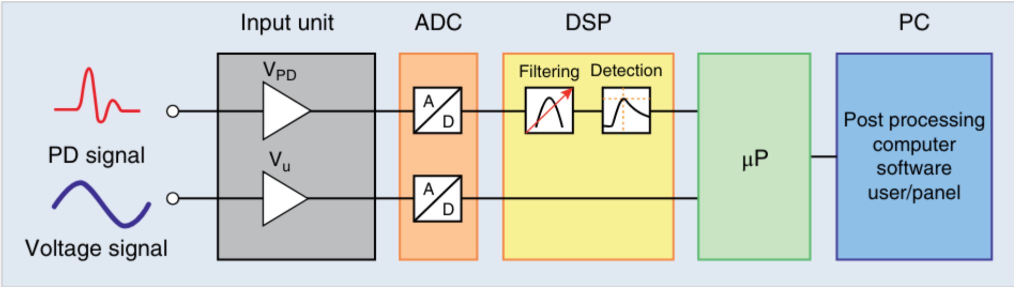

Figure 17. *Full digital PD processing (schematically).*

2.2.5 Measurement Principles:

In order to highlight the significance of partial discharge (PD) signals in high-voltage equipment diagnostics, this section concentrates on the concepts and methods for monitoring PD signals. The measurement principles are broken down into multiple subsections, each of which covers a distinct method of processing and measuring PD signals, along with the pertinent frequency ranges.

Narrow-Band Measurement :

- Frequency Range: Bandwidth f between 9 and 30 kHz with a recommended middle frequency of about 30 kHz up to 1 MHz.
- Description: Early PD measurement techniques employed narrow-band methods using analog filters to set the cutoff frequencies. These methods could not record raw pulses but could analyze PD signals within a limited frequency range. The narrow-band system responses were characterized by their amplitude spectra and bandwidth, affecting the PD signal's integration and detection accuracy [30, 31, 32].

Wide-Band Measurement:

- Frequency Range: Lower cutoff frequency f1 of 30 kHz up to 100 kHz and an upper cutoff frequency f2 to a maximum of 1 MHz with a bandwidth f of 900 kHz.
- Description: Wide-band measurement extends the frequency range, improving the detection and analysis of PD signals. The system processes a broader spectrum, enabling more accurate characterization of PD events [30, 31, 33, 34, 35, 36].

Time Domain Integration :

- Frequency Range: Upper corner frequency should significantly exceed 1 MHz.
- Description: This method involves directly integrating the entire PD signal over time, assuming the signal remains undistorted. The document highlights the importance of a wide measurement bandwidth to capture the complete PD signal accurately. Time

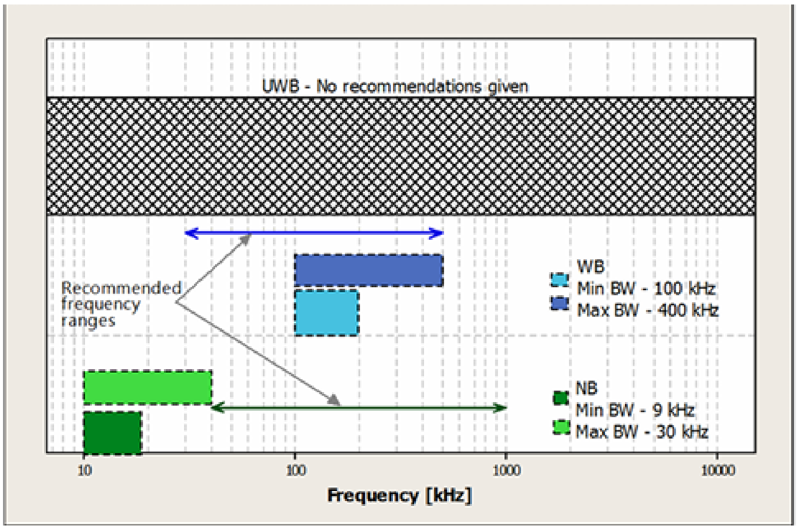

Figure 18. Illustration of frequency recommendations according to IEC 60270

domain integration is particularly useful for estimating the PD charge [30, 31, 33, 32].

Radio Interference Voltage (RIV) Measurement:

- Frequency Range: Bandwidth 9 kHz with a corner frequency between 15 kHz and 30 MHz.
- Description: RIV measurement quantifies disturbances in radio broadcast transmissions caused by PDs, mainly in overhead lines. This technique uses a band-pass filter and a quasi-peak detector to measure the PD signal's envelope, providing insights into the magnitude of the PD charge. RIV measurements are strongly dependent on the PD pulse rate [30, 31, 37, 38].

Synchronous Measurement for Multichannel Application :

- Frequency Range: Not specified, but the method involves synchronization using fiber optic links, real-time Ethernet, or GPS signals to handle multiple channels.
- Description: This advanced technique allows for simultaneous measurement of PD signals from multiple channels, improving the ability to distinguish between PD pulses and external noise. Multichannel systems are crucial for monitoring three-phase apparatus and distinguishing crosstalk effects[33, 39].

2.2.6 Noise Suppression and Reduction:

Introduction:

The presence of several noise sources that can overlap and skew the measurement findings is explained in this section, along with the importance of noise suppression and reduction strategies in PD testing .

Noise Sources:

The disturbances and EM noise may be caused by several sources (Figure19) [1, 32, 33, 37, 38]:

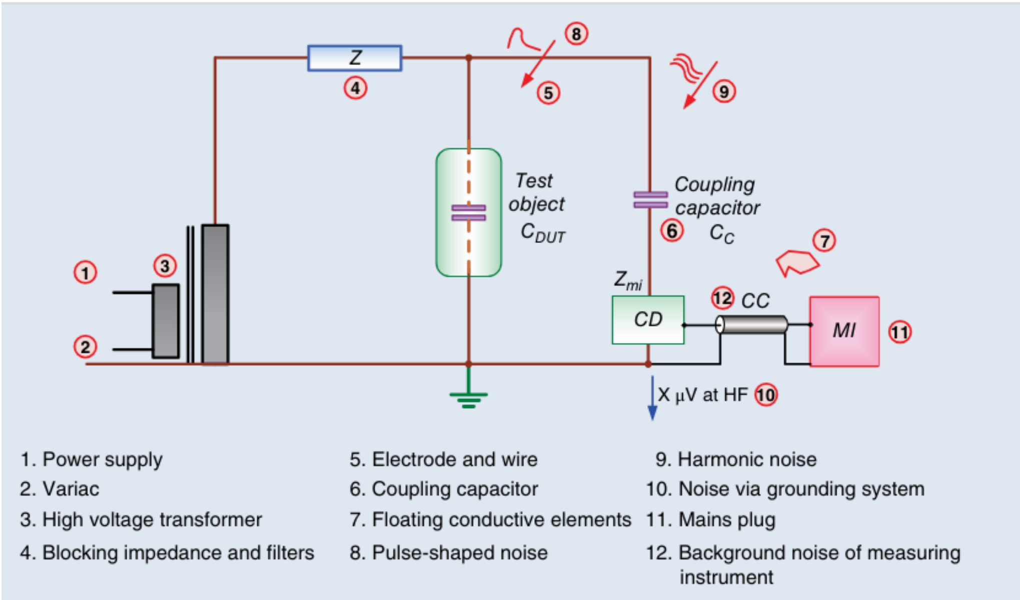

Figure 19. *Possible sources for disturbances and noise in PD test circuit (schematically).*

- Conducted Coupled Noise: This type of noise is produced by blocking impedances, high-voltage transformers, variable transformers (variacs), and power supplies.
- Radiatively Coupled Noise: Radiatively coupled high-frequency disturbances can be produced by sources such as electronic equipment, inverters, and fluorescent lights.
- Noise from Wire Loops or Grounding Systems: Wire loops or improper grounding systems can produce inductive noise.
- Background Noise of Measurement Devices: Particularly at low PD levels, thermal noise or white noise can interfere with measurements.

Denoising Methods

A thorough examination of ways for improving partial discharge (PD) measurement accuracy by lowering noise is given in the section on denoising techniques [1, 34, 35, 36, 39].

- Shielding: To lessen the effects of radiated coupled disturbances. This technique offers a controlled environment for PD measurements and is very good at reducing radiated noise. However, it can be costly and complicated to install in already-existing laboratories and requires correct design and implementation, incorporating all connection lines into the shielding idea.
- Analog and Digital Filters: Used to mitigate the effects of coupled noise. Analog filters can greatly increase the signal-to-noise ratio (SNR) prior to analog-to-digital (A/D) conversion, but digital filters are more flexible and can be tailored to particular noisy conditions. The drawbacks include the requirement for exact design in analog filters and the substantial processing power needed in digital filters, which could also have stability problems with single pulse occurrences.
- Equilibrium Bridge: The balanced PD bridge method is used in measurements to eliminate or reduce external electromagnetic (EM) noise. With differential amplifiers, this method offers great sensitivity and efficient noise reduction, especially in cases where the bridge's branches are symmetrical. Small variations in signal travel time might increase noise, making practical applicability limited. Nevertheless, design and execution can be difficult (Figure 20).

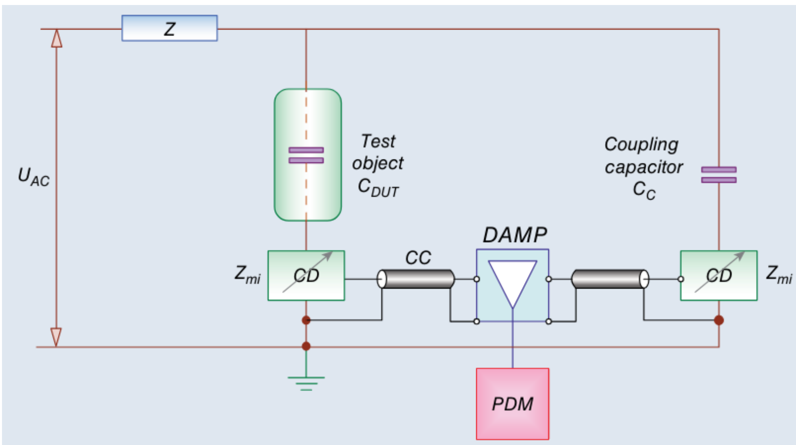

Figure 20. Balanced bridge PD measurement for noise suppression.

- Windowing: Uses the test voltage's phase angle to suppress noise signals. It works well to filter out noise during a designated window of time, and its movable windows can adjust to different noise levels. PD signals, however, can be overlooked if noise and PD signals happen at the same time. Furthermore, windowing can only be used under standards that limit deactivated measurement time slots (Figure 21).

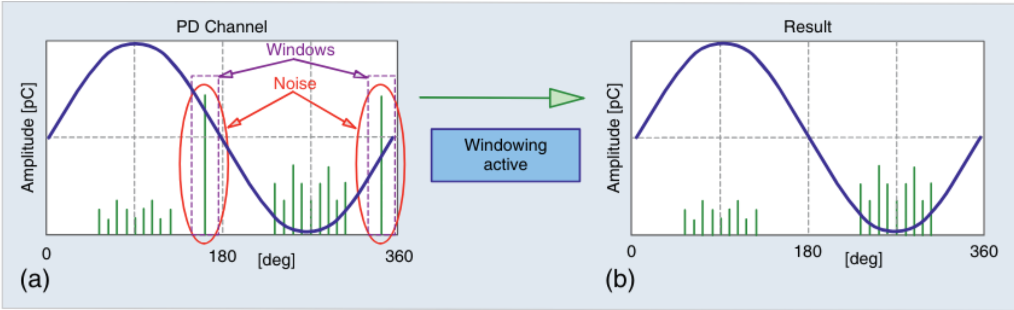

Figure 21. PD pulse diagram with (a) noise and related window positions and (b) PD pulse diagram with activated windows.

- Gating: By sensing stochastic noise using a second channel and turning on gating circuitry, gating suppresses it. When applied to stochastic noise sources, this technique works quite well, and inverse gating can guarantee that PD signals are measured even in noisy settings. The drawbacks include the requirement for an extra gating channel and associated logic software, as well as the possibility of decreased efficacy in cases where the noise properties closely resemble the PD signals (Figure 22).

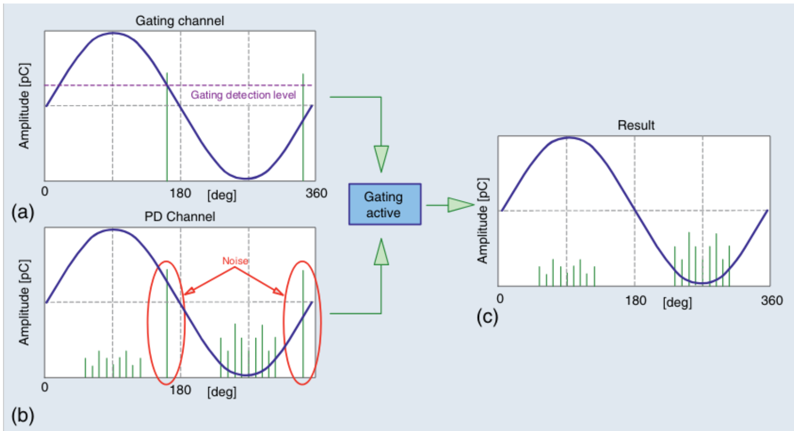

Figure 22. PD pulse diagram with (a) gating signals, (b) noise, and (c) PD pulse without noise at active gating.

- Clustering: Divides PD signals and noise according to their distinctive characteristics using sophisticated digital signal processing. This technique is quite good at distinguishing between noise and other PD sources, allowing clusters to be visualized for simpler processing and identification. But it needs fully digital measurement devices with sophisticated postprocessing capabilities, and the accuracy of the measurement relies on the quantity of collected data points and the performance of the clustering algorithms (Figure 23).

The choice of denoising technique depends on the kind and source of noise as well as the particular needs of the PD measuring setup. Each denoising method has pros and cons of its own [1, 34, 35, 36, 39].

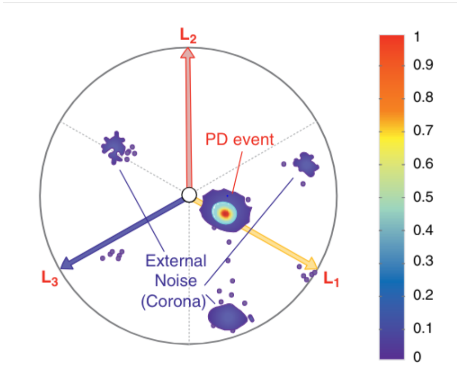

Figure 23. Three-phase star diagram with three typical clusters (blue) for each phase due to external noises as well as a single cluster (colored), indicating that a PD defect is located in phase L1 of the investigated power transformer.

2.2.7 Calibration:

The test item and the full PD test circuit must be calibrated, but the high-voltage source must be switched off. Recalibration is necessary whenever a circuit component is changed.

A calibrator generates unipolar step voltage pulses with conditions:

- Charge uncertainty: ±5% or 1pC
- Rise time uncertainty: ±10%
- Pulse frequency uncertainty: 1%

Finding the scale factor (Sf), which is the ratio of the reading value (Mc) from the measuring device to the proper apparent charge (Qa), is the aim. A reference response is generated by the calibrator pulse and is compared to the given charge. The scaling factor is computed as

$$Sf = Q0/Mc \tag{2.1}$$

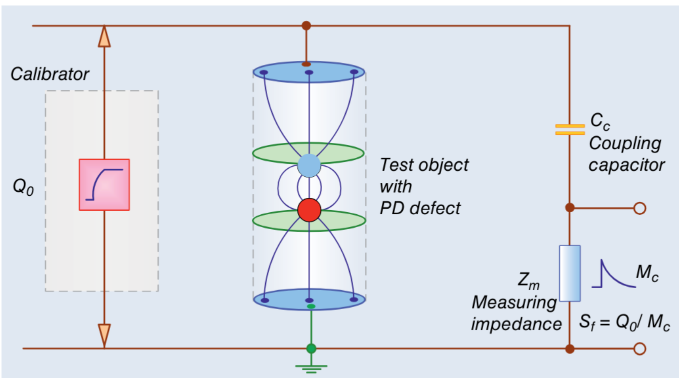

Figure 24. Equivalent circuit for calibration.

For PD testing, the measured charge (Mp) is used with the scale factor to calculate the apparent charge:

$$Qa = Sf * Mc \tag{2.2}$$

Calibration involves specific pulse characteristics:

- Rise time: 60ns
- Time to steady state: 200ns
- Step voltage duration: 5s
- Voltage deviation: 0.03 U0
- Fall time: 100s

To reduce errors caused by stray capacitances, calibration should inject pulses across the test object terminals, preferably near the high-voltage terminals. Calibration capacitance for test objects, such as power cables longer than 200 meters, should not be greater than 1nF [30, 31, 33, 32, 40].

2.3 Electromagnetic Methods for PD Detection

Electromagnetic (EM) waves in the high-frequency (HF), very-high-frequency (VHF), and ultra-high-frequency (UHF) ranges, from 3 MHz to 3 GHz, are produced by partial discharge (PD), which generates incredibly fast pulse currents. HF/VHF PD measurement and UHF PD measurement are the two main categories into which EM PD measurement falls in practice. The test equipment that is available plays a major role in selecting between these procedures. Furthermore, the type of sensor, instrumentation, and measuring methods, in addition to other variables, affect the PD test findings, as does the EM wave from the PD source. The parameters required or anticipated for the process of measurement, analysis, and interpretation define these factors.

2.3.1 PD Measurement by HF and VHF Sensors:

Capacitive Couplers:

A high-voltage coupling capacitor is used by capacitive couplers to identify PD signals. They use a measurement impedance (resistor and inductor) to transform the PD signals into voltage after capturing them via the coupling capacitor. The lower cutoff frequency of the high-pass filter created by the coupling capacitor and measurement impedance has an impact on the recorded PD signals. To monitor PD activity, capacitive couplers produce a high-pass filter with a particular lower cutoff frequency (flo). Their main purpose is to

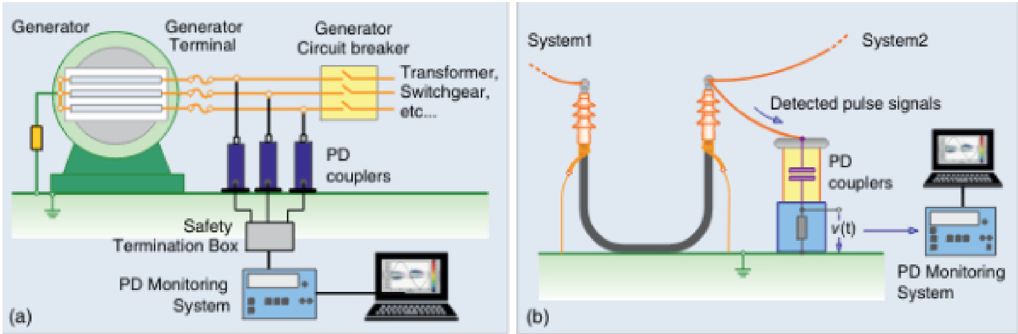

Figure 25. CCs for on-line PD measurement of (a) rotating machine; (b) underground cable system.

perform online PD measurements. Using two or one CC per phase, PD measurement with CCs can be carried out [30, 31, 33].

- Advantages: Non-intrusive and versatile, suitable for various equipment. High accuracy in detecting small PD signals.
- Limitations: Prone to external electromagnetic interference. Requires careful calibration and installation. High-frequency components may experience attenuation and distortion.

Inductive Couplers:

Partial discharge (PD) currents are detected by inductive couplers, such as Rogowski coils and high-frequency current transformers (HFCT), through inductive coupling. They use the PD current in the primary conductor to create a voltage in a secondary coil. Since the induced voltage is usually modest and needs to be amplified, it is proportional to the rate of change of current (di/dt). By sensing only alternating or transitory currents without making direct electrical contact with the wire, inductive couplers function as high-pass filters. For both online and offline PD measurements, they are frequently utilized [34, 35, 36].

- Advantages: Non-intrusive and safe, requiring no direct contact. High sensitivity and wide bandwidth, suitable for detecting fast transient PD events.
- Limitations: Susceptible to electromagnetic noise, needing proper shielding. Effectiveness can vary with installation environment.

PD Measurement by Direct Coupling Systems (DCS)

A Directional Coupler Sensor (DCS) is a passive tool that may be used for both online and offline PD measurements in the frequency range of 2–500 MHz. It is used to monitor PD in subterranean cables and joints. Depending on the way PD pulses propagate, the DCS couples the energy they produce to different output ports. An output is produced at one

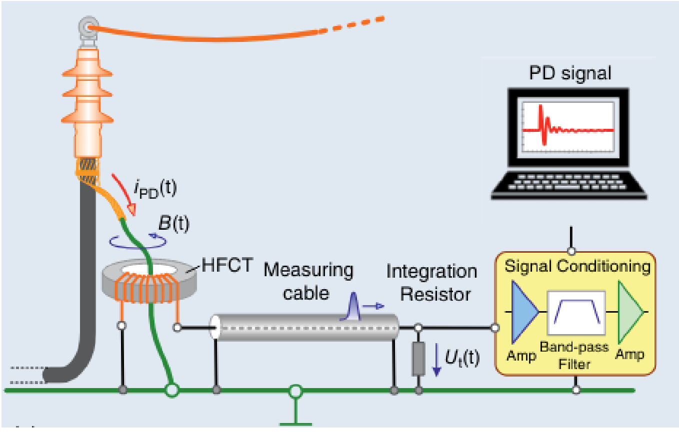

Figure 26. Application of HFCT for PD measurement of underground cable (a) diagram; (b) on-site underground PD measurement.

port by energy moving in one direction, while an output is produced at a different port by energy moving in the opposite direction [39, 40]. Key characteristics:

- Coupler Factor: Shows how well the DCS can couple energy from PD signals. Greater coupling capabilities are exhibited by larger DCS devices; however, signal pickup may be diminished by increased conductivity and/or thicker insulation.
- Directivity: The DCS's capacity to compare the voltage amplitudes at each port in order to ascertain the direction of the PD pulse

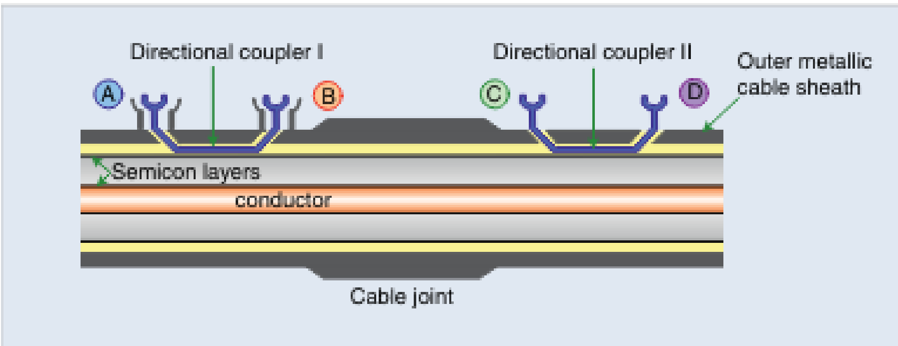

Figure 27. Principle setup of two DCS applied for PD measurement of cables and joints

Application for Cable and Joint PD Measurement

To find and quantify PD signals in and around cable junctions, DCS devices are employed. Installed on opposing sides of the cable connection, they are shielded from outside noise by the outer metallic sheath. The left side of the joint generates PD signals, which couple to ports A and C, while the right side couples to ports B and D. PD signals inside the body couple to port C.A fake PD pulse is injected at one port, and the output is measured at other ports to confirm the performance. For example, if a pulse is applied to DCS 1's port

B, DCS 2's ports C and D will measure the output. The outputs are measured at ports A–D if the PD source is inside the joint; port B has a greater signal than port A, and port C has a higher signal than port D. The outputs at ports A and C are higher than those at ports B and D when the PD source is located on the left side of the joint. Accurate localization and detection of PD activity in cable junctions are guaranteed by this configuration [34, 35, 36].

2.3.2 PD Measurement by UHF Method:

Theory

Ultra-high-frequency (UHF) sensors are an efficient way to detect high-frequency electromagnetic (EM) waves released by partial discharges (PD) in high-voltage equipment. Because of its excellent signal-to-noise ratio and high sensitivity, this approach is beneficial for identifying Parkinson's disease (PD) in noisy surroundings. While UHF PD measurements preclude traditional calibration in accordance with IEC 60270 standards, this method is especially helpful for online and on-site PD monitoring.
The high-voltage equipment's structure and design have an impact on the attenuation of UHF signals produced by PD occurrences. Signal attenuation is caused by elements such as the skin effect, which results in energy loss because of metallic enclosures' resistance, and internal barriers within the device. Compared to simpler designs, compact designs with multiple internal barriers show higher attenuation. For UHF PD measurement devices to be effective, it is vital to comprehend these variables [30, 31, 33].

UHF Sensors:

UHF sensors, which are essential for PD detection, are classified as internal or external, depending on where they are installed. Disc, cone, and loop sensors are examples of internal sensors that are installed into high-voltage equipment throughout the production process to provide continuous electromagnetic field monitoring. For continuous PD detection and diagnosis, these sensors are perfect. External sensors, on the other hand, can be installed on existing equipment and are used for periodic readings, providing flexibility without requiring significant alterations. They come in especially handy for upkeep and inspection [34, 35, 36].

UHF PD Measurement System:

A UHF PD measurement system's sensitivity and bandwidth influence how effective it is. For on-site and online measurements, narrow-band frequency domain approaches are the best due to their higher PD sensitivity and superior noise suppression. Verifying sensitivity

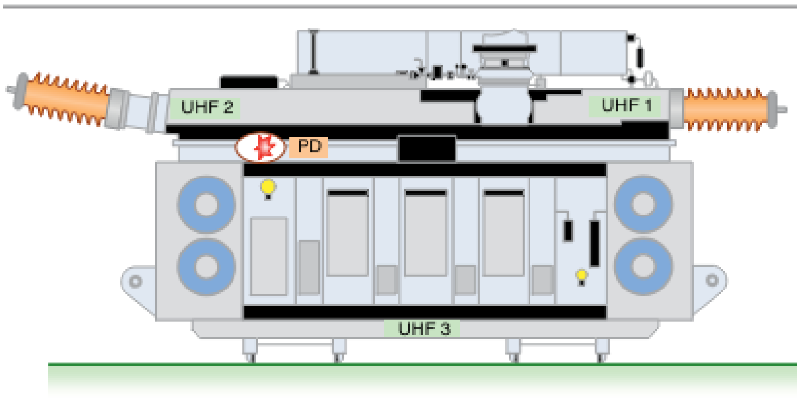

Figure 28. UHF sensor positions of the investigated power transformer.n

is an essential component, particularly for gas-insulated lines (GIL) and substations (GIS). In order to confirm that on-site UHF sensors can detect PD signals at the necessary levels, this verification entails creating an artificial PD pulse in a lab, calibrating its amplitude to match a known reference, and using this calibrated pulse [39, 40].

Applications:

Transformers, GIS, GIL, and other complicated electrical systems are among the high-voltage equipment types that can be measured using UHF PD systems. In GIS and GIL systems, UHF sensors identify flaws like interior protrusions, voids, and moving particles by detecting PD. On-site detection is improved by locating PD events through the analysis of detected electromagnetic waves. When used in conjunction with acoustic sensors, UHF PD measurement in transformers enables both on-site and online monitoring to identify PD sources and evaluate the health of the transformer. Furthermore, novel sensor types have been developed for PD detection in generator slots, such as the stator slot coupler (SSC), extending the applicability of UHF PD measurement to high-voltage equipment and rotating machinery [34, 35, 36].

2.4 Optical PD Measurement

2.4.1 Theory

PD events in gas media, notably corona discharges, often occur at point electrodes, sharp edge electrodes, and surface roughness on conductors due to gas ionization. This ionization releases energy in the form of ultraviolet light (UVA–UVC) and audio signals. Intense corona discharges can be observed in the dark after the observer's vision adjusts. The light spectrum emitted by corona discharge depends on the surrounding medium and discharge energy, ranging from ultraviolet to infrared. In air, the optical spectrum of

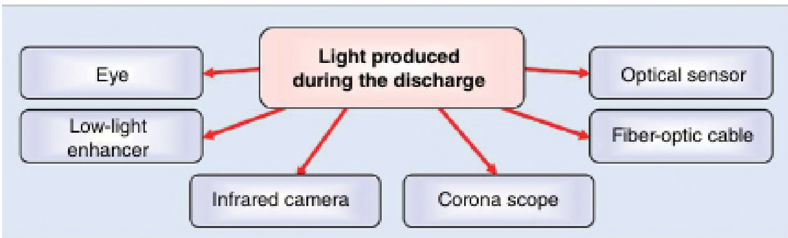

Figure 29. Approaches and devices for optical PD measurement

corona discharges is dominated by nitrogen, while in oil-immersed transformers, hydrogen provides the main optical spectrum with some infrared. The light spectrum from PDs in air typically falls within the ultraviolet range of 300–400nm and can be detected by a corona camera, useful for on-site inspection of high-voltage equipment. In contrast, the emission spectrum of discharges in SF6 gas insulation is in the ultraviolet and blue-green regions. Surface discharges produce a more complex light spectrum influenced by the solid material and surrounding gases. In liquid insulation like mineral oil, the emission spectrum is primarily formed by hydrogen and hydrocarbons, ranging from 350–700nm [41, 42, 43].

2.4.2 Principle

Optical PD detection, based on light generated during ionization, excitation, and recombination processes, is a challenging technique that can uncover the complex mechanisms of discharge. Different optical sensors and approaches are summarized in Figure 29. Corona cameras, used for detecting corona and surface discharges around conductors and high-voltage equipment, come in two types: nonsolar blind and solar blind. Nonsolar blind cameras, intended for nighttime use, are sensitive to UVa and UVb, making them ineffective during the day. Solar blind cameras, with filters that block most sunlight frequencies except UVc, can detect discharges in daylight. Corona cameras must meet specifications for minimum discharge detection, UV sensitivity, spectral range, and focus distance, alongside considerations for power consumption, display, data processing, and storage [44, 45, 46].
Recent developments in optical PD measurement for internal high-voltage equipment detection have used sensors like photomultipliers (PMTs), photodiodes, and optical fibers. Laboratory research compares optical PD measurement with conventional techniques per IEC 60270. Figures 30 show that optical PD detection can reveal fast-impulse PDs in liquid insulation systems, with rise times of about 5 ns and pulse durations of 20 ns. This technique can also detect PD signals in air excited by impulse test voltage, highlighting its advantages over conventional methods [47, 48, 49].

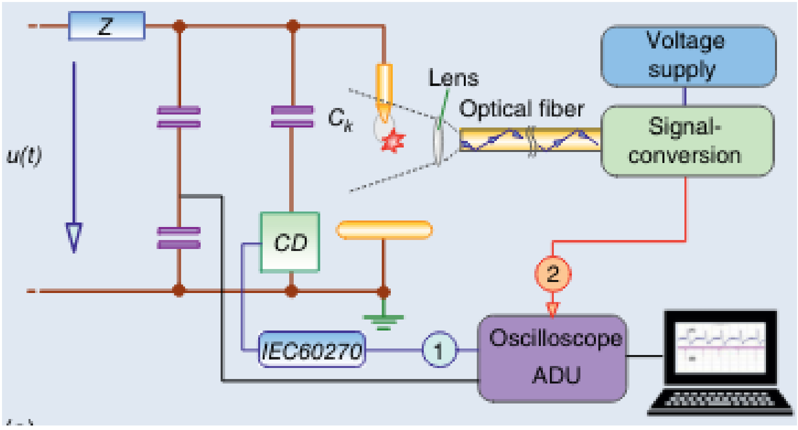

Figure 30. Laboratory PD detection by optical fiber with lens and conventional PD measurement(test circuit diagram)

2.4.3 Application

- Insulators, Transformer Bushings, Surge Arrestors, Transmission Lines, and Fittings: Corona cameras inspect corona and surface discharges around high-voltage parts of insulators, transformer bushings, surge arrestors, and transmission lines. Although corona may sometimes be visible in high-voltage stress areas, this is rare.
- Rotating Machines: Corona and surface discharges from the stator part of a rotating machine can be detected using a corona camera during hi-pot testing in the maintenance period [50, 51, 41].

2.5 Acoustic Emission PD Measurement

2.5.1 Theory

Partial discharge (PD) activity produces electromagnetic waves, acoustic waves, current PD pulses, and various byproducts. These transient acoustic signals arise from superheated gas bubbles, defective insulation, and "bouncing particles" within high-voltage equipment. The characteristics of Acoustic Emission (AE) PD signals depend on the PD source, propagation medium, and AE sensors used. Key parameters for analyzing AE signals include amplitude, rise time, frequency, pulse duration, and the number of AE PD pulses. Acoustic waves from PD sources generate wide-band AE signals, typically around 1 MHz, which can propagate through air and insulation materials, reaching sensors via direct propagation, internal barriers, or structure-borne paths [52, 53, 54].

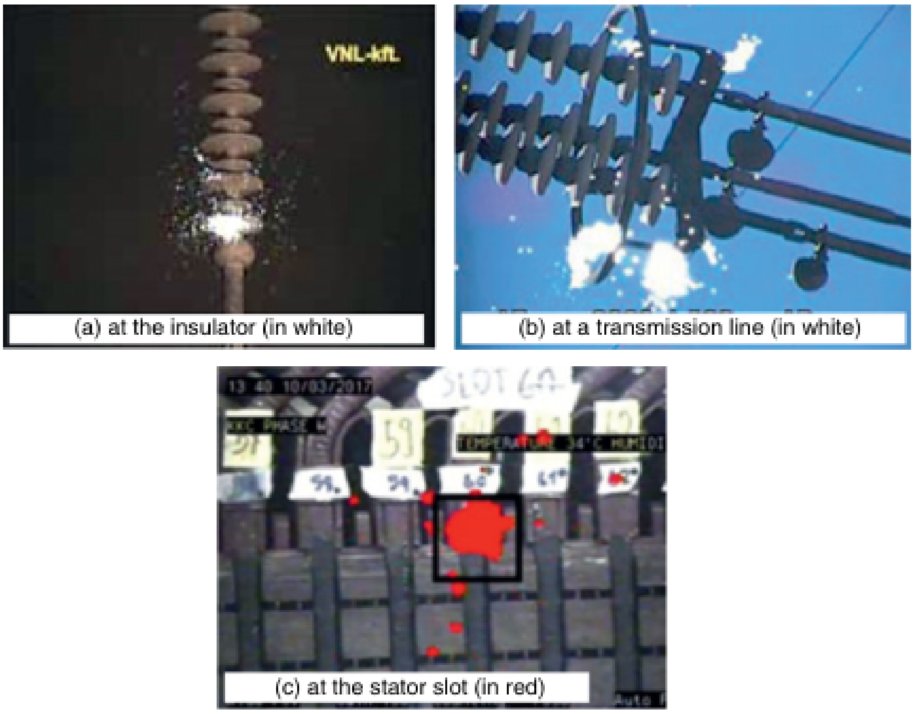

Figure 31. Application of corona discharge and surface discharge measurement by optical PD detection (a) at the insulator (in white); (b) at a transmission line (in white); (c) at the stator slot (in red)

2.5.2 Acoustic Receivers and Acoustic Sensors

There are two techniques for detecting AE PD signals: hand-held AE PD receivers and instrument-based AE detection.

Hand-Held AE PD Receivers:

Airborne Ultrasonic Probes: These probes detect ultrasonic waves emitted by corona discharge from high-voltage conductors and outdoor insulators. They convert ultrasonic signals (20 to 100 kHz) to audible ranges (100 Hz to 3 kHz) for analysis. An ultrasonic wave concentrator (UWC) can enhance sensitivity for long-distance detection. Ultrasonic Probe with a Pointed-Tip Extension: Used for detecting moving particles or loose components inside high-voltage enclosures (GIS, GIL), these probes detect AE PD signals through a pointed-tip extension pressed on the surface. The signals are then amplified and converted to audio for interpretation [55, 56, 57]. Based AE PD Detection

This technique involves attaching AE PD sensors to high-voltage components like transformers, GIS, GIL, and underground cables. It is often combined with other PD detection methods to confirm and locate PD sources. Sensors can be external, using piezoelectric materials like PZT, or internal, such as hydrophones using waveguide types [58, 59, 60].

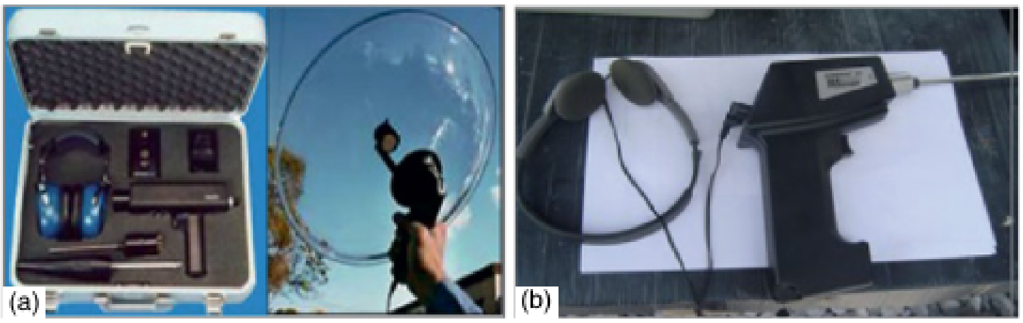

Figure 32. Hand-held AE PD receivers: (a) ultra-probe with its accessories and ultrasonic wave concentrator; (b) ultra-probe with a pointed tip

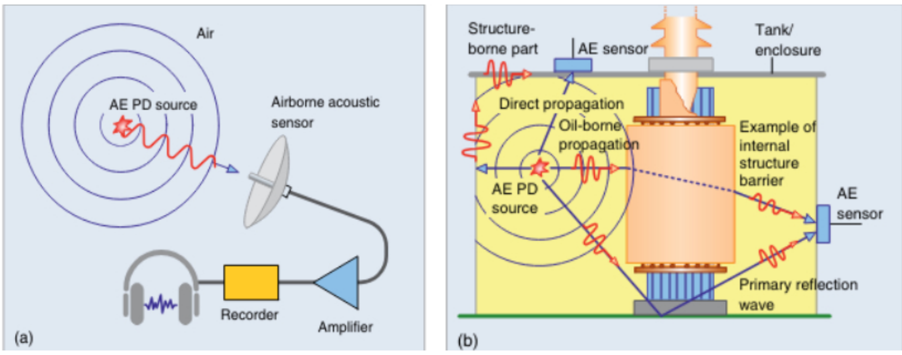

Figure 33. AE PD signal propagation in various media: (a) AE PD signal propagation through the surrounding air; (b) AE PD signal propagation inside a transformer tank.

2.5.3 General Idea for AE PD Measurement

Sensitivity Check for AE PD Measurement

The sensitivity check, recommended by IEC 62478, is performed similarly on-site and in laboratories. It establishes the relationship between the acoustic signal level and a known apparent charge in picocoulombs (pC) from a real PD source. This involves recording the frequency spectrum of the detected AE signal and using an artificial AE signal emitter for reference.

AE PD Measurement

AE PD measurement effectively detects external PD phenomena like corona and surface discharges in transmission lines and substations. For PDs within high-voltage apparatus, AE sensors detect signals transmitted to an AE measurement device for display, storage, and analysis. This method is non-destructive, quick to set up, and precise in identifying PD sources. However, it often needs to be combined with other PD detection methods to improve accuracy due to difficulties in correlating AE PD signals with electrical PD levels [61, 62, 63].

2.5.4 Application of Acoustic PD Measurement for High-Voltage Apparatus

Acoustic PD measurement detects corona and surface discharges from outdoor insulators or high-voltage conductors in AIS, transmission lines, and distribution systems. This is achieved using airborne ultrasonic probes or directional microphones. In transformers, AE PD sensors measure and localize PD, with internal sensors detecting higher-intensity signals compared to external sensors. For GIS and GIL, AE PD sensors detect PD signals from stationary defects and moving particles, ensuring accurate detection and localization of PD sources. This contributes to the reliability and safety of high-voltage electrical systems [64, 65, 66].

2.6 Chemical Byproducts

2.6.1 Theory

Partial Discharge (PD) activity generates measurable signals, including chemical byproducts. These byproducts tend to dissolve in the liquid insulation or react with a catalyst to form corrosive gases. Detecting and identifying these chemical byproducts can help identify PD problems in the insulation system of high-voltage equipment. The two main techniques used for this analysis are Dissolved Gas Analysis (DGA) and Decomposition Gas Analysis.

Dissolved Gas Analysis for Liquid Insulation

DGA is a standard diagnostic technique for detecting faults such as PD, arc discharge, or overheating in high-voltage apparatus using dielectric oils and oil-impregnated papers (OIPs) as insulation. During the degradation of liquid insulation, gaseous byproducts form and dissolve in the oil. Quantitative analysis determines the type and concentration of these gases, facilitating fault prediction and preventative measures. Common gases produced include hydrogen (H2), methane (CH4), acetylene (C2H2), ethylene (C2H4), ethane (C2H6), carbon monoxide (CO), and carbon dioxide (CO2). Additional gases like propylene (C3H6) and propane (C3H8) may also be required. The amount and type of gas generated depend on the oil temperature.

To perform DGA, the liquid dielectric must be sampled from the high-voltage apparatus. Gas extraction from the liquid sample is carried out using methods such as vacuum extraction, stripper column extraction, or headspace sampling. The extracted gases are introduced into a gas chromatograph for separation and individual detection. Finally, a

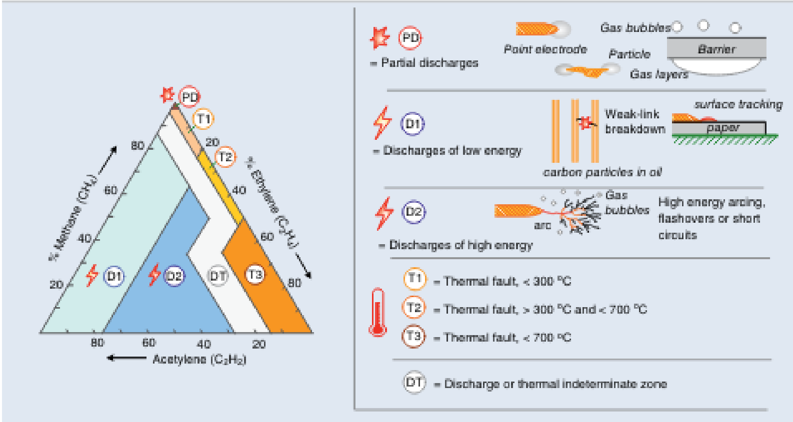

Figure 34. 9uval Triangle 1 applied for transformers filled with mineral oil and fault zones.

DGA interpretation scheme, like Duval Triangle or IEC ratios, is selected to interpret the data [67, 68, 69].

Decomposition Gas Analysis

Decomposition Gas Analysis is crucial for monitoring PD activity in gas-insulated high-voltage equipment. SF6 is commonly used in gas-insulated equipment due to its high dielectric strength and chemical inertness. PD, sparking, or arcing inside gas-insulated equipment causes SF6 gas to decompose, creating new chemical byproducts like SF4, SF2, SOF2, SO2F2, SOF4, SO2, H2S, HF, F, CF4, and CO2. The amount and rate of SF6 decomposition depend on parameters such as PD intensity, duration, electric field stress, and the presence of solid material.

Not all SF6 byproducts are suitable for determining PD activity. Suitable byproducts should increase with higher PD amplitude, intensity, and duration. Extremely unstable and highly reactive gases are unsuitable for determining PD activity levels.

2.7 PD Localization

2.7.1 PD Localization Techniques for the Internal Insulation

PD localization approaches for internal insulation, including pulse time arrival, auscultation, triangulation, and bouncing particle localization, are detailed below.

The Pulse Time Arrival

One method for localizing partial discharges (PD) in high-voltage equipment is the pulse time arrival (PTA) method. The time it takes for PD signals to travel from their source to several sensors positioned at certain places is measured using this technique. It is possible to triangulate the position of the PD source by timing the pulses' arrivals at these sensors. The PTA technique is predicated on the idea that electromagnetic waves pass through the apparatus at a set speed. The sensors pick up the EM waves as they radiate from the source during a PD event. The distance between each sensor and the PD source is computed using the difference in arrival times at each sensor. The precise position of the PD source within the apparatus is then ascertained using this information.

This method is highly effective for pinpointing the exact location of PD sources, which is critical for maintenance and repair activities. Accurate localization helps in identifying specific areas of insulation degradation, allowing for targeted interventions and reducing the risk of equipment failure.

The PTA method is particularly useful in complex high-voltage systems where direct visual inspection is not possible. It provides a non-invasive means of identifying potential issues before they lead to significant damage, enhancing the reliability and longevity of high-voltage equipment [70, 71, 72].

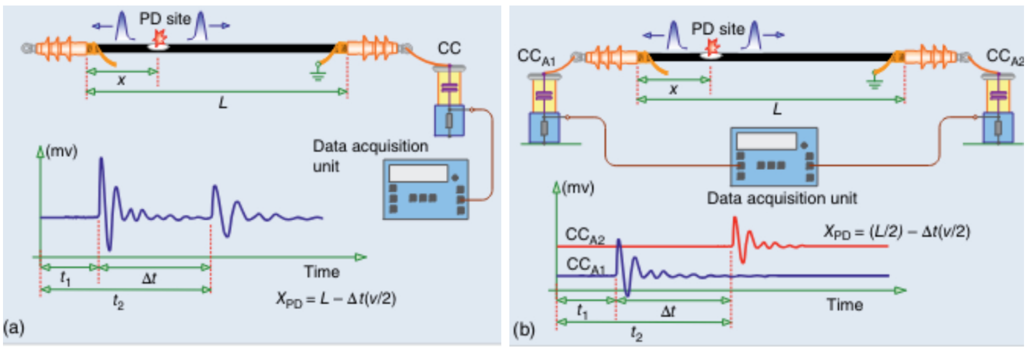

Figure 35. Application of the CC for PD measurement and PD localization (a) one CC per phase and (b) two CCs per phase.

Auscultatory Method

The Auscultatory Method employs one or more movable Acoustic Emission (AE) PD sensors to detect acoustic signals generated by partial discharges (PD). This technique is based on the principle that the detected AE PD signal attenuates in both magnitude and frequency as the distance between the sensor and the PD source increases. In other words, the further the sensor is from the PD source, the weaker the signal and the lower the frequency components detected. Additionally, the shape of the detected AE PD signal varies depending on the type of PD, the propagation medium, and the specific characteristics of the sensor and detection system components.

In practical applications, when one or more sensors detect PD activity, the sensors that detect weaker signals are moved closer to the source of the strongest signal to pinpoint the PD location. This method assumes the presence of a single PD source and requires the

sensors to be repositioned as close as possible to the suspected PD source.
For example, a High-Frequency Current Transformer (HFCT) and four AE PD sensors are utilized in a transformer. The external surface of the transformer has these sensors positioned at different locations. The closest sensor (AE1) picks up the strongest signal during a PD event, whereas the remaining sensors (AE2-AE4) pick up weaker signals. To verify that the identified signals are, in fact, related to Parkinson's disease, the HFCT simultaneously records the PD signal [73, 74, 75].

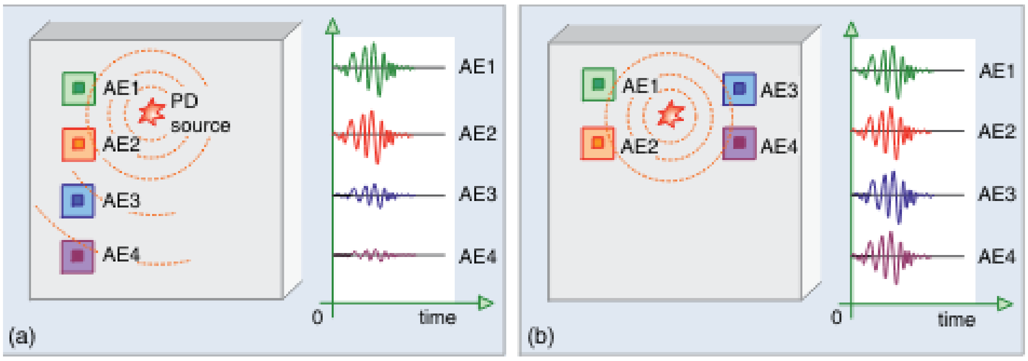

Figure 36. PD localization by the auscultatory method: (a) first stage to get AE PD signals with different intensity; (b) second stage after relocation PD sensors.

Triangulation Method

The process of triangulating the location of a partial discharge (PD) source involves using acoustic emission (AE) PD sensors and considering variations in the travel times of the AE PD signals. When a PD event occurs, signals propagate through the medium and reach the sensors at different times. Analyzing these time differences helps determine the exact location of the PD source. An electrical PD sensor is often paired with an acoustic AE PD sensor to accurately determine the origin time of PD events.
method is applied in a Cartesian coordinate system, where the positions of the sensors are represented in three-dimensional space. The traveling times of the PD signals are used to pinpoint the PD source by solving a set of equations. For transformers, UHF sensors are recommended by CIGRE 676, with at least four sensors positioned at known coordinates. In cases where only two UHF sensors are available, the suspected PD area is determined by solving another pair of equations.
complex structure of transformers and the characteristics of acoustic signals pose challenges for accurate PD source localization. Acoustic methods often suffer from uncertainties due to signal reflections and noise from the transformer tank walls, while AE PD sensors struggle to differentiate between mechanical sounds and true PD signals, making signal processing labor-intensive.

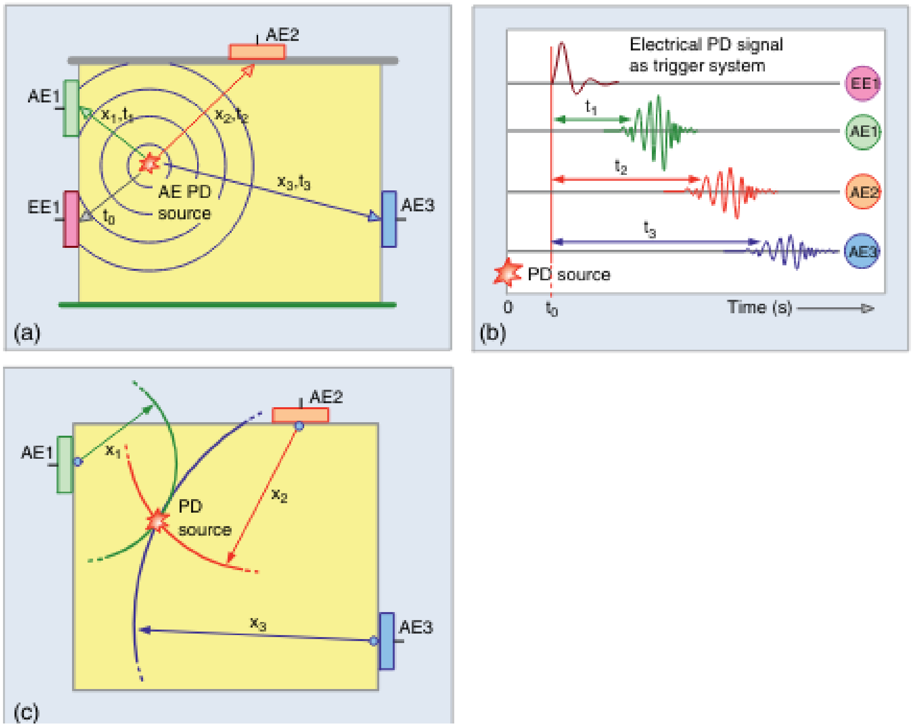

Figure 37. PD localization by the triangulation method: (a) AE PD sensors with an EE PD sensor for PD location; (b) EE PD and AE PD signals registered at the sensors with different times of flight;(c) PD position by triangulation method.

To simplify the localization process, the flat problem technique is employed, which involves scanning the suspected area with AE PD sensors and placing three sensors in a straight row on the transformer tank. This approach provides a more manageable way to achieve PD source localization while accommodating inherent complexities and limitations [76, 77, 64].

Bouncing Particle Localization Method:

An ultrasonic probe with a pointed tip is pressed against the GIS or GIL exterior surface to detect the AE PD signal produced by a bouncing particle. In order to detect the strongest AE PD signal where the suspected particle is located, the tip's position is adjusted. The detected ultrasonic wave's ultrasonic frequency range is then converted to an audio frequency range and sent to the headphones for interpretation [78, 79, 80].

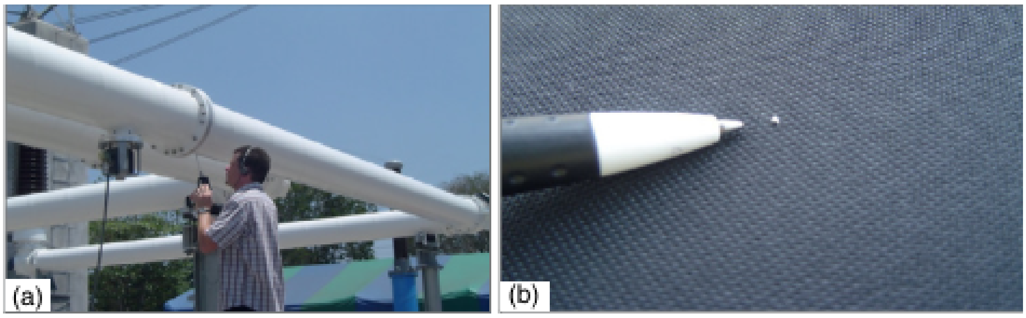

Figure 38. Application of the ultrasonic probe for detecting a bouncing particle (a) application of ultra-probe with a pointed tip used for field test; (b) zoom of particle found in GIL.

2.7.2 PD Localization Techniques for the External Insulation

The corona camera or airborne acoustic probe can be used for external insulation PD localization, offering superior optical and acoustic measurements compared to conventional electrical measurements. These methods require simple procedures to locate the PD source and are unaffected by electromagnetic interference, making them ideal for both onsite and online testing [74, 79, 75].

Application of the Corona Camera

Corona inspection can be conducted from various locations, including ground, insulated truck-mounted platforms, or airborne using helicopters or unmanned aerial vehicles (UAVs). The distance between observers and high-voltage equipment is determined by personnel safety. A corona camera can detect existing corona discharge or surface discharge, with UV emissions overlaying visible images. This method efficiently locates the source of PD, with UV radiation shown in white, red, or blue. Field tests using the corona camera can check for corona discharges and surface discharges [70, 78, 74].

Application of the Airborne Acoustic Probe

An airborne ultrasonic probe is commonly used to locate a potential discharge source for corona discharge or surface discharge of external insulation. The probe is pointed at the suspected source, providing the strongest AE PD signal. If the probe is long-distance, an ultrasonic wave concentrator is used to increase sensitivity. The detected ultrasonic wave is then down-sampled to the audio frequency range for interpretation [79, 80, 75].

2.8 Monitoring of PD Behaviour

Partial discharge (PD) measurement is a crucial technique for assessing the insulation integrity of high-voltage equipment. It plays a vital role in detecting localized defects during transportation and installation, as well as monitoring the aging process of the insulation system. PD presence can lead to equipment failure, making early detection of insulation problems essential for reliable operation.
PD monitoring increases the operational reliability of high-voltage equipment by observing PD behavior in insulation systems and detecting changes during operation. This process provides localized defect information and can reveal aging processes in rotating machines. Both off-line and on-line PD measurements are employed; off-line measurements are performed periodically, while on-line measurements can be conducted continuously. Insulation deterioration varies depending on material, PD types, service stresses, and operating conditions, so maintenance should allow adequate time to detect and address harmful PD signals to prevent equipment failure [1, 72].

2.8.1 OFF-Line PD Monitoring

Off-line PD monitoring of high-voltage equipment requires a separate power supply since the equipment is isolated from the power system during the process. Typically, PD measurements are conducted periodically based on a time-based maintenance strategy. However, if significant insulation deterioration is detected, the frequency of off-line PD measurements must be increased. Additionally, off-line PD monitoring is used to further investigate any unusual results obtained from on-line PD monitoring. The benefits and drawbacks of off-line PD monitoring are summarized below [1, 81, 71, 82].

Advantages:

- PD activity can be measured at various voltage levels and with different voltage waveforms.
- Critical information such as PD Inception Voltage (PDIV) and PD Extinction Voltage (PDEV) can be obtained, which is valuable for assessment.
- Off-line monitoring provides a baseline fingerprint of PD activity, facilitating further trend analysis.
- It offers a higher signal-to-noise ratio, leading to increased sensitivity and selectivity.
- Reliable criteria are provided to support the interpretation and diagnosis of PD test results.

Disadvantages:

- Requires an external voltage supply.
- Testing is time-consuming.
- It is expensive.
- The PD signals obtained are not influenced by the actual operating conditions of the high-voltage equipment.
- An outage is necessary to conduct the testing.

2.8.2 ON-Line PD Monitoring

On-line PD measurement is a widely accepted method for monitoring high-voltage equipment that is connected to the power system. The detected PD signals are influenced by various operating stresses, such as thermal, electrical, mechanical, and atmospheric conditions. On-line PD monitoring can be conducted in two ways: periodic and continuous. Periodical PD measurement is suitable for slow insulation deterioration or PD symptom failure, such as in rotating machines. In comparison, continuous PD will continuously be performed to acquire the stream PD data. Some PD sources are active at higher temperatures. On-line PD monitoring devices typically consist of a PD sensor and data acquisition unit. A signal transducer converts the detected signal into an information stream, and software characterizes the PD signal parameters. Special software is employed to monitor and trend the derived PD parameters, which are displayed on a display. The monitoring device generates an automatic warning if preset limits of the derived PD parameters or trends exceed the threshold.

Advantages:

- Suitable for power plants in remote, hard-to-access locations.
- Reduces risk for in-service high-voltage equipment in hazardous gas (Ex/ATEX) zones or other dangerous areas.
- Easier to trend PD data over time for real-time condition assessment, enabling detection of changes in PD activity.
- Provides an initial fingerprint of PD for the machine under operating conditions.
- No external power sources are needed, so there is no service interruption.
- Cost-effective.

Disadvantages:

- Noise and disturbances can affect the detected PD signal.
- May not obtain PD Inception Voltage (PDIV) and PD Extinction Voltage (PDEV).

- Different PD test results may arise from the same PD source when online PD monitoring employs different PD sensor types or varying analysis and diagnosis techniques.

Noise and disturbances in on-line PD monitoring can significantly impact PD test result analysis. However, advanced analog circuits and software algorithms can mitigate these issues effectively.
The CIGRE working group for gas-insulated switchgear (GIS) condition assessment recommends temporary continuous PD measurement, which offers certain advantages compared to periodic and continuous on-line PD measurement.
On-line PD measurement technology has advanced significantly, and experience in PD monitoring is growing. However, online PD diagnosis alone is insufficient to fully assess insulation conditions. Combining on-line PD data with off-line PD measurements, particularly PDIV and PDEV, enhances the reliability of PD diagnosis. Additional factors such as insulation type, load profile, and dielectric test results from various techniques are also crucial for accurate insulation condition assessment.
On-line PD monitoring data is regularly updated, while off-line PD data is updated only when new measurements are conducted, typically during scheduled testing. Different on-line PD sensors and technologies may yield varying diagnostic results, potentially leading to different interpretations of defect types or severity. Therefore, users must understand the accuracy of the PD test techniques and analysis tools to determine which measurements are the most reliable for making critical decisions [1].

2.9 In-House and On-Site PD Testing

An overview of PD testing for high-voltage equipment, covering the entire lifecycle from prototype development to the end of the equipment's operational life.

2.9.1 In-House PD Testing

In-house PD testing serves two main purposes: product research and development (RD) and product quality verification.

PD Testing for Product Research and Development:

PD testing is a critical component of the RD process in manufacturing high-voltage equipment. During this phase, prototype equipment is evaluated and adjusted to meet operating parameters and to identify potential improvements or modifications before full-scale production. For instance, PD testing is used to determine the optimal impregnation time in the transformer manufacturing process.

PD Testing for Product Verification:

Product verification is a crucial part of the in-house quality control process for final products. PD testing during this phase ensures that the final product will operate reliably and efficiently throughout its lifespan. This step is essential to confirm that the equipment meets all necessary performance standards before it reaches the market.

2.9.2 On-Site PD Testing

On-site PD testing is generally classified as either commissioning tests or diagnostic tests:

PD Commissioning Tests:

These tests are performed after the on-site installation of high-voltage equipment. The purpose is to determine whether any significant damage occurred during transportation and installation, ensuring the equipment is in good condition before it starts operation.

PD Diagnostic Tests:

These tests are conducted during scheduled maintenance and after major repair work. During maintenance, PD testing assesses the insulation condition. Data from the initial PD diagnostic test of newly installed equipment provides a set of reference values (a diagnostic fingerprint). After significant repairs, PD diagnostic testing ensures that the equipment is ready to return to service.

2.10 Standards

Several international standards and technical brochures from the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE), and the International Council on Large Electric Systems (CIGRÉ) provide comprehensive methodologies and best practices for partial discharge measurement and interpretation. These documents cover a range of equipment, including power transformers, cables, switchgear, and gas-insulated substations (GIS). They also address different measurement techniques, from conventional methods conforming to IEC 60270 to unconventional methods such as ultra-high frequency (UHF) and acoustic detection.
The following tables summarize key standards from IEC and IEEE, as well as technical brochures from CIGRÉ, relevant to partial discharge measurement. These references serve as essential resources for professionals involved in high-voltage equipment testing,

maintenance, and reliability assessment.

3.

Table 1. *IEC PD testing standards.*

No.	**Name**	**Year**
IEC 60270:2000+AMD1 CSV	High-Voltage Test Techniques – Partial Discharge Measurements (Consolidated Version)	2015
IEC TS 62478	High Voltage Test Techniques – Measurement of Partial Discharges by EM and Acoustic Methods	2016
IEC TR 61294	Insulating Liquids – Determination of the Partial Discharge Inception Voltage (PDIV) – Test Procedure	1993
IEC 60076-3:2013+AMD1: CSV	Power Transformers – Part 3: Insulation Levels, Dielectric Tests, and External Clearances in Air (Consolidated Version)	2018
IEC 60034-27-1	Rotating Electrical Machines – Part 27-1: Off-line Partial Discharge Measurements on the Winding Insulation	2017
IEC 60034-27-2	Rotating Electrical Machines – Part 27-2: On-line Partial Discharge Measurements on the Stator Winding Insulation of Rotating Electrical Machines	2012
IEC/TS 61934	Electrical Insulating Materials and Systems – Electrical Measurement of Partial Discharges (PD) under Short Rise Time and Repetitive Voltage Impulses	2011
IEC 60034-18-41:2014+AMD1 CSV	Rotating Electrical Machines – Part 18-41: Partial Discharge Free Electrical Insulation Systems (Type I) Used in Rotating Electrical Machines Fed from Voltage Converters – Qualification and Quality Control Tests (Consolidated Version)	2019
IEC 60885-2	Electrical Test Methods for Electric Cables. Part 2: Partial Discharge Tests	1987
IEC 60885-3	Electrical Test Methods for Electric Cables – Part 3: Test methods for Partial Discharge Measurements on Lengths of Extruded Power Cables	2015

Continues...

Table 1 – *Continues...*

No.	Name	Year
IEC 62271-203	High-Voltage Switchgear and Controlgear – Part 203: Gas-Insulated Metal-Enclosed Switchgear for Rated Voltages above 52kV	2011

3.

Table 2. *IEEE PD testing standards.*

No.	Name	Year
IEEE C57.113	IEEE Recommended Practice for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors	2010
IEEE C57.127	IEEE Draft Guide for the Detection, Location and Interpretation of Sources of Acoustic Emissions from Electrical Discharges in Power Transformers and Power Reactors	2018
IEEE 436	IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers	1991
IEEE C57.124	IEEE Recommended Practice for the Detection of Partial Discharge and the Measurement of Apparent Charge in Dry-Type Transformers	1991
IEEE C57.160	IEEE Guide for the Electrical Measurement of Partial Discharges in High-Voltage Bushings and Instrument Transformers	2018
IEEE 1434	IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery	2014
IEEE 2862	IEEE Approved Draft Recommended Practice for Partial Discharge Measurements under AC Voltage with VHF/UHF Sensors during Routine Tests on Factory and Pre-molded Joints of HVDC Extruded Cable Systems up to 800 kV	2020
IEEE 400.4	IEEE Guide for Field Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current (DAC) Voltage	2015

Continues...

Table 2 – *Continues...*

No.	Name	Year
IEEE 400.2	IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)(less than 1 Hz)	2013
IEEE 400.3	IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment	2006
IEEE C37.301	IEEE Standard for High-Voltage Switchgear (Above 1000 V) Test Techniques – Partial Discharge Measurements	2009
IEEE C37.122.1	IEEE Guide for Gas-Insulated Substations Rated Above 52 kV	2014
IEEE 1291	IEEE Guide for Partial Discharge Measurement in Power Switchgear	1993

3.

Table 3. *CIGRE technical brochures for PD testing.*

No.	Name	Year
662	Guidelines for Partial Discharge Detection Using Conventional (IEC 60270) and Unconventional Methods	2016
502	High-Voltage On-Site Testing with Partial Discharge Measurement	2012
444	Guidelines for Unconventional Partial Discharge Measurements	2010
366	Guide for Electrical Partial Discharge Measurements in Compliance to IEC 60270	2008
226	Knowledge Rules for Partial Discharge Diagnosis in Service	2003
676	Partial Discharges in Transformers	2017
581	Guide – Corona Electromagnetic Probe Tests (TVA)	2014
728	On-Site Partial Discharge Assessment of HV and EHV Cable Systems	2018

Continues...

Table 3 – *Continues...*

No.	**Name**	**Year**
297	Practical Aspects of the Detection and Location of PD in Power Cables	2006
674	Benefits of PD Diagnosis on GIS Condition Assessment	2017
654	UHF Partial Discharge Detection System for GIS: Application Guide for Sensitivity Verification	2016
525	Risk Assessment on Defects in GIS Based on PD Diagnostics	2013
703	Insulation Degradation under Fast Repetitive Pulses	2017

Chapter 3 Results and Discussion

3.1 Introduction

After covering the theoretical aspects, we proceeded to initiate our experiments. Following an extensive search in the industrial sector and consulting with numerous experts, we regretfully discovered that this type of testing is not available in Algeria. Consequently, we divided the work into two main parts. The first part focused on learning how to interpret data from various webinars hosted by internationally renowned companies with extensive experience in the field, such as Omicron, Doble, EA Technology, and Megger. The second part was a long vist to the filed and it involved observing factory acceptance tests for equipment such as transformers, cables, and various diagnostic tools.

3.2 Webinars session

After attending numerous online webinars, we have gained a comprehensive understanding of various PD patterns and the methods for analyzing Phase-Resolved Partial Discharge (PRPD) patterns. The analysis are made according to EA [83]

3.2.1 Phase-Resolved Partial Discharge

Partial Discharge (PD) patterns are critical for analyzing the health of high-voltage insulation systems. Two primary types of PD patterns are used for problem analysis: phase-resolved PD (PRPD) and PD pattern with polarity count. The PRPD technique is generally preferred because it can be applied to almost all types of high-voltage equipment. In contrast, the PD pattern with polarity count is specifically useful for analyzing PD problems in rotating machines, as the number of PD pulses (both negative and positive) can indicate the location of PD within the insulation system.

The PRPD pattern consists of the apparent charge amplitude (q) and the phase angle (Ø) of the PD pulse at a specific test voltage. Typically represented as a two-dimensional plot, this pattern shows the amplitude of the apparent charge in relation to the phase position. Recently, a three-dimensional PRPD pattern has been proposed, which includes the apparent charge amplitude, the phase position, and the number of PD pulses registered during the test, indicated by color.

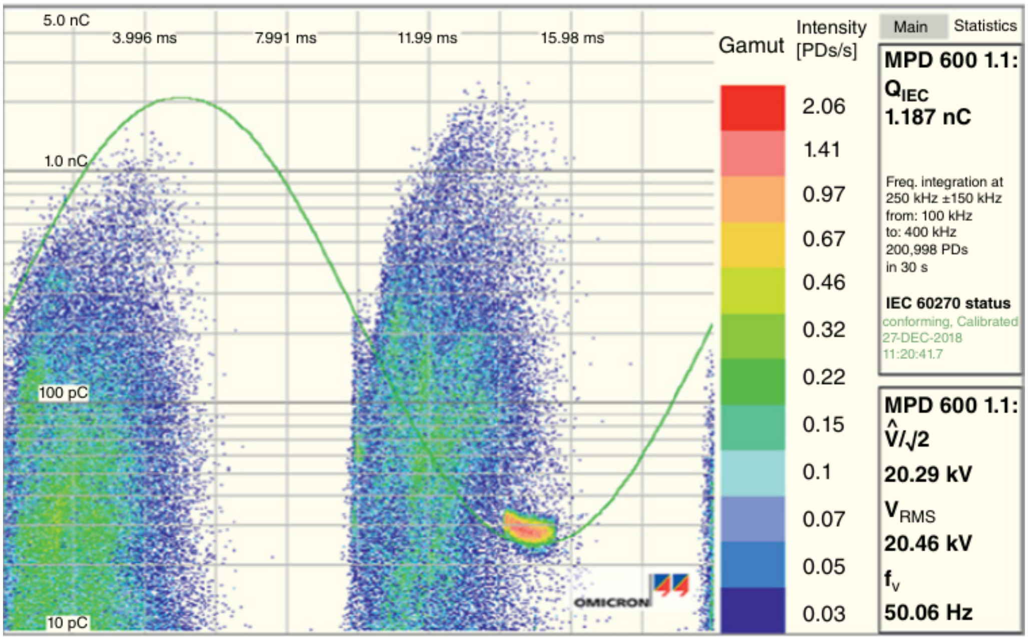

Figure 39. PRPD pattern (omicron).

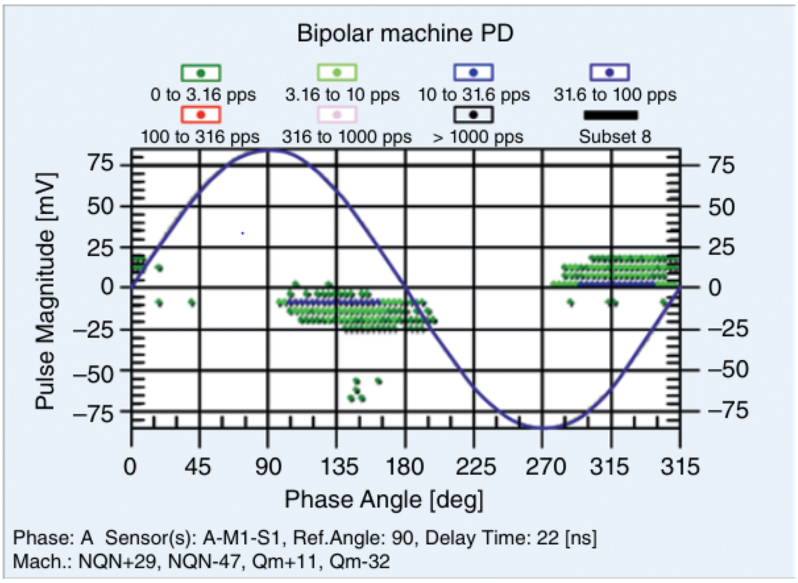

Figure 40. PD pattern with polarity count for problem analysis (IRIS)

3.2.2 PD patterns for Electromagnetic detection

Internal void, single phase

The first type of discharge shown in figure 41 is an internal void single-phase discharge. It is single-phase because there is one pair of clusters, 180 degrees apart. The discharge occurs within the bulk of the insulation, indicated by the consistent amplitude on both halves of the cycle.

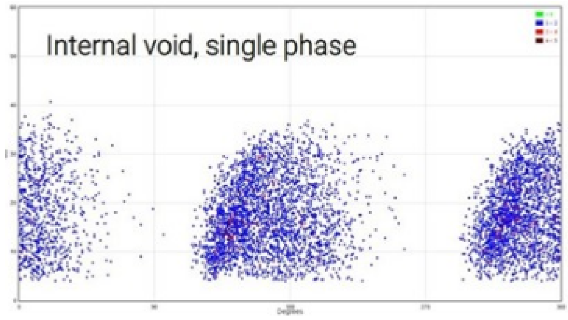

Figure 41. PRPD of an Internal void, single phase acc. EA

Characteristics of internal void discharges include:

- A wave-like pattern.
- More intense front ends of the clusters, known as the leading edge, determined by the cavity's dimensions and physical characteristics.
- A trailing cluster caused by the byproducts of the discharge remaining in the cavity and not dissipating immediately.

If two wave clusters are observed 180 degrees apart with a low repetition rate (1-3 pulses per cycle), it signifies a classic internal solid insulation internal void discharge.

PD inside oil filed transformer

The figure 42 shows partial discharge (PD) inside an oil-filled transformer. This pattern is important for testing transformers and oil switchgear. In oil PRPD patterns, the discharge occurs in fluid insulation, not in a defined cavity. This results in the formation of bubbles around the discharge site and lacks the surface charge buildup typical in solid insulation.

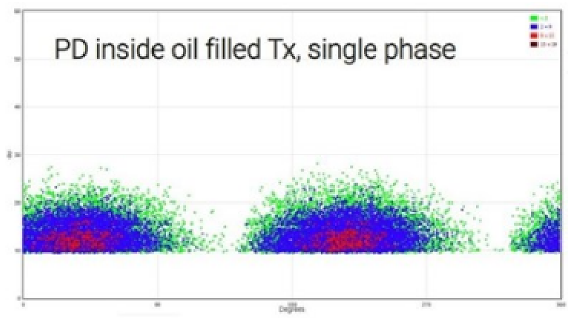

Figure 42. PRPD of a PD inside oil filed transformer acc. EA

Key characteristics of PD in oil-filled transformers include:

- A cloud-like structure with two sets of clusters, 180 degrees apart.
- Higher intensity in the center of the cloud.
- Relatively high amplitude.
- A higher discharge rate, with intensity levels ranging from 9 to 15 pulses at specific points.

In contrast, internal void discharges in solid insulation have a lower discharge rate, with intensity levels of 2 to 4 pulses. The presence of a cloud shape with high intensity in the middle suggests discharge activity within the oil insulation. This can be further verified through a Dissolved Gas Analysis (DGA) test.

Contact/ Floating point metalwork

The figure 43 shows a contact or gap type discharge involving floating metalwork. In this scenario, there is a defined gap between two conductors, leading to a breakdown and discharge similar to a capacitor. Unlike enclosed cavities, there is no surface charge buildup or changes in amplitude caused by a semiconductor layer.

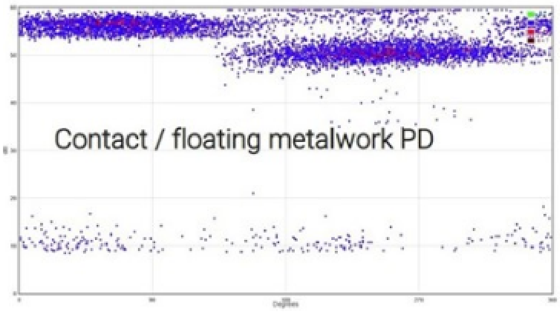

Figure 43. PRPD of a Contact/ Floating point metalwork acc. EA

Key characteristics of contact or gap type discharge include:

- Very flat lines across 180 degrees, as the discharge occurs at almost the same amplitude each time.
- Consistent amplitude across cycles due to the absence of surface charge buildup.

This type of discharge can vary in significance depending on the application. In some switchyards, it may not pose a problem, while in other instances, it can be significant. The discharge pattern is also influenced by whether the discharge occurs over a flat surface or specific point areas. Overall, contact floating metalwork type PD is characterized by two large flat lines.

Internal void, near earth or phase conductor

The figure 44 shows the effect of a void located near either the earth or the phase conductor. In this instance, the first cluster is dominant while the second cluster is almost non-existent.

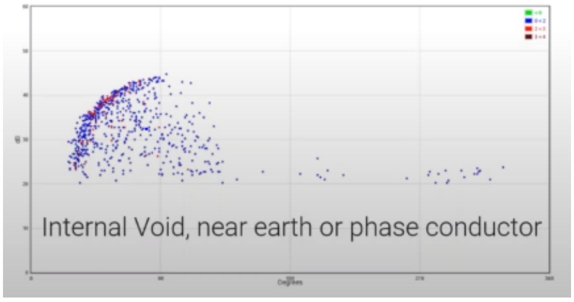

Figure 44. PRPD of an Internal void, near earth or phase conductor acc. EA

Key characteristics of this discharge include:

- Dominance of the first cluster.
- Near absence of the second cluster.

This pattern indicates that the void is close to either the earth or the phase conductor. While this information might not be directly useful for rectifying the problem, it provides additional insights for diagnosing the situation. Understanding the void's proximity to the conductor helps in building a comprehensive diagnosis of the discharge activity.

3.2.3 PD patterns for Ultrasonic detection

Corona discharge

The figure 45 shows a corona discharge pattern. This type of discharge occurs on just one half of the cycle, consistently.

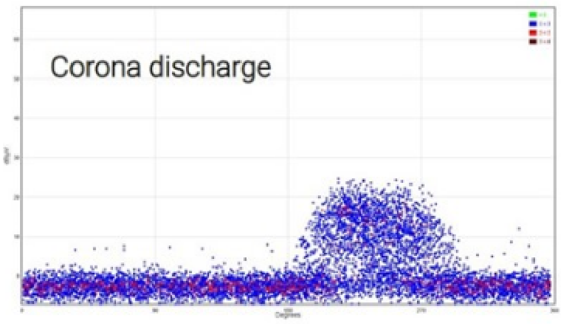

Figure 45. PRPD of a Corona discharge acc. EA

Key characteristics of corona discharge include:

- Activity on only one half of the cycle.
- Consistent pattern.

This pattern is a clear indicator of corona discharge. Additionally, corona discharge produces a deeper sound if you are listening to it.

Surface discharge

The main distinction with surface discharge is between single-phase and multi-phase discharges, determined by the length of the clusters.

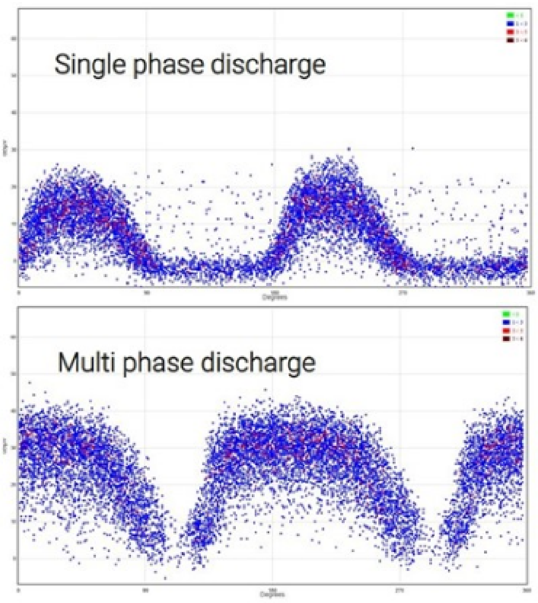

Figure 46. PRPD of a Surface discharge acc. EA

Key characteristics include:

- Single-phase surface discharge: Exhibits sharp clustering with distinct off periods. It occurs over shorter periods within the 360-degree cycle.
- Multi-phase surface discharge: Shows extended clustering periods, occurring over longer periods within the 360-degree cycle due to the involvement of more than one phase.

Single-phase discharges have longer off periods compared to multi-phase discharges. Both types involve high levels of discharge and numerous pulses, with surface tracking being a common feature.

Gap / Contact discharge

The contact discharge detected using the electromagnetic technique, which occurs across a gap, is also observable with ultrasonic methods. This is because an air path is typically present beside the problem area.

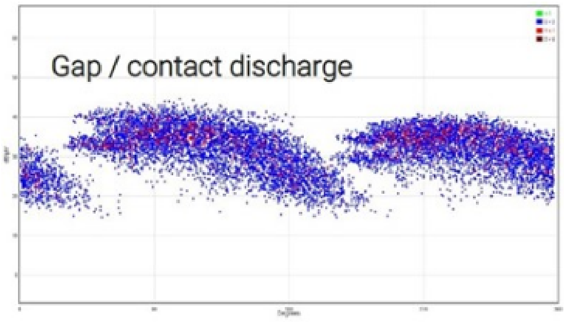

Figure 47. PRPD of Gap / Contact discharge acc. EA

Key characteristics of contact discharge include:

- Relatively long flat lines of activity on both halves of the cluster.
- Occasional slight curving, but generally flat.

These long flat lines indicate contact floating metal work and type discharge. This pattern can be observed consistently in both electromagnetic and ultrasonic detection methods.

3.2.4 Case studies

Case study 1:

This is Case Study Number One, involving an ultrasonic test using a flexible microphone within an air-insulated chamber. The phase plot reveals a contact PD across a gap caused by surface PD, detectable by the ultrasonic microphone.

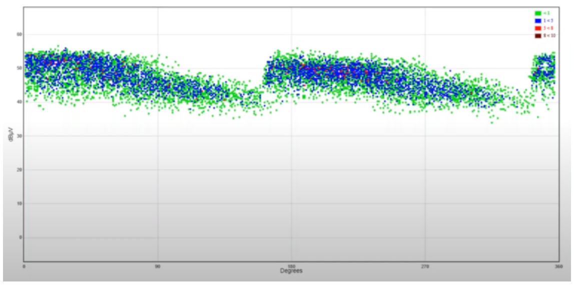

Figure 48. PRPD of case study 1

Key observations include:

- Rectangular shapes in the PD plot: Indicate sparks jumping across the gap.
- The phase plot shows involvement of a second phase, extending across the plot.

The phase plot suggested a contact type problem, likely phase-to-phase, which was confirmed upon inspection. This highlights a phase-to-phase contact issue that will get worst over time, potentially burning through insulation and causing further problems. This case study effectively demonstrates the identification and confirmation of surface PD and contact problems using phase plots and visual inspection.

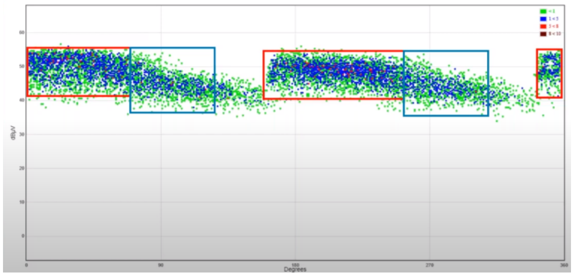

Figure 49. Interpretation of PRPD of case study 1

In this case, visual inspection confirmed the cause of PD: reduced clearances between two 11 kV conductors at a cable termination. The outside of these terminations started to discharge towards each other. This is evident in the center photograph, where white dags of material grow towards each other.

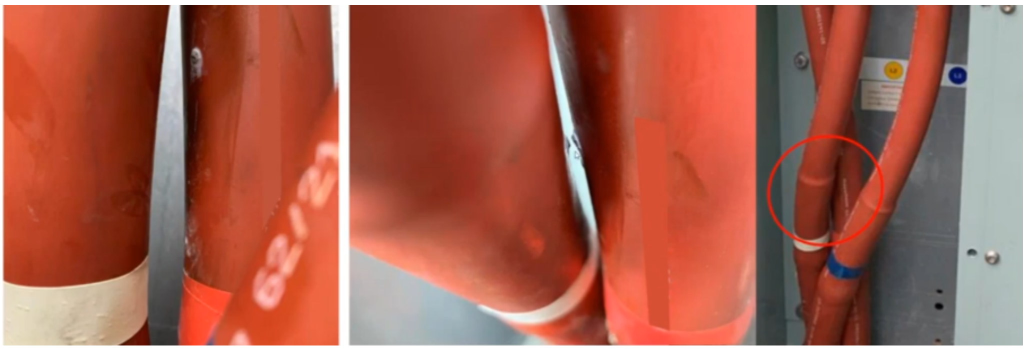

Figure 50. Visual inspection of case study 1

Case study 2

This is Case Study Number Two, involving an electromagnetic TEV test on a pitch-filled 11 kV cable box. The phase plot reveals five internal voids, all on the same phase, indicating a single-phase problem with multiple voids.

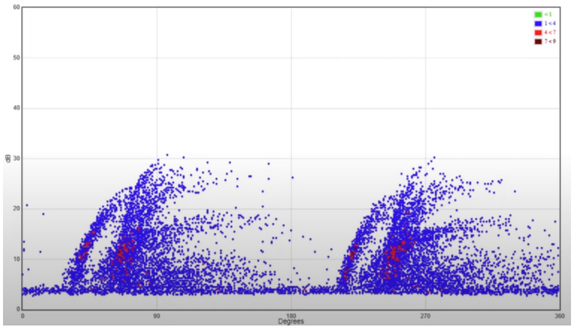

Figure 51. PRPD of case study 2

Key observations include:

- Five internal voids: The phase plot shows streaky patterns, each representing an individual defect within the insulation.
- Defect identification: The first defect is highlighted in red. The second defect is identifiable nearby. The third defect is visible further along. The fourth defect is apparent. The fifth defect is lower down, showing a streaky pattern.
- A cloud pattern is observed, indicating space charges discharging within the cavities. This occurs when an initial spark jumps the gap, and the remaining charge in the sine wave and cavity impurities cause a subsequent discharge at a lower amplitude.

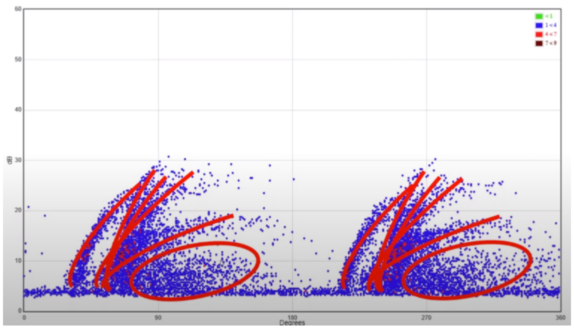

Figure 52. Interpretation of PRPD of case study 2

This test was conducted on a cable box filled with pitch, which moves and opens cavities over time, leading to discharges. The phase plot effectively identifies and distinguishes multiple voids and discharge patterns within the insulation.

Figure 53. Visual inspection of case study 2

Case study 3

This is Case Study Number Three, involving a contact type problem detected using four different test methods: TEV, ultrasonic and HFCT.

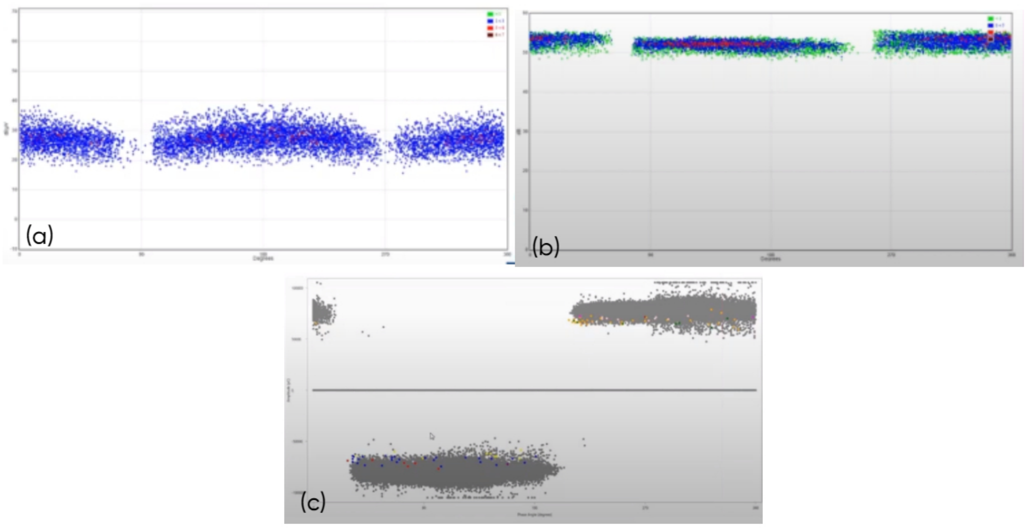

Figure 54. PRPDs of case study 3: (a)TEV , (b)Ultrasonic,(c) HFCT.

Key observations and methods:

- TEV test: Shows long rectangular clouds, consistent with a contact problem.
- Ultrasonic test: Displays a long rectangular shape indicating a contact type issue.
- HFCT test: Captures a similar pattern.

The cause of the defect was identified as improperly earthed 11 kV cables. The earth screens from the cable terminations were not bolted down, resulting in floating near metalwork. This led to discharges as the sine wave rose and fell, causing sparks to jump across the gap. Visual inspection confirmed the presence of discharge sources near the metalwork.

Figure 55. Visual inspection of case study 3

This case study demonstrates the consistency of contact type discharge patterns across different testing methods and highlights the importance of proper earthing to prevent such issues.

Case study 4

This is Case Study Number Foor, involving an electromagnetic TEV test on a pitch-insulated 11 kV chamber. The phase plot reveals four sources of internal void type PD on three separate phases.

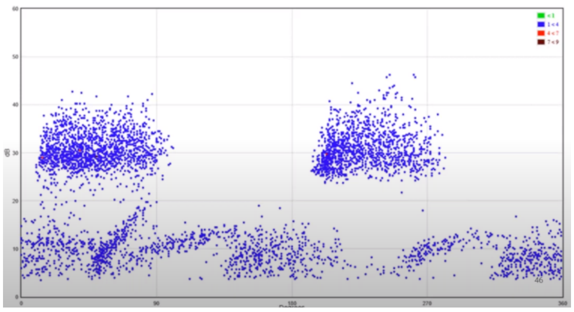

Figure 56. PRPD of case study 4

Key observations include: Four sources of PD:

- First source (circled in red): High-level single-phase surface PD, indicating a significant defect in the middle of the insulation as it discharges on both halves of the sine wave.
- Second source (circled in green): A single-phase defect on the second phase, 120 degrees onwards from the first phase, visible on both peaks of the three-phase system.
- Third source (circled in blue): A defect on the third phase with clusters on both sides of the sine wave, indicating it is in the middle of the insulation.
- Fourth source (circled in purple): A cavity close to either the HV conductor or the earth conductor, with no corresponding phase plot on the other side of the sine wave. It is in phase with the first source.

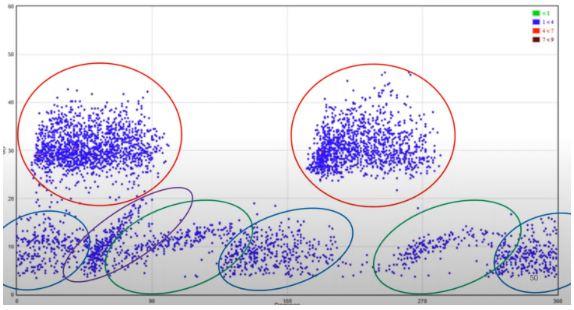

Figure 57. Interpretation of PRPD of case study

These observations were made in a pitch-filled insulation cable box, where voids in the insulation lead to discharges. The phase plot shows distinct patterns for each defect, helping to identify the location and nature of the PD sources across the three phases.

3.3 Feild experience

3.3.1 Transformer's manufacturing and testing:

Our first station was the "Winding Industrie" company, an enterprise renowned for its expertise in manufacturing and repairing transformers and rotating machines. Upon our arrival, we were greeted with a comprehensive tour of their facility, where we observed the intricate processes involved in transformer manufacturing and repair. The level of precision and attention to detail in each step was truly impressive, reflecting the company's commitment to quality and excellence.

Figure 58. Active part of a distribution transformer

Figure 59. Transformer testing area 1

We had the unique opportunity to participate in several essential tests to ensure the reliability and efficiency of the transformers. These tests included:

- Turn Ratio Test: This test measures the ratio of the number of turns in the primary winding to the number of turns in the secondary winding of a transformer. It ensures that the transformer operates correctly and provides the expected voltage transformation.
- Resistance Measurement Test: This test measures the electrical resistance of the windings in a transformer or rotating machine. Low resistance indicates good

conductor material and proper winding, while high resistance may indicate damage or poor connections.

- Dielectric Liquid Breakdown Test: This test evaluates the insulating properties of the dielectric liquid (such as oil) used in transformers. It involves applying a high voltage to the liquid until it breaks down or conducts electricity, indicating its maximum dielectric strength.
- Short Circuit Test: This test determines the short circuit impedance and copper losses in a transformer. It involves short-circuiting the secondary winding and applying a reduced voltage to the primary winding, measuring the resulting current and voltage.
- Open Circuit Test: This test measures the core losses and magnetizing current in a transformer. It involves leaving the secondary winding open and applying the rated voltage to the primary winding, measuring the resulting current and losses.
- High Voltage Test: Also known as a dielectric withstand test, this test applies a high voltage to the insulation system of a transformer or rotating machine to ensure it can withstand operating voltages without breaking down.
- Induced Voltage Test: This test involves applying a high frequency voltage to the secondary winding of a transformer to test the insulation and the ability to withstand overvoltages without causing damage.

Figure 60. Transformer testing area 2

Observing these tests firsthand and grasping their importance gave us invaluable insights into the rigorous quality control measures essential for ensuring transformer safety and reliability. Our hands-on experience at Winding Industrie not only expanded our technical knowledge but also highlighted the crucial role of meticulous testing throughout the lifecycle of electrical equipment. This visit was a pivotal moment in our journey, laying a strong foundation for the experiments and research ahead. However, the absence of a partial discharge test, as previously mentioned, was a notable shortcoming.

3.3.2 The dissipation/power factor tan(δ)

The next stop was the GRTE transmission station, where we observed the process of disconnecting a 120MVA 220kV power transformer from service to perform a tan delta test. This test measures the insulation quality of the transformer by evaluating the dissipation factor, which indicates the condition of the insulation system. The dissipation factor, or tan delta, measures the dielectric losses in the insulation system of the transformer, providing an indication of deterioration or contamination in the insulation materials. After completing the test, the transformer was reconnected to the grid.

Figure 61. 120MVA power transformer

Although we did not have access to the detailed data, the initial results suggested that the transformer bushings were suspect. This was likely due to the bushings not being cleaned before the test, which can affect the accuracy of the readings. Once the bushings were cleaned, the results showed a significant improvement, indicating that the contamination had been the primary issue affecting the initial test results.

Understanding the concept and application of tan delta testing reinforced our belief in its effectiveness and accuracy for assessing the overall health of a transformer. Tan delta testing is widely recognized as a reliable method for detecting insulation issues, providing valuable insights into the condition of the transformer's insulation system. However, the test does have its limitations. If the device under test is already suspect or in a critical state, the tan delta test does not specify the type of fault or its exact location. It simply indicates that there is an issue that requires further investigation.

Figure 62. Preforming Tandelta

Moreover, during our visit, all the workers and experts we spoke with confirmed that they do not use partial discharge (PD) testing. Partial discharge testing is another diagnostic method that can provide more detailed information about insulation defects by detecting and locating partial discharges within the transformer. Despite its advantages, it was clear that PD testing was not part of the standard testing procedures at the GRTE transmission station even if it officially becomes a routine test for transformers rated above 90KV according to IEC standards. This omission could be due to various reasons, such as the availability of equipment, expertise, or the specific testing protocols in place.

Figure 63. Tandelta device

Overall, the visit to the GRTE transmission station was highly educational, providing us with practical insights into transformer maintenance and testing procedures. The experience underscored the importance of thorough preparation and cleanliness in testing, as well as the need for comprehensive diagnostic methods to ensure the reliability and safety of power transformers.

3.3.3 Cable's manufacturing and testing:

Our last station was EL Sewedy Electric, where we witnessed the process of manufacturing cables and cable accessories. After observing the production process, we proceeded to perform factory acceptance tests on the cables. The tests included the high voltage test, resistance measurement test, and partial discharge (PD) test, which has become necessary according to standards to ensure that the cable is in good condition.

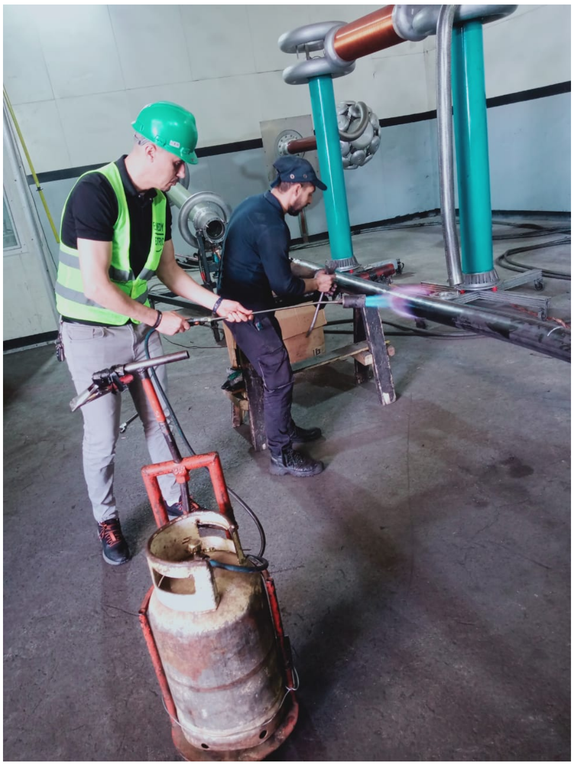

Figure 64. Preparing HV cable for connection

We witnessed tests for medium voltage (MV) and high voltage (HV) cables, which were conducted in a shielded room to eliminate noise and ensure accurate results. The voltage source used for these tests was a resonant AC test system manufactured by High Voltage Company, known for its excellent sensitivity and reliability. This voltage source was connected to an inductor, creating an RLC (resistor-inductor-capacitor) model to stabilize the test conditions.

Figure 65. Resonant AC test system

Figure 66. Connecting the cable to the water pumping termination

The procedure started with the high voltage test, which is essentially a withstand test. For MV cables, this test involves applying a voltage equal to 3.5 times the rated voltage for 5 minutes. For HV cables, the voltage applied is 2.5 times the rated voltage for 30 minutes. During these tests, HV cables must be connected to water-pumping terminations to ensure they do not overheat. The goal is to see if the cable can withstand this elevated voltage without breaking down. If the cable passes this test, we proceed to PD testing.

Figure 67. Running the PD test

PD testing involves applying a voltage of 1.73 times the rated voltage for 1 minute for MV cables and 1.5 times the rated voltage for 1 minute for HV cables. During this test, we observe the phase-resolved partial discharge (PRPD) diagram and measure the amount of charge. According to IEC standards, the PD level must be less than 10pC.

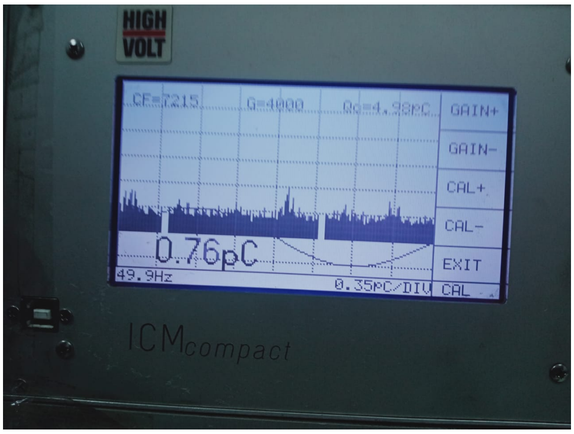

Figure 68. PRPD of the tested cable

If the cable fails the PD test, we use Time Domain Reflectometry (TDR) by Megger to locate the sources of partial discharge. TDR is a method that sends a signal through the cable and measures reflections to identify and locate faults or discontinuities within the cable.

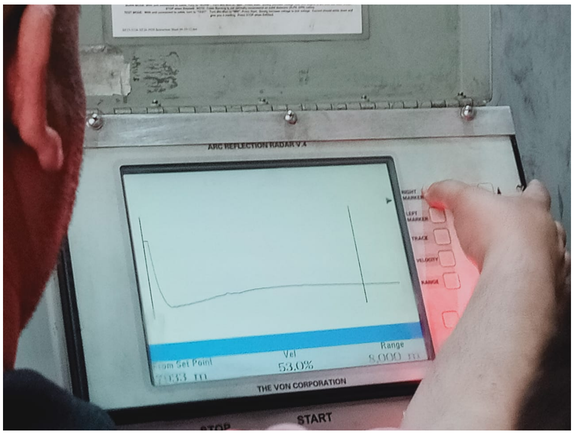

Figure 69. TDR device

Additionally, the resistance measurement test was conducted to ensure that the cables meet the required specifications for conductivity and performance. This test checks the electrical resistance of the cables, confirming that they have the appropriate level of resistance for their intended use.

Overall, the visit to EL Sewedy Electric was highly informative, providing us with a comprehensive understanding of cable manufacturing and the critical tests required to ensure product quality and reliability. Witnessing the factory acceptance tests firsthand highlighted the importance of rigorous testing protocols in maintaining high standards and ensuring the safety and performance of electrical cables.

3.3.4 Recommendations and Suggestions

At the end of our field visit, we observed that the high voltage test is beneficial to a certain extent because it determines if the equipment can withstand excessive voltage up to 3.5 times the rated value. This can provide an indication that the equipment will last many years under normal conditions. However, this type of test has limitations. High voltage testing may not detect some types of defects, such as voids or cavities within the insulation. Additionally, if voids or cavities are present, the high voltage test can cause them to grow larger, potentially accelerating equipment failure. To confirm our recommendations, we conducted an in-depth search and analysis of case studies comparing various diagnostic methods. Specifically, according to [84] 50/60 Hz offline partial discharge (PD) testing could detect the types of defects that high voltage testing, as well as other types of tests such as HiPot DC and Very Low Frequency (VLF) testing.

While tan delta testing is an accurate diagnostic tool for assessing insulation quality, it cannot specify the exact problem or fault location. This limitation means that, although it can indicate the overall health of the insulation, further investigation is often necessary to pinpoint specific issues. On the other hand, partial discharge (PD) testing can sometimes be inaccurate due to noise interference, making it challenging to obtain precise results. Despite its potential for detailed fault detection, the presence of noise can compromise the accuracy of PD testing.

Combining tan delta testing with partial discharge testing provides a more comprehensive diagnosis. Tan delta testing can indicate the overall health of the insulation, while PD testing can help locate specific defects. Implementing both tests together compensates for their individual limitations, ensuring a thorough and reliable assessment of the equipment's condition. This integrated approach enhances the accuracy and effectiveness of transformer and cable testing, leading to better maintenance and longer equipment lifespan.

General Conclusion

This report has provided an in-depth exploration of partial discharge (PD) theory and measurement in high-voltage insulation systems, emphasizing their critical role in maintaining electrical infrastructure reliability and safety. By examining the factors influencing PD initiation, various types of PD, and advanced measurement techniques, we have created a comprehensive framework for understanding and diagnosing PD phenomena.

Our findings highlight the superiority of PD testing over traditional hipot testing, particularly in medium and high voltage (MV/HV) cables and joints. The presented case studies demonstrate the effectiveness of PD testing in identifying potential failures, thus enhancing maintenance strategies.

The integration of PD testing within Algeria's electrical systems is shown to significantly improve the reliability and safety of high-voltage installations. Advanced PD measurement techniques, including electromagnetic, optical, and acoustic methods, offer precise diagnostics and better system performance. Interpreting PD measurements, however, requires substantial expertise and experience, underscoring the need for skilled professionals in this field.

While this report marks the conclusion of our project, it is merely the beginning of our real work in addressing field challenges. The practical application of our findings will involve tackling real-world problems, requiring ongoing innovation and dedication to refining diagnostic techniques and ensuring the operational integrity of electrical systems.

In conclusion, this study underscores the vital importance of partial discharge testing in high-voltage insulation systems. Future efforts should aim at enhancing PD localization techniques and incorporating these advanced methods into routine diagnostics to ensure the ongoing safety and efficiency of electrical systems in Algeria and beyond.

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