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Detecting and Monitoring Insulation Failure: A Review of Partial Discharge (PD) Detection Techniques

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ABSTRACT: The reliability and efficiency of electrical systems vitally depend on electrical insulation to prevent electricity leakage during transmission. However, due to various operational and environmental factors such as humidity, thermal stress, and others, insulation materials degrade over time. Therefore, detecting and monitoring insulation degradation at an early stage is essential to prevent catastrophic losses, ensure system reliability, and extend the operational life of electrical equipment. This paper reviews the relevance of recognizing the early stages of insulation failure and deterioration. The focus is on Partial Discharge (PD) analysis, a widely used technique, and the various test configurations employed to evaluate insulation performance, highlighting the importance of predictive maintenance to increase the lifespan and safety of insulation systems by summarizing experimental case studies that investigated the PD method detection of a 30 MVA transformer and 6/10kV XPLE cable.

Keywords: insulation failure, partial discharge measurements, transformer insulation, XLPE insulation

I. INTRODUCTION

Insulation integrity is essential in electrical systems. It serves as a bulwark against unwanted electrical discharges during power transmission by the conductor, especially in high-voltage equipment. The effectiveness of electrical transmission depends on reducing losses by decreasing the transmitted current, which is possible due to the manufacture of high-voltage devices such as power transformers, capacitors, bushings, etc [1]. These High-Voltage Equipment (HVE) are generally insulated to ensure efficient functioning and durability. The insulation forms a critical barrier that safeguards components from detrimental external influences while maintaining safe operational standards.

Due to the stresses of the power system and HVE, insulation can be liquid, solid, or gaseous [1]. Insulators are generally made of various materials, such as ceramic, glass, rubber, silicone, plastic, oil, dry cotton, wood, and quartz[2]. Porcelain, ceramics, and tempered glass are the most common materials used to manufacture electrical insulators due to their superior resistance to electrical, mechanical, and environmental degradation[3].

Electrical engineering and maintenance face significant challenges related to insulation degradation and eventual failure in electrical systems and machinery. These insulation materials can degrade over time due to a combination of environmental factors (such as humidity, fog, rain, and snow) [4, 5], electrical stress, and mechanical strain. Figure 1 shows the primary cause of insulator failure. Insulator defects can significantly increase leakage current flow along their surfaces. Because of their vulnerability to such failures, human operators must regularly inspect them manually [6].

Deterioration or breakdown of electrical insulation systems causes operational inefficiencies, precipitates significant energy losses and significant costs, and exposes the system to potentially hazardous scenarios [2, 7, 8]. The rate in percentage of frequency of insulation failure in high-voltage equipment is as follows: Switchgear 95%, Underground Cable 89%, Transformer 84%, and Generator 49% [9].

Figure 1: Major causes of insulator failure [2].

The importance of early identification and monitoring of insulation deterioration cannot be underestimated. Prompt action can significantly improve the reliability and safety of the system and equipment. Multiple effective methods are available to monitor insulation performance and detect earlystage failure in high-voltage (HV) electrical equipment. One technique is Time-Frequency Domain Reflectometry (TFDR) and Time Domain Reflectometry (TDR), which detects local insulation faults and is commonly used for fault localization in cable [10-12]. Dissolved Gas Analysis (DGA) is another effective technique for identifying insulation faults in electrical devices, especially transformers. It involves collecting dispersed gases, namely Hydrogen (H2), Methane (CH4), Ethane (C2H6), Ethylene (C2H4), and Acetylene (C2H2), in insulating oil[13, 14]. Therefore, experts can assess the severity of insulation damage and detect potential faults such as arcing, partial discharges, thermal stress, stray gases, and the presence of moisture by examining the various concentrations and types of gases[15, 16]. Thermal imaging (IR) is a method used to detect insulation breakdowns and hot spots during visual inspections. This technique enables early problem identification using IR cameras that convert emitted infrared energy into thermal images [17]. However, the accuracy of IR thermography is mainly influenced by temperature, wind speed, insulation, and pipe diameter[18].

Among these methodologies, partial discharge (PD) techniques stand out as crucial instruments for monitoring healthy and damaged insulation properties. Partial discharge is a major contributor to the aging and failures of insulated equipment in medium and high-voltage systems and has a significant effect on grid reliability. Approximately 85% of defects in equipment subjected to these voltages are linked to partial discharge, with the most frequent failures occurring in insulation materials[19].

This paper provides a detailed review of contemporary strategies for monitoring insulation integrity in high-voltage equipment, particularly emphasizing Partial Discharge techniques. By dissecting both theoretical frameworks and practical applications, the discussion will highlight their efficacy in enhancing the reliability of high-voltage electrical systems and mitigating the risk of unscheduled outages. By reviewing two case studies about PD detection, the paper aims to contribute to the existing body of knowledge by elucidating advancements in insulation monitoring practices specific to high-voltage equipment and their implications for effective electrical system management.

II. PARTIAL DISCHARGE

The first evidence of insulating material deterioration is partial discharges (PDs) [19]. As the definition of PD is "a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor," as stated in the High-Voltage Test Techniques Partial Discharge Measurements technical standard, IEC 60270[20]. IEC 60270 emphasizes the necessity of precise and standardized procedures for measuring partial discharge. The standard also describes measurement circuits, sensors, and signal processing methods. To detect potential insulation problems, the standard provides instructions for evaluating the results and determining the degree of partial discharge activity.

Internal discharges (including treeing discharges and cavities), surface discharges, and corona discharges are the three main types of partial discharges (PD). These electrical discharges usually occur in faulty areas, such as joints or voids, and manufacturing defects in the insulation systems, which continue to extend with normal operation, leading to the total failure of the insulation of high-voltage components, including transformers, transmission lines, power generators, and electrical cables [21].

Critical characteristics such as quadratic rate (D), accumulated apparent charge (qa), inception voltage (Ui), average discharge current (I), cumulative energy function (CE), and discharge power (P)[20]are used to evaluate the intensity of partial discharge and the condition of insulation in high-voltage equipment.

2.1 TECHNIQUES FOR PARTIAL DISCHARGE DETECTION

Partial discharges (PDs) involve acoustic waves, heat, vibrations, current pulses, electromagnetic waves, and other physical phenomena[22]. As Table 1 and Figure 2 show, several diagnostic (Electrical, Acoustic, Optical, Chemical, or Gas presence and Electromagnetic) techniques[22-24] are most widely used to identify these characteristics or phenomena in high-voltage equipment and electrical insulation systems, each offering distinct advantages and disadvantages.

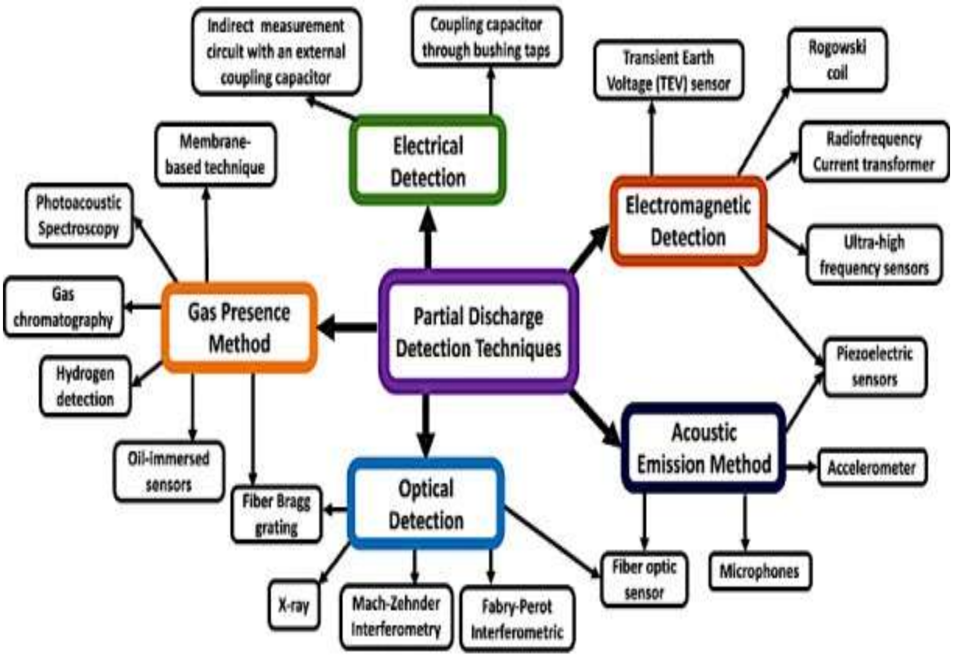


Figure 2: Methods for detecting partial discharge[22].

Partial Discharge detection in High-Voltage Equipment (HVE) is effectively carried out using conventional methods outlined in IEC60270 and unconventional methods, commonly referred to as ultra-high-frequency (UHF) and high-frequency (HF) techniques[25-27]. This essential process can be executed offline or online during equipment shutdown while the equipment operates during the evaluation of the internal condition of High Voltage Equipment. Both processes have their own merits and demerits, which are summarized in Table 2.

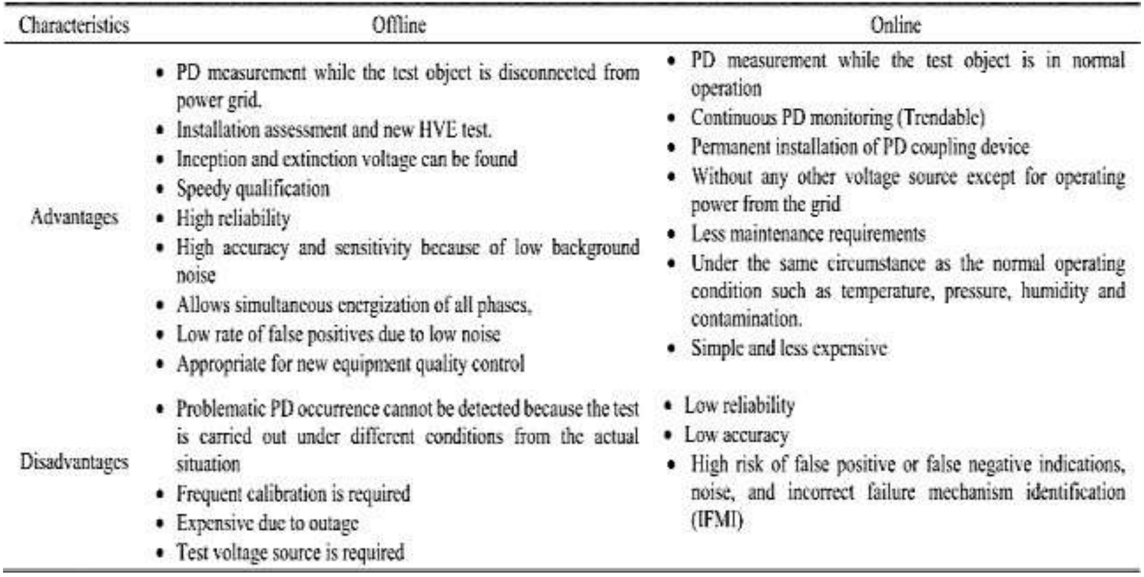
Table 1: Comparison of PD Detection Techniques and Sensors[26].

Technique	Advantages	Disadvantages	Sensor	Applications
Electrical	• Proper calibration • Implementation simplicity • Highest sensitivity with quantitative measurement in laboratory • Low signal attenuation • High accuracy in measurements • Minimal noise level due to the protective effect of the transformer.	• Less sensitivity during online detection due to the high noise level • Measurements affected by internal and external interferences • Vulnerable to noise • Incompatible for a longer span • Sensitive to temperature variations	• Coupling capacitor • Pulse capacitive coupler • HFCT	All HVE
Electromagnetic	• Source, location, type, and intensity of PD are assessable • Suitable solution for continuous online PD measurement	• Electromagnetic interference is high • Comparatively expensive • Limited range during wireless detection • No calibration technique is available. • More sensitive to environmental temperature	• Inductive • Capacitive	All HVE
Acoustical	• High electrical noise immunity • Effective for PD localization • Comparatively cheaper • Good performance in real time monitoring • Sensitivity is unaffected by the capacitance of test object	• Signal intensity is low • Not suitable for continuous online PD measurement • Low sensitivity to internal discharge • More prone to environmental noise • More sensitive to environmental pressure and humidity	• Condenser microphones • Piezo-electric transducers	• GIS • Transformer
Optical	• High electrical noise immunity • Highly sensitive • Sometimes effective for PD localization • Impulse voltage condition testing is possible • Light weight and small size	• PD magnitude is inaccessible • More sensitive to pressure and humidity variations	• Optical fibre • Photomultiplier tube • UV detector	• Transformer • GIS • Cable
Chemical	• High electrical noise immunity • Measurement is easy • Highly sensitive • Excellent PD signal recording under laboratory conditions • Deliver important information for go/no go decisions • Less affected by environmental conditions	• Source, location, type, and intensity of PD are inaccessible • Sometimes induces uncertainty in the measurement	• SF6 Sensors • DGA Sensors	• Transformer • GIS • Cable

Using unconventional techniques to measure partial discharge (PD) has several advantages. First, these methods are less affected by outside interference. Second, sensors can pinpoint the location of PD by analyzing when signals arrive. Third, the high-voltage circuit does not require an electrical connection to the sensors. Overall, regular PD monitoring can help users make better decisions, saving both money and time while providing more accurate data[27, 28].

Implementing online PD testing is complex using conventional methods. Hence, offline PD tests are commonly linked with the conventional method of PD measurement, while online tests are linked to unconventional methods. Continuous data logging and equipment monitoring improvements are advantageous for online testing connected to unconventional approaches. Various techniques are advised for more thorough results, as one technique may not always be sufficient to evaluate the insulation condition.

Table 2:A comparison between online and offline methods for measuring PD[26].



Characteristics	Offline	Online
Advantages	• PD measurement while the test object is disconnected from power grid. • Installation assessment and new HVE test. • Inception and extinction voltage can be found • Speedy qualification • High reliability • High accuracy and sensitivity because of low background noise • Allows simultaneous energization of all phases, • Low rate of false positives due to low noise • Appropriate for new equipment quality control	• PD measurement while the test object is in normal operation • Continuous PD monitoring (Trendable) • Permanent installation of PD coupling device • Without any other voltage source except for operating power from the grid • Less maintenance requirements • Under the same circumstance as the normal operating condition such as temperature, pressure, humidity and contamination. • Simple and less expensive
Disadvantages	• Problematic PD occurrence cannot be detected because the test is carried out under different conditions from the actual situation • Frequent calibration is required • Expensive due to outage • Test voltage source is required	• Low reliability • Low accuracy • High risk of false positive or false negative indications, noise, and incorrect failure mechanism identification (IFMI)

2.2 PARTIAL DISCHARGE MONITORING STRATEGIES

Implementing sophisticated monitoring, such as online systems, enables real-time detection and analysis of PD levels, which is crucial for identifying potential problems early. By adopting a proactive monitoring strategy, companies can intervene in a timely manner to prevent equipment damage and increase asset durability.

Figure 3 shows the main steps used to monitor PD as follows: first, the PD signal detection sensors are connected to the HVE to capture signals or aggregate data from electrical[29, 30], electromagnetic [31, 32], optical [33], acoustic[34, 35], thermal, and chemical sources from the machines. Then, signal processing and feature extraction, such as Fast Fourier Transform (FFT), wavelet transform, or digital filters, are used to extract features like pulse magnitude, frequency, and phase angle. Third, important aspects transform the raw PD signals into a set of recognizable and discriminatory features or patterns[36]. By analyzing the PD signal derived from various fault features, such as statistical, (Time Resolved Partial Discharge) [37], and (Phase-Resolved Partial Discharge)[38, 39] have been quantified for fault identification and localization. Lastly, the PD defects in highvoltage equipment are separated using mathematical tools, classification, or clustering [40, 41] and transmitted through the PC interface.

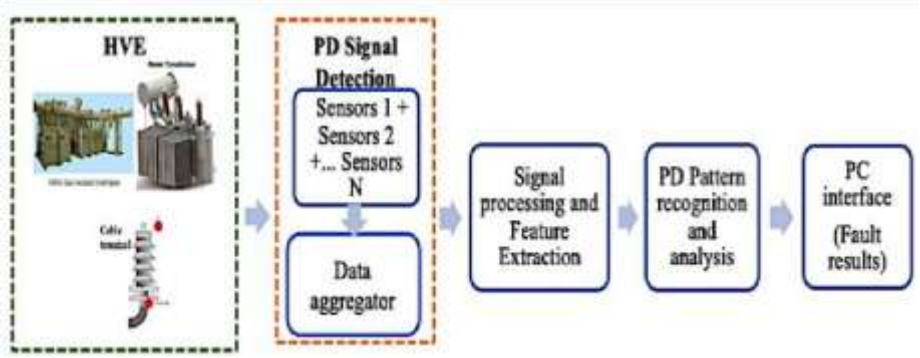


Figure 3:PD monitoring system configuration.

III. CASE STUDIES OF INSULATION SYSTEM FAILURES IN HIGH-VOLTAGE EQUIPMENT

3.1 TRANSFORMER

The power transformer is a costly component in the distribution and transmission system[42]. Transformer failure, particularly in insulation systems, can result in considerable losses. Studies indicate that dielectric defects or faults are present in over 30 percent of transformers (European substations) operating under 100 kV to 500 kV voltage[43]. Oil contamination, moisture in cellulose insulation, and partial discharges are the leading causes of insulation failures. Due to high corrective maintenance costs and operational losses from unexpected failures, it is crucial to develop efficient monitoring methods as an early indication of possible failures for their health.

Evaluating power transformers for partial discharge (PD) typically includes these stages[44]:

1. Identifying partial discharges;
2. Examining data to detect insulating defects and comparing patterns with known defects.
3. Assessment of the risk of transformer insulation degradation.

A case study of insulation failure detection and monitoring in a 30 MVA transformer has been investigated[45]. This study evaluates a custom online monitoring system developed to detect PDs in real-time by applying the electrical method in power transformers, which measures electrical pulses of current or voltage at the object's terminals using specific circuits.

The measurement setup configuration was based on IEEE C57.113 standards[46] and IEC 60270[20], as shown in Figure 4(a). It involves connecting a measuring instrument (M_i) to a coupling device (D_c) via a cable (M_c). The measurement impedance (Z_m) linked to the transformer bushing test tap was measured using a coupling device. When connected, Zm and the bushing's internal capacitances (C_1 and C_2) create a voltage divider that must be optimally sized for precise readings. In order to minimize electromagnetic interference and reduce inductance, the cable between the measuring instrument and the coupling device should be short and free of PDs. This connection guaranteed great measurement quality. Additionally, the test tap and coupling device should be connected directly without requiring extra cables[45].

Figures 4(b) and 5(b) show the online monitoring system schematic developed in the study, which features three main units for coupling, data acquisition, and processing.

As illustrated in Figure 5 (a), partial discharges (PD) were identified by connecting the coupling unit directly to the transformer bushing tap to extract high-frequency signals. By grounding the test tap during strong transient currents, a 3.3 µF capacitor (Z_m) connected in parallel with a protection circuit is intended to protect the bushing from extreme occurrences such as lightning and switching impulses, hence avoiding damage to the internal capacitor.

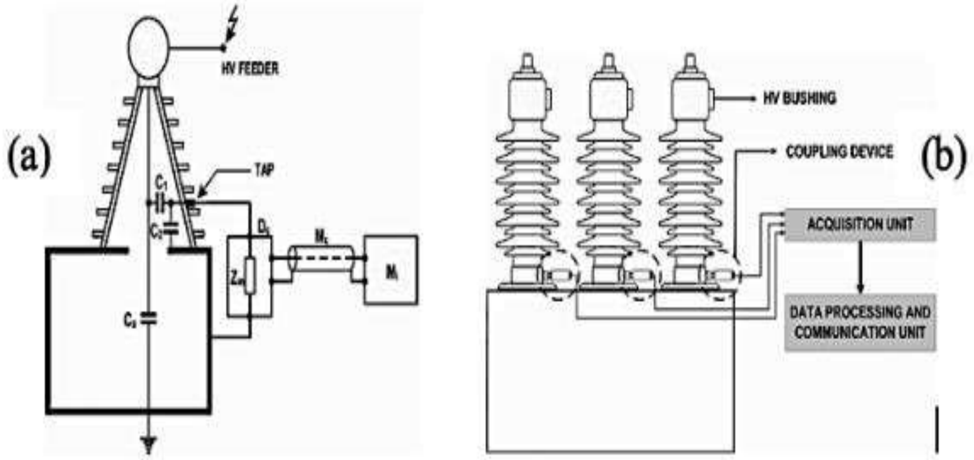


Figure 4:(a) PD measurement configuration; (b) online monitoring system

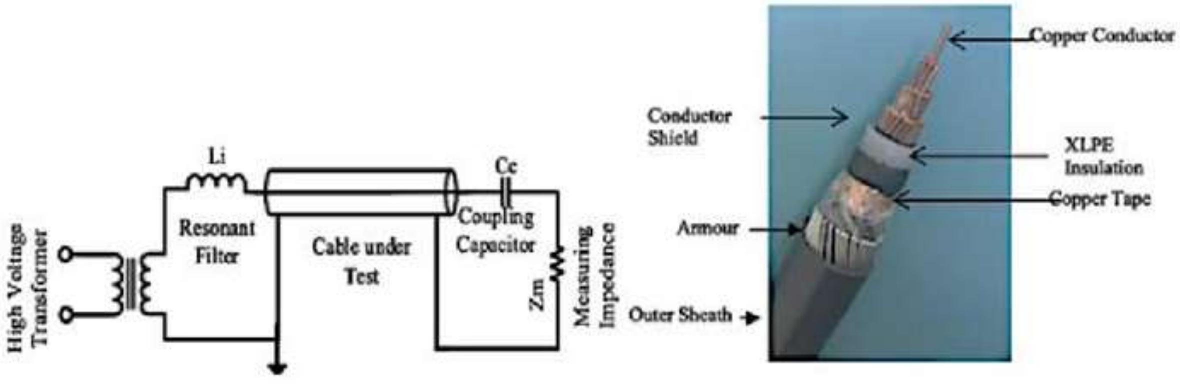
(a) (b)

Figure 5: (a) Device for coupling to detect PDs; (b) Monitoring system (30 MVA transformer).

The acquisition unit converts tap signals to digital for the data processing unit. It includes a 2 GSa/s oscilloscope with 10-bit resolution and 200 MHz bandwidth, capturing partial discharges (PD) in under 1 µs. The data processing unit measures PD in pico coulombs per IEC standards, sending real-time values to the utility's SCADA system.

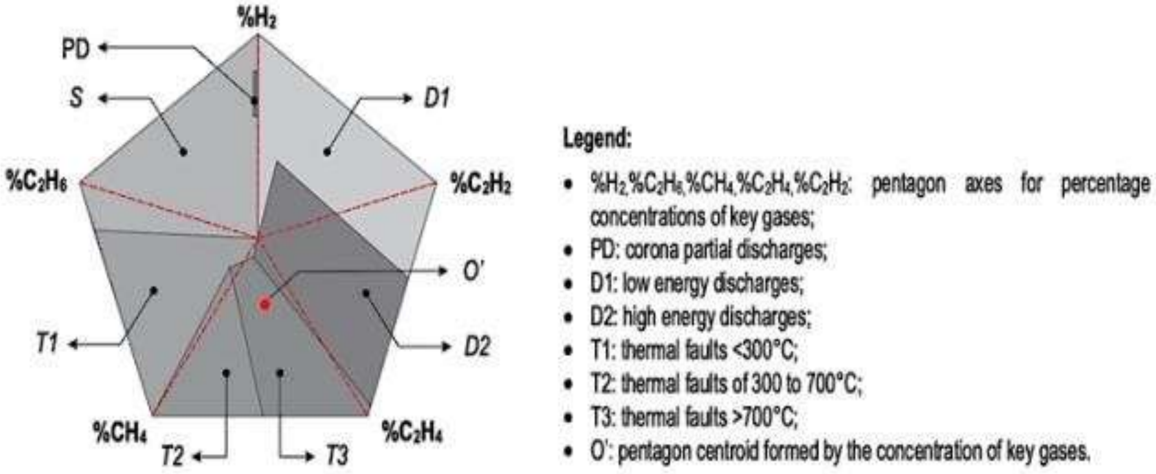
Table 3: Gas Concentration in Oil Over three days.

Gas	Concentration Dissolved in Oil (ppm)		
	Day 1	Day 2	Day 3
Hydrogen (H_2)	59	276	327
Oxygen (O_2)	3980	9230	14700
Nitrogen (N_2)	15650	60140	52620
Methane (CH_4)	58	296	280
Carbon monoxide (CO)	100	258	256
Carbon dioxide (CO_2)	972	2710	1756
Ethylene (C_2H_4)	16	389	564
Ethane (C_2H_6)	19	180	132
Acetylene (C_2H_2)	-	4	6



(a) (b)

After configuring the sensor and parameters, the relationship between partial discharges and gases dissolved in oil was diagnosed. A monitor mounted on the transformer recorded the changes in the oil's dissolved gas levels due to sudden changes in circumstances, as shown in Table 3. The alert regarding elevated gas levels in oil led to the analysis of gas concentrations (H2, C2H2, C2H4, CH4, and C2H6) on day 3 using the Duval pentagon for diagnosis. The centroid of the pentagon indicated a thermal failure at temperatures above 700 °C, as shown in Figure 6.



Legend:

- $\%H_2, \%C_2H_6, \%CH_4, \%C_2H_4, \%C_2H_2$: pentagon axes for percentage concentrations of key gases;
- PD: corona partial discharges;
- D1: low energy discharges;
- D2: high energy discharges;
- T1: thermal faults <300°C;
- T2: thermal faults of 300 to 700°C;
- T3: thermal faults >700°C;
- O': pentagon centroid formed by the concentration of key gases.

Figure 6: Dissolved gases measured in oil on day 3, using the Duval Pentagon method.

Day 3 measurements of partial discharges (PDs) revealed increased apparent charges in phases B and C, particularly phase C, indicating significant insulating problems. As shown in Figure 7, a teardown examination showed deterioration in the low-voltage (LV) windings' Y connection. This resulted in gas-filled bubbles and the introduction of solid particles into the oil. Although internal transformer couplings may prevent them from occurring on the HV side, these gases caused PDs to be found on the HV bushings.

Figure 7:LV winding failure in the Y connection.

3.2 6/10 KV XLPE INSULATED POWER CABLE

The case study measures partial discharge (PD) in 6/10 kV cross-linked polyethylene (XLPE) insulated cables to examine insulation condition monitoring in high-voltage power cables[47]. The study analyzes the PD levels of new and thermally aged cables and focuses on how thermal stress affects cable insulation. The PD measurement setup was configured with a high-voltage transformer connected to the test cable via a resonant filter. Key components included a coupling capacitor, a measuring impedance, and a comparator to capture PD pulses. Figure 8(a) the configuration circuit and 8(c) experimental PD measurement test setup.

(c)

Figure 8: (a) Circuit configuration for PD test; (b) 6/10 kV XLPE cable used sample; (c)Experimental PD test configuration.

The structure of the 6/10 (12) kV single-core XLPE cable sample utilized for PD measurements is depicted in Figure 8(b). Features a stranded, compacted copper conductor, a black extruded semiconducting compound, natural XLPE insulation, and a metallic screen made of copper tape and wires. The outer sheath is PVC. The parameters used in the experimental setup are detailed in Table 4.

Table 4: Parameters used in laboratory test setup.

S No.	Components	Value/Ratings
1	Rated Voltage	6/10kV
2	Overall Diameter of cable	46.8mm
3	No. of cores	One
4	Conductor size	300sqmm
5	Diameter over Outer sheath	46.8mm
6	Diameter over Copper Tape	32.5mm
7	Diameter over Conductor	21.9mm
8	No. of Strands	37

The study was conducted according to IEC 60502 standards, and PD measurements were conducted using continuous AC voltage. To analyze PD values, test samples were evaluated at the rated voltage (6kV) and (12kV) rated voltage. The results are presented below.

3.2.1 PD MEASUREMENT ON FRESH CABLE SAMPLE

Figure 9: (a) PD pulse voltage level and (b) PD pulse histogram pattern at 6kV.

The PD value at 12kV peaked at 2.77pC and was 2.13pC before thermal. The histogram in Figure 10 (b) shows that higher voltage levels lead to higher PD values, validating high PD pulse occurrences across the whole phase.

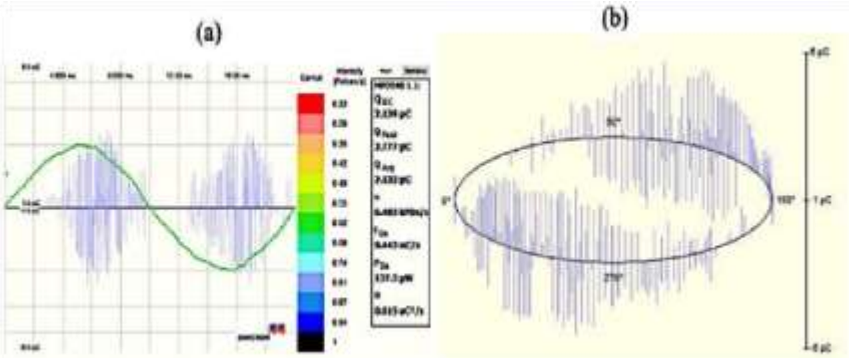


Figure 10: (a) PD pulse voltage level and (b) PD pulse histogram pattern at 12 kV.

3.2.2 PARTIAL DISCHARGES ON CABLE MEASUREMENT AFTER THERMAL PROCESS

Thermal stress was generated by heating the cable sample with current until it reached a steady-state temperature of 5– 10 degrees Celsius greater than the highest operating temperature. The cycle is repeated 20 times and lasts 8 hours, including 2 hours at steady state and 3 hours of natural cooling. Following this heat stress, PD measurements were performed on the same sample.

At 6 kV, PD measurements show a pulse value of 1.55 pC and a peak of 2.0 pC, as seen in Figure 11 (a). After thermal stress, the value increases to 1.55 pC compared to the fresh sample, and the histogram remains scattered with higher peak values, illustrated in Figure 11(a).

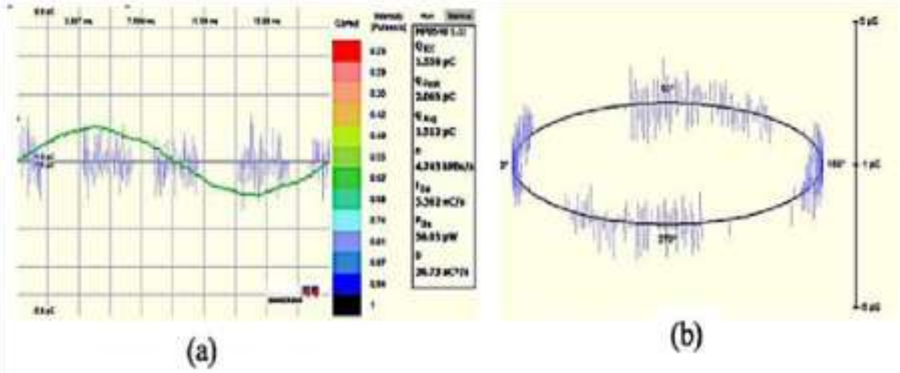


Figure 11:(a) PD pulse voltage level and (b) Histogram pattern at 6kV after thermal stress.

Figures 12(a) and 12(b) display PD measurements at 12kV, showing an average of 2.52pC and a peak of 3.80pC. These results confirmed the impact of thermal stress on insulation. Higher voltage levels result in elevated peak PD values.

IV. CONCLUSION

In conclusion, this review highlights the significance of partial discharge (PD) detection methods for maintaining the integrity of high-voltage (HV) equipment, particularly regarding insulation degradation. Early monitoring and detection of PD are crucial for avoiding costly maintenance, operational failures, and capital losses due to insulationrelated issues. The review includes two case studies that illustrate the practical applications of PD monitoring.

The first case study demonstrates the effectiveness of an online monitoring system for PD in 30 MVA power transformers, emphasizing the need for ongoing assessments of insulation conditions to mitigate dielectric failures. The second case study reveals how thermal stress and voltage variations affect 6/10kV cable insulation, with findings indicating that increased voltage corresponds to higher PD levels. Overall, these insights underscore the importance of proactive PD monitoring to enhance the reliability of electrical systems.

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