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Detection Method of Partial Discharge on Transformer and Gas Insulated Switchgear: A Review

Zulbirri Faizol [1,*], Farid Zubir [2,*], Norhafezaidi Mat Saman [3], Mohd Hafizi Ahmad [3], Mohamad Kamal A. Rahim [4], Osman Ayop [4], Muzammil Jusoh [5], Huda A. Majid [6] and Zubaida Yusoff [7,*]

[1] Department of Communication Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[2] Wireless Communication Centre, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[3] Institute of High Voltage & High Current, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[4] Advanced RF & Microwave Research Group (ARFMRG), Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[5] Faculty of Electronic Engineering & Technology, UniMAP Pauh Putra Main Campus, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia.
[6] Faculty of Engineering Technology, Pagoh Higher Education Hub, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia.
[7] Faculty of Engineering, Multimedia University, Persiaran Multimedia, 63100 Cyberjaya, Selangor, Malaysia.
* Correspondence: ahmadzulbirri@graduate.utm.my, faridzubir@utm.my, zubaida@mmu.edu.my;

Abstract: Detection of partial discharge (PD) activities in high-voltage equipment can be done according to the several mechanisms of signal detection, which are electromagnetic wave signal detection, acoustic signal detection, chemical reactions, electrical signal detection, or optical emission detection. Recently, multiple methods of detection and localization of partial discharge activities occurred in power transformers and gas-insulated switchgear (GIS) have been proposed to monitor the health condition of high-voltage equipment, especially when the awareness regarding preventive maintenance has been emphasized at the industrial level and electrical providers. In aligning the needs of industrial and the improvement of PD detection methods, this manuscript focused on reviewing the current practice methods for the detection and localization of PD signals in high-voltage equipment and comparing their efficacy, in summarizing the future direction of research work-related methods of PD detection. The comparative reviews are discussed in terms of the mechanism of PD signal detection, indication parameters, calibration technique, advantages, and limitations of each method of PD measurement in detail.

Keywords: partial discharge; power transformer; gas-insulated switchgear

1. Introduction

Power transformers are essential equipment in power delivery systems in stepping up and down the voltages to reduce the power dissipated [1, 2]. Therefore, it is crucial to sustain the operation of this equipment in good condition without the occurrence of unpredicted breakdown phenomenon in preventing and minimizing any potential power supply interruption that could cause substantial financial losses during corrective action [3]. However, the exposure of power transformers to certain conditions, such as thermal ageing, mechanical stress, electrical stress, and vulnerable environment, might trigger and result in insulation failure. Therefore, preventive maintenance is necessary for monitoring the performance of the power transformer to prevent a major breakdown of the essential equipment. The outcomes from the monitoring aid in identifying further action whether the power transformers can work well in the power delivery system or preventive action need to be made accordingly. Implementing performance monitoring on the power equipment is crucial to avoid disruption of the electricity supply and ensure the continuous and reliable functioning of power system utilities [4]. Generally, the method of condition monitoring of power transformers listed such as dissolved gas analysis (DGA) [5, 6], partial discharge measurement [7], power factor measurement [8], frequency response analysis (FRA) [9], vibration plus acoustic analysis [10], dielectric spectroscopy [11], differential protection [12], transformation ratio [13], and insulation resistance [14].

The power transformer is a multifaceted entity that is susceptible to encountering diverse forms of anomalies, which can be classified as either endogenous or exogenous faults. As depicted in Figure 1, various types of faults may arise in distinct regions, including on the winding, tank, insulating oil, core, terminal, cooling system, and tap changer, as highlighted in reference [15]. The external faults commonly manifest as a result of external short circuits within the power system, over-flux phenomena, or overloading. According to the findings presented in Figure 2, the fault locations pertaining to transformers can be identified within the sub-station, specifically those with a voltage rating exceeding 100 kV, as reported in reference [16]. Conversely, the causes of internal faults in transformers are diverse and include factors such as axial displacement, buckling deformations, disc space variation, short-circuited turns, core insulation failure, shorted laminations, open leads, loose connections, short circuits, overheating, and other issues such as described in references [9, 17-20]. Globally, the majority of transformer faults, approximately 70%–80%, are attributed to internal faults [21]. The aforementioned deficiencies generally originate as partial discharge within the insulation of the transformer, which occurs swiftly and culminates in total failure.

The identification of the health condition of a power transformer is of utmost importance in guaranteeing the uninterrupted functioning of electrical utilities. This is because the severity of the different types of defects might increase from time to time [22]. One of the measurements considered in the preventive maintenance of power transformers is the measurement of partial discharge activities. Partial discharge is a pre-breakdown phenomenon that indicates the electrical discharge that partially bridges the dielectric medium between two conduction parts. One of the measurements considered in the preventive maintenance of power transformers is the measurement of partial discharge activities. Under the influence of high voltage stress, partial discharge (PD) is a pre-breakdown phenomenon defined in the IEC 60270 standard as a localized electrical discharge that only partially bridges the insulation between conductors and can or cannot occur adjacent to a conductor [23]. As mentioned in the standard, a PD pulse refers to the current or voltage pulse that typically occurs due to a partial discharge activity within the object under test. PD usually begins due to the imperfections of the insulation medium, such as the presence of voids or gas-contained bubbles on the dielectric materials [24]. Commonly, imperfections on the insulation medium are present due to improper manufacturing processes. Chemical by-products and particle bombardment produced by PD activity also degrade the properties of the insulating medium. Protracted PD may eventually lead to insulation breakdown.

Generally, the PD testing method of power transformers can be done either online or offline way. Comparatively, offline testing is preferred compared to online testing despite the lack of its dependability [2]. In order to obtain reliable outcomes from the measurement of PD activities, the appropriate calibrated PD measurement system needs to be used, and it must be performed according to the standard of commercial PD measurement techniques. Nevertheless, the PD measurement technique conducted offline has limitations, especially in accounting for the authentic electrical and thermal circumstances experienced by the insulation while the transformer is in operation line [25].

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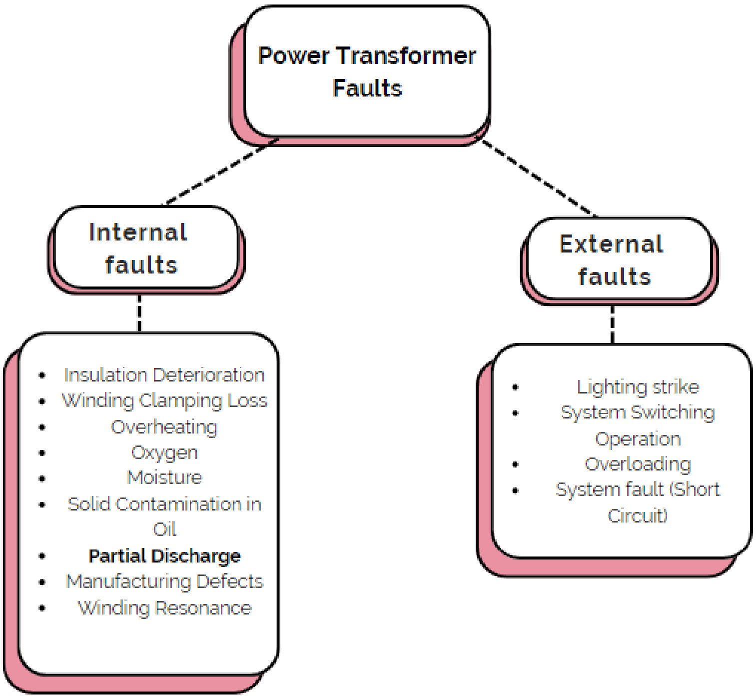

Figure 1. Power transformer failure classification [15].

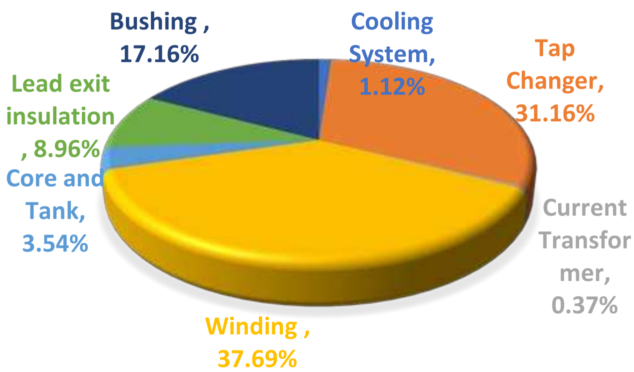

Figure 2. The substation's high-voltage (>100 kV) transformer detonated [16].

Therefore, in sustaining the performance of installed power transformers, online detection of the partial discharge phenomenon must be conducted accordingly. Recently, several prevalent techniques have been conducted to monitor the PD characteristics in power transformers.

As stated, PD is considered to be the primary factor responsible for the deterioration of insulation in transformers, which can ultimately result in failure [26, 27]. Various techniques for PD detection have been performed in condition monitoring to detect, identify, and diagnose PD [28]. In addition, numerous methodologies have been developed to identify and detect partial discharge (PD), including electrical detection [29-33], electromagnetic detection [26, 34-38], optical detection [39-41], acoustic detection [42-46], gas presence detection [6, 47-49], and integrated approaches [42, 50, 51]. In order to pinpoint the spots and PD activities, these methods have been utilized to determine the PD signals. In online PD monitoring, it has been found that there are challenges to detecting the PD signals and their exact proposition due to the complicated geometrical of power transformers, the shielded structure of power transformers, and interruption of noise (i.e., noise interference). For instance, electrostatic and electromagnetic interference, radio frequency interference, and cross-talk brought on by nearby cables are all examples of external disturbances which may lead to noise interference in PD detection. Besides, the transformer's core and windings produce the majority of the internal noise. Therefore, an applicable method to detect PD is needed to prevent any breakdown happen in power transformer or gas-insulated switchgear. There are some of the best methods that currently used to detect PD such as UHF method. The UHF method utilizes UHF sensors or antennas placed near the transformer or GIS to capture and analyze the electromagnetic emissions generated by PD events. This method offers high sensitivity, accurate PD localization, and the ability to detect PDs in their early stages. It is commonly used for both online and offline monitoring [52, 53]. Other than that, Transient Earth Voltage (TEV) method also can be used to detect PD. The TEV method detects the radiated electromagnetic waves resulting from PD events in power transformer or GIS. It involves placing sensors on the transformer's surface or GIS surface to measure high-frequency transient signals. The TEV method is non-intrusive, highly sensitive to PD events, and suitable for online monitoring systems [54, 55]. Apart from that, Acoustic Detection also is one of the methods that currently being used to detect PD. Acoustic PD detection relies on the measurement of sound waves produced by PD events. Acoustic sensors or ultrasonic detectors are used to capture and analyze the acoustic emissions. This method is effective for detecting PDs in power transformers or in gas-filled compartments of GIS and provides information about the discharge location based on time-of-flight analysis [56, 57].

2. Method of PD Detection Based on Different Types of Signals Emitted During PD Activities

2.1. Electromagnetic

W. R. Rutgers was the first to apply the EM method to a power transformer in 1997 [58]. UHF signals can be detected using conical, spiral, and Vivaldi antennas [26, 59]. UHF sensors are the subject of extensive research since they have benefits that include immunity to low-frequency signals, an insignificant impact of signals caused by internal transformer construction, and the absence of corona-free pulse interference [34, 60]. Radio interference and switching events might make UHF detection more difficult.

For its measurements, the UHF electromagnetic technique depends on the PD activation of electrical resonance at frequencies up to 1.5 GHz. This technique can also detect and pinpoint a PD source [61, 62]. The UHF method offers multiple benefits, for instance low decibel levels as a sequence of the transformer's shielding effect and extremely low signal losses. The measurement frequency band of 100 MHz of such UHF process fits precisely between the 300 and 1500 MHz of the entire wavelength range, permitting it to avoid local interference over the entire range. Because the UHF sensor is linked within the transformer, this technology is noise-free. The secondary winding is safe and dependable against induced current since there is no electrical interrelation between power transformer and UHF sensor. The secondary winding of a power transformer is safe and reliable against induced current.

Figure 3 is a circuit diagram for a power transformer that was used in [63] to analyze the impact of various PD types on UHF calibration. Researched causes of PD include surface discharge on polyethylene, surface discharge on pressboard, internal discharge, and corona discharge. There are six drain valves that facilitate the placement of various UHF probes. The optimal detection frequency range for measuring the UHF signal in terms of PD activities was introduced by the authors in [63]. They also showed how inefficient the UHF probe was because of the difficulty in reducing calibration errors caused by active transformer components. However, a maximum charge estimation approach was presented in [63], where the UHF quantier parameter and IEC apparent charge are measured in the laboratory to achieve the least feasible ratio.

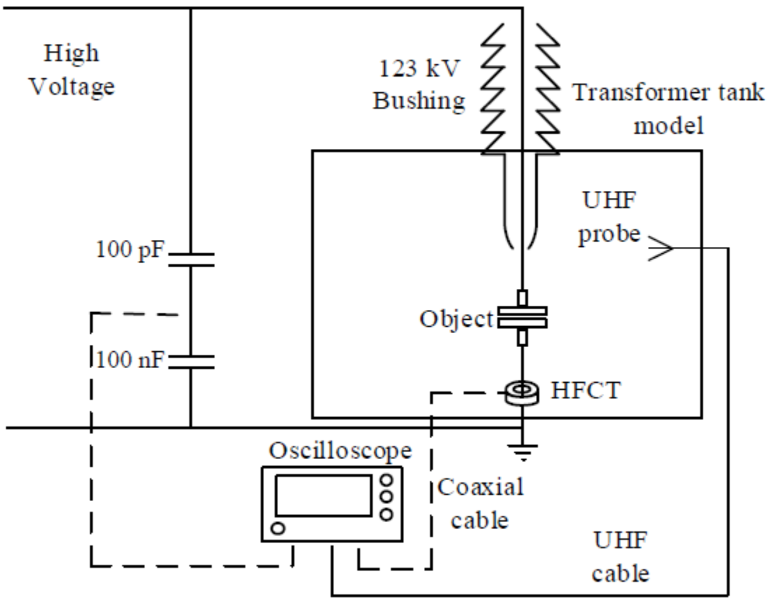

Figure 3. Schematic depicting the effects of various PD types on UHF calibration in a power transformer reprinted by [63].

Extensive research has been conducted on various types of current transformers, such as Rogowski coils, high-frequency current transformers (HFCTs), and radio-frequency current transformers (RFCTs), for their application as PD detection sensors in power transformers [64-66]. The electromagnetic (EM) technique has proven effective in localizing multiple PD sources and identifying their unique characteristics through the use of feature extraction and denoising strategies. These strategies are used in PD detection through the EM signal approach to accurately identify and analyze PD signals in power transformers.

2.2. Electrical

One of the electrical measurement approaches for detecting PD is the pulse capacitive coupler method. In a pulse capacitive coupler arrangement, the PD induced current is gathered and measured in the detecting coil, which is coupled in a loop with some impedance to the ground line [67]. Quantitative approaches are highly sensitive and simple to implement. However, because of its high sensitivity, it is prone to false alarms, making it unsuitable for continuous transformer monitoring.

EE detection techniques utilize the existing pulse-produced signal to detect PD. The circuit is connected to the spotted areas, allowing it to detect current pulses that indicate PD activity [68]. The International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) both utilize similar techniques [69]. This method may be used to determine the PD charge and evaluate the insulation's state. The assessment of PD detection systems in power transformers has been advised by the International Council on Large Electric Systems (CIGRE) [70]. The electrical detecting techniques most often used for power transformer status monitoring are shown in Figures 4(a) and 4(b), which include the indirect measuring circuit with external coupling capacitor and the coupling capacitor via bushing taps [23, 71]. A coupling capacitor (C_k) is connected in parallel with the capacitance of the insulation system being tested (C_A) in the measurement setup shown in Figure 4(a). When a measuring impedance is connected to a PD meter, an apparent charge (Z_M) can be determined.

The use of a large voltage coupling capacitor makes this technology impractical for online testing. However, online testing is feasible if the power transformer has available bushing taps, as depicted in Figure 4(b). Currently, there are limitations in identifying PD activities using existing techniques. The presence of electromagnetic interference during online testing poses challenges [72, 73]. Therefore, offline testing is preferred, although it may not fully represent the conditions of online

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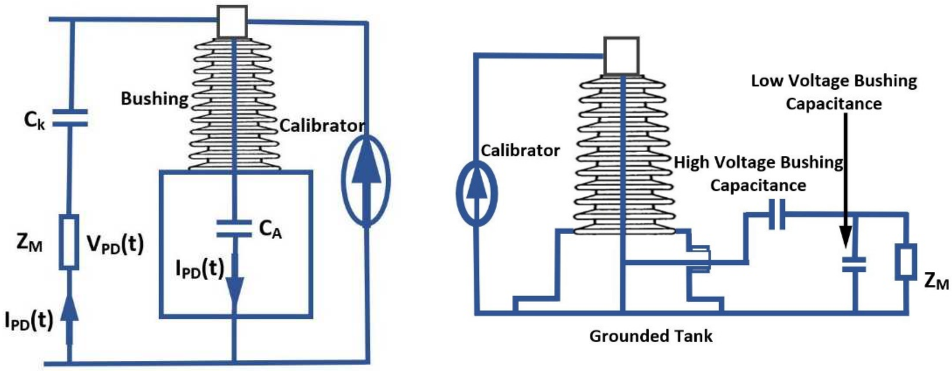
operation. For regular tests of produced goods or pre-commissioning routine tests, offline testing is still useful. Even with these drawbacks, this method offers useful insights into the comprehension of the insulation performance.



(a) **(b)**

Figure 4. (a) IEC 60270 based indirect measurement circuit using external coupling capacitor. (b) Coupling capacitor through bushing taps reprinted by [23].

2.3. Chemical Presence

Chemical testing procedures, which depend on the analysis of gas and oil specimens extracted from the PD activities, are essential for identifying PD in high-voltage applications. High-performance liquid chromatography (HPLC) and dissolved gas analysis (DGA) are two frequently used methods for measuring chemicals. HPLC is employed to study the by-products of PD, such as glucose in its degenerated forms resulting from insulation breakdown [74, 75]. On the other hand, DGA utilizes differential gas chromatography to analyze the entire volume of gas generated by PD activities [74]. These approaches provide valuable insights into the chemical composition of PD-related substances, aiding in the detection and assessment of PD in high-voltage systems.

A variety of online testing methods have been developed to detect partial discharge (PD) in power systems. These approaches include oil-immersed sensors with fiber Bragg gratings [76], photoacoustic spectroscopy [77], and oil-immersed sensors [78]. Other than that, photoacoustic spectroscopy with membrane-based methods [79], and hydrogen detection [76]. Figure 5 [80, 81] shows a typical gas chromatography setup. In this configuration, the oil specimen undergoes vaporization near the injection port, and the resultant gases—which include some of the lighter gases including argon, the element helium nitrogen, and hydrogen—are then fed into the column. The column separates the gases based on their retention times before they reach the heat detectors [80]. The data collection system records and plots the identified PD signals, generating chromatograms. The gas concentration and retention time are then used to determine the identity of the gases. Hydrogen gas detection has become the preferred method due to its high accuracy and has largely replaced other detection methods. If the hydrogen gas level exceeds the safety threshold during overheating and discharges, it indicates a need to diagnose the internal insulations [82]. FBG sensors have been extensively used in various studies to measure the concentration of hydrogen gas within power transformer tanks operating at typical temperatures ranging from 60°C to 90°C. The remarkable sensitivity of hydrogen gas detection at 80°C, combined with its minimal interference from other gases, points towards a promising outlook for this technology [83]. Furthermore, there have been advancements in the development of Pd-capped Mg-Ti thin-film-based hydrogen sensors (improved FBG), which exhibit enhanced sensitivity over a broader temperature range from 10°C to 80°C and significantly surpass the sensitivity of traditional FBG sensors [84].

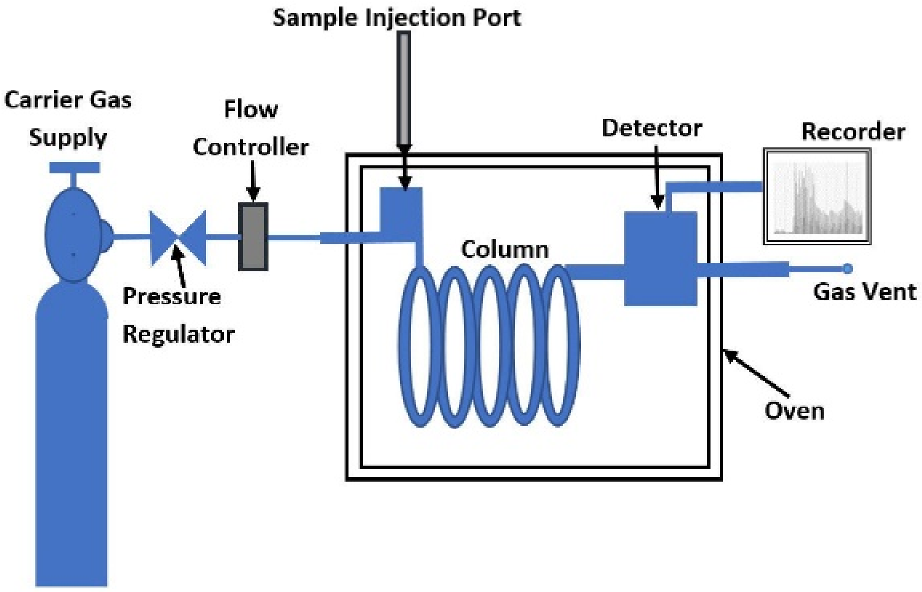


Figure 5. Gas chromatograph in its usual form [80].

2.4. Acoustic

The mechanical explosion that causes AE in the power transformer is caused by the evaporation of oil in the area of the streamer, the electrical arc, and the mechanical vibration [85]. Ultrasonic signals, with a frequency of 40 kHz to hundreds of kHz, [86, 87], can be used to estimate the location of the AE source, which sends off pressure waves with characteristics exclusive to that source. Nevertheless, the signals of PD can be affected by high-frequency signals and can be removed if using denoising technique.

The AE approach has become the preferred technique to detect PD in power transformers due to its effectiveness and low cost in eliminating electromagnetic interference. The block diagram of the recording system used by the power transformer during normal operation to identify AE signals from PD is shown in Figure 6 [88]. Many ultrasonic systems use broadband piezoelectric transducers as their transduction element. These AE signal detectors are attached to the transformer tank at a certain point using a magnetized holder. The AE signals are then transferred into the AE analyzer, where they are amplified, filtered, and recorded.

Multiple PD causes can be identified using the AE technique [86]. The AE method is often used in conjunction with others, such as UHF, optical detection, and electrical detection, to compensate for its limitations in PD level detection and calibration. Complex acoustic emission behavior, weak detected signals, and a high price tag are all downsides of this approach. Microphones [89], piezoelectric transducers [86], acceleration sensors [86], and fiber optic (FO) sensors [90] are all examples of equipment that can be used to detect AE. Fiber Optic sensors have been shown to be the most effective AE detection devices because of their high signal-to-noise ratio (SNR) and their ability to detect over a wide acoustic field. The internal design of the transformer can be optimized and noise reduced using denoising techniques, allowing for the detection of several PD sources. The biggest issue with the AE method is the inability to pinpoint the PD source in the transformer winding due to the quick attenuation of the signal as it travels through the various media [91].

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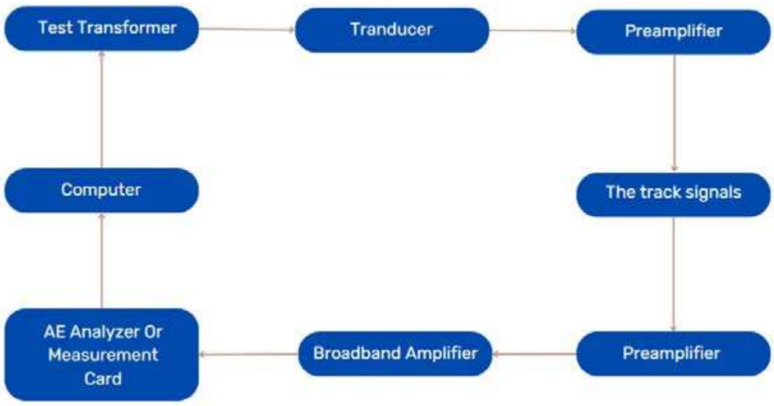

Figure 6. An AE signal recording system from a power transformer is available for PD detection [88].

2.5. Optical

Power transformer oil can be tested for PD activities using the optical technique. Scientists have used a variety of light detection techniques to conduct PD analysis on transformer oil/paper insulation. Mach-Zehnder interferometry, Fabry-Perot interferometry, and fiber Bragg grating are typical examples of optical sensors used for detecting PD [33]. Using a single-mode fiber and laser, MZI was the first optical fiber-based sensor. At first, a fiber coupler separates the incoming light into two separate fibers. The first detecting fiber optic coil is placed in the oil tank's PD signal zone, while the second fiber serves as a reference for the light's raytracing path. The EFPI sensor incorporates a silica diaphragm inside a capsule-shaped silica glass tube to create a single optical fiber. Because of their excellent dielectric property and immunity from electromagnetic interference, FBG sensors are currently employed in power transformers and kept directly in the oil. For a visual representation of the FBG's operating principle, see Figure 7 [92]. Narrowband reflective optical sensors, FBGs operate because they reflect only one wavelength of light and let through the rest.

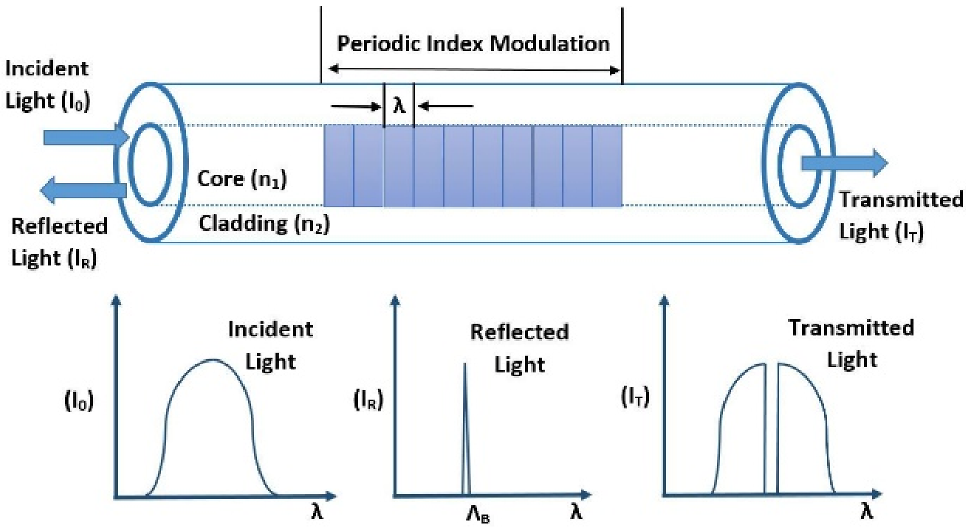

Figure 7. Fiber Bragg Grating Sensor Operation [92].

At first, it was determined that fluorescent optical sensors could only detect PD from light emission in air, and not in transformer oil. In 2013, it was discovered that the optical method, using the fluorescent sensor and an unconventional technology, was accurate for PD measurement in power transformer However, the fluorescent sensor research for PD detection in transformer oil produced dubious results with numerous shortcomings. The attempts to establish a link between photon activity, PD via optical signal, and PD charge restrictions in oil have been conducted aggressively. Based on [93], the measurement was made possible in oil-immersed transformer. This, however, proved difficult, especially when dealing with dated transformer oil [94]. This technique can measure a wide variety of chemical elements and physical properties, and it has the advantages of having a high frequency response and being immune to electromagnetic interference [32]. Major limitations include the inability to calibrate PD detection, a lack of data on PD size, and the inability to reliably identify discharges within transparent material. Current research is focused on improving methods for detecting and locating PD in transformer oil. Since this method of detection does not require the complicated geometry of a power transformer, it is also being studied.

2.6. Combinational Method of PD Detection

The combination of dissolved gas analysis (DGA) and acoustic emission (AE) practices has been employed to identify and localize the partial discharge (PD) anomalies occurs inside power transformers. This integration enables the detection and pinpointing of PD anomalies by using both DGA and AE methods. The detection process involves initially conducting offline dissolved gas analysis (DGA) to assess the gas content, followed by implementing acoustic emission (AE) detection for a duration of 24 hours to identify the sources of PD. This approach aims to replicate the daily load cycle and has been documented in reference [95]. An example of the integration of Acoustic Emission (AE) and Dissolved Gas Analysis (DGA) methods is Photo-Acoustic Spectroscopy (PAS). The operational concept of PAS is illustrated in Figure 8, as described in reference [96]. In this technique, fault gases interact with an infrared source, receiving kinetic energy. The pressure signals are detected by a microphone and converted into electrical signals. By analyzing the amplitude of the sound waves generated and filtering them through optical filters, different gases can be identified.

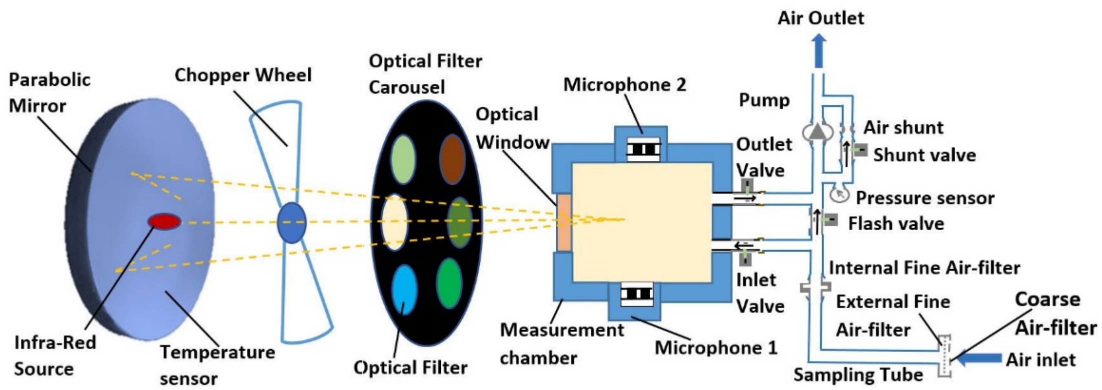

Figure 8. A DGA system utilizing photo-acoustic spectroscopy [96].

The integration of electromagnetic (EM) and acoustic techniques has also been employed. Ultrasonic and ultra-high frequency (UHF) sensors, configured in various geometries, have shown remarkable effectiveness in detecting the origin of partial discharge (PD) within a specific range, as reported in reference [97]. A proposed approach involves the use of a hybrid PD detection system that combines acoustic emission sensors plus transient earth wire voltage (TEV) [98]. Novel techniques for detecting acoustic emission (AE) involve the use of AE sensors to identify the presence of partial discharge (PD) based on a reference time obtained from electrical equipment (EE) signals. This approach enables the localization and validation of the detected signal, ensuring it is not attributed to external noise [99].

The technique for identifying PD by combining acoustic emission (AE), electrical equipment (EE), and dissolved gas analysis (DGA) to evaluate the transformer's entire insulating state, as reported in reference [100]. Noise rejection system for PD detection might be created by combining

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AE and EE approaches. The information gathered via EE detection could be utilized to pinpoint the PD's origin. The sensitivity of the AE method can be enhanced by integrating using EE technique, where the latter serves to initiate events.

Combination of AE and optical techniques involves the use of a Fabry-Perot fiber as an AE sensor for localizing PD. In addition, a fluorescent optical fiber acts as an optical sensor to verify signal of reference originates from PD source, as documented in reference [101]. Table 1 provides a comparative analysis of the advantages and limitations of various techniques used for detecting PD inside power transformers.

Table 1. Summary of the Advantages and Disadvantages of Different Partial Discharge Detection Methods.

	Electrical Detection	**Chemical Detection**	**Acoustic Detection**	**Optical Detection**	**UHF Detection**
Advantages	Good recording of PD signals in the laboratory environment	Good recording of PD signals in the laboratory environment	Has noise immunity for application to do online PD detection	It is possible to employ a wide range of chemical and physical characteristics	Possibility of online PD detection
	High sensitivity	High sensitivity	Good results in real-time	More sensitivity	Enhanced resistance to outside noise
	Due to the transformer's shielding, there is less background noise		Position information of PD possible using sensors at multiple locations	Anti-electromagnetic interference protection	Extremely sensitive and non-interfering
	High precision measurements				Dependable and risk-free from any induced current
				Smaller and lightweight	Less difficult establishing up the experiment
Disadvantages	Extremely challenging to implement in site	The level of dissolve gas does not correlate with the specific type of fault	Interference of signals by environmental noise	For both solid as well as liquid insulation, not being detected is practical.	Unable to supply the PD charge quantity.

	Over-sensitivity causes false alarms	Creates uncertainty because there is no known relationship between the level of glucose and the severity of insulation breakdown	Low sensitivity	Is not calibratable	Calibration issue
	Not suited for use in continuous monitoring of transformers				
	Affect by electromagnetic interference				

3. Type of Sensor Used to Detect PD Signals

3.1. Electrical-electromagnetic sensor

PD is an electrical discharge occurrence characterized by a spark or discharge that occurs when a small section of insulation is partially bridged. It happens when two conductive electrodes with high densities of positive and negative charges become separated. When the applied voltage exceeds a specific critical value called PD inception voltage, transient gas ionization leads to a localized discharge within the insulated system. PD is considered a pre-breakdown phenomenon. PD occurs on micro/nano-sized of voids/cavities/gas-contained bubbles even though the power transformers still can operate. Without PD detection/PD mapping/preventive action, the PD activities keep occurring on the power transformers making the voids/cavities/gas-contained bubbles more significant, and eventually forming a conductive path which completely bridges the two conduction parts; eventually, leading to the major breakdown.

The identification and detection of partial discharge (PD) in power transformers are vital in industrial and power delivery system to prevent to the failure of high-voltage equipment [102, 103]. The use of UHF sensors for PD detection in gas-insulated substations (GIS) is depicted in Figure 9(a). These sensors have shown to be successful in both on-site PD testing and laboratory PD measurement. The use of a UHF sensor to evaluate compatibility of power transformers on DN50/DN80 gate valves is also demonstrated in Figure 9(b). The sensor provides alternative methods for estimating PD, and the illustrated setup, referred to as bushing-tap, is specifically designed for measuring galvanically connected decoupling. Figure 9(c) depicts a configuration of an inductive UHF sensor used to take a reading on the power cable termination [104].

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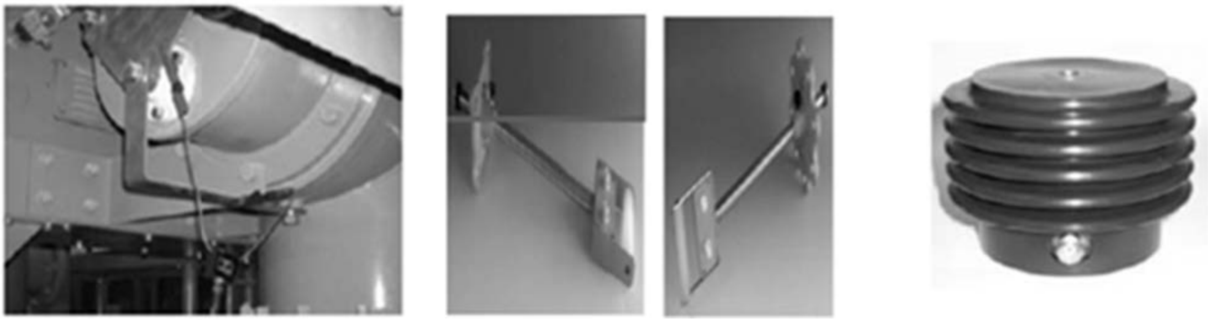
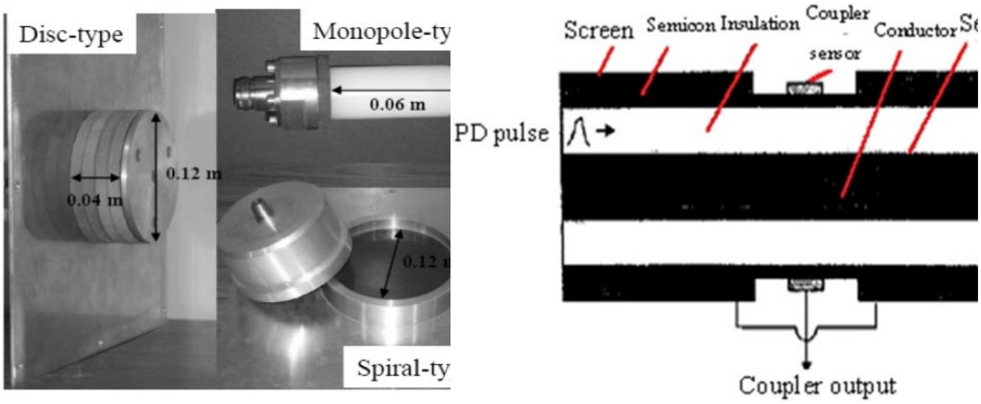


(a) (b) (c)

Figure 9. There are three types of electrical sensors: (a) a UHF sensor attached to a GIS grounding bar, (b) an oil valve sensor for the reactor of a power transformer [left side] for use with a DN 50 gate valve and (right side] for a DN 80 gate valve, (c) an inductive UHF sensor for the termination of a power cable [104].

Figure 10 (a) illustrates three distinct UHF sensors that are suitable for the purpose of PD detection on both power transformers and gas-insulated switchgear. Conventionally, the three types of sensors utilized for PD detection, according to reference [105], are disc-type, monopole-type, and spiral-type sensors. Recent research has revealed that these sensors accumulate a significant amount of energy, demonstrating their excellent sensitivity in detecting emitted signals [105]. Meanwhile, Figure 10 (b) depicts a capacitive coupler used in a high voltage cable for PD detection. The capacitive sensor is linked through a 40-mm tin tape encircles the uncovered cable. The insulation measurement on the cable remains unaffected by the capacitive sensor coupler due to its effective connection at UHF, wherein it functions as the power frequency ground, as stated in reference [106].



(a) (b)

Figure 10. (a) Disc-type, Monopole-type, and Spiral-type UHF Sensors b) Capacitive Coupler Schematic. Reprinted by [105, 106].

3.2. Acoustic sensor

The evaluation of partial discharge (PD) in high-voltage equipment, including power transformers and HV cables, can be accomplished acoustically using a piezoelectric film sensor. Figure 11(a) illustrates the setup of the sensor, while Figure 11(b) shows its configuration. The piezoelectric sensor film, designed in the shape of a disc-shaped crystal, is capable of operating at low resonant frequencies. As explained in reference [107], this precise arrangement makes it simple to determine resonances.

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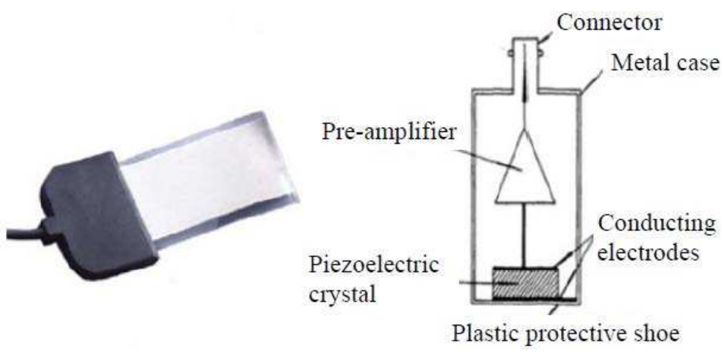
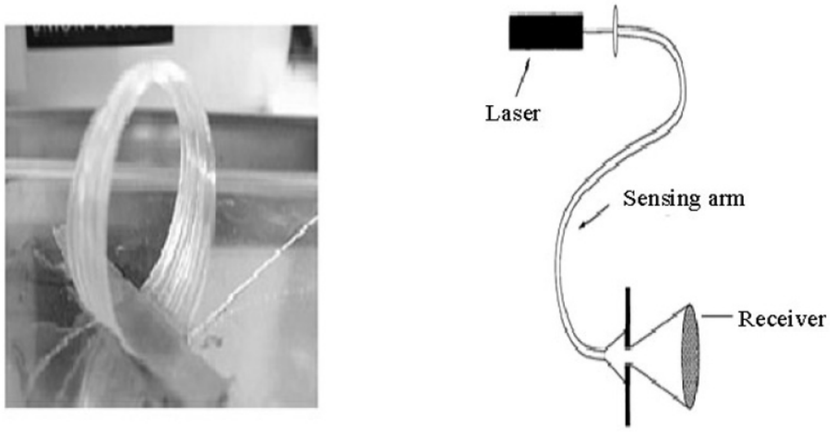


(a) **(b)**

Figure 11. (a) A connectorized piezoelectric film sensor and (b) conventional piezoelectric [107].

3.3. Optical sensor

The prevailing technique to detect (PD) occurs in HV transformers and GIS equipment's are by optical detection technique utilizing fiber intrinsic sensor coil. Figure 12(a) presents a depiction of the sensor coil, which is created by coiling 8 meters of fiber around a former, resulting in a coil with a 25-millimetre diameter. The intrinsic sensor, based on Mach-Zehnder fiber interferometers, operates using single-mode optical fiber typically submerged inside oil along the transformer being tested to measure its PD characteristics [108]. Figure 12(b) illustrates the optical fiber sensor specifically designed for PD detection in GIS [109]. Furthermore, Figures 13(a) and 13(b) showcase the extrinsic Fabry-Perot interferometer sensor and extrinsic microelectron-mechanical system sensor, respectively, both utilized for measuring PD in oil-cooled high voltage transformers [110].



(a) **(b)**

Figure 12. Optical (intrinsic) sensors, including (a) a Mach-Zehnder fiber interferometer-based optical fiber intrinsic sensor and (b) an intrinsic multimode optical fiber sensor. Reprinted by [108, 109].

(a)

(b)

Figure 13. Extrinsic optical sensors. Both (a) and (b) are the Fabry-Perot interferometer and the microelectromechanical system are examples of external sensors [110].

4. Partial Discharge Measurement Using Different Types of Sensors on the Power Transformer and GIS

4.1. Electric-Electromagnetic

When the insulating materials (i.e., solid, liquid, or gas) are subjected to a high electric field, and the electric field exceeds the PD inception electric field, PD activities will occur rapidly [111]. The phenomenon of partial discharge can be explained according to the Townsend theory that stated the discharge mechanism happened due to the electrons emitted from the cathode having obtained enough energy in the electric field, which collides with gas molecules contained in the gas-contained bubbles. This effective collision will ionize the gas molecules and increase the number of charged particles by forming electrons and holes [112]. As the bubbles contain unknown gas, the dielectric constant is typically lower than the surrounding liquid dielectric. As a result, the electric field within the bubbles is greater than the local electric field formed on the liquid insulation. The liberated electron from the cathode will accelerate to the anode through the bubbles, and the gas molecules contained in the bubbles will be ionized as the molecules collided with the electron. This process also can be described as an avalanche process. However, the discharge process is a stochastic phenomenon because not every collision leads to ionizing the gas. This is because if the electron's kinetic energy is not enough, it could not be able to remove another electron upon collision. The electron with a negative charge will apparently accumulate on the bubble walls near the anode, while the ionized molecule with a positive charge will accumulate on the bubble walls nearby the cathode. The accumulation of electron and positive ion molecules will form two streamer channels with opposite polarity of charge. This streamer's channel formed by the transferred charge will create an electric field that opposed and distorted the local electric field produced by the external supply. This phenomenon is rapidly and continuously occurring until the electric field produces by the electron and positive ion in the void is greater than the specific value of the extinction electric field. Then, the partial discharge will be extinguished, which partially bridges the liquid dielectric between the two conduction parts [113].

A coupling capacitor in the range of 0.1 nF to 1 nF can be used to detect the impulse produced during the discharge process. The PD-induced impulse's granularity, polarity, and arrival time are all recorded [114]. The signal produced by PD activity would have a frequency between 300 MHz and 3 GHz (UHF band), given the nanosecond (ns) duration of PD-induced impulses. Detected PD signals can be considered to diagnose the insulation condition of the GIS, transformer, and cable with the right calibration technique. The mechanism of detection has a large detection range, excellent

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sensitivity, and low background noise [115]. Keeping an eye on PD characteristics is crucial for ensuring the insulation performance [116]. The fast-rising duration of the PD current pulse (100 ps in SF6), [117], is a key factor in the efficacy of the UHF approach for measuring PD in the GIS. Commonly, a UHF sensor mounted near the drain/oil valve is capable to detect the PD signal upon its occurrence. Disc-shaped and cone-shaped sensors typically used for the onsite and laboratory measurements, whereas monopole sensor is used for the laboratory measurement. The input power source used in this technique must have a lower discharge rate than the value being measured.

4.1.1. Gas Insulated Switchgear

In SF6, a common insulating gas, the rise time of the PD pulse current is less than a nanosecond (ns). The electromagnetic wave generated by PD is primarily lies in the ultra-high frequency (UHF) range. The antenna and sensor can capture the electromagnetic signal generated by PD as it passes through the GIS tank. If the frequencies of the UHF signals are high enough, they will not be interfered with by other radio or cellular transmissions. Using the data on PD phenomenon in SF6 gasoline, the GIS can simply evaluate breakdown risk [118]. When used in combination with the acoustic method of measurement, the UHF PD measuring technique may enhance PD positioning accuracy. The power dissipation generated by the metallic container can greatly attenuate the PD electromagnetic wave. Experimental observations have indicated the presence of a remarkably low attenuation coefficient, typically measuring around 2 dB/km (with theoretical estimates ranging from 1 dB/km to 2 dB/km) [115]. A quintessential measurement configuration for GIS-based UHF PD detection is shown in Figure 14. A computer, digitizer, pre-amplifier, as well as UHF field probe sensor round out the system. A pre-amplifier with a 25-dB gain and a 1 GHz bandwidth is used to enhance the output. The digitizer samples the UHF signal at 20 ns intervals with a trigger delay during the test [119].

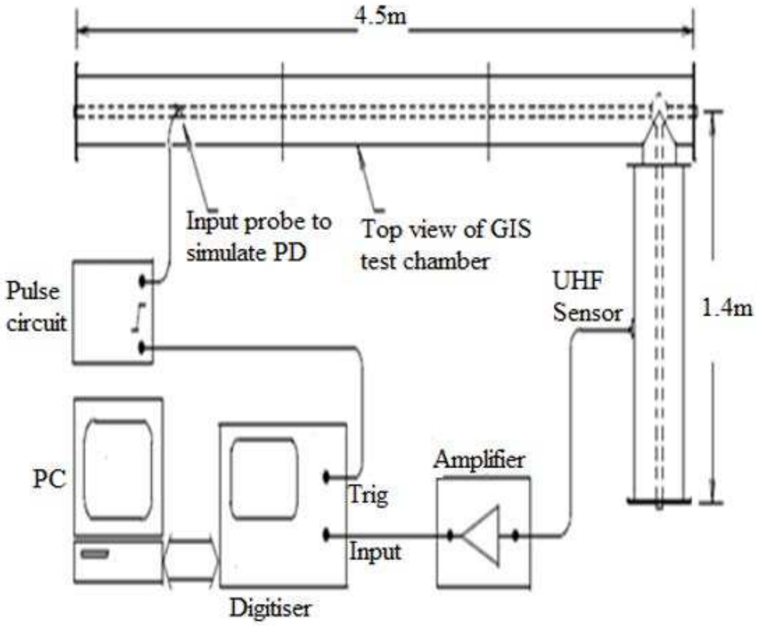
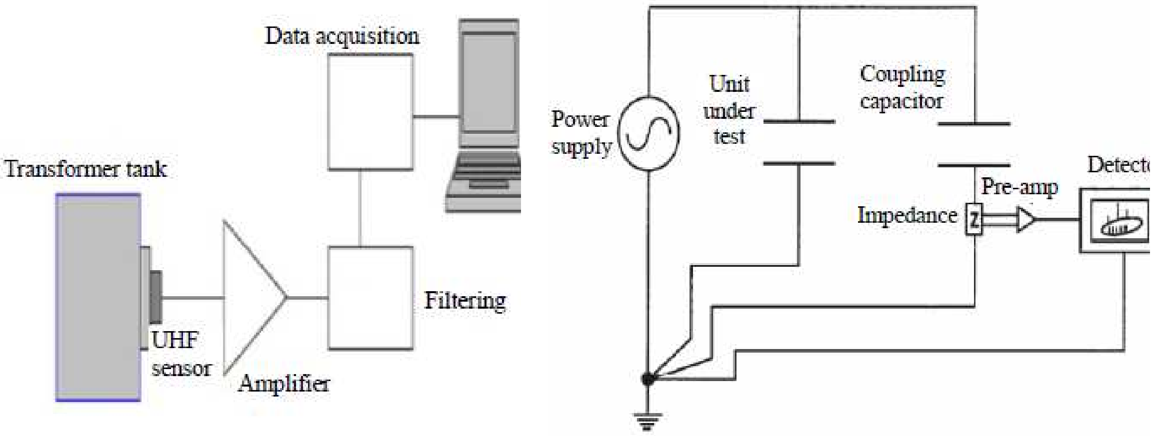


Figure 14. Instrumentation for PD measurements and a typical setup for modelling the measurement on GIS [119].

4.1.2. Transformer

The UHF PD detection technique is widely employed for routine maintenance and monitoring of high voltage transformers. When applied to transformers, the UHF PD detection method benefits from low noise levels due to effective shielding. Additionally, the attenuation of signals in oil insulation is minimal, resulting in excellent measurement sensitivity in on-site conditions. In laboratory settings, the PD measurement setup for transformers typically involves a partially enclosed metallic tank measuring 1.0 m × 0.5 m × 0.5 m. The setup includes a needle sphere PD source and two similar disc-sensors. The transient reading record has a bandwidth of approximately 3 GHz, and no additional amplification is necessary as the output quality from the pre-amplifier is satisfactory. The UHF technique has gained popularity for testing power transformers, offering superior sensitivity compared to AE methods [120]. A typical UHF monitoring system setup, shown in Figure 15(a), consists of filtered and amplified signals from the sensors, which are then detected and digitized. The digitization process enables dynamic utilization of the signals, and the phase reference and clock information are logged along with the digitized data. The recorded PD pulses are considered to originate from a point source in real time, with the amplitude of the pulse calibrated against the UHF signal energy [62]. The coupling capacitor does this by enabling UHF transmissions to get through while filtering out the low-frequency noise based on the Figure 15 (b). Since the testing tools are corona-free, they can be connected to transformers of various power.



(a) **(b)**

Figure 15. (a) The basic UHF monitoring system for PD and its guiding principle and (b) Principle of a typical Ultra High Frequency [62].

4.2. Chemical

Chemical changes in the composition of insulating materials in transformers and GIS can be utilized for the chemical detection of PD signals. By observing these changes, it is possible to identify PD activity occurring within the equipment. The use of DGA or HPLC are used to analyze the chemical characteristics. The DGA study sought to determine the concentrations of several gases, including hydrogen, ethylene, acetylenes, carbon dioxide, and methane, in a sample of fluid from an oil-cooling transformer's container or gas from the GIS [121]. These levels must not be higher than those specified in the occurrence of oil insulation or insulation material malfunction. Unfortunately, no scientific or experimental link or calibration has been established between DGA readings, dissolved gas levels, and fault types. The HPLC test quantifies the by-products of transformer or GIS insulation breakdown. When a transformer's insulation fails, glucose is produced. Real-time monitoring of PD byproducts through the collection and analysis of sufficient quantities of insulation breakdown byproducts is time-consuming. Due to the lack of a consistent association between the glucose concentration emitted during insulation failure and the kind and severity of high voltage transformer malfunction, both HPLC and DGA tests are prone to the same degree of ambiguity. Inaccurate localization of the PD signal source and evaluation of insulation deterioration are also beyond the chemical approach's capabilities. As a result, the chemical technique cannot provide real-time, online monitoring.

4.2.1. Transformer

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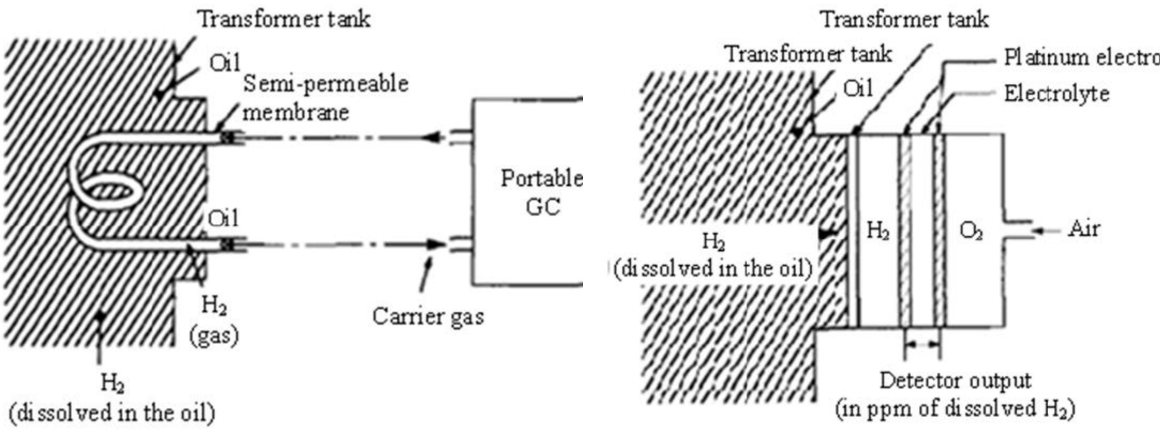
Figure 16(a) illustrates a hydrogen-oil detector. A portable gas chromatograph is connected to a semipermeable membrane, which is then located in the transformer's oil tank. The portable gas chromatograph can test the concentration of hydrogen gas at predetermined time intervals. The fuel-cell type detectors are used in the second profit-oriented version of the DGA testing for power transformer, as illustrated in Figure 16 [122].



(a) **(b)**

Figure 16. The two most common chemical methods for detecting PD are the (a) hydrogen-in-oil detector and (b) continuous monitoring [122].

4.3. Acoustic

The PZT ultrasonic sensor is sensitive to signals generated by PD in oil at wideband frequencies (from 10 kHz to 500 kHz). Most of the PD detection and monitoring devices use on acoustic sensors, which are usually located far from high-voltage hardware. A PD coupler is required for acoustic detection equipment that detects harmonic distortion. The vaporization of the oil's molecule results in a mechanical energy explosion, which a pressure field is produced from which sonic wave emerges. The capacitive properties of PD are unimportant when acoustic technique is used due to its insensitive to changes in the capacitance of the test object [118]. When comparing the two PD signal detection systems, the acoustic one has a lower sensitivity than the electrical one. On the other hand, by measuring the time differences of arrival (TOA) of acoustic signals at multiple sensors deployed, it is possible to estimate the location where partial discharge occurs.

4.3.1. Gas Insulated Switchgear

The GIS is designed as a sealed structure, filled with pressurized gas. As an insulator, SF6 gas is more effective than air because it exhibits higher dielectric strength, acts as an electronegative medium to capture free electrons and prevent electrical discharges, is non-flammable, possesses an extremely stable molecular structure, and serves as a cooling medium. The acoustic emission (AE) reflected off the metal walls of the GIS can be used to discern PD. The acoustic waves created by PD have a wide frequency range (20 kHz - 250 kHz) and a radical symmetry. The PD measurement at GIS can be conducted using a touch sensor, as shown in Figure 17.

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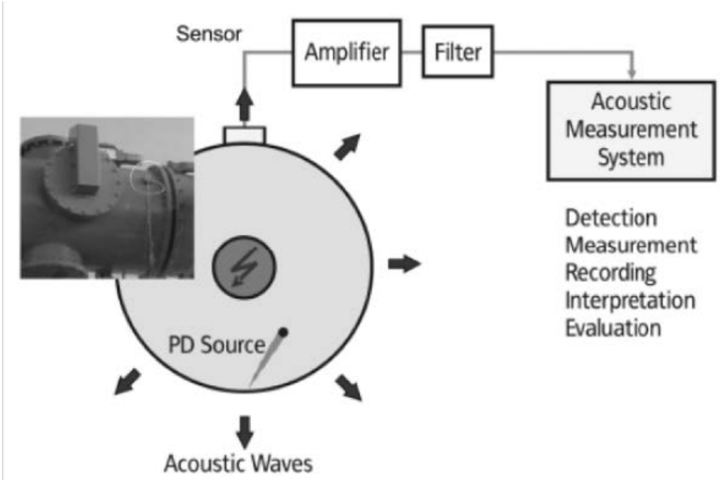

Figure 17. The touch sensor practically used to detect PD in GIS.

4.3.2. Transformer

The maximal temperature and insulation tolerance are crucial factors in determining a transformer's operational lifespan, which has a significant economic impact on the operation of an electrical power network. Any malfunctioning transformer reduces network dependability and increases maintenance expenses. Before analysis, the acoustic signals generated by partial discharges PD in oil-cooled transformers are detected using a decoupler and amplified with a low-noise amplifier to assure high sensitivity. In laboratory tests, PD must be simulated using three varieties of electrode structures: plane-plane, needle-plane, and wire-wire. When these structures are stimulated, they simulate partial discharges in the transformer's oil-filled walls. Increasing the alternating current (AC) voltage from 0 to 50 kV rms (refer Figure 18) induces PD in the oil-immersed electrode system. On the outer surface of the transformer tank, an acoustic emission sensor is installed to detect the PD-induced acoustic signals. These signals are then transmitted to an oscilloscope via a low-noise amplifier with a frequency bandwidth of 1.6 kHz to 1.6 MHz and a 3-dB mid-band frequency bandwidth. Depending on the electrode system, the frequency ranges of the acoustic signals range from 45 kHz to 25 kHz for the plane-plane configuration, 60 kHz to 279 kHz for the needle-plane configuration, and 50 kHz to 180 kHz for the wire-wire configuration. Specifically, the detected frequencies for the needle-plane electrode were 145 kHz, and for the wire-wire electrode, they were 121 kHz. Using three acoustic sensors to capture the PD-induced acoustic signals, the location of the PD can be determined to within a 1% margin of error [119].

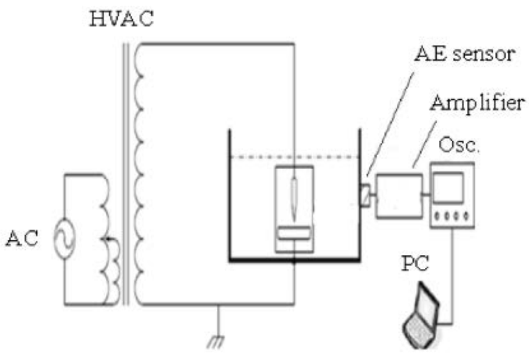

Figure 18. The experimental setup for PD measurement by replicating the PD stimulate in a transformer using a PD test cell [119].

4.4. Optical

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Fiber optic cable has long been utilized as a sensor because to its many advantages, including its resistance to protection against chemical decay, electrical sparks, a wide variety of measures, and response, tolerance to high sensitivity, wide bandwidth, extreme temps, and compact size. Detection of optical properties such as wavelength, intensity, polarity, and phase are based on minute changes in optical properties. As a result, four types of optical sensors can be utilized for various applications, including spectral analysis, intensity measurements, polarization, and interferometry. The fiber optic acoustic sensor is one such sensor that combines acoustic and optical technologies. It includes a fiber optic intrinsic transducer, such as a Mach-Zehnder or Michelson interferometer, multimode fiber, and a fiber optic external device, such as a Fabry-Perot interferometric sensor. Detection method of the fiber optic acoustic sensors relies on leveraging the photo elastic effect of silica fiber to convert acoustic signals into optical signals. When a sound wave intersects with a fiber optics, its shape is distorted. This distortion will influence fibre length and refractive index. As a result of this change, a passing laser beam may undergo some modulation. The silica fiber's low photo elastic effect to be increased in improving the sensitivity.

4.4.1. Transformer

In general, PD originated inside a huge oil-filled power transformer, where its detection is notoriously difficult to be performed by using an external acoustic sensor. To spot and determine the PD with sufficient sensitivity, an acoustic sensor, for example a fiber-optic coil, are required. A previous approach to acoustic detection involved utilizing fiber optic essential interferometers, such as the fiber Michelson and Mach-Zehnder interferometers. These fiber sensors employed a single mode fiber and laser technology. A fiber coupler divides the light into two strands with intensity differences of 3 dB from the original source. One fiber serves as a reference, while the other as a sensor. To generate noise signals, either transmission, as in the Michelson interferometer, or reflection, as in the Mach-Zehnder interferometer, merges the light from the two shafts. Although the source light is in the reference shaft, the sensor arm is vulnerable to PD-induced sonic wave disturbance. The sonic wave will have affected the initial light source as viewed by the detecting arm. The essential fiber interferometer sensor achieves excessively high sensitivity when a long fiber is utilized in the detection procedure. In Figure 19, an experimental setup is shown for monitoring PD signals using a submerged coil of fiber optic sensor into oil inside transformer. Light source in the system, a single-mode optic fiber, an optoelectronic transducer which converts light beam into an electrical signal, two electrodes, and a high voltage input to generate simulated PD events that would produce acoustic emission. The phase of the optical signal would alter if an acoustic wave struck the fiber optic sensor coil. As a by-product of consecutive phase difference, the visible light in the sensor coil has the tendency to be modulated. The electrical signal created by the sensor coil's light source is then amplified and inspected [120].

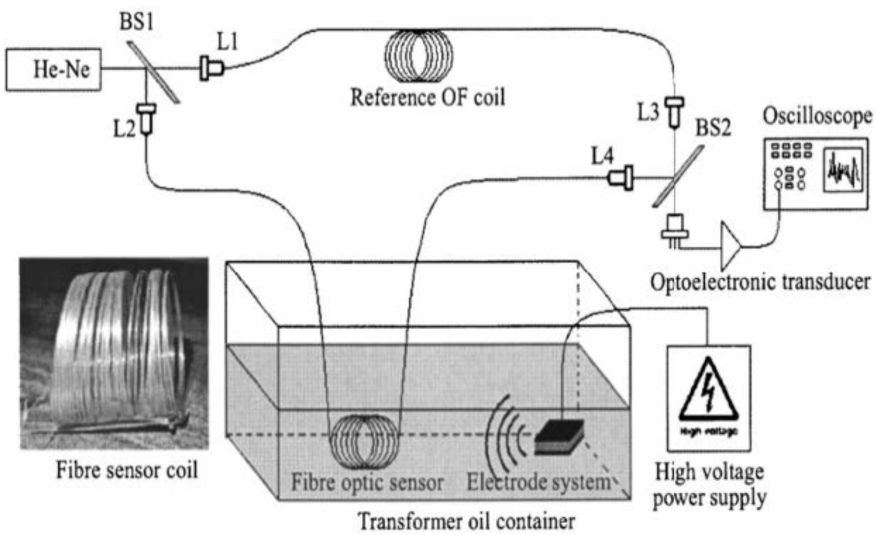

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Figure 19. The Mach-Zehnder interferometer was used in an experiment to detect PD in the laboratory.

The Fabry-Perot interferometric sensor has a wide range of applications, including the detection of acoustic waves generated due to PD events [121]. It consists of two reflective surfaces that form a small sensing element known as Fabry-Perot cavity. The operational principle of the Fabry-Perot interferometer sensor is depicted in Figure 20. The 22-coupler was used with a light source. A single-mode fiber is attached to one of the coupler arms and fused to the sensor head. The optical signal is transformed into an electrical signal via a photodetector connected to the opposite arm simultaneously. The electrical signal undergoes amplification before being sent to a high-speed signal processor or a digital oscilloscope. The silica diaphragm and single-mode fiber Fabry-Perot interferometer sensor is built within the sensor lead. The Fabry-Perot interferometer sensor's capacity to track acoustic signals produced by partial discharge inside the transformer has been proven in multiple testing.

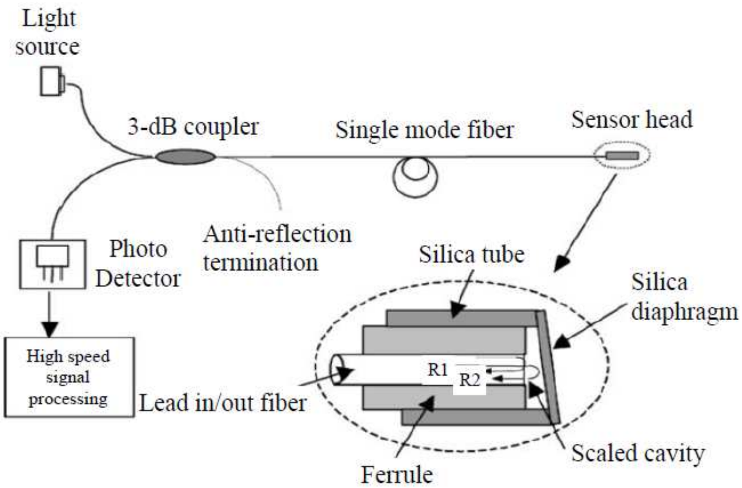

Figure 20. The illustration of the principle of the Fabry-Perot interferometric sensor.

On the other hand, Table 2 and Table 3 show the recent timelines of Partial Discharge activities in Power Transformer and Gas Insulated Switchgear, respectively.

Table 2. Recent timeline of Partial Discharge activities inside Power Transformer.

Reference, Year	Artificial defect/PD test cell/electrodes configuration	Techniques	Significant Outcomes
[123], 2018	Needle-plane model	A three-phase oil-filled transformer's whole internal structure was employed to research the propagation properties of electromagnetic waves	The EM signal's amplitude reduces nonlinearly as its distance from the PD source grows, and the rate of dampening slows as it does so

[45], 2018	Needle-plane electrode	Transformer oil characteristics for a temperature range of 30-75 C may be identified via the AE technique	Due to alterations in factors like viscosity and BDV, the AE signal's amplitude decreased from 65C to 75C at 17 kV
[124], 2018	Needle-plane electrode	Fabry-Perot optical fiber sensor array-based AE technique with a Steered Response power sound-source localization algorithm	Enhanced accurateness compared to the more common piezoelectric transducer
[51], 2019	Artificial PD defect/source	BA combinational method: The UHF probe's tip is inserted with an AE sensor.	When compared to direct acoustic wave detection, the integrated sensor is more sensitive.
[125], 2019	Water Content of Transformer Insulation Paper	Use of optical fiber sensors for optical detection	Ties well to a water activity probe that works with various dielectric oils
[122], 2019	Void, surface, and floating electrode		When compared to three or more PD sources, the multi-step discrimination approach can detect and differentiate mixed signals with similar forms that the one-step method was unable to do. It can also enhance the differentiation capabilities in subclasses.
[126], 2021	Suspended metal defect	Use multiplexed optical ultrasonic sensors	Signal processing and analysis techniques were applied to identify partial discharge events. A localization algorithm was likely employed to determine the precise location of the partial discharge within the transformer. The combination of these techniques demonstrates a potential solution for detecting and addressing partial discharge defects in power transformers
[127], 2021	Localized breakdown in electrical insulation	Use high sensitivity optical fiber interferometer sensor	To enhance the early detection of such defects

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[128], 2021	Localized breakdown in electrical insulation	Use Rogowski coil sensor	Analyzing the time delay between the arrival of PD signals at different locations inside the transformer windings.
[129], 2022	Defect in oil	Acoustic emission technique	The use of fuzzy logic aids in approaching acoustic emission technique for PD detection

Table 3. Recent timeline of Partial Discharge activities in Gas Insulated Switchgear.

Reference, Year	Artificial defect/PD test cell/electrodes configuration	Techniques	Significant Outcomes
[130], 2018	Voids and containments	Integration of optical fiber and ultra-high frequency (UHF)	Usage of both methods at once provides comprehensive approach for PD detection
[131], 2018	Conductor protrusions	Power-frequency partial discharge test	The test asses the dielectric integrity of GIS equipment by detecting weak discharge under AC voltage
[132], 2018	Free moving particles, protrusions, floating metallic parts, as well as cavities due to voids and cracks in spacers	Uses ultra-high frequency (UHF) for PD measurement	A new approach to diagnose unknown phase-shifted PDs in GIS using a decision tree method, based on UHF measurement and extracted parameters
[133], 2019	Voids, impurities, or mechanical stresses	Employing an optical fiber sensor	Optical fiber sensor technique offers advantages such as high sensitivity, immunity to electromagnetic interference, and the ability to perform remote monitoring of PD activity in GIS.
[134], 2020	Cracks, floating particles, free particles, protrusions on conductors (POC), protrusions on enclosures (POE), particles on spacers (POS), and voids	Use autoencoders	Aims to identify and classify these PD defects in GISs.

[135], 2021	Fault diagnosis of Gas Insulated Switchgear (GIS)	Micro built-in optical sensor along with a UHF (Ultra High Frequency)	These techniques enhance the accuracy and effectiveness of PD fault diagnosis in GIS equipment.
[136], 2021	Insulation degradation, equipment failure	Fluorescent optical fiber sensor	Offers the advantage of non-invasive and real-time monitoring, which can help in identifying and addressing potential insulation problems before they escalate into major failures.
[137], 2022	Latent insulation fault	Ultrahigh frequency (UHF) flexible planar biconical antennas	new flexible planar biconical antenna design method for PD detection in GIS. This technique offers improved detection sensitivity and adapts to the curved structure of GIS.
[138], 2022	Insulation voids	Multiscale fusion simulation	involves the use of a numerical model based on the Finite Element Method (FEM). The FEM model considers the complex structure and material properties of the GIS, including the insulation void defects.
[139], 2022	Corona discharge	UV sensors	A new method for detecting corona discharge in Gas Insulated Switchgear based on UV light emissions. The technique offers non-intrusive and real-time monitoring capabilities, enabling timely detection and maintenance actions to ensure the reliable operation of GIS systems.

5. Conclusions

Monitoring the PD phenomenon in high-voltage power systems and equipment is considered a necessary measurement for the preventive maintenance of equipment that is under operation or for the performance assessment of new equipment manufactured by the industries. Hence, the capability and suitability of the use of appropriate sensors with certain properties and methods of PD measurement in obtaining reliable outcomes of PD measurement on power transformers and GIS is the gap which potentially can be gratified and included to be the critical concerns in extending the research in future. Based on the collective review of PD detection on power transformers and GIS, it has been found that advanced online monitoring technology was preferred in PD detection, especially the technique that uses directly integrated sensors on high-voltage equipment. This is because the online monitoring technique allowed the PD detection to be conducted without the need of isolating the power system and giving out realistic results based on the equipment's actual peripherals. Therefore, the research on designing and improving the capability of sensors can be summarized as an impactful study for future research on PD detection, including the technique to enhance sensitivity and accuracy in obtaining high precision of PD data collection.

The UHF detection approach is currently an excellent tool for identifying PD in power transformers and GIS. Capturing and analyzing the electromagnetic signals released by PD occurrences is required for UHF detection. It employs UHF antennas that are purpose-built to detect

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and receive these signals. The advantage of UHF monitoring is its capacity to detect PD actions early on, allowing for timely maintenance and prevention of future deterioration. To ensure effective detection, UHF sensors can be carefully placed near crucial portions of the equipment. UHF detection has a number of advantages, including high sensitivity, a broad frequency bandwidth, and the ability to detect PD in both power transformers and GIS. It is a widely accepted and reliable method for PD detection in these types of electrical equipment. However, please note that the choice of PD detection method should consider the specific requirements and characteristics of the equipment being monitored. Consulting industry standards and experts in the field is recommended to determine the most suitable method for a particular application.

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References

1. Akbari, A., et al., Transfer function-based partial discharge localization in power transformers: a feasibility study. IEEE Electrical Insulation Magazine, 2002. 18(5): p. 22-32.
2. Meira, M., et al., Power transformers monitoring based on electrical measurements: state of the art. IET Generation, Transmission & Distribution, 2018. 12(12): p. 2805-2815.
3. Abbasi, A.R., M.R. Mahmoudi, and Z. Avazzadeh, Diagnosis and clustering of power transformer winding fault types by cross-correlation and clustering analysis of FRA results. IET Generation, Transmission & Distribution, 2018. 12(19): p. 4301-4309.
4. Saponara, S., et al., Predictive diagnosis of high-power transformer faults by networking vibration measuring nodes with integrated signal processing. IEEE Transactions on Instrumentation and Measurement, 2016. 65(8): p. 1749-1760.
5. Duval, M., A review of faults detectable by gas-in-oil analysis in transformers. IEEE electrical Insulation magazine, 2002. 18(3): p. 8-17.
6. Faiz, J. and M. Soleimani, Dissolved gas analysis evaluation in electric power transformers using conventional methods a review. IEEE Transactions on Dielectrics and Electrical Insulation, 2017. 24(2): p. 1239-1248.
7. Kawaguchi, Y. and S. Yanabu, Partial-discharge measurement on high-voltage power transformers. IEEE Transactions on Power Apparatus and Systems, 1969(8): p. 1187-1194.
8. Zhang, S., Analysis of some measurement issues in bushing power factor tests in the field. IEEE transactions on power delivery, 2006. 21(3): p. 1350-1356.
9. Hashemnia, N., A. Abu-Siada, and S. Islam, Detection of power transformer bushing faults and oil degradation using frequency response analysis. IEEE Transactions on Dielectrics and Electrical Insulation, 2016. 23(1): p. 222-229.
10. Secic, A., M. Krpan, and I. Kuzle, Vibro-acoustic methods in the condition assessment of power transformers: A survey. IEEE Access, 2019. 7: p. 83915-83931.
11. Wang, M., A.J. Vandermaar, and K.D. Srivastava, Review of condition assessment of power transformers in service. IEEE Electrical insulation magazine, 2002. 18(6): p. 12-25.
12. Oliveira, M. and A. Bretas. Application of discrete wavelet transform for differential protection of power transformers. in 2009 IEEE Bucharest PowerTech. 2009. IEEE.

13. Yao, C., et al., Improved online monitoring method for transformer winding deformations based on the Lissajous graphical analysis of voltage and current. IEEE Transactions on Power Delivery, 2015. 30(4): p. 1965-1973.
14. Saha, T.K., Review of modern diagnostic techniques for assessing insulation condition in aged transformers. IEEE transactions on dielectrics and electrical insulation, 2003. 10(5): p. 903-917.
15. Cardoso, A. and L.M. Oliveira, Condition monitoring and diagnostics of power transformers. 1999.
16. Tenbohlen, S., et al. Development and results of a worldwide transformer reliability survey. in Proceedings of the CIGRE SC A2 Colloquium, Shanghai, China. 2015.
17. Fu, Q., et al., Online condition monitoring of onboard traction transformer core based on core-loss calculation model. IEEE Transactions on Industrial Electronics, 2017. 65(4): p. 3499-3508.
18. Christina, A., et al., Causes of transformer failures and diagnostic methods–A review. Renewable and Sustainable Energy Reviews, 2018. 82: p. 1442-1456.
19. Han, Y. and Y. Song, Condition monitoring techniques for electrical equipment-a literature survey. IEEE Transactions on Power delivery, 2003. 18(1): p. 4-13.
20. Bigdeli, M., M. Vakilian, and E. Rahimpour, Transformer winding faults classification based on transfer function analysis by support vector machine. IET electric power applications, 2012. 6(5): p. 268-276.
21. Li, S. and J. Li, Condition monitoring and diagnosis of power equipment: review and prospective. High Voltage, 2017. 2(2): p. 82-91.
22. Medeiros, R., F. Costa, and K. Silva, Power transformer differential protection using the boundary discrete wavelet transform. IEEE transactions on power delivery, 2015. 31(5): p. 2083-2095.
23. High-voltage and high-current test techniques. 2000, International Standard. p. 99.
24. Bhatt, S.M., D. Kumar, and K. Patel. Partial discharge analysis in time and time-frequency domain of solid dielectric in power transformer. in 2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON). 2018. IEEE.
25. Kumar, A.S., et al. Online partial discharge detection and location techniques for condition monitoring of power transformers: A review. in 2008 International Conference on Condition Monitoring and Diagnosis. 2008. IEEE.
26. Darwish, A., et al., On the electromagnetic wave behavior due to partial discharge in gas insulated switchgears: State-of-art review. IEEE Access, 2019. 7: p. 75822-75836.
27. Liao, R.-j., et al., Aging condition assessment of transformer oil-paper insulation model based on partial discharge analysis. IEEE Transactions on Dielectrics and Electrical Insulation, 2011. 18(1): p. 303-311.
28. Fuhr, J. and T. Aschwanden, Identification and localization of PD-sources in power-transformers and power-generators. IEEE Transactions on Dielectrics and Electrical Insulation, 2017. 24(1): p. 17-30.
29. Mor, A.R., et al., A new design of a test platform for testing multiple partial discharge sources. International Journal of Electrical Power & Energy Systems, 2018. 94: p. 374-384.
30. Rubio-Serrano, J., et al., Electro-acoustic detection, identification and location of partial discharge sources in oil-paper insulation systems. IEEE Transactions on Dielectrics and Electrical Insulation, 2012. 19(5): p. 1569-1578.
31. Bräunlich, R., et al. Assessment of insulation condition of large power transformers by on-site electrical diagnostic methods. in Conf. Record of the 2000 IEEE Inter. Symposium on Electrical Insulation, IEEE Publication 00CH37075. 2000.
32. Yaacob, M., et al., Review on partial discharge detection techniques related to high voltage power equipment using different sensors. Photonic sensors, 2014. 4: p. 325-337.
33. Khan, Q., et al., Partial discharge detection and diagnosis in gas insulated switchgear: State of the art. IEEE Electrical Insulation Magazine, 2019. 35(4): p. 16-33.
34. Sinaga, H., B. Phung, and T. Blackburn, Partial discharge localization in transformers using UHF detection method. IEEE Transactions on Dielectrics and Electrical Insulation, 2012. 19(6): p. 1891-1900.
35. Chen, M.-K., J.-M. Chen, and C.-Y. Cheng, Partial discharge detection by RF coil in 161 kV power transformer. IEEE Transactions on Dielectrics and Electrical Insulation, 2014. 21(3): p. 1405-1414.
36. Jahangir, H., et al., UHF PD measurements on power transformers-advantages and limitations. IEEE Transactions on Dielectrics and Electrical Insulation, 2017. 24(6): p. 3933-3940.
37. Ariannik, M., et al., UHF measurement in power transformers: An algorithm to optimize accuracy of arrival time detection and PD localization. IEEE Transactions on Power Delivery, 2019. 34(4): p. 1530-1539.

38. Beura, C.P., M. Beltle, and S. Tenbohlen, Positioning of UHF PD sensors on power transformers based on the attenuation of UHF signals. IEEE Transactions on Power Delivery, 2019. 34(4): p. 1520-1529.
39. Biswas, S., et al., A methodology for identification and localization of partial discharge sources using optical sensors. IEEE Transactions on Dielectrics and Electrical Insulation, 2012. 19(1): p. 18-28.
40. Razzaq, A., et al., Transformer oil diagnostic by using an optical fibre system: a review. IET Science, Measurement & Technology, 2019. 13(5): p. 615-621.
41. Baug, A., et al., Identification of single and multiple partial discharge sources by optical method using mathematical morphology aided sparse representation classifier. IEEE Transactions on Dielectrics and Electrical Insulation, 2017. 24(6): p. 3703-3712.
42. Refaat, S.S., et al. A review of partial discharge detection techniques in power transformers. in 2018 Twentieth International Middle East Power Systems Conference (MEPCON). 2018. IEEE.
43. Hooshmand, R.A., M. Parastegari, and M. Yazdanpanah, Simultaneous location of two partial discharge sources in power transformers based on acoustic emission using the modified binary partial swarm optimisation algorithm. IET Science, Measurement & Technology, 2013. 7(2): p. 119-127.
44. Wang, Y.B., et al., Partial discharge localisation methodology for power transformers based on improved acoustic propagation route search algorithm<? show [AQ ID= Q1]?>. IET Science, Measurement & Technology, 2018. 12(8): p. 1023-1030.
45. Shanker, T.B., et al., Effects of transformer-oil temperature on amplitude and peak frequency of partial discharge acoustic signals. IEEE Transactions on Power Delivery, 2018. 33(6): p. 3227-3229.
46. Wang, Y.-B., et al., Acoustic localization of partial discharge sources in power transformers using a particle-swarm-optimization-route-searching algorithm. IEEE Transactions on Dielectrics and Electrical Insulation, 2017. 24(6): p. 3647-3656.
47. Dai, J., et al., Dissolved gas analysis of insulating oil for power transformer fault diagnosis with deep belief network. IEEE Transactions on Dielectrics and Electrical Insulation, 2017. 24(5): p. 2828-2835.
48. Mackenzie, E., et al. On-line monitoring and diagnostics for power transformers. in 2010 IEEE International Symposium on Electrical Insulation. 2010. IEEE.
49. Faiz, J. and M. Soleimani, Assessment of computational intelligence and conventional dissolved gas analysis methods for transformer fault diagnosis. IEEE Transactions on Dielectrics and Electrical Insulation, 2018. 25(5): p. 1798-1806.
50. Wang, X., et al., Acousto-optical PD detection for transformers. IEEE transactions on power delivery, 2006. 21(3): p. 1068-1073.
51. Si, W., C. Fu, and P. Yuan, An integrated sensor with AE and UHF methods for partial discharges detection in transformers based on oil valve. IEEE Sensors Letters, 2019. 3(10): p. 1-3.
52. Lu, Y., et al. The Application of High Frequency and Ultra High Frequency Partial Discharge Detection to Gas Insulated Switchgear. in 2022 4th Asia Energy and Electrical Engineering Symposium (AEEES). 2022. IEEE.
53. Sinaga, H., B. Phung, and T. Blackburn. Partial discharge measurement for transformer insulation using wide and narrow band methods in ultra high frequency range. in 2009 Australasian Universities Power Engineering Conference. 2009. IEEE.
54. Shi, R., et al. The application of transient earth voltage in the partial discharge of power transformers. in 2017 1st International Conference on Electrical Materials and Power Equipment (ICEMPE). 2017. IEEE.
55. Ren, M., et al. Application of Transient Earth Voltage method in PD detection in GIS. in Proceedings of 2011 International Symposium on Electrical Insulating Materials. 2011. IEEE.
56. Nagamani, H., et al. Acoustic emission technique for detection and location of simulated defects in power transformers. in 2005 IEEE Russia Power Tech. 2005. IEEE.
57. Qi, B., et al. Partial discharge detection for GIS: A comparison between UHF and acoustic methods. in 2010 IEEE International Symposium on Electrical Insulation. 2010. IEEE.
58. Rutgers, W. and Y. Fu, UHF PD-detection in a power transformer. 1997.
59. Wiesbeck, W., et al. Influence of antenna performance and propagation channel on pulsed UWB signals. in 2007 International Conference on Electromagnetics in Advanced Applications. 2007. IEEE.
60. Jiang, T., et al., Improved bagging algorithm for pattern recognition in UHF signals of partial discharges. Energies, 2011. 4(7): p. 1087-1101.
61. Judd, M.D., L. Yang, and I.B. Hunter, Partial discharge monitoring for power transformer using UHF sensors. Part 2: field experience. IEEE Electrical Insulation Magazine, 2005. 21(3): p. 5-13.

62. Judd, M.D., L. Yang, and I.B. Hunter, Partial discharge monitoring of power transformers using UHF sensors. Part I: sensors and signal interpretation. IEEE Electrical Insulation Magazine, 2005. 21(2): p. 5-14.
63. Jahangir, H., et al., Possibility of PD calibration on power transformers using UHF probes. IEEE Transactions on Dielectrics and Electrical Insulation, 2017. 24(5): p. 2968-2976.
64. Gaouda, A., et al., On-line detection and measurement of partial discharge signals in a noisy environment. IEEE Transactions on Dielectrics and Electrical Insulation, 2008. 15(4): p. 1162-1173.
65. Seo, J., H. Ma, and T.K. Saha, A joint vibration and arcing measurement system for online condition monitoring of onload tap changer of the power transformer. IEEE Transactions on Power Delivery, 2016. 32(2): p. 1031-1038.
66. Abd Rahman, M., P. Lewin, and P. Rapisarda, Autonomous localization of partial discharge sources within large transformer windings. IEEE Transactions on Dielectrics and Electrical Insulation, 2016. 23(2): p. 1088-1098.
67. Timperley, J.E., Incipient fault identification through neutral RF monitoring of large rotating machines. IEEE Transactions on Power Apparatus and Systems, 1983(3): p. 693-698.
68. Giussani, R., I. Cotton, and R. Sloan. Comparison of IEC 60270 and RF partial discharge detection in an electromagnetic noise-free environment at differing pressures. in 2012 IEEE International Symposium on Electrical Insulation. 2012. IEEE.
69. IEEE Recommended Practice for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors. 2010. p. 1-47.
70. Judd, M.D. Experience with UHF partial discharge detection and location in power transformers. in 2011 Electrical Insulation Conference (EIC). 2011. IEEE.
71. Fuhr, J., Procedure for identification and localization of dangerous PD sources in power transformers. IEEE Transactions on Dielectrics and Electrical Insulation, 2005. 12(5): p. 1005-1014.
72. Xie, Q., et al., Location of partial discharge in transformer oil using circular array of ultrasonic sensors. IEEE Transactions on Dielectrics and Electrical Insulation, 2013. 20(5): p. 1683-1690.
73. Zheng, S., et al., Location of PDs inside transformer windings using UHF methods. IEEE Transactions on Dielectrics and Electrical Insulation, 2014. 21(1): p. 386-393.
74. Bartnikas, R., Partial discharges. Their mechanism, detection and measurement. IEEE Transactions on dielectrics and electrical insulation, 2002. 9(5): p. 763-808.
75. Karmakar, S., N. Roy, and P. Kumbhakar. Partial discharge measurement of transformer with ICT facilities. in 2009 International Conference on Power Systems. 2009. IEEE.
76. Ma, G.-M., et al., Fiber Bragg grating sensor for hydrogen detection in power transformers. IEEE Transactions on Dielectrics and Electrical Insulation, 2014. 21(1): p. 380-385.
77. Skelly, D. Photo-acoustic spectroscopy for dissolved gas analysis: Benefits and Experience. in 2012 IEEE International Conference on Condition Monitoring and Diagnosis. 2012. IEEE.
78. Lima, S.E., et al., Mandrel-based fiber-optic sensors for acoustic detection of partial discharges—A proof of concept. IEEE Transactions on Power Delivery, 2010. 25(4): p. 2526-2534.
79. Sheng, J. and G. Wu. Study on gas and oil separating plant used for online monitoring system of transformer. in Conference Record of the 2004 IEEE International Symposium on Electrical Insulation. 2004. IEEE.
80. Sparkman, O.D., Z. Penton, and F.G. Kitson, Gas chromatography and mass spectrometry: a practical guide. 2011: Academic press.
81. Bakar, N.A., A. Abu-Siada, and S. Islam, A review of dissolved gas analysis measurement and interpretation techniques. IEEE Electrical Insulation Magazine, 2014. 30(3): p. 39-49.
82. Jiang, J., et al. Dissolved hydrogen detection in power transformer based on etched fiber Bragg grating. in 2015 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings. 2015. IEEE.
83. Mukhtaruddin, A., et al. Techniques on partial discharge detection and location determination in power transformer. in 2016 3rd International Conference on Electronic Design (ICED). 2016. IEEE.
84. Mak, T., et al., Optical fiber sensor for the continuous monitoring of hydrogen in oil. Sensors and Actuators B: Chemical, 2014. 190: p. 982-989.
85. Kalathiripi, H. and S. Karmakar. Partial discharge study in transformer oil using acoustic emission technique and UV-visible spectroscopy. in 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON). 2017. IEEE.

86. Qian, S., et al., High sensitivity detection of partial discharge acoustic emission within power transformer by sagnac fiber optic sensor. IEEE Transactions on Dielectrics and Electrical Insulation, 2018. 25(6): p. 2313-2320.
87. Kweon, D.-J., et al., The analysis of ultrasonic signals by partial discharge and noise from the transformer. IEEE transactions on power delivery, 2005. 20(3): p. 1976-1983.
88. Boczar, T., A. Cichon, and S. Borucki, Diagnostic expert system of transformer insulation systems using the acoustic emission method. IEEE Transactions on Dielectrics and Electrical Insulation, 2014. 21(2): p. 854-865.
89. Kučera, M., et al. Visualisation and measurement of acoustic emission from power transformers. in 2019 12th International Conference on Measurement. 2019. IEEE.
90. Kim, D.-g., et al. A fiber-optic multi-stress monitoring system for power transformer. in 2017 25th Optical Fiber Sensors Conference (OFS). 2017. IEEE.
91. Sikorski, W., et al., Location of partial discharge sources in power transformers based on advanced auscultatory technique. IEEE Transactions on Dielectrics and Electrical Insulation, 2012. 19(6): p. 1948-1956.
92. Sarkar, B., et al., Condition monitoring of high voltage transformers using Fiber Bragg Grating Sensor. Measurement, 2015. 74: p. 255-267.
93. Jiabin Zhou, M.Z., Yuxin Yun, Jiagui Tao and Fan Liu, Partial Discharge Optical Pulse Signal Characteristics for Corona Defect in Oil Immersed Transformer. 2013. 5: p. 5.
94. Fabian, J., et al., State of the art and future trends of unconventional PD-measurement at power transformers. Journal of Energy and Power Engineering, 2014. 8(6).
95. Shanker, T.B., V. Vaidhyanathan, and A.S. Mohamed. Comparison of Partial Discharge Performance of Identical Generator Transformers in a Thermal Power Station by Acoustic Emission Technique-Case Studies. in 2019 International Conference on High Voltage Engineering and Technology (ICHVET). 2019. IEEE.
96. Qi, Z., et al. Study on the online dissolved gas analysis monitor based on the photoacoustic spectroscopy. in 2012 IEEE International Conference on Condition Monitoring and Diagnosis. 2012. IEEE.
97. Yongfen, L., et al., Comparison of DOA algorithms applied to ultrasonic arrays for PD location in oil. IEEE Sensors Journal, 2014. 15(4): p. 2316-2323.
98. Kim, Y.-J. and M. Hikita. A proposal for hybrid PD sensor identifying absolute distance from PD source. in 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena. 2013. IEEE.
99. Hauschild, W. and E. Lemke, High-voltage test and measuring techniques. Vol. 1. 2014: Springer.
100. Kraetge, A., et al., Robust measurement, monitoring and analysis of partial discharges in transformers and other HV apparatus. IEEE Transactions on Dielectrics and Electrical Insulation, 2013. 20(6): p. 2043-2051.
101. Yin, Z., et al. An all-fiber partial discharge monitoring system based on both intrinsic fiber optic interferometry sensor and fluorescent fiber. in 2013 International Conference on Optical Instruments and Technology: Optical Sensors and Applications. 2013. SPIE.
102. Markalous, S.M., S. Tenbohlen, and K. Feser, Detection and location of partial discharges in power transformers using acoustic and electromagnetic signals. IEEE Transactions on Dielectrics and Electrical Insulation, 2008. 15(6): p. 1576-1583.
103. Pinpart, T. and M. Judd. Experimental comparison of UHF sensor types for PD location applications. in 2009 IEEE electrical insulation conference. 2009. IEEE.
104. Tian, Y., P. Lewin, and A. Davies, Comparison of on-line partial discharge detection methods for HV cable joints. IEEE Transactions on Dielectrics and Electrical Insulation, 2002. 9(4): p. 604-615.
105. Dukes, R. and E. Culpan, Acoustic emission: its techniques and applications. IEE Proceedings A (Physical Science, Measurement and Instrumentation, Management and Education, Reviews), 1984. 131(4): p. 241-251.
106. Lamela-Rivera, H., C. Macia-Sanahuja, and J. Garcia-Souto, Detection and wavelet analysis of partial discharges using an optical fibre interferometric sensor for high-power transformers. Journal of Optics A: Pure and Applied Optics, 2002. 5(1): p. 66.
107. Cosgrave, J., et al., Acoustic monitoring of partial discharges in gas insulated substations using optical sensors. IEE Proceedings A (Science, Measurement and Technology), 1993. 140(5): p. 369-374.
108. Deng, J., et al., Optical fiber sensor-based detection of partial discharges in power transformers. Optics & Laser Technology, 2001. 33(5): p. 305-311.

109. Gorablenkow, J., T. Huecker, and U. Schichler. Application of UHF partial discharge monitoring and expert system diagnosis. in Conference Record of the 1998 IEEE International Symposium on Electrical Insulation (Cat. No. 98CH36239). 1998. IEEE.
110. Judd, M.D. and O. Farish. High bandwidth measurement of partial discharge current pulses. in Conference Record of the 1998 IEEE International Symposium on Electrical Insulation (Cat. No. 98CH36239). 1998. IEEE.
111. Nattrass, D.A., Partial discharge measurement and interpretation. IEEE Electrical insulation magazine, 1988. 4(3): p. 10-23.
112. Negm, T.S., M. Refaey, and A.A. Hossam-Eldin. Modeling and simulation of internal Partial Discharges in solid dielectrics under variable applied frequencies. in 2016 Eighteenth International Middle East Power Systems Conference (MEPCON). 2016. IEEE.
113. Korobeynikov, S., et al., Study of partial discharges in liquids. Journal of Electrostatics, 2020. 103: p. 103412.
114. Montanari, G. On line partial discharge diagnosis of power cables. in 2009 IEEE Electrical Insulation Conference. 2009. IEEE.
115. Sarathi, R., A. Giridhar, and K. Sethupathi, Analysis of partial discharge activity by a conducting particle in liquid nitrogen under AC voltages adopting UHF technique. Cryogenics, 2010. 50(1): p. 43-49.
116. Shen, Z. and E. El-Saadany. Localization of partial discharges using UHF sensors in power transformers. in 2006 IEEE Power Engineering Society General Meeting. 2006. IEEE.
117. Kemp, I., Partial discharge plant-monitoring technology: present and future developments. IEE Proceedings-Science, Measurement and Technology, 1995. 142(1): p. 4-10.
118. Kil, G.-S., et al., Measurements and analysis of the acoustic signals produced by partial discharges in insulation oil. Current Applied Physics, 2009. 9(2): p. 296-300.
119. Schwarz, R., T. Judendorfer, and M. Muhr. Review of partial discharge monitoring techniques used in high voltage equipment. in 2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena. 2008. IEEE.
120. Macià-Sanahuja, C., H. Lamela, and J. García-Souto, Fiber optic interferometric sensor for acoustic detection of partial discharges. Journal of Optical Technology, 2007. 74(2): p. 122-126.
121. Claus, R., et al., Extrinsic Fabry-Perot sensor for strain and crack opening displacement measurements from-200 to 900 degrees C. Smart Materials and structures, 1992. 1(3): p. 237.
122. Belanger, G. and M. Duval, Monitor for hydrogen dissolved in transformer oil. IEEE Transactions on Electrical Insulation, 1977(5): p. 334-340.
123. Zhu, M.X., et al., Discrimination of three or more partial discharge sources by multi-step clustering of cumulative energy features. IET Science, Measurement & Technology, 2019. 13(2): p. 149-159.
124. Ozgonenel, O. and S. Karagol, Power transformer protection based on decision tree approach. IET Electric Power Applications, 2014. 8(7): p. 251-256.
125. Wu, M., et al., An overview of state-of-the-art partial discharge analysis techniques for condition monitoring. IEEE electrical insulation magazine, 2015. 31(6): p. 22-35.
126. Zhou, H.-Y., et al., A multiplexing optical partial discharge sensing system for power transformer using a single photodetector. IEEE Transactions on Power Delivery, 2021. 36(3): p. 1911-1913.
127. Zhou, H.-Y., et al., A high sensitivity optical fiber interferometer sensor for acoustic emission detection of partial discharge in power transformer. IEEE Sensors Journal, 2019. 21(1): p. 24-32.
128. Sharifinia, S., et al., A new application of Rogowski coil sensor for partial discharge localization in power transformers. IEEE Sensors Journal, 2021. 21(9): p. 10743-10751.
129. Hashim, A.H.M., et al., Partial discharge localization in oil through acoustic emission technique utilizing fuzzy logic. IEEE Transactions on Dielectrics and Electrical Insulation, 2022. 29(2): p. 623-630.
130. Li, J., et al., A novel GIS partial discharge detection sensor with integrated optical and UHF methods. IEEE Transactions on Power Delivery, 2016. 33(4): p. 2047-2049.
131. Wu, Z., et al., Effectiveness of on-site dielectric test of GIS equipment. IEEE Transactions on Dielectrics and Electrical Insulation, 2018. 25(4): p. 1454-1460.
132. Kim, S.-w., et al., New diagnosis method of unknown phase-shifted PD signals for gas insulated switchgears. IEEE Transactions on Dielectrics and Electrical Insulation, 2018. 25(1): p. 102-109.
133. Ma, G.-M., et al., A high sensitivity optical fiber sensor for GIS partial discharge detection. IEEE Sensors Journal, 2019. 19(20): p. 9235-9243.

 doi:10.20944/preprints202307.0333.v1

134. Thi, N.-D.T., et al., Anomaly detection for partial discharge in gas-insulated switchgears using autoencoder. IEEE Access, 2020. 8: p. 152248-152257.
135. Ren, M., J. Zhou, and J. Miao, Adopting spectral analysis in partial discharge fault diagnosis of GIS with a micro built-in optical sensor. IEEE Transactions on Power Delivery, 2020. 36(2): p. 1237-1240.
136. Wu, S.-Y. and S.-S. Zheng, Detection of partial discharge in GIS and transformer under impulse voltage by fluorescent optical fiber sensor. IEEE Sensors Journal, 2021. 21(9): p. 10675-10684.
137. Zhang, G., et al., A Flexible Planarized Biconical Antenna for Partial Discharge Detection in Gas-Insulated Switchgear. IEEE Antennas and Wireless Propagation Letters, 2022. 21(12): p. 2432-2436.
138. Song, H., et al., Multiscale fusion simulation of the influence of temperature on the partial discharge signal of GIS insulation void defects. IEEE Transactions on Power Delivery, 2021. 37(2): p. 1304-1314.
139. Lu, B., et al., The study on a new method for detecting corona discharge in gas insulated switchgear. IEEE Transactions on Instrumentation and Measurement, 2021. 71: p. 1-8.