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TOPICAL REVIEW

Review on Partial Discharge Diagnostic Techniques for High Voltage Equipment in Power Systems

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ABSTRACT In modern power systems, condition based monitoring and diagnosis is essential to ensure the effective and reliable operation of different high voltage equipment (HVE). Compared to other monitoring techniques, partial discharges (PD) measurement is considered as a key method for assessing the insulation health condition. The benefits of PD condition monitoring of HVE can be extended by proper detection, identification, and interpretation of PD signal. Among both online and offline PD monitoring techniques, online PD monitoring is a very promising technique that assists in robust monitoring system which reduces the power failure incidents in power system components. Therefore, to understand recent developments and trends in theory and in practice, it is necessary to establish a holistic analysis of current online PD monitoring techniques for HVE in power systems. This paper presents an intensive literature review of current online PD monitoring techniques used for different high voltage electric components in power system. Finally, a smart PD monitoring techniques based on wireless sensor board is proposed. The proposed smart PD monitoring framework may be used to correctly estimate the insulation degradation in HVE and enhance the overall performance of power systems.

INDEX TERMS Detection methods, feature extraction, high voltage equipment (HVE), online partial discharges (PD) measurement, PD monitoring, PD classification.

I. INTRODUCTION

In electric power systems, insulation degradation is the major cause of the failure of various electric components. During normal operation of any electric equipment, the electric field stresses are uniformly distributed across the healthy insulation between the electrodes. However, when the insulation contains some defects (impurities, voids, air bubble, or electric trees), the non-uniform distribution of electric field stresses are produced across the insulation between the electrodes. This is because of different dielectric insulation characteristics of healthy and defective insulation. Depending on the type and size of defect, partial discharges (PD) occur at a specific level of applied voltage. During PD activity, the electric field strength is sufficiently high that provides the force to the charges to penetrate through the insulation material.

Generally, each insulation system of electric equipment shows characteristic defects that depend on multiple factors including insulation dielectric properties, thickness, load profile, etc. For instance, thermal loading on the solid insulation material containing of oil impregnated paper dominates the

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aging of a transformer. In generators and electric motors, the aging is influenced by the multiple electrical, thermal, and mechanical load processes. Similarly, the lifetime of switchgear is affected by the degradation of bushing, cable termination, current transformers (CTs), and potential transformers (PTs). In summary, the lifetime expectancy and the degradation of any electrical insulation system depends on the TEAM stresses [1], [2].

This paper aims to present all the important PD measurement, diagnostics, and monitoring techniques and comprehensively gather them with the list of research papers added for quick reference. Several topics of the modern research associated with PD including PD measurement techniques, PD signal visualization and de-noising techniques, features extraction and PD pattern classification are discussed. Furthermore, the comparison of PD measurement techniques, their advantages, limitations, performance, and applications are presented. The future research trend and challenges are also discussed. The comprehensive recent bibliography on the PD is helpful for asset engineers, academicians, and researchers working in the field.

The remainder of the paper is organized as: Section II presents the PD phenomenon. The PD monitoring system is detailed in Section III. Section IV presents the PD signal detection and measurement techniques, their comparison and applications. Section V presents the PD signal visualization and de-noising techniques. Section VI presents several feature extraction methods and PD pattern classification methods. Section VII presents the proposed smart PD monitoring system. In Section VIII, conclusions are drawn.

II. PARTIAL DISCHARGE PHENOMENON

According to International Electro-technical Commission (IEC) 60270 technical standard, High-Voltage Test Techniques – Partial Discharge Measurements, the PD is defined as "*a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor*" [3], [4]. Mostly, PD appears as current or voltage pulses having a very small duration. These pulses are highly dependent on the applied voltage (U_a), the nature of dielectric material and environmental conditions. The main causes of PD are [5]:

- Surface contamination and irregularities in the solid insulation.
- Voids produced in the solid insulation material at the time of manufacturing.
- Cracks produced in the solid insulation due to mechanical breakdown.

To comprehend the PD phenomenon, it is necessary to understand the electrical mechanism of PD activity and mathematical formulation behind the various types of PD. PD can be mainly classified into three categories including surface discharges, internal (cavity and treeing) discharges and corona discharges. The key concepts behind PD phenomenon are presented in [6] and [7]. The PD characteristics can be assessed using several parameters related to the PD signal, which provide information about the PD severity and the condition of insulation in HVE. They include PD inception voltage (U_i), Accumulated apparent charge (q_a), cumulative Energy (CE) function, average discharge current (I), discharge power (P), and quadratic rate (D) [3].

III. PD MONITORING SYSTEM

PD activity can be monitored using different measurable phenomena including heat, vibration, light, decomposition of gas, and the emission of electromagnetic radiation. These phenomena can be detected using a variety of detectors including electrical [8], [9], [10], [11], [12], [13], [14], [15], [16], electromagnetic [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], optical [27], [28], acoustic [11], [12], [16], [19], [21], [29], [30], [31], thermal and chemical sensors [10]. The main steps used in the analysis of PD signals are the detection of PD signals, feature extraction, and the representation of PD signals, as presented in Fig. 1 [32].

Each type of PD defect has a separate pattern and behavior represented by some specific features [33]. These features are extracted by pre-processing the raw PD data obtained from the sensors [34]. The significant features convert the raw PD signals into a set of discriminatory identifiable features. For the fault detection and localization in HVE, the quantification of statistical features [35], time resolved PD (TRPD) features [36], and phase resolved PD (PRPD) features [37] have been made by processing the PD signal obtained from multiple PD defects. To process the features of PD signals, several mathematical tools including Distance classifier (k-NN), Neural Network (NN), Support Vector Machine (SVM), Pulse Sequence Analysis (PSA), fuzzy logic, and decision function classifiers are used to separate the PD defects in HV equipment either using clustering or classification [38], [39], [40].

IV. PD MEASUREMENT TECHNIQUES

PD measurement and diagnosis play a vital role in assessing the lifetime of the insulation system, in addition to the routine and type testing [42], [68], [69]. When PD event occur in the insulation system, the detectable quantities including high frequency voltage and current pulses, decomposed gases, violet glow, hissing noise and electromagnetic waves are produced [70]. Based on the parameters detected by the PD sensor, the PD detection methods are divided into different classes. The application of each PD detection method is based on the detection range and physical quantity. Table 1 presents the various PD measurement techniques used in electric power system.

The different physical quantities including PD pattern and linearity are measured through both conventional and non-conventional methods [71], [72], [73]. The conventional PD detection technique is based on electric detection methods that measure the current, resistance, and frequency response of the captured signal. The electric detection techniques include Coupling Capacitor Method [8], [16], [42], [43], Pulse Capacitive Coupler Method [9], [12], [13], [14], [15],

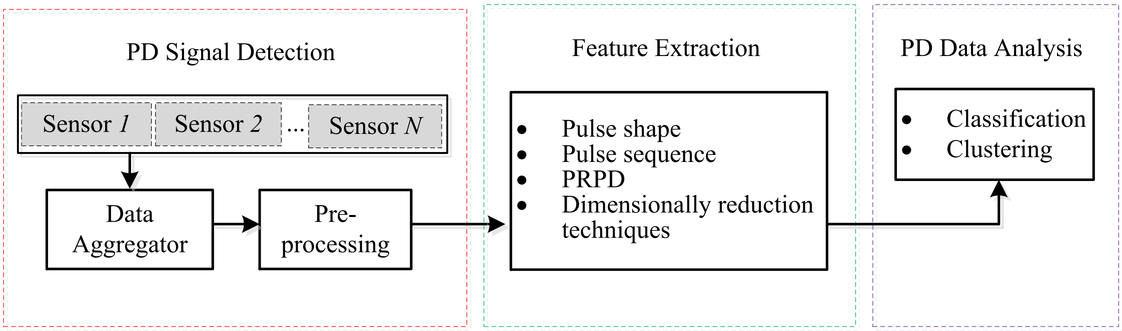

FIGURE 1. PD monitoring system based on the three components.

[44], [45], and High Frequency Current Transducer (HFCT) Method [18]. Due to the presence of noise during online PD measurement, the conventional PD detection technique may have low sensitivity than laboratory measurements.

The non-conventional PD measurement is much more suitable for on-site and online PD measurement in which the external interferences largely influence the measured signal. The detection range of PD signal is increased using modern non-conventional electrical coupling techniques that involve foil electrodes and current transducer methods [74], [75]. The most common system for continuous PD monitoring with minimum physical contact is based on various types of UHF sensors for the quantification of electromagnetic interference produced due to PD activity [75]. Wireless PD sensors based on radio frequency (RF) detection and analysis techniques provide a cost-efficient alternative to hardwired sensors for HV equipment [76], [77], [78]. The radio receivers are used to detect and measure the electromagnetic signal emitted from a 1-1000 ns current pulse during a PD event, eliminating the need to install any additional hardware [79]. The electromagnetic PD signal is similar to a classical decaying oscillation [80], in a range of bandwidth from 50- 1000 MHz, depending on the type and structure of the fault [81]. However, this bandwidth is usually limited to 50-800 MHz due to the high-frequency attenuating metallic structures in the environment [82]. They are capable of providing real-time monitoring of PD activity and can be used for predictive maintenance. However, the application of wireless PD sensors in condition monitoring for power system assets is still limited due to several issues i.e., interference and noise, limited range, and vulnerable to cyber-attacks.

Based on the noise and vibration, the PD detection in the sealed components without any opening for the sensor is made using acoustic sensors [39], [57], [83]. The occurrence of PD in the gases cause the excitation process and a violet glow is produced due to the ionization which can be detected by the optical sensor [60], [61]. PD activities in oil or gas insulated object can react chemically, emitting a by-product of the chemical reaction [8], [66], [67]. The development of chemical and optical methods for PD detection is still in progress [39].

A. HYBRID PD MEASUREMENT TECHNIQUE

Generally, the electrical detection techniques are preferred for PD measurement under offline condition or the laboratory environment whereas electromagnetic and acoustic detection methods can be applied under both offline and online conditions. The efforts have been made to combine the two techniques in order to overcome drawbacks of each method. In particular, a combined solution is effectively applicative on transformer and GIS. This kind of integrated approach can detect PD occurrence with accuracy and scalable quantity in a low noise environment. Fig. 2 presents the PD measurements in power transformer using UHF (UHF 1–UHF 3) and acoustic (A1– A6) sensors.

Fig. 3 presents the online PD measurement using both HFCT and UHF sensors in GIS with five types of insulation defects including corona in GIS (A), internal defects (B and C) in GIS, corona in cable (D), rupture in cable terminal (E) and termination defect [18].

B. CONVENTIONAL VS NON-CONVENTIONAL PD MEASUREMENT TECHNIQUES

The overall comparison of conventional and non-conventional PD measurement techniques have been investigated in [84]. According to IEC 60270 and non- conventional methods, PD measurement systems are measuring different quantities including apparent charge, electromagnetic waves, acoustic signal, light signal, etc., even when they come from the same source. The comparison of both methods is given in Table 2 [71], [72], [73], [85], [86], [87].

C. ONLINE VS OFFLINE PD MEASUREMENT SYSTEM

Both offline and online PD diagnostics tests used for evaluating the internal condition of HVE have their own merits and demerits, so they are complementary [88], [89], [90]. The main characteristics of both offline [88], [91] and online [4], [92], [93] PD measurements are presented in Table 3.

V. PD SIGNAL VISUALIZATION AND DE-NOISING

A. PD MONITORING VISUALIZATION

To analyze the PD signal, an appropriate display pattern visualization of PD signal is very important. The trend of PD

TABLE 1. **Different conventional and non-conventional PD measurement techniques.**

Technique	Advantages	Disadvantages	Sensor	Applications	Refs
Electrical	• Proper calibration • Implementation simplicity • Highest sensitivity with quantitative measurement in laboratory • Low signal attenuation • High accuracy in measurements • Minimal noise level due to the protective effect of the transformer.	• Less sensitivity during online detection due to the high noise level • Measurements affected by internal and external interferences • Vulnerable to noise • Incompatible for a longer span • Sensitive to temperature variations	• Coupling capacitor • Pulse capacitive coupler • HFCT	All HVE	[8, 9, 11-16, 41-45]
Electromagnetic	• Source, location, type, and intensity of PD are assessable • Suitable solution for continuous online PD measurement	• Electromagnetic interference is high • Comparatively expensive • Limited range during wireless detection • No calibration technique is available. • More sensitive to environmental temperature	• Inductive • Capacitive	All HVE	[18, 22, 23, 39, 40, 46-55]
Acoustical	• High electrical noise immunity • Effective for PD localization • Comparatively cheaper • Good performance in real time monitoring • Sensitivity is unaffected by the capacitance of test object	• Signal intensity is low • Not suitable for continuous online PD measurement • Low sensitivity to internal discharge • More prone to environmental noise • More sensitive to environmental pressure and humidity	• Condenser microphones • Piezo-electric transducers	• GIS • Transformer	[10, 11, 25, 30, 39, 56-59]
Optical	• High electrical noise immunity • Highly sensitive • Sometimes effective for PD localization • Impulse voltage condition testing is possible • Light weight and small size	• PD magnitude is inaccessible • More sensitive to pressure and humidity variations	• Optical fibre • Photomultiplier tube • UV detector	• Transformer • GIS • Cable	[8, 9, 55, 60-65]
Chemical	• High electrical noise immunity • Measurement is easy • Highly sensitive • Excellent PD signal recording under laboratory conditions • Deliver important information for go/no go decisions • Less affected by environmental conditions	• Source, location, type, and intensity of PD are inaccessible • Sometimes induces uncertainty in the measurement	• SF6 Sensors • DGA Sensors	• Transformer • GIS • Cable	[8, 66, 67]

analysis is based on computer aided solutions [33]. The PD pattern can be visualization using several techniques including phase resolved PD (PRPD), Time resolved PD (TRPD), and 3-phase amplitude relation diagram (3 PARD).

PRPD was proposed in the late 1970s. This method is the most popular among almost all commercial PD measurement system and has proven to be one of the most powerful tools to interpret PD signal [33], [94]. As the name implies, PD signal is presented with respect to the test voltage as its phase resolved spot, as shown in Fig. 4(a). The most relevant information shown in PRPD is the measured PD signal with pulse magnitude, the phase angle at which PD occur, and the number density [95], [96], [97]. Because PRPD simply shows the most relevant quantities of PD, PRPD

TABLE 2. Characteristics of conventional and non-conventional PD measurements.

Characteristics	Conventional	Non-conventional
Technical Standard	IEC 60270	IEC 62478 (standard draft)
Type of sensor	Measuring impedance (capacitive, inductive-HFCT, and Rogowski coil)	Electric, acoustic, chemical, and optical
Frequency band	Wide (30-500kHz)/f=100-400kHz Narrow(50kHz-1MHz)/Δf=9-30kHz	HF (3 – 30 MHz)* VHF(30 – 300 MHz)** UHF(300 – 3 GHz)*** AE (20 to 250 kHz, and 0.1 to 3 kHz)
Calibration	Must be calibrated	Sensitivity check Performance check
Measuring unit	Usually pC, µA	Amperes, mV, V/mm, and dB
Measuring quantity	Apparent charge	Transient earth voltage (TEV) or current pulses (electromagnetic wave), acoustic, optical spectrum, and chemical by products
Measuring system	Coupling instrument, transmission system, and measuring device	Sensing instruments, transmission system, data acquisition device
Noise level	Comparatively high	Comparatively low
Type of applications	Generally offline in laboratory or on-site measurements, and online for transformer application	More suitable for on-site and online

*For VHF/HF, typical narrow bandwidth is 2MHz, **Typical wide bandwidth is 50MHz or greater, ***Zero span mode for individual or specific frequencies range is between 4 – 6 MHz or greater

TABLE 3. Comparison of offline and online PD measurement techniques.

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

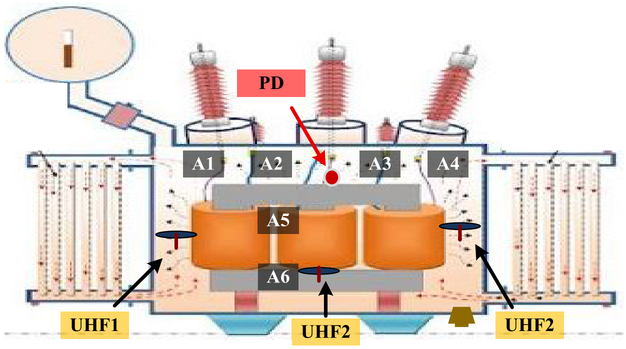

FIGURE 2. Detection of PD defects in transformer using both UHF and acoustic sensors.

analysis of each measurement has played an important role to identify possible fault types on specific measured test objects [85], [98].

Similarly, PD display based on measuring time is known as time resolved PD data, as shown in Fig. 4(b). Since this visualization focuses on more on the timing of PD occurrence, time resolved data can provide information about PD localization with several sensors placed at different spots rather than PD magnitude. Other applications of time resolved data is a Q-T diagram which uses the time between two consecutive discharges shown in [100]. Time versus frequency analysis (TF map) conducted in [101] is the analysis methods on time based PD measurement clustered by a fuzzy logic classifier which has been realized by Techimp.

3-PARD, or a star diagram, is cross talk between more than one phase on each measurement [87], [102]. So called multi-terminal measurement, measuring three phases with three couplers, can acquire synchronous PD data for all three phases of the test object such as three phase transformer or GIS. This method makes it possible to compare the magnitude of PD occurrence on each phase, help to locate the PD source

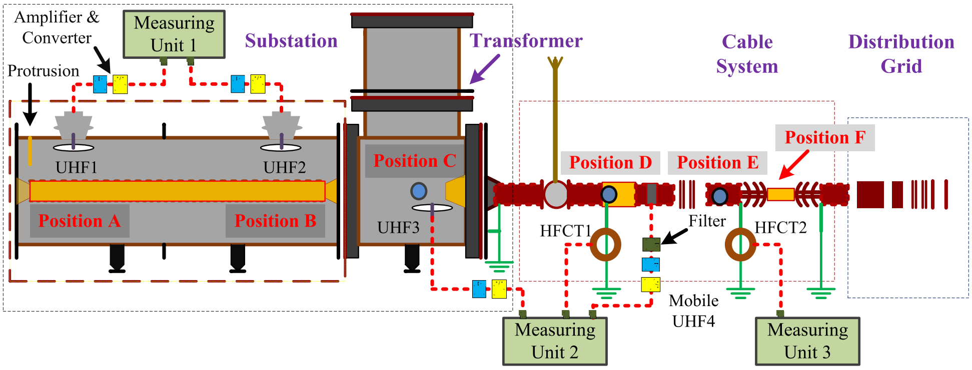

FIGURE 3. Detection of PD defects in GIS insulation using both HFCT and UHF sensors.

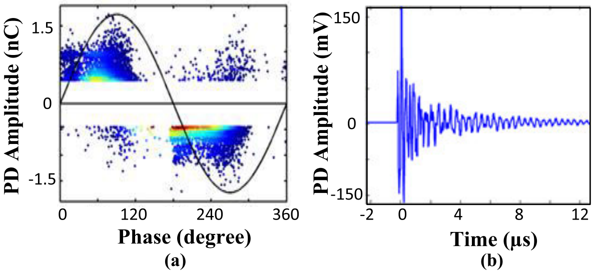

FIGURE 4. (a) Phase resolved PD pattern, (b) Time resolved PD pattern (waveform).

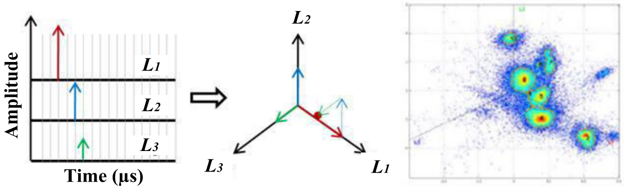

FIGURE 5. PARD comparing PD magnitude on each phase [99].

occurring in perhaps one of the three phases, and eliminate the external noise. The 3-PARD is a plot with a 120° phase shift of the three phase axis, as shown in Fig. 5. This method has been developed by the Technical University of Berlin [99].

B. DE-NOISING OF PD SIGNAL

The important issue during PD measurement is the presence of noise. Especially, during online PD measurements, high level noise signals remain present that can cover a true PD signal [103], [104]. Therefore, it is difficult to assess the features of true PD from detected signal for PD identification and classification of different types of defects. The de-noising process can be achieved by understanding the noise characteristics and eliminating them from the true PD signal [105], [106]. Typical noise during PD measurement can be categorized into sinusoidal noise, pulse type (repetitive or random) noise, and white noise. The noise signals can be successfully captured and reduced by several de-noising techniques, as presented in Table 4.

VI. PD FEATURES EXTRACTION AND PATTERN CLASSIFICATION

PD feature extraction is the process of detecting true PD data to obtain the PD characteristics and possibly classified as different defects by a classification process. In other words, the purpose of feature extraction is to decrease the dimensionality of true PD pattern with calculation of certain properties of the pattern [53]. Several effective tools are used to extract the significant features from PD data. The statistical parameters and cumulative energy function are used to investigate the time and frequency domain characteristics of PD signal [34], [38]. Also, the features of PD signal are extracted using different image processing [107], [108] and signal processing [56] techniques. In addition, Fractal features, cross wavelet spectrum, wavelet coefficient, two pass split window (TPSW) scheme [38], [109], and PD pulse shape analysis [110] are used to extract the significant features of PD signal.

Features extraction through statistical parameters is suitable for quick and efficient identification of large PD datasets. However, the results may be affected by noise and other factors [111]. Image processing and signal processing techniques extract the features of PD signals with high accuracy and precision. However, these techniques require high quality PD signals and a large amount of computational power, which can be expensive and time consuming [38]. S-transform provides a more accurate representation of the signal in both time and frequency domains. The accuracy of the signal representation is dependent on the choice of parameters used in the S-transform, which can be difficult to determine [112]. Fractal features can accurately model the complex shapes and natural phenomena that cannot be adequately represented by existing mathematical methods. Fractal features are invariant to signal scaling, shifting, and rotation, which makes them well-suited for PD signal analysis. However, fractal features are sensitive to the selection of parameters, making them difficult to tune and optimize for a specific application [39]. The cross wavelet spectrum can be used to locate regions in

TABLE 4. **PD signal de-noising techniques.**

De-noising Technique	Characteristics	Refs
Fast fourier transform (FFT)	Mainly remove the sinusoidal noise. Two kinds: Constant threshold FFT and Frequency dependent threshold FFT	[104]
Wigner-Ville distribution (WVD)	A quadratic time frequency analysis technique. The signal is divided into blocks	[105]
Least means squares (LMS)	An adaptive, iterative gradient search method. Low computational cost and less efficient. Three kinds: Pilot LMS, Clipped LMS, and Normalized LMS.	[105]
Morphology filters	Feature-oriented technique to eliminate white noise	[106]
Wavelet transform (WT)	Different classes of WT are used including thresholding WT and Mallat's algorithm	[104]
Machine learning (ML)	Various ML techniques are used including fuzzy classifier, artificial NN, etc.	[107]
Singular value decomposition (SVD)	Eliminate sinusoidal and white noise	[108]
Empirical mode decomposition (EMD)	Decompose the PD signal into mono-components. No requirement for the manual selection of mother wavelets	[109]
Spectral power clustering	For noise identification, the characterization of pulses is in high frequency	[110]
Adaptive	Estimate the frequency spectrum of PD pulses and differentiate the noise signal from PD pulses	[105], [107]
Band pass	Remove the electrical and mechanical noises using ultrasonic detectors	[105], [107]
Notch filtering	Mainly eliminate the sinusoidal noise. Two kind: direct and lattice filter	[105]

the frequency-time domain where two signals share a high amount of power. The wavelet coefficient is able to capture the nonlinear correlations between different frequency components [38]. However, it can be difficult to interpret the results due to the complexity of the wavelet transforms [113]. The TPSW technique proved to be effective in features extraction and pre-processing method in various applications like sonar signal processing and speech recognition. The TPSW scheme is relatively easy to implement and does not require complex signal processing algorithms [114].

The pattern classification of PD data is used for identification and separation of PD defects in the insulation system [115]. For this purpose, different methods have been introduced including artificial NN, fuzzy logic, genetic algorism, and SVM [116], [117]. Mostly, these methods require prior knowledge with respect to feature vectors of PD measurement.

Counter propagation networks (CPN) is used to calculate an approximation of a function based on a set of desired input-output pairs and their inverse relationship. A probabilistic NN (PNN) utilizes a probability density function (PDF) and competitive learning based on the winner-takes-all principle, with its foundation being the multivariate probability distribution. The extension NN (EXNN) is a novel NN that combines NN and extension theory to provide a unique distance measurement for pattern recognition and leverage parallel computing and learning capabilities [118]. The ANNs are also prone to overfitting. Fuzzy logic provides a nonexclusive method of classification which enables each pattern to be assigned multiple classes, each with an associated degree of membership. This is highly advantageous for cable fault monitoring, as it allows for more flexible decisions to be made depending on the particular arrangement of the fuzzy classification result [38]. SVM is a supervised learning machine that is capable of dealing with complex pattern classification problems. SVM uses a linear classification to map data into a higher dimensional space, and is particularly useful for small sample sizes, high dimensional data, and nonlinear pattern recognition tasks [119].

Table 5 presents the several PD signal detection, PD features extraction, and PD classification techniques to classify the PD defects in the insulation.

VII. PROPOSED SMART PD MONITORING SYSTEM

For reliable operation of advance power systems, the assessment of insulation health condition is important to evaluate the lifetime and the probability of failure in HVE. By adding the value of smart grid concept, an approach to use a smart PD sensing and monitoring system is essential for HVE installed at remote locations. The PD voltage or current pulses are measured using coupling capacitor, HFCT, or electromagnetic couplers in conjunction with the transmission system. The PD monitoring system can be upgraded using wireless PD sensors for the smart condition monitoring and service application of HVE. Furthermore, the smartphones may be used for the computation by acquiring PD data of the HVE using wireless sensors through a compatible local communication in the power system. These sensors with a battery backup may be installed at various field components of the electric power system either in standalone or act as a network. The integration of PD sensors with other condition monitoring devices is also important to use already measured electrical quantities, thus reducing the time and cost required to perform field measurements. For the accurate detection of PD faults,

TABLE 5. PD signal detection, PD features extraction, and PD classification techniques.

PD sensor	Feature extraction	PD classification/ clustering	Description	Refs
CC	Statistical and pulse shape characteristics of cumulative energy (CE) function	K-mean clustering algorithm	Multiple features of CE function including peak value, dispersion, symmetry, sharpness, similarity, and shape are used to develop a six-dimensional feature space for PD signals separation using K-mean clustering.	[34]
CC	Mathematical morphology gradient (MMG)	Clustering by improved density-based spatial clustering of applications with noise (IDBSCAN)	MMG operation is employed to time domain CE and frequency domain CE functions to describe their variation characteristics based on IDBSCAN to discover clusters.	[120]
UHF	Blind source separation (BSS) algorithm		Individual source signals are acquired by introducing a maximizing signal-to-noise ratio (MSNR) BSS algorithm supported by complex wavelet transform.	[121]
Current probe and UHF	Deep learning, sparse auto-encoder (SAE)	Soft-max classifier	The desirable classification results (more than 96%) are achieved by employing deep learning network of SAE and soft-max classifier.	[122]
HFCT	Pulse shape analysis	PD clustering algorithm	Several significant features related to PD pulse shape are evaluated using signal feature generation algorithms to separate the PD signals in different clusters.	[123]
UHF	S-transform and SVD	SVM optimized by particle swarm optimization algorithm	Each PD signal is decomposed into a time-frequency matrix with 24-dimensional feature vector using S-transform and SVD to separate the PD signals from the noise signals	[112]
UHF	Multifractal detrended fluctuation	SVM	Minimum effect of interference and appropriate for on-site PD diagnostics.	[111]
PTM	PRPD-AC and STFT-OIV		Comparison between AC and OIV voltages under PD inception and insulation breakdown conditions.	[65]
HFCT & UHF sensor	PRPD pattern	Clustering	WT is used for de-noising and clustering algorithm for the separation of PD signal.	[18]
UHF (microstrip antenna)	Features extraction by mRMR method	SVM	The severity levels of PD activity include normal level, attention level, serious level, and dangerous level.	[124]

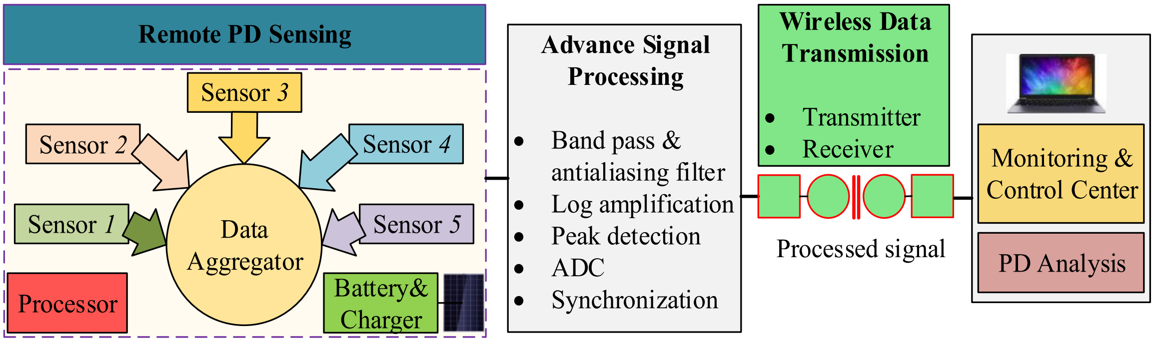

FIGURE 6. Proposed smart PD monitoring system.

high speed data conversion rates are essential. However, use of fast data conversion causes an increased cost, high power dissipation and poor efficiency of the sensors. Therefore, it is important to design sensors with high efficiency and low power consumption.

The PD data of the field component captured by the smart sensor may be stored and transmitted to the monitoring and control center through wireless transmission system. However, the communication of a bulk amount of data is also a task. The implementation of advance signal processing techniques can be made to resolve the problems in wireless sensors i.e. limited computation capacity and energy constraints. We should obtain PD energy at a specific bandwidth over a long period of time. This PD energy will be sensed by the sensor to detect the intensity of PD. A proposed approach for smart PD monitoring system is presented in

Fig. 6. The proposed smart PD monitoring framework may be used for correctly estimating the insulation degradation in HVE and enhancing the overall performance of power systems.

In future, this system will be implemented in a substation for online field trials, and be able to analyze and log defects as they are recorded. Additionally, it will report pertinent information to the asset managers when necessary. Furthermore, the integration of PD detector with an energy scavenging system will be made, allowing the device to be self-powered from the substation environment.

VIII. CONCLUSION

In power utility companies, it is important to guarantee high reliability of HVE by identifying the insulation defects effectively. As highlighted in this paper, PD monitoring can be considered a very powerful tool to assess insulation condition of HVE in power systems. Furthermore, PD diagnostics tests have been widely used for commissioning and new equipment installation for several decades. The online monitoring on power system components by means of PD measurement enhances the condition based effective HVE monitoring. The most significant benefits provided by continuous online PD monitoring are:

- Trend of insulation condition in real time.
- HVE monitoring while the system components are in operation.
- The monitoring under the real operating condition.
- Location specific information regarding the insulation condition and possible fault types.
- PD monitoring can be applied to all kinds of HVE.

The credible PD analysis and online monitoring make the electric equipment (GIS/GITL, etc.) a low maintenance solution for the power utility companies for long time operation without failure. The accurate fault detection and diagnoses at initial stages regulate the performance of maintenance system. However, the practical installation of online condition monitoring system for HVE is still a developing area which needs more research and experience. The addition of the PD measurement sensors in the present protection panels and SCADA systems leads the overall system very expensive. In addition, a bulk amount of data acquisition of such high frequency signals for PD analysis is required to determine the prior maintenance schedule. These challenges need to be addressed in future research work.

In summary, more advance detection and analysis techniques with more precise diagnostic algorithms are further required. More advanced PD sensors with perfect response for different type of defects are still needed.

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