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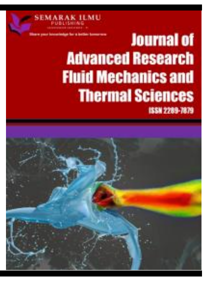

A Contemporary Review of High Voltage Partial Discharge Detection and Recognition Techniques

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ABSTRACT

This review article provides a summary of the most advanced approaches and advancements in the detection and recognition of high voltage partial discharge (PD). It discusses numerous detecting technologies, such as electrical, acoustic, and optical approaches, as well as their merits and disadvantages. It also discusses current developments in signal processing and pattern recognition algorithms used for PD detection and classification. Lastly, the study covers the challenges and limitations in high voltage PD detection and identification studies, as well as potential future solutions.

1. Introduction

Partial discharge detection technology is a method for identifying and locates partial discharges (PD) in electrical equipment. PD are minuscule sparks or electrical discharges that originate within electrical equipment insulation[1,2]. These discharges can induce insulation deterioration, resulting in device failure or possibly catastrophic failure. On other hand, PD recognition technology is a diagnostic tool used in electrical systems to recognize and identify partial discharges (PD). When there is a breakdown of insulation inside an electrical system, it can cause device failure or even system failure[2–4].

The research on PD detection and recognition has been started over the last century ago. Basically, the drive to measure PD is due to an unplanned power transformer breakdown. Since then, few methods of detection have been developed and utilized; optical, chemical by-product, acoustic, and electrical methods. Whereas, for PD recognition most of the recognition methods depend on

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manipulating the collected PD signal from measurement to validate the type of PD. The utilization of AI to determine the PD severity is limited to gas-insulated switchgear and cables.

Generally, PD can damage the insulation material, diminishing its capacity to resist high voltages. Following that, insulation degradation: frequent PD can cause physical damage to the insulation system, such as cracking, charring, and erosion, which can weaken its dielectric strength even further [5]. The insulation material will therefore suffer from thermal deterioration as a result of the increased heat generation [6]. Also, it will hasten ageing: PD might hasten the ageing process of insulation materials, limiting their estimated service life. Finally, there is an increased chance of failure: PD can be an early sign of insulation failure, suggesting that the system is prone to rapid failure.

Partial discharge is a prevalent issue in high voltage electrical systems and can cause insulation failure and device damage. The following measures can be used to fix partial discharge issues. The first step in resolving partial discharge issues is determining the source of the discharge. This may be accomplished by thoroughly inspecting the electrical system and equipment. Insulation flaws, surface contaminants, and mechanical strains are all common causes of partial discharge.

Next, after determining the cause of the partial discharge, the following step is to determine the severity of the problem. This is accomplished by monitoring partial discharge activity with proper test equipment. This will aid in determining the amount of danger connected with the partial discharge and the best course of action to pursue. Lastly, put the corrective action into action and test its efficacy. It is critical to test the effectiveness of remedial action once it has been applied. This can be realized by doing follow-up checks to evaluate partial discharge activity and inspecting the equipment for indicators of ongoing insulating breakdown.

2. Methodology of PD Detection and Recognition

2.1 PD Detection Techniques

As demonstrated in Table 1, detection schemes for PD incidence use four primary categories: optical technologies, chemical by-products, acoustic emissions, and electrical techniques. In the paragraph, each applied method will be concisely defined and explained.

Table 1
Conventional PD detection method for HV equipment

Method	Detection Apparatus
Optical Method	Photo-multiplier Detector
Chemical by Product	Gas Chromatography, Dissolved Gas Analysis (DGA)
Acoustic Emissions	Accelerometers, Ultrasonic Acoustic
Electrical Method	Coupling Capacitor, UHF Antenna

The first method for PD detection is using an optical sensor via a photomultiplier detector. Primarily, when breakdown happened in gas inside a dielectric medium according to the Streamer Theory, it will create electrons, positive, and negative ions, and also photons [7–9]. The photon itself was regularly producing a light output due to gas ionization, excitation and recombination after a PD occurred. As illustrated in Figure 1, photons triggered by discharge activity may be measured using a photomultiplier. Virtually, photomultiplier equipped with quartz lenses that can measure UV radiation [10, 11]. The benefit of utilizing this technique is the uncovering for PD corona occurrence that emits between 280 to 405 mm spectral range and this emission is visible to human vision [12–14]. While, if the PD materialize in the power transformer oil, the emission generated happened at a higher spectral range (between 400 to 700 mm) and produced methane, ethane and ethyl that needs oil sampling and lab testing to confirm this condition [13–15]. Thus, this optical method is more suitable for a certain type of PD that is observable.

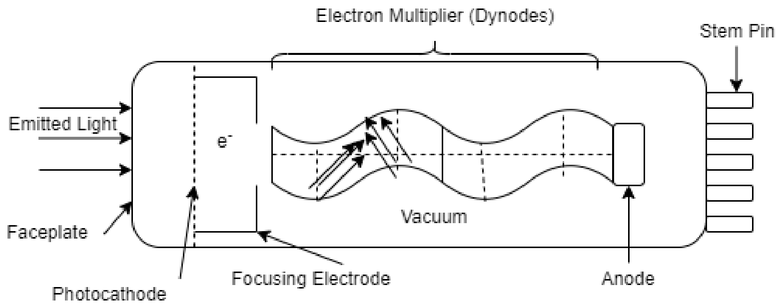


Fig. 1. Basic structure of photo multiplier sensor that involved deflection of photon using appropriate optics [16]

Next, the second PD detection category used the dissolved or created gasses after the gas breakdown was initiated. Normally, sulphur hexafluoride (SF6) is mainly used as an insulation medium for switchgear, power transformer, or circuit breaker to protect the equipment during operation. This SF6 gas typically decomposed during production, and chemical bonding separating generated sulphur tetrafluoride (SF4) gas, which was reported to be very volatile by nature. The SF4 gas will therefore react with stray water vapour to produce new stable by-products, specifically thionyl fluoride and sulphuryl fluoride, which may be identified using gas chromatography.

The amounts of these substances were determined using a mass spectrometer using the gas chromatography technique, as illustrated in Figure 2. The disadvantage of this approach is that it is highly reactive when connected with a big amount of SF6 and requires longer timeframes for petrol evaluation for at least 10 hours [17–20]. In contrast, this procedure for power transformer oil normally needs to be taken from shutdown power transformers after it is in services for some time and needs more outage times, especially for PD suspected power transformers. Truly, the concentration of gases is interpreted using either using Roger's ratio method, IEC method, Doernenburg ratio method, or Duval triangle method [21–24]. Ultimately, these gas concentration ratio methods purposely determine the level of insulation degradations; among the indicator are PD, low discharge energy, high discharge energy, and others[25–29]. Therefore, this gas method is an invasive way and considered to be time-consuming to analyze the gas concentration for power transformer PD activity.

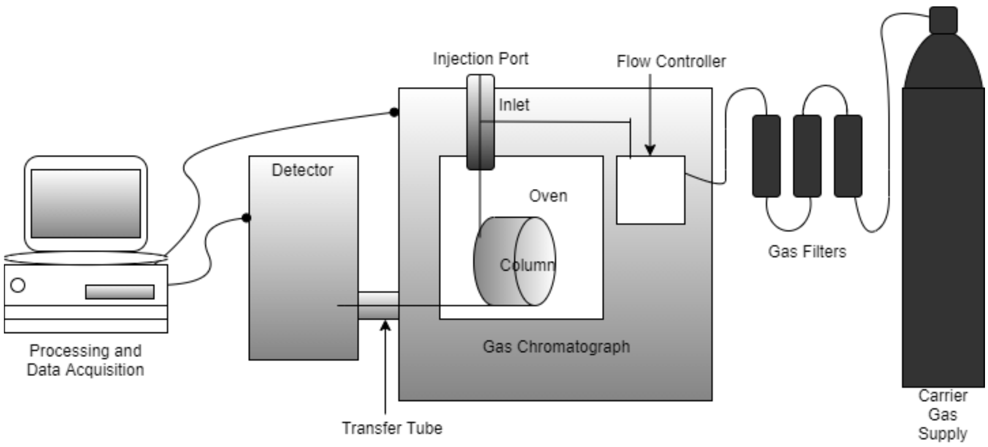


Fig. 2. The gas chromatography techniques measuring configuration to assess gas content [21]

Then, in the third category of PD detection using acoustic emissions using piezoelectric sensors. Both free particulate, fauna, and PDs capable of producing waves that generated acoustic or sound impulses were present in the electricity network. The acoustic waves were mostly created by PD that changed at different rates and was represented in the boundary between the components [30–32]. This pattern was often seen using very accurate vibration signal detectors using a piezoelectric sensor, as shown in Figure 3.

Furthermore, there is a distinct advantage to using this framework; it is a non-intrusive method if the sensor is already embedded; however, the major drawback for old power transformers is the requirement for power transformer shutdowns as well as an adequate and secure retrofitting operation to configure the sensor prior to re-energizing the power transformer. Typically, the measurement is conducted by integrating internal detects, which are employed and have the capacity to foresee the PD locations, but numerous sensors must be arranged to enhance precision. [31, 33–35]. None the less, this approach has several drawbacks, such as being readily disrupted by ambient noise sounds from the apparatus vibration itself, surrounding gear, and wildlife, where effective noise filtration is required before proceeding with thorough acoustic signal examination.

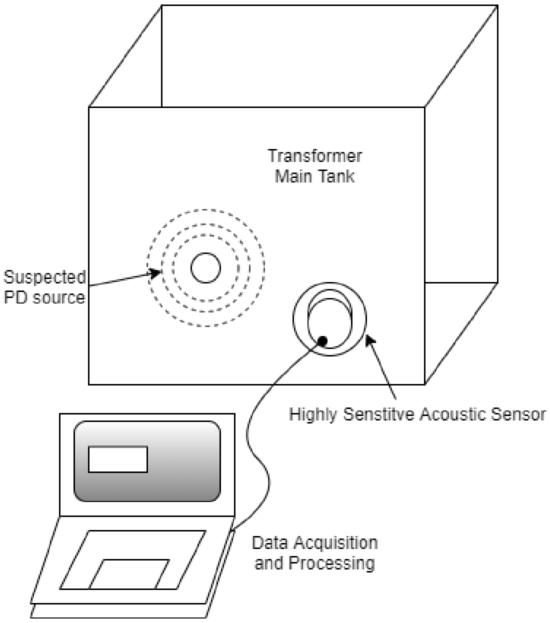


Fig. 3. Acoustic emission configuration for problem power transformer identification near the emission source [36–38]

Principally, PD detection implementation has always been linked with invasive approaches and generally needs for planned power transformer outages to evaluate and examine the power transformer insulation health condition. Consequently, there is a necessity to develop a new non-intrusive or non-invasive mode to assess the power transformer inner insulation condition wirelessly and safely. Currently, few researchers are exploring the different antenna designs to collect electromagnetic (EM) signals generated from PD activity [39–43]. The research currently focused on the uniqueness of the UHF sensors or antennas that are almost free from EM interference for integrated antenna design. Generally, by using this sensor, it can capture the small transient voltage in the form of EM signal waves with high accuracy with an appropriate sensitivity [40, 43–46]. The integrated PD antenna was not considered in this research due to compatibility issues and aftereffect of retrofitting task, especially for aging and in-operation power transformer. Therefore, few researchers proposed a solution of PD antenna based on microstrip patch antenna that utilizing different types of substrates, overall sizing and configuration [40, 47–49]. Based on current research work implemented on developing the antenna for detecting PD, there are 33 few researchers currently employed fire retardant level 4 (FR-4) substrate as more cost-effective, reliable, and proven repeatability is due to numerous mass manufacturing electronic components especially printed circuit board (PCB) based on FR-4 material utilized in the market [23, 50, 51].

Fundamentally, FR-4 substrate is made of glass-reinforced epoxy laminate material. As consideration of the substrates themselves, first, the surface wave excitation of FR-4 is relatively higher compared to other types of substrates due to its high permittivity. Excitation of the surface wave will be affected the capability of the antenna to efficiently collect signals. This attribute is related to the loss of energy due to the radiation on the surface of the antenna. Usually, higher surface waves will make the antenna less efficient and reduction in its directivity. On the other hand, FR-4 also possesses the desirable mechanical properties with thin and lightweight properties suitable for PD antenna. Importantly, for the mechanical properties per se, mechanical shown the relation between the capability of the substrate to be rapidly handled during development and fabrication process. Additionally, FR-4 substrate is also relatively robust and suitable for a compact and miniaturized design that is suitable for PD antenna applications from low frequency (LF) until stretched to the UHF range. Hence, the substrate weight, solderability, and substrate robustness are crucial to operating in the real power transformer environment. Furthermore, FR-4 substrate has a dielectric constant dispersion between 3.4 to 4.8 that helps for better signal assemblies. In terms of dielectric, and copper loss of this substrate is acceptable due to several electronic appliances using this type of substrate and operating accordingly and it is important to do detailed sanding on the copper surface during antenna development to avoid more losses. Also, the dielectric loss and copper loss are related to substrate material and quality of copper embedded on the surface of the substrates. The better-quality manufactured substrates by the manufacturer ensure better antenna developed later. Finally, because of its cheap industrialization expense, variety, and ease of production, FR-4 material is the most often utilised material in antenna studies [23, 50]. The base is made of woven fibreglass fabric including an epoxy coating binder and is intended to be fire-resistant and long-lasting.

Fundamentally, the electrical as well as physical factors are crucial in designing a PD antenna centred on a microstrip patch antenna. The electrical parameters related to material or substrates to build up the main antenna structure; among the popular material to be selected as substrates are FR-4 epoxy, Rogers RT Duroid 5880 (TM) Polytetrafluoroethylene (PTFE) composites, Taconic TLC-27 Polytetrafluoroethylene (PTFE), Roger RO4003, GML1000, and Bakelite [52–55]. Whereas, the physical parameters are the ground plane, feed point, and top patch normally improved to accomplish designated resonant frequency with a good reflection coefficient of minimum of -10 dB and wider frequency bandwidth of more than 100 MHz [44, 56–58]. At present, the conventional and portable UHF antenna applied by reputable condition monitoring manufacturers uses both monopole and dipole antenna whereas modern technology uses a singular microstrip patch resonator [59, 60]. The use of a dual antenna was intentionally to decrease the white and stray noises that existed adjacent to the equipment. However, this eventually will increase the cost for an additional module, and it is time-consuming for redundant measurement for both antennas as illustrated in Figure 4.

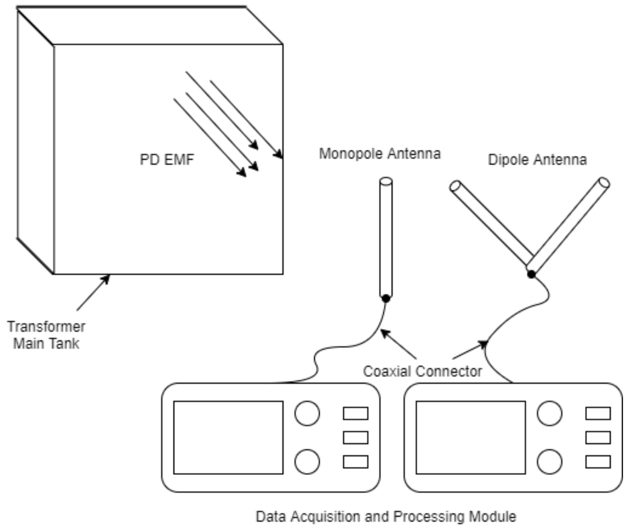


Fig. 4. The dual antenna pd measurement setup for power transformer[57]

2.1.1 PD UHF Antenna Design and Related Design Improvement

As edified in the previous section, UHF devices are commonly utilized in electronic apparatuses to identify defective structure cracks, shift, and tilt in wireless radio frequency recognition systems as well as high-voltage PD readings. Today, sensor output has a considerable influence on PD detecting device precision and reaction. As the UHF approach has been around for many decades, much research has been put into designing PD UHF sensors, especially for detection and design. The type, sizing, its directivity characteristic, and intended application are mentioned and contrasted in Table 2. Each design has its own uniqueness and suitable application. There is different antenna directivity either omnidirectional or unidirectional represented by a different antenna design.

Table 2
The available design, size, directivity and weakness of PD UHF antenna proposed in the previous research

Antenna Design	Size (mm)	Antenna Directivity (type)	Weakness	Application	References
Meandered Line	70	Unidirectional	Low efficiency antenna	Power transformer	[47,61]
Vivaldi	100	Omnidirectional	High cross-polarization problem	Cable, Power transformer, HV Switchgear	[43,62]
Monopole	100	Omnidirectional	Vulnerable to interference	Power transformer, Switchgear	[63–65]
Conical	100	Omnidirectional	Element mutual coupling issue	HV Switchgear	[66]
Hilbert Fractal Antenna	90/100	Unidirectional	Need multi-substrate configuration	Cable, Power transformer	[16,67,68]
U-Shaped	215	Unidirectional	High surface excitation	Cable, Power transformer, HV Switchgear	[69,70]
Square Patch	232	Unidirectional	Exposed to interference	Power transformer, HV Switchgear	[48,49,71]
Archimedean/ Log Spiral	80/150	Unidirectional	Not suitable for UHF range application	Power transformer, Cable	[44,72,73]
Circular Patch	100	Omnidirectional	Unprotected from nosiness	Power transformer, HV Switchgear	[74–76]

In the omnidirectional antenna, the radiation pattern normally shapes of "donut" indicating the antenna covers 360° around the antenna and the most common omnidirectional antenna applied in PD detection is monopole antenna. Whereas unidirectional antenna has a balloon-like radiation pattern that its directivity is normally prone to one direction and the most common design is the fishbone antenna. Omnidirectional is more desirable because of has better coverage detection and higher sensitivity especially for detection nevertheless unidirectional is also good for focused and fixed signal propagation antenna in a single direction. Later, in the following paragraph, the frequency range in Table 2 related to PD UHF antenna are discussed and explained to ascertain the suitable range for PD detection.

Presently, the widest, applicable and reliable network of telecommunication is the 4G LTE and 5G network due to better connectivity speed and better overall coverage in both urban and rural areas. In Table 3, each current application for a different frequency range in the UHF band between 300 MHz to 3 GHz is presented. Basically, the phased-out third-generation (3G) telecommunication network employed frequency of 700 and 900 MHz are being replaced with the state-of-the-art fourth-generation long-term evolution (4G LTE) telecommunication network.

From Table 3, by referring to the frequency range between 1600 to 2600 MHz there is a frequency bandgap at telecommunication network band that is suitable for PD antenna application, especially for PD dual-band detection. Besides, selection of precise design frequency, it is also significant to integrate a different modification at each available component of the patch antenna. This step is crucial for improving antenna performance with proven modifications are reviewed thoroughly in the next paragraphs

Table 3
Frequency range and current application

Range of Frequency (MHz)	Important Signal Application	Note
300 to 500	Fixed Mobile Mobile Satellite Communication Meteorological Satellite and Aids	Nil
500 to 1000	Broadcasting Radio Navigation Mobile GSM Telecommunication 3G Communication Network	Nil
1000 to 1600	Aeronautical Navigation and Mobile Radionavigation Satellite	Nil
1600 to 2600	Space Research 4G LTE Band 3 at 1800 MHz (60 MHz) 4G LTE Band 1 at 2100 MHz (BW 60 MHz) 4G LTE Band 7 at 2600 MHz (BW 70 MHz)	*Band gap between Band 3 and Band 1 at 1600 to 1790 MHz *Band gap between Band 1 and Band 7 at 2160 to 2580 MHz
2700 to 3000	Radio Astronomy and Space Research	Nil

In the aspects of improvising the performance of the antenna, there are a few methods to improve the overall performance started with ground reduction, feed leg modifying, the addition of both slots, and parasitic patch after design frequency selection is completed. Firstly, reducing ground plane design reduction implemented by a few researchers proved beneficial to improve antenna overall performance [50,77]. The improved or reduced ground plane will be beneficial to reduce antenna weight and parameters for better compactness and portability while enhancing the overall performance.

Theoretically, asymmetrical antenna feed will influence the ability of the antenna to produce a better front-to-back ratio (F/B ratio) with improved reflection coefficient (dB) as revealed before

[76,78]. This modification of the feed point will facilitate improved PD detection design and characteristics with reliable F/B ratio magnitude.

Moreover, an initial patch slots designed antenna created by Alan Blumlein in 1938 can increase antenna efficiency both in terms of bandwidth and gain [70,74,79,80]. Thus, this is feasible a good alternative in designing wider bandwidth and high gain PD antenna. Few researchers exploring geometrical shape patches integrated onto the top patches and resulting in a better performed and compact antenna [50,81].

At last, the conventional method to reduce signal noises is by adding an additional electronic filtering circuit. Usually, what happens when this filter circuit is applied, there is unneeded harmonics that need tuning for fixed frequency and not to mention the increased of total harmonics distortion. The amount of interference in the surroundings, the performance of the pulse discrimination system (PDS), the configurations of the input filter, and, last but not least, well-performed calibrate all have a part in the success of this PD sensing approach.

A PDS is included in most current PD measuring systems. The PDS, which are focused on removing signals not originating from the examined items, allow for the suppression of disturbance from the environment [82–84]. In Figure 5, the important components co-existed to provide a complete PDS for important noise suppression filter operation.

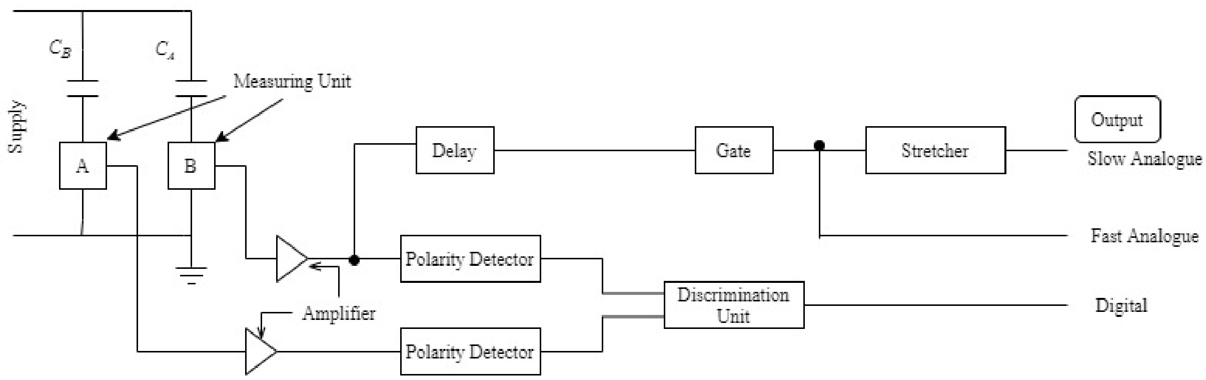


Fig. 5. Pulse Discrimination System (PDS) important components [83]

Alternatively, a filter antenna is an alternative solution for this problem. Filter antenna can be designed either using a synthesis method, slots, or alphabetical resonator either T or U shape antenna. The purpose of filtering antenna or filtenna is to design an antenna that possessed the same filtering ability to radiate not only energy but also selective frequency band capability. The attribute shows that this type of antenna is better in collecting the intended signals and reducing the captured interference in general. According to Yin *et al.,* [74], the integration of a T-slot resonator coupled with copper tapes in the antenna feed leg is proven to be efficiently operated as a bandpass filter antenna while collecting the targeted signals.

According to Wu et al., the best approach to design a microwave filter antenna is via three main methods; The most common technique is synthesis, this method originated basically from the synthesizing of the lumped network element [58,85,86]. The synthesized network is set with the antenna physical dimensioning. The final method to integrate filter in the patch antenna is by introducing parasitic patch that reduces the overall antenna sizing without jeopardizing the antenna detection capability. The representation of the parasitic patch with its equivalent circuit is exhibited in Figure 6. These three components existed electrically; *Lp* is the parasitic patch inductance, *Cp* is the parasitic patch capacitance and *Rp* is the parasitic patch resistance [24,47].

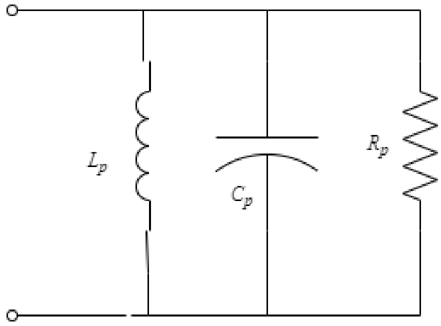


Fig. 6. Parasitic patch equivalent circuit representation

2.2 PD Recognition Techniques

Generally, PD recognition utilized to clarify the category of PDs occurred to have a better understanding of the initial PD occurrence. In electrical systems, PD pattern recognition algorithms are used to recognize and analyze partial discharge occurrences. Partial discharges are electrical discharges that occur within insulating materials, most commonly in high-voltage equipment like transformers, cables, and switchgear. If not discovered and corrected, these discharges can cause insulation deterioration and eventual failure. For this reason, every recognition process requires the extraction of vital characteristics or features to distinguish between occurrence. The summary of available PD recognition methods and its applications are presented in Table 4 including statistical parameters, signal processing, image processing and machine learning methods.

The basic goal of a PD pattern recognition algorithm is to reliably identify, categories, and locate partial discharge activity. This entails analyzing the electrical signals generated during discharge occurrences. PD signals display distinct patterns, including amplitude, frequency, and temporal characteristics, which might give useful information on the insulation system's state.

The typical algorithm steps involved;

Data Acquisition: Electrical signals are acquired from the equipment under test using specialized sensors or measuring devices. The signals may be obtained through direct measurement or by using coupling techniques.

Preprocessing: The acquired signals are preprocessed to remove noise and interference, enhance signal quality, and eliminate artifacts that may affect the accuracy of the analysis. This step may involve filtering, amplification, and calibration.

Feature Extraction: Relevant features are extracted from the preprocessed signals. These features capture the essential characteristics of the PD events, such as magnitude, duration, shape, and frequency content. Feature extraction techniques may include time-domain analysis, frequency-domain analysis, wavelet transforms, or statistical methods.

Pattern Recognition: The extracted features are then used to classify the PD events. Pattern recognition algorithms, such as artificial neural networks, support vector machines, or decision trees, are employed to identify the different types of partial discharges and distinguish them from other sources of noise or interference.

Localization: In some cases, it is important to determine the spatial location of the partial discharge source. Localization algorithms utilize information from multiple sensors or measurement points to estimate the position of the discharge within the equipment.

Condition Assessment: The final step involves analyzing the results of the PD pattern recognition algorithm to assess the condition of the insulation system. This assessment helps determine the severity of the detected PD activity and enables informed decisions regarding maintenance or repair actions.

Table 4
The available PD recognition method that explored by researchers

Type of Recognition	Methods	References
Statistical Parameters/ Techniques	Phase Resolved PD Data (PRPD), Time-Resolved Data,	([87–89]
Signal Processing	Fourier Transform, Wavelet Transform or Analysis	[90–92]
Image Processing	Fractal Feature Analysis	[68,93,94]
Machine Learning/ Self Learning	ANNs, Self-Organizing Maps (SOM), Static Vector Machine (SVM)	[95–97]

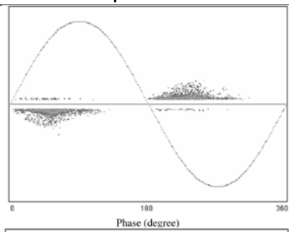
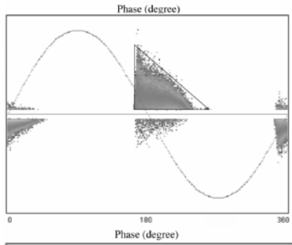
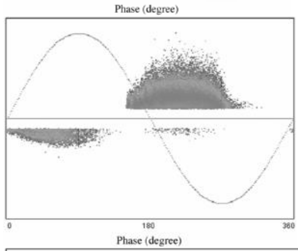
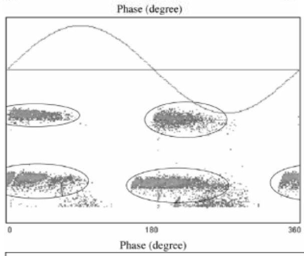
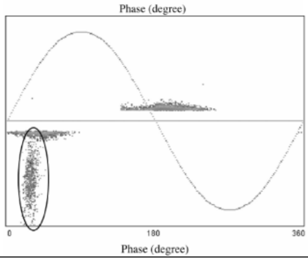
2.2.1 PRPD Recognition Method

The most common PD recognition method in statistical parameter type applied currently is the PRPD method. This technique characterizes discharge frequency content corresponding to Hudon and Tang *et al.,* [98,99], who mentioned that PRPD is resolved by the practical and phase properties. PRPD presentation analysis showed significant strength and efficacy compared to other models.

Table 5 summarized newly discovered PD types and their characteristics for the PRPD database based on IEEE Standard 1434 [45,46,100]. These features are vital to obtaining reliable clues to improve the PRPD database for better authentication processes [98,101]. Regrettably, because diverse discharges produced identical patterns, this PRPD approach required competent and knowledgeable engineers to interpret it. PRPD is mostly used to determine the kind of PD source. The inaugural PRPD repository facilitates quick and more intuitive online diagnostics with just few complications. Currently, the PRPD method employed has a setback on the reduction of a single artificial neural network pattern [16,102].

Additionally, the problem with the PRPD method that only focused on PD form and not the sternness of the PD occurrence. The current approach is beneficial and accurate considering the detection of the type of PD that happened inside the power transformer. However, the PD severity is more important to be focused on since that this situation is frequently overlooked and undetected over the power transformer maintenance regime processes. Hence, based on thorough review and study conducted in the previous paragraph obviously severity assessment of PD is critical and credential to be discriminated on the affected power transformer. This allows for better and enhanced CBM scheduling and strategies.

Table 5
Summary of PD type and its characteristics based on IEEE Std 1434-Rev 2014 [1,103]

Type of PD	Important Characteristics	The 3D Representation
Internal Discharges	Amplitude: low to intermediate It has a synonymous shape at each half cycle	
Slot Discharges	Amplitude: intermediate Slot discharge is represented by the distinctive triangular shape, which occurs predominantly even during half of the input	
External PD	Amplitude: intermediate to high Asymmetry in favour of discharge mostly during negative half is typically slightly rounded than those of the PD position.	
Void or Gap Discharges	Amplitudes: average to high Generally, it forms clouds horizontal.	
Surface Tracking	Amplitude: Very high. Upward cloud approximately 30 degrees to 40 degrees during the positive half cycle, and often observed across both half cycles.	

2.2.2 Wavelet Analysis PD Recognition Method

Basically, one of the proven ways for PD identification through data analysis is wavelet analysis (WA). Fundamentally, this methodology analyses and determines the mother wavelet using a time-localized oscillatory function. [20,35]. In addition, the WA divides the signal into shifted and scaled replicas of the originating mother wavelet. There are two sorts of study that may be conducted: temporal investigation with the constricted, high-frequency copy of the archetypal wavelet and spectral analysis with the dilated, low-frequency variation of the identical wavelet [27,91]. The WA process commences with wavelet choice, aggregation scale, and noise or threshold estimate. The Low Pass Filter (LPF) and High Pass Filter (HPF) are indeed the filter kinds employed in this procedure (HPF) [91]. The LPF analyses the low-frequency portion of the PD signal, whereas the HPF analyses the high-frequency phase. The sort of emergent movement may be distinguished using these two criteria. WA's weakness is the poor signal-to-noise ratio (SNR) created and the subsequent loss of critical info for PD detection. Other than that, WA is required to be trained with the prior waveform and supervised before recognition can take place with significant results. However, the current WA method still focuses on the type of PD, rather than PD severity.

2.2.3 Fractal Feature Analysis PD Recognition Method

The PD recognition that falls into the image processing category is fractal feature analysis. This type of PD recognition is inspired by snow fractal geometry formed naturally. Fundamentally, referring to the concept of fractal by Mandelbrot, and the pattern is in the geometry of chaos that keeps either converging, diverging, or constant [104,105]. Normally, the fractal PD recognition started with raw PD data converted into 3D PRPD data. Next, the converted 3D PRPD based on selected features was used to quantify the plot. This 3D plotted data using known single source PD phenomena such as internal void, internal delamination, slot discharge, surface discharge, and gas type discharge [68,75]. Finally, the polar plot does the clustering or classification for PD recognition. This method is proven efficient for recognition but needs to select the most reliable feature during the 3D plot, and this will provide a good recognition result. However, this method has some drawbacks on intricate processes beforehand especially on transforming the PD data into 3D representations that require higher computation time and computer memory. Other than that, numerous estimators are needed to deliver a better estimation algorithm for improved confidence. Lastly, prior knowledge of the algorithm behaviour will influence the final signal characterizations.

2.2.3 SVM PD Recognition Method

Basically, for machine learning, the optimum method for PD recognition uses SVM recognition. This scheme uses the central Kernel concept number of learning tasks. Additionally, SVM has significant advantages in determining small sample, non-linear, and substantial size pattern recognition problems. For PD recognition, SVM uses the capability to classify and recognize the type of PD. SVM is applied at the later stages for classification purposes after the raw PD data is pre-processed with first for adaptive denoising, and then with feature extraction and fusion [35, 106]. SVM is a supervised neural network; therefore, it needs to be trained before it can perform well. The advantage of applying SVM is that generated significant separation with high dimensional spaces. However, the limitation of this method is on the estimation accuracy reduced when applied to noise signal and overlapping data that usually happen in PD data collection. Additionally, the computation times required are higher compared to other self-learning methods such as SOM.

2.2.3 SOM PD Data Recognition Method

Back in 1990, Kohonen discovered the Self-Organizing Maps (SOMs) known as the Kohonen Map.[107,108]. Kohonen Map or SOM was based on unsupervised learning neural network that falls into the self-learning category. Self-Organized is described as the capacity to cluster and visualise data that is arranged on a low-dimensional neuron. Simultaneously, the maps specified the features to examine the degree of accuracy of the finished mapping's foundation input data [107, 109, 110]. Currently, the SOM maps are depicted by Unified Matrix to facilitate further on the classified data as shown in Figure 7.

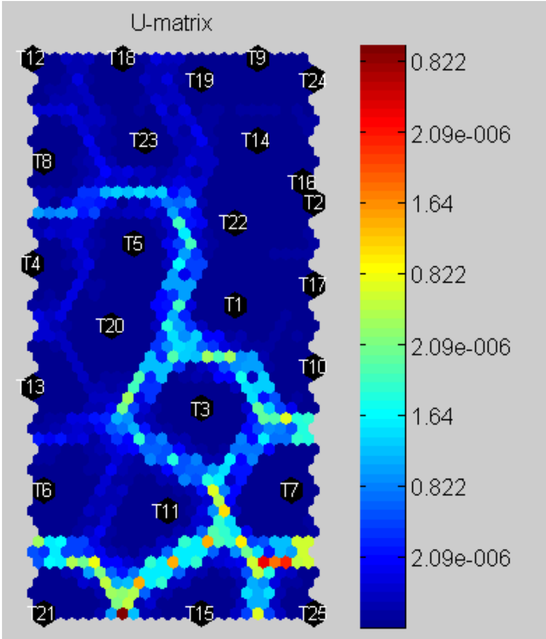


Fig. 7. A U-Matrix representation of classified data

SOMs are essentially a collection of nodes linked by either a rectangular or a hexagonal structure. Figure 8 depicts the basic rectangular architecture of SOMs, with each square representing a node. Weights are assigned to the interactions in between sources and the nodes, so every node has its own set of weights. The group of weights produces a vector W_{xy} with x = 1, 2, 3,..., k_x and y = 1, 2, 3,..., k_y, which is also referred as a neuron or codebook vector. The row count in rectangular SOM is k_x, while the total number of columns is k_y. According to Eq. (1), the dimension of the codebook vector is the same as the number of inputs.

$$W_{xy} = \{W_{xy1}, W_{xy2}, W_{xy3}, \dots \dots . W_{xyN}\} \tag{1}$$

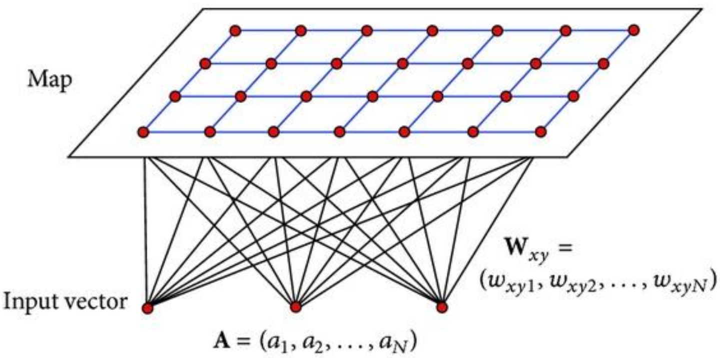


Fig. 8. Two-dimensional SOM consists of input and computational layer

Based on four main PD recognition methods reviews, the SOM classification method possessed substantial benefits such as; solving the problem via iterative training, being easy to interpret and implement using a simple two dimensional (2D) structure, and being capable of organizing complexity input data and massive data mapping [107,109]. These are the important attributes that are desirable for an efficient and crucial PD recognition method.

3. Identification and Synthesized Research Opportunities and Gaps

3.1 Research Gaps and Opportunities

The main research gaps existing in available PD detection and recognition are summarized in Table 6. The current method for PD detection is based on assessing the abnormalities physical residue either in terms of dissolved substances or gases or generated sound waves. Basically, all methods posed different benefits and weaknesses; among the prominent drawback is the lack of internal PD detection, required a power transformer structure modification, time-consuming and intrusive method except for the UHF method.

Table 6
Summary on The Reviewed PD Detection and Recognition Methods

Method	Cate-gory	Researcher	Advantage	Research Gaps
Photo-multiplier Detector	Detection	[11,13,14]	Detection for PD corona detection in gas or air insulated equipment PD by product; Photon detection capability	Internal PD is almost invisible to especially on power transformer main tank (Invisible PD occurrence)
Gas Chromatography, Dissolved Gas Analysis (DGA)	Detection	[27,36]	Established oil analysis method Extensive available ratio method for certain PD type	Required power transformer shutdown and oil sampling (Intrusive method) Oil sampling, transporting and analysis process (Tedious process and time-consuming)
Ultrasonic Acoustic	Detection	[30,31,34], [38,111]	Non-intrusive method using magnetic probes Has PD locating capability	Highly sensitive piezoelectric sensor (Easily influenced by nearby noises)
UHF Antenna	Detection	[40,49,63], [64,112]	Non-intrusive Method Not affected by other sound waves or noises because only measure EMF (for integrated) Flexible design and multi substrates available	Monopole antenna collected all EMF signal along with white noise (Influenced by outdoor EMF signals) Required dual antenna and module to reduce collected noise (Added costing and reduce portability)
PRPD	Recognition	[98,101, 113,114]	Established graphical interpretation Following IEEE standard for different PD type	Required trained personnel to examine (Inaccurate PD interpretation) Focus only on type of PD and the severity (Severity not analyze)
Wavelet Analysis	Recognition	[63,115, 116]	Ability to denoising signal collected to recognize PD type Can operate as HPF and LPF for signal conditioning	Low SNR and need trained signal upper hand (Improper signal denoising) Focus only on type of PD and the severity (Severity not analyze)
Fractal Feature Analysis	Recognition	[68,101]	The ability to clustering cluttered data for recognition Projected into lower order dimension-suitable for low sampling	Demand 3D PRPD interpretation for accuracy (Complicated and intricate process) Setback on estimation algorithm – need multiple estimators (more computation time) Focus only on type of PD and the severity (Severity not analyze)

Static Vector Machine	[91,94,113]	Provide simple out of error generalization Produce unique and simple solutions Ability to recognized type of PD with proper parameters	Lack of recognition transparency Need complicated hyperparameter representation (Complicated recognition method) Focus only on type of PD and the severity (Severity not analyze)
Self-Organizing Maps	[107,117, 118]	Capability to address high dimensional data into low dimensional neurons Easy interpretation mapping result Capability to organize complex input data	High computational time for high dimensional data (Required additional pre-processing data beforehand) Need variable neurons value for classification (Need specific neurons sizing)

Still, for the UHF method, the current dual antenna employed has certain limitations, especially for the measurement redundancy and modules. While for PD recognition, the current methods are based on AI system and posed different benefits and weaknesses; among the prominent drawback is the need for a trained individual to examine the plotted PRPD signal, required trained AI network, complicated and multiple estimators, need hyperparameter representation and all PD recognition methods does not possess PD severity study or evaluation. The PD detection and recognition are summarized as listed in Table 6.

From the review, it can be seen that some gaps existed in the current PD detection and recognition method. Among the identified gaps are invisible PD occurrence, intrusive measurement method, tedious process and time-consuming, easily influenced by nearby sound noises and outdoor EMF signals and portability issue. To match these gaps, the new optimized PD antenna is proposed with the integration of a noise filter or patch for PD detection. Whilst the gaps for PD recognition are inaccurate PD interpretation, improper signal denoising, complicated and intricate process, complicated recognition method, and severity not analyzed. To match these gaps, the new hybridized PD AI method is proposed with severity assessment for PD activity.

4. Conclusions

As a conclusion, this review paper provides a complete overview of existing and new technologies for partial discharge detection and recognition applied in high-voltage energy system equipment. In regard to implementation and a new recommended approach, this research demonstrates the major benefits of the proposed tactic above typical detection systems. The basics of hypothetical PD are described, which can help scholars in apparatus design as well as performance evaluation via simulation and experimentation. The significant issues in the general application of the existing and innovative approaches are addressed, indicating future research subjects that would contribute to advancements in PD detection and identification. There are few ideas for future researchers on how to proceed with this field of research are tabulated in Table 7.

Table 7
Identified research gaps and oppurtunities with future proposed solutions

Research Gaps	Category	Solution
Invisible PD occurrence	Detection	Non-intrusive sensor design
Intrusive Method		Need wireless sensor while power transformer still energized
Tedious process and time-consuming		Fast and accurate detection sensor
Easily influenced by nearby sound noises and outdoor EMF signals		Noise filtering circuit
Added costing and reduce portability		Proposed an appropriate new sensory design
Inaccurate PD interpretation	Recognition	Proposed a simple and suitable method
Improper signal denoising		Early denoising implementation
Complicated and intricate process		Simplifying the recognition process
Complicated recognition method		
Severity not analyze		Need different PD recognition method that is robust

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