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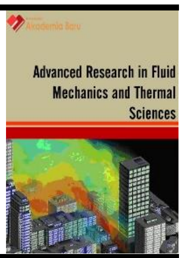

A Brief Review of Partial Discharge (PD) Detection, Recognition and Location Techniques for Liquid and Gas Insulated High Voltage Equipment

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ABSTRACT

High voltage (HV) equipment condition monitoring has become compulsory in the power utility supplier activity since the discovery of multiple failures on HV equipment during operation. The total cost of replacement and installation of HV equipment will cost millions of dollars and the loss of revenue of no supply period during the breakdown. Insulation parts in the HV equipment are the most important component that closely related to the reliability of the electrical system. The insulation part can be solid, liquid, or gaseous form eventually degraded due to existing stresses (electrical, chemical, and mechanical) in the equipment. One common phenomenon called Partial Discharge (PD) associated with HV equipment insulation degradation highlighted in this manuscript, and these situations intensively researched over the century. In this review paper, there are few conventional detections, recent detections, recognition techniques, and location techniques are discussed to explore the available methods to analyze further on the area for the future researcher. The objective of this review to present the latest PD associated techniques and facilitate and convey new information for a future research project.

Keywords:
Partial Discharges; Detection; Recognition; Locations; Insulation Degradation; Liquid; Gaseous

1. Introduction

High voltage (HV) equipment was among the important invention of the last millennium. Without this invention, the possibility of transmitting energy via AC power would be impossible [1-3]. HV transformer first invented by three Hungarian scientists in the mid-1800s and completed and patented by England Scientist by the name Williams Stanley by the end of the century [1-3]. It took about 50 years to produce the first reliable transformer in terms of efficiency, sizing, and capacity.

As popular W. Stanley quotes about HV transformer, "It is such a complete and simple solution for a difficult problem. It so puts to shame all mechanical attempts at regulation. It handles with such ease, certainty, and vast economy loads of energy that are instantly given to or taken from it. It is so

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reliable, strong, and certain" [1]. This quote shows the true capability and importance of HV transformers in a nutshell. During the early operation of HV transformers, most of the researchers focused the design on increasing the efficiency, capacity, and sizing without taking into account the transformer condition, especially during operation. Multiple transformer failures during operation that lead to the realization of the importance of the established method to assess specifically on equipment insulation conditions. One of the phenomena that happened to degrade the insulation parts is Partial Discharges (PD) [5, 6].

According to NFPA 70B, insulation breakdown is the main contributor to electrical failures for any HV equipment. Insulation breakdown happened at 84% of transformers and 89% of cables due to PD activity [7]. Partial Discharge (PD) is defined by localized insulation dielectric breakdown when void or gaseous existed in the insulating parts with an appropriate amount of electrical stress [8-10]. Partial Discharge happened in the HV equipment when the incomplete breakdown occurred between two conductors that worsening by existing electrical stress and finally led to major insulation failure.

The term 'partial' refers to the incompletion flows of current. Since the 1920s, interference in radio signals produced by PD has been recognized, especially in overhead lines and insulators [11]. PD happens at any installation carrying voltage more than 3.3kV (High Voltage, HV, or Medium Voltage, MV) between phases [12]. It typically occurred in power cables, stators, transformers, and switchgear. Gas (air, SF6, hydrogen) will experienced electrical stress when it is exceeding 3kV/mm of space, resulting in electrons is disbanded from the gas. This scenario will produce current according to $I=\delta Q/\delta t$; when an electron moves through space and time, it will induce a small current.

Partial discharge (PD) can harm insulation materials in HV devices such as energy cables, transformers, and switchgear boards in either Gas Insulated Substation (GIS) or Air Insulated Substation (AIS). PD occurrence can result in major power failures and energy losses [2, 13, 14]. Therefore, PD monitoring is a crucial and non-destructive strategy used to diagnose the state of a power transformer insulated parts. Normally, PD measurement only conducted during facility acceptance tests, on-site commissioning, and periodic maintenance inspections to uncover major flaws and defects estimation but not monitored during equipment operation.

Electrical engineers usually monitor PD activities to determine the health level of the insulating system and the dielectric degradation caused by stress from electrical, mechanical, or chemical. PD that degrades the dielectric condition occurs in gaseous, liquid, solid, or phase combo [4, 15]. Problem with current PD equipment technology are

i. The intrusive method, – HV equipment needs to shut down, dismantle, and locate the abnormality by the trace of treeing carbon traces, or insulation damage.
ii. Oil or gas analysis needs to get oil or gas sampling that needs outage to collect the samples, and the possibility of contamination is high during the handling period before arriving at the lab. This method is time-consuming even it is effective to detect the insulation conditions.
iii. Stray noises that existed in each substation from other equipment and environment polluted the recorded acoustic signals.
iv. Electrical methods are the most suitable method, but each HV equipment must ready equipped with suitable sensory, and the calibration of this device is quite impossible, especially for HV equipment that installed for important loads.
v. Stray communication signals from telecommunication, broadcasting, and radio transmission collected along with the PD signals; therefore, proper signal filtering is a necessity to produce better UHF signal interpretations.
vi. Most of the readily used equipment in the market is expensive and required trained personnel to use it.

Whereas in Table 1, all the research gaps, and deficiencies of current research for the PD detection, recognition, and location techniques listed

Table 1
List of Research Gaps, and Research Deficiencies

Research Gaps	Deficiencies in Research	References
Data Gathering	- Intrusive method – need a shutdown - Not suitable for in-service HV equipment	[19-21], [24]
Data or Signal Processing	- Other external or internal noises – cluttered signals or data	[8-9],[16],[30- 34],[36-38]
Insulation Medium Sampling	- Required shutdown - Exposed to electrical hazards - Contamination before arrived at the laboratory	[20],[24],[29]
Equipment Involved	- Expensive and Complicated Equipment - Required Trained Personnel to use it	[19-23],[29]

In this review paper, the established and current trending methods are presented to further explained the method and their strengths and weaknesses. The in-depth understanding of this PD detection, recognition, and location will enable future researchers to design better PD monitoring methods.

2. Established Methods for PD Detection, Recognition, and Location

Internal breakdown may result in excessive harm to the HV machinery and lead to unplanned interruptions for many days, varying on the severity of the disturbance itself. Current practices by power utility companies usually applied the condition monitoring strategy to prevent these scenarios even happen. The standard method of condition monitoring strategy consists of relevant to PD detection, recognition, and location techniques and further discussed in the next sub-chapter.

2.1 Detection Methods

Four main categories employed in detection methods for PD occurrence, namely light output, chemical by-product, acoustic emissions, and electrical methods, as shown in Table 2 and one conventional method for each type, are listed below in the table. In the sub-chapter, the method will concisely define

Table 2
List of PD Detection Method

Techniques	Example application
Light output	Photo-multiplier detector
Chemical by-product	Gas Chromatography
Acoustic emissions	Accelerometers
Electrical methods	IEC Publication 270

2.1.1 Light output

Gas discharge comprises electrons, positive and negatives ions, and photons [17-18]. A PD activity was normally producing a light output in the form of a photon. Photon produced from this discharges activity can be detected via photo-multiplier [19-21], as shown in Figure 1. Practically, photo-multiplier with quartz lenses used because of its ability to measure UV radiation. The problem with this technique is, but it lacks locating ability and needs proper precaution during measurements [21-23].

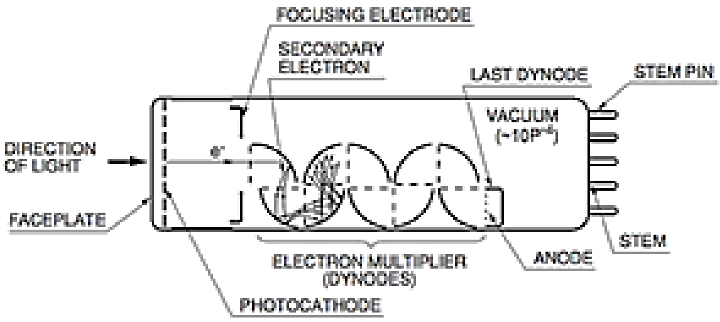

Fig. 1. Construction of Photo-multiplier [22]

2.1.2 Chemical by product detection method

Sulphur Hexafluoride (SF6) mainly filled in switchgear, transformer, or circuit breaker as an insulating medium [20, 24]. This SF6 gas normally went through the decomposition process during operation and produced sulfur tetrafluoride (SF4) and SF4 gas known to be highly reactive [25-26]. When SF4 reacts with stray water vapored, it will generate new stable by-products; thionyl fluoride and sulphuryl fluoride, that can be detected using a gas chromatography [27-28]. The gas chromatography method, as shown in Figure 2, measured the concentrations of these compounds through a mass spectrometer. However, the setback of this method is quite insensitiveness when associated with a large volume of SF6 and takes longer times for the gas analysis (10 hours at least) [29]. The long process will jeopardy HV equipment integrity and contaminates the sample.

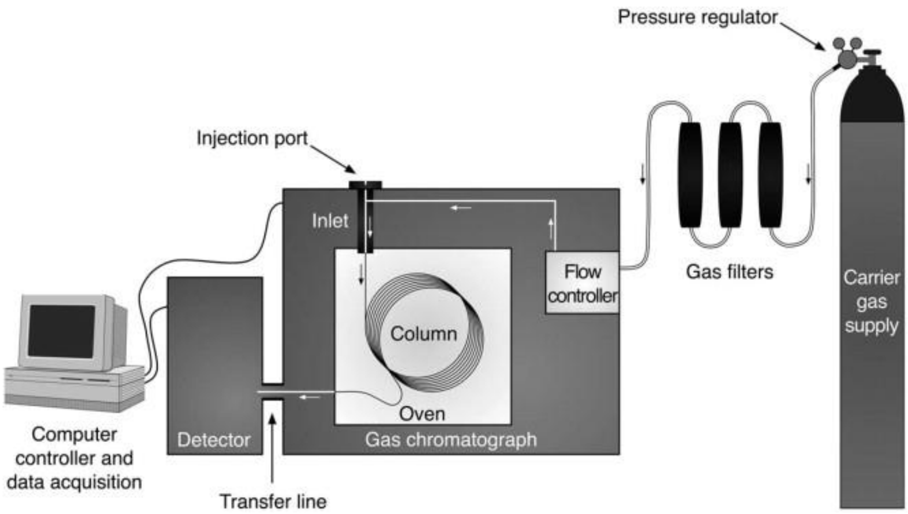

Fig. 2. Gas Chromatography Methods [29]

2.1.3 Acoustic emissions detection method

In the substation, both free particles and PDs capable of developed waves that stimulated sound signals [9, 16, 30, 31]. These waves that were created by PD shifted at various speeds and expressed in the boundary between the materials that consequently formed acoustic waveform. This waveform observed by utilizing acoustic emission sensors, as seen in Figure 3 [9],[32]. The advantage of adopting this approach is it is a non-intrusive procedure. Measurement performed by integrating internal detectors, used and the capacity to predict PD positions, but with multiple sensors to maximize precision. The flaw with this method is the interruption of slow ambient noises from nearby equipment and environment where adaptive noise filtering is compulsory before continuing with detailed acoustic signal analysis.

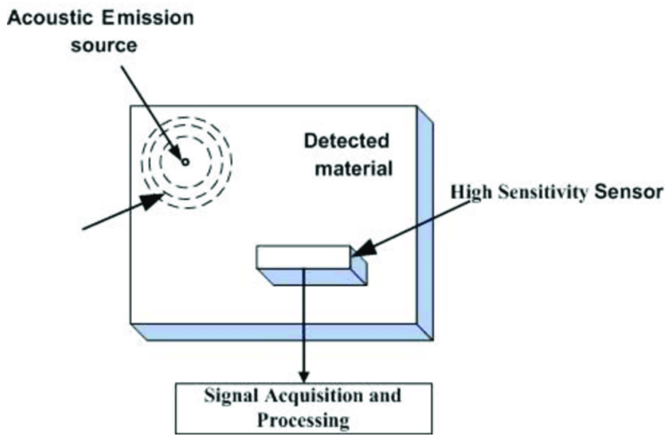

Fig. 3. Acoustic Emission Sensors [31]

2.1.4 Electrical detection methods

In IEC Publication 270, the electrical methods divided into two main categories; the conventional and the UHF method. In the conventional method, the test circuit measure flowing charges through the capacitor using quadrupole and detector [31-33]. Normally, PD created pulses with a short duration of less than one nanosecond [34, 35]. Once the pulse diminished, the coupling capacitor will experience a reduction in stored charge, and this indicates PD activity in the system. The problem with this method is it needs to perform in a shielded environment, which is impossible for conventional substation and also needs a proper shutdown.

While, for the UHF method, the ability of the antenna is used to detects the PD generated Electromagnetic (EM) signal. This method has developed since the 90s, and bandwidths ranging from 0.3 to 3 GHz. UHF antenna used the resonance frequency to recorded unusual waves pattern associated with PD [8-9][34-37]. It employed high sensitivity and the ability to do PD localization with multiple configurations. Currently applied UHF PD sensors are using monopole and dipole UHF antenna, as shown in Figure 4, which can easily capture unnecessary signals from telecommunication, television, and radio broadcasting that polluted the overall data[8, 38].

Fig. 4. UHF Dipole Antenna [35]

2.2 Recognition Methods

For the recognition method, the most applied method is phase-resolved PD methods, and this method proven beneficial for the characterization of PD activity. The artificial intelligent hybrid method is the new applied and continue improving over the years of research.

2.2.1 PRPD pattern recognition method

Hudon *et al.,* [39] simulated sources of discharges activities that occurred on generators, and this acquired by using a spectrum analyzer in phase-resolved data. The pattern of phase-resolved partial discharges (PRPD) represented by dominant features and discharge frequency content. They are investigated to identify the type of discharge source. The preliminary PRPD database allows engineers to implement a rapid and better recognition method of online generator diagnosis with a marginal impact.

PRPD representation analyses have shown significant strength and effectiveness compared to other types [15, 40]. New discovered characteristics presented in this paper used as additional data for an applied PRPD database [39]. This characteristic is important to produce solid evidence in improving the PRPD database for a better identification process. Pattern shape, as in Figure 5, will be investigated in detailed to categorize more types of discharge sources. This method required trained and experienced engineers to examine it.

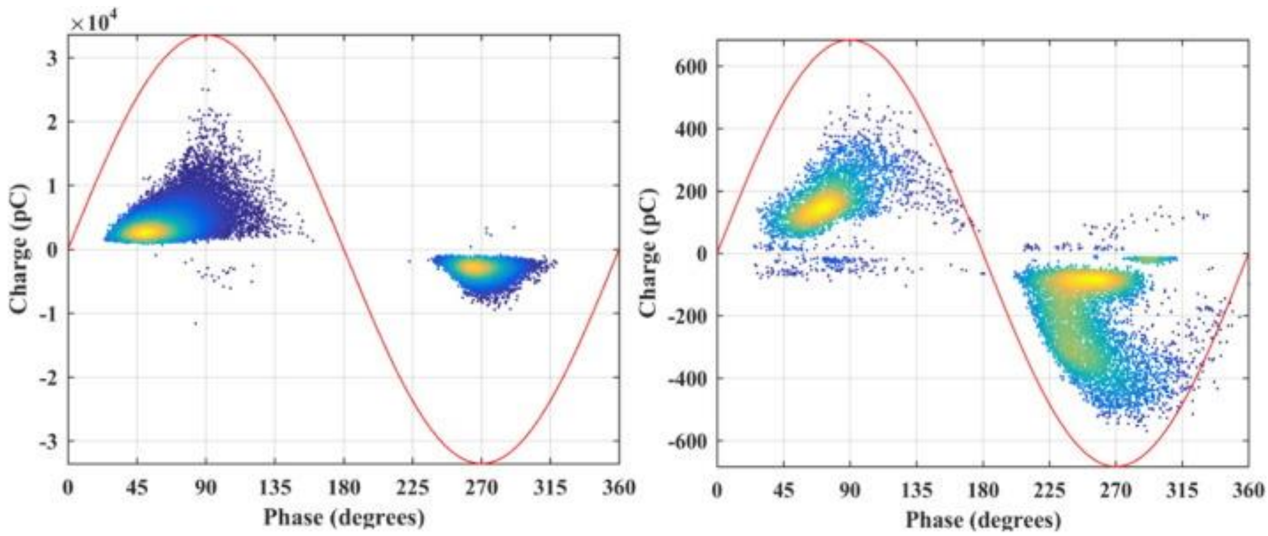

Fig. 5. Example of Plotted PRPD Signal [39]

2.2.2 Multiple Electrodes Hybrid with Neural Network Recognition Method

Okamoto *et al.,* [41] characterized a PD using several electrodes. The input is in distribution patterns, then analyzed using a neural network. Both learning and recognition characteristic showed, and the ability is establishing the foundation of PD recognition. The results significantly proved the ability of the combination recognized PD type.

2.3 Location Methods

Fundamental of PD location method, especially for enclosed equipment, multiple probes or sensors needed. The concentration and time of each signal (EM, or acoustic) recorded compared and calculated using an algorithm to investigate the PD location.

2.3.1 Multiple antenna sensor location method

This method applied for enclosed HV equipment by detecting the generated electromagnetic radiations from a PD event [34],[44]. The system involved multiple sensory to estimate the most accurate time of arrivals (TOA). TOA was measured in several samples within radio frequency bands between 1 to 5 GHz and proceed by the antenna array, as shown in Figure 6, to determine the coefficient of the sensors signal waveform.

The multiple antenna configurations suggested were to eliminate iron core electromagnetic interference, and it couple with a hybrid algorithm to increase signal to noise ratio (SNR) and quantify TOA. From these results, a final Hyperboloid-Genetic algorithm (HGA) to locate the discharge [1]. The experimental study using lab single phase transformer. The established results demonstrated the validity of the scheme and exhibited that the location error in 16 cm, mostly, is about several cms.

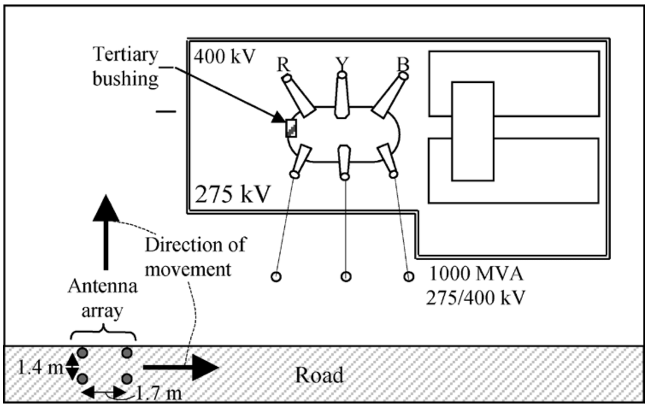

Fig. 6. Antenna Array Configuration [44]

2.3.2 Fiber-optic acoustic sensor location method

PD activity attenuated an alien acoustic signal in the power transformer. The author in [45-46] designed a fiber-optic acoustic sensor that combines the detection and location of transformer PD activity, as depicted in Figure 7. The process of detection involved acoustic measurement and location sensors with the triangulation method in the main transformer tank. In this system, the sensor directionality should be as flat as possible within at least 40 mm from the sensor axis and up to 150 kHz for a frequency. The plane wave approximation methodology configured the setup sensor to achieve the directionality output desired for the application.

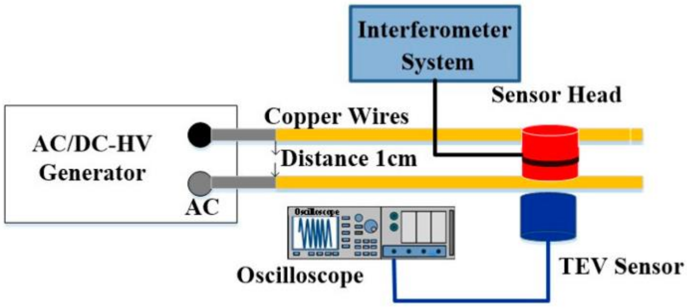

Fig. 7. Fiber-Optic Acoustic Sensor (Red Cylinder) For Location [46]

The directionality is acceptable for the application of PD location in high-voltage transformers. The directionality of a fiber coil acoustic sensor tested using the gating procedure for frequencies start from 50 until 300 kHz. Further, enhance exploration and experimentation need to reduce these glitches in the future research project. Still, the experimental results indicate that the fiber coil sensor and the detection circuits established in this work can operate successfully for the detection of PD in power transformers, but the location is still not proven the capability. This method is only applicable to low band frequency signals.

3. Latest Development in PD Techniques

All present technologies available for PD identification, recognition, and localization algorithms listed in the next paragraphs, and all these approaches seem to have their long term benefit and significant disadvantage accordingly.

3.1 Detection Method

The latest development of PD detection manipulated an existing medical, photonics, and telecommunication finding to a different arena of HV equipment, and the impacts analyzed by a few researchers in the below sub-chapters. The new detection method brings slight improvement compared to previous methods.

3.1.1 D-dot sensor detection method

Hussain *et al.,* [47] presented in his research paper that several PD events measured via the standard method (IEC standard 60270), but the electromagnetic signal calculated by the D-dot sensor as per Figure 8. Both parameters (EM energy and apparent charge) shown a second-degree polynomial relation, and plots reveal a pattern indicating multiple PD faults. This research proved that the ability to do detection for more than one PD event exists in the equipment is promising, and the severity showed by scatter plots. The further distance from the axis proved more intense PD and the opposite situation for normal PD. PD severity assessment can enable engineers to predict the current insulation degradation, but the setback is the lack of capability for PD location.

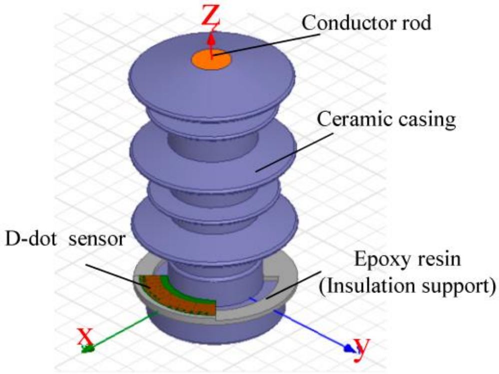

Fig. 8. D-Dot Sensor Installation

3.1.2 UV vision detection method

Karmakar *et al.,* [48] applied UV vision-based spectroscopy (UV-Vis) hybrid with Fourier transform infrared (FTIR) techniques to determine the transformer's insulation fluid. The PD's aging condition was imitated using old transformer oil from the substation. The quality of transformer oil analyzed in detail through the UVVis, while FTIR examines the functional group existed in the oil. The findings validate the ability of optical techniques to evaluate transformer insulation oil property, especially for the in-service transformer. The oil also tested for Breakdown Voltage (BDV) after being subjected to PD. BDV results significantly deteriorated after exposed to PD.

The spectroscopic UV-Vis experiment conducted showed that the peaks of the absorption spectrum are also larger as the aging accelerated. The existence of impurity enhanced the aging process experienced by evaluating various old samples, i.e., old without impurity, and samples aged with copper pieces. Besides, the findings of the FTIR spectroscopy put distinct functional groups (alkanes, aromatics, and alcohols) and corresponding bond levels current in old oil models. They were increasing the concentration of functional groups proportional to the state of aging liquid. Therefore, these methods have confirmed that they can gage the transformer oil condition with more rapid results.

3.1.3 Nature inspired monopole antenna detection

A nature-inspired and customized sensor, as in Figure 9, obtained by developing a printed monopole antenna (PMA) in conjunction with PD's EM signal characteristics [49]. An ultra-wideband (UWB) antenna was obtained using the compressed ground plane technique. The patch layout was eco-inspired by that of the Inga Marginata leaves, contributing to a significant reduction in size. Observations have been held out in an anechoic chamber to verify the PMA's operating frequency and gain. The findings indicate that the working antenna spectrum includes almost all of the PD event ranges of frequencies. The antenna also had a reasonable sensitivity (mean 3.63 dBi gain).

Fig. 9. Example Nature Inspired Monopole Antenna

The antenna performance was evaluated using findings of comparative with the standard IEC 60270 procedure. Concurrent tests conducted for this reason in a PD generator system comprised of an oil cell with point-to-plane electrode configurations. The advanced PMA categorized as an adaptive sensor for PD identification and appropriate for substation implementation as it is capable of measuring PD emitted pulses with half the voltage concentrations acquired from the IEC technique and is resistant to corona discharges.

3.2 Recognition Method

The detection method still based on the conventional method but with a twist on the analysis side where AI and statistical patterns manipulated to do the recognition process. There are still a few researchers still focused on contacts or probes arrangement to do the recognition. These new methods generated better recognition results in comparison with the conventional method.

3.2.1 Lyapunov exponential patterns recognition method

For recognition technique, Fan *et al*., [50] introduced a chaotic characteristics based signal in a power transformer. Feature extractions are developed using Lyapunov exponents and proved to have the ability of acknowledged PD patterns. The successful rate of PD pattern recognition is higher compared to conventional methods.

3.2.2 Electrical contacts arrangement recognition method

Kubarev *et al.,* [51] stated that the PD features efficiently recognized through the electrical contact arrangement. The features obtained are aligned with GOST and IEC standards that subsequently delivered more than enough details during the separation of electrical circuits. The disadvantage with a bulky flood of information prolongs data analysis and the fast communication phase. Investigation attributes of PD in a semi-auto mode alleviate the deficiency in processing outputs and will provide the appliances mostly with completely fresh macro-level data and information.

3.2.3 LBP and HOG recognition method

The new PD recognition method via high-level image detection presented by the author in [52]. This method suitable either for single or multiple sources. The established data are phase resolve partial discharges (PRPD) manipulated to make defect models with an algorithm. The information set, first processed into grayscale images, and then each image constitutes a unique defect state. The pictures collected were further gathered via Local Binary Patterns (LBP) and the Histogram of Oriented Gradient (HOG) to derive certain attributes from greyscale images [52]. The product from LBP and HOG feature extraction procedure, successively recommended a procedure, seems to have 10 percent better accuracy concerning the precision of the present statistical model.

3.3 Location Method

Current locating methods based on the signals and timing analysis where the fundamental is the PD location will indicate a higher concentration or amplitude of captured signal compare to the normal side because the signal becomes weaker when traveled over long distances.

3.3.1 RF signal pattern matching location method

Ephraim *et al.,* [53] proposed a localization method utilizing RF signal pattern matching. Pure RF signal used as an input for PD locator. A hypothesis of PDs will generate unique RF patterns and the PD information collected by manipulating two important frequency bands, whereas correlation feature selection (CFS) used to select the most suitable feature hence reduced dimension itself. Via the CFS method, the accuracy and time for computation tremendously decreased. The effectiveness of this technique determined by the KNN algorithm. Mean error cut by near 37% and about 80 % for the computational load.

3.3.2 TDOA of multiple UHF antenna location method

Kalyan *et al.*, [54] informed that PD location relies mostly on Time differences of Arrival (TDOA) of PD itself and multiple UHF sensors located around the power transformer main tank. PSO algorithm manipulated to evaluate the recorded TDOA information. Emergent discharges from conducting particle producing UHF PD signal in the oil-filled transformer. The error of the detected location is about 3cm from the experimental setup and most suitable for the industry with a small budget.

3.3.3 Impulse voltage EM wave characteristics location method

Maki *et al.,* [55] introduced a novel polarity reversion method by applying the finite difference time domain to determine the EM wave (EMW) characteristics. The characteristics compared between AC voltage and impulse voltage and finally, PD activity location constructed via impulse voltage. Impulse voltage was found to facilitate better EMW concentration that helps to produce a fast and accurate PD locator.

4. Conclusions

To conclude, this article offers a short and detail overview of developed and recent technology used within high-voltage energy system equipment for partial discharge detection, recognition, and localization. Compared to conventional detection methods in terms of their execution and fresh recommended method, the major benefits of the present technique shown in this paper. The fundamentals, which are vital for theoretical PD, are outlined, which can help scholars in both simulation and experimental work in the design of instruments and performance analysis. The main challenges of the broad introduction of the established and recent procedure are cited, implying future research fields that will lead to improvements in PD identification, recognition, and localization.

For future researchers, there are few suggestions to proceed with this area of research

i. Develop a non-intrusive method that integrates the detection wirelessly without power outages.
ii. The equipment automatically records data sampling methodology for online HV equipment.
iii. Design a good adaptive filter and with proper calibration.
iv. The cost of new equipment developed must be cost-effective and efficiently operated

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