

The Performance Of High Frequency Acoustic and Electromagnetic Sensors on Insulators and Joints Using Partial Discharge Detection

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Abstract- The increasing demand for reliable electrical power systems has intensified the need for accurate and non-invasive insulation condition monitoring techniques. Partial discharge (PD) remains a major indicator of insulation deterioration in electrical insulators and joints; however, conventional detection approaches are often limited by poor sensitivity, electromagnetic interference, and difficulty in identifying early-stage defects. This study investigates the performance of high-frequency acoustic and electromagnetic sensors for partial discharge detection on electrical insulation systems. A mathematical modelling framework was developed using partial discharge apparent charge, electromagnetic pulse propagation, acoustic pressure wave generation, sensor sensitivity, signal-to-noise ratio, frequency spectrum energy, and a combined sensor performance index model. A dataset containing ten insulation conditions, ranging from healthy insulation to advanced ageing, was developed using applied voltage levels of 8.5–18.5 kV, defect sizes of 0–5 mm, apparent charge values of 5–820 pC, and PD repetition rates of 2–240 pulses/s. The acoustic and electromagnetic responses were evaluated based on signal amplitude, frequency characteristics, noise immunity, and detection accuracy. The results demonstrated that acoustic sensor amplitude increased from 12.4 mV to 315.6 mV, while electromagnetic amplitude increased from 18.6 mV to 468.3 mV as insulation degradation progressed. The dominant frequency response increased from 25 MHz to 120 MHz, indicating higher-frequency energy concentration during severe defect conditions. Furthermore, the signal-to-noise ratio reduced from 32.5 dB to 23.8 dB due to increased interference associated with insulation deterioration, while detection accuracy remained consistently high between 98.7% and 96.2%. The proposed sensor performance index framework produced values ranging from 0.77 to 0.95, providing a comprehensive evaluation method for selecting suitable sensing technologies. The study supports the adoption of high-frequency acoustic and electromagnetic monitoring techniques within modern asset management policies, emphasizing early fault identification, predictive maintenance, reduced unplanned outages, and improved reliability of high-voltage electrical infrastructure.

Keywords: Partial discharge detection; High frequency electromagnetic sensor; Acoustic emission sensing; Insulation condition monitoring; Sensor performance index.

I. INTRODUCTION

The reliability of electrical power systems depends largely on the condition of their insulation systems. Insulation deterioration can result in partial discharge (PD), flashover, equipment damage, and unexpected power interruptions. Partial discharge is a localized electrical discharge that occurs within or along an

insulation system without completely bridging the insulation between conductors. Although individual discharge events release relatively small amounts of energy, repeated occurrences can gradually weaken insulation and eventually lead to serious electrical faults [1], [2]. Therefore, early and reliable PD detection is essential for effective condition monitoring, preventive maintenance, and improved operational safety of high-voltage electrical equipment [3].

Electrical insulators and cable or conductor joints are particularly susceptible to partial discharge because of defects such as cracks, voids, contamination, loose connections, and localized electric field concentrations [4]. These vulnerabilities may increase where different insulation materials meet or where electrical stress is unevenly distributed. Furthermore, moisture, ageing, manufacturing imperfections, and mechanical damage can alter insulation properties and encourage discharge initiation [3]. Conventional inspection methods may fail to identify such defects during their early stages. Consequently, non-invasive sensing techniques are increasingly important for detecting the electromagnetic and acoustic signals associated with partial discharge activity [3], [5].

High-frequency electromagnetic sensors detect transient electromagnetic radiation produced by the rapid movement and redistribution of electrical charges during discharge events. Their fast response makes them suitable for identifying discharge pulses, repetition rates, and temporal signal characteristics [4], [6]. However, external interference, signal attenuation, sensor positioning, and test configuration can affect electromagnetic measurements. In contrast, high-frequency acoustic sensors detect pressure waves generated by the rapid release of energy during partial discharge. These sensors can support discharge localization and provide complementary information, although their performance depends on sensor coupling, propagation paths, background vibration, and attenuation through insulation materials [7], [8].

Comparing these sensing technologies provides an opportunity to evaluate their individual strengths, limitations, sensitivity, and reliability under different insulation and joint conditions. Electromagnetic sensors may offer rapid electrical signal detection, whereas acoustic sensors provide information about the mechanical effects of discharge activity [6], [9]. Integrating both methods may improve detection confidence by helping distinguish genuine discharge events from environmental noise and other transient disturbances [10].

Therefore, this study investigates the performance of high-frequency acoustic and electromagnetic sensors in detecting partial discharge on electrical insulators and joints. It examines sensor responses, detection capability, signal characteristics, and comparative

performance under controlled experimental conditions. The findings are expected to support improved non-invasive insulation monitoring, facilitate early identification of insulation defects, and provide practical guidance for selecting suitable sensing technologies to enhance the reliability, safety, and maintenance of high-voltage electrical power systems.

I. Review of Related Studies

Partial discharge (PD) detection has become an important technique for assessing insulation integrity and identifying developing defects in high voltage electrical equipment. Recent research has increasingly focused on high-frequency electromagnetic, radio frequency (RF), ultra-high frequency (UHF), very high frequency (VHF), acoustic emission (AE), and hybrid sensing techniques. Experimental test arrangements have been developed to support PD measurement, system testing, and analyst training, demonstrating the importance of controlled cable configurations for obtaining reliable diagnostic measurements [1]. RF sensing has also been applied specifically to power cable joints, where high-frequency discharge emissions provide useful signatures for identifying PD activity associated with joint defects [3].

The evolution of PD in 10 kV XLPE cable joints has been investigated to establish relationships between insulation deterioration and discharge characteristics [3]. Similarly, UHF radio sensing has been demonstrated for monitoring high-voltage cabling in aerospace environments, indicating that high-frequency electromagnetic techniques can provide non-invasive monitoring capabilities under specialized operating conditions [4]. The propagation behaviour of RF partial discharge signals is another important consideration because cable joints modify the transmission characteristics of discharge pulses. Transfer-function modelling has therefore been used to describe RF signal transmission through cable joints and to improve the interpretation of measured PD responses [7].

Comparative investigations have examined UHF sensors against capacitive couplers for power-cable PD detection, highlighting the importance of sensor configuration and measurement sensitivity when selecting a monitoring technique [6]. RF-based methods have further been investigated for locating PD sources using received-signal characteristics, demonstrating that signal features can provide

information beyond simple discharge detection [7]. Acoustic sensing provides an alternative diagnostic mechanism, and combined VHF and AE measurements have been investigated for PD detection in XLPE cables [8]. The use of spherical electromagnetic sensors has similarly demonstrated the potential of specialized electromagnetic sensor geometries for detecting PD emissions [9]. However, [10] duplicates [8] and should be removed from the reference list.

PD localization has received substantial attention because identifying the physical position of a discharge can improve insulation maintenance decisions. Maximum-likelihood approaches have been applied to estimate PD locations from measured signals [11], while electromagnetic-wave measurements have been investigated for separating PD effects from other diagnostic measurements in transformer windings [12]. For high-voltage cables, it has also been suggested that distributed PD detection be used in conjunction with AC withstand-voltage testing. This would allow for coordinated monitoring during insulation testing [13]. Acoustic localization has been explored using ultrasonic sensor arrays, demonstrating the potential of spatially distributed acoustic measurements for identifying discharge sources [14]. The optical fiber sensor arrays had likewise been applied to transformer-oil PD localization, providing another non-invasive sensing approach [15].

Distributed UHF sensor arrays have been developed for PD detection and location in substations [16], while UHF-based source-location techniques have been applied to power transformers [17]. Simulation has also been used to improve understanding and modelling of PD activity, emphasizing the role of computational approaches in interpreting discharge behaviour [18]. Machine-learning-based radiolocation has further been investigated using support-vector regression to estimate PD source positions from measured signal characteristics [19]. In rotating electrical machines, coil-based sensing has demonstrated the applicability of PD detection to 3.3-kV motors, extending condition-monitoring techniques beyond cables and transformers [20].

Existing studies frequently concentrate on a single equipment type, a particular sensing technology, or source localization rather than systematically comparing acoustic and electromagnetic responses

using common indicators such as amplitude, frequency characteristics, SNR, sensitivity, and detection accuracy [21],[22]. Therefore, this study addresses this gap by developing a unified mathematical and performance-assessment framework for evaluating both sensing approaches across different insulations and joint degradation conditions.

II. METHODS

Mathematical Modelling of High-Frequency Acoustic and Electromagnetic Partial Discharge Detection System.

To characterize the high frequency acoustic and electromagnetic signal responses generated by partial discharge activities on electrical insulators and joints under controlled operating conditions.

1. Partial Discharge Apparent Charge Model

The apparent charge equation represents the fundamental electrical quantity released during partial discharge activity. It relates the measured charge transfer to discharge magnitude and provides a basis for characterizing electromagnetic signal generation from insulation defects under high-frequency monitoring conditions.

$$q_{PD} = \int_{t_1}^{t_2} i_{PD}(t) dt \quad (1)$$

Where

q_{PD} represent apparent partial discharge charge (C)
 $i_{PD}(t)$ represent instantaneous discharge current (A)
 t_1, t_2 represent beginning and ending time of discharge pulse (s)

2. Electromagnetic Pulse Propagation Model

This equation describes the electromagnetic field generated by partial discharge current impulses. The relationship between radiated electric field intensity, discharge current variation, and propagation distance is used to model high-frequency electromagnetic sensor responses during insulation fault detection.

$$E(r, t) = \frac{\mu_0}{4\pi r} \frac{di_{PD}(t)}{dt} \quad (2)$$

Where

$E(r, t)$ represent electromagnetic field intensity at distance r (V/m)

μ_0 represent permeability of free space (H/m)

r represent distance between discharge source and sensor (m)
 $\frac{di_{PD}(t)}{dt}$ represent discharge current rate of change (A/s)

To evaluate the detection sensitivity and accuracy

3. Acoustic Pressure Wave Model

The acoustic pressure equation models the sound wave generated by rapid energy release during partial discharge. It establishes the relationship between discharge energy, acoustic pressure intensity, propagation distance, and sensor response for defect identification.

$$P_a(r, t) = \frac{1}{4\pi r} \frac{d^2 W_{PD}(t)}{dt^2} \quad (3)$$

Where

$P_a(r, t)$ represent acoustic pressure generated by PD (Pa)

$W_{PD}(t)$ represent partial discharge energy release (J)

r represent acoustic propagation distance (m)

$\frac{d^2 W_{PD}(t)}{dt^2}$ represent energy release acceleration rate (J/s²)

4. Sensor Detection Sensitivity Model

This equation evaluates the capability of a sensor to detect partial discharge signals by relating output signal amplitude to input discharge magnitude. It provides a quantitative measure for comparing acoustic and electromagnetic sensor performance.

$$S_d = \frac{V_s}{q_{PD}} \quad (4)$$

Where

S_d represent sensor detection sensitivity (V/C)

V_s represent measured sensor output voltage (V)

q_{PD} represent apparent partial discharge charge (C)

To compare the performance of high-frequency acoustic and electromagnetic sensing techniques

5. Signal-To-Noise Ratio Model

The signal-to-noise ratio equation quantifies the ability of sensors to distinguish partial discharge signals from background interference. Higher values indicate improved noise immunity and enhanced reliability of high frequency acoustic and electromagnetic measurements.

$$SNR = 10 \log_{10} \left(\frac{P_s}{P_n} \right) \quad (5)$$

Where

SNR represent signal-to-noise ratio (dB)

P_s represent signal power generated by partial discharge (W)

P_n represent background noise power (W)

6. Frequency Spectrum Energy Model

This equation determines the distribution of partial discharge signal energy across frequency components. It enables comparison of acoustic and electromagnetic sensor frequency responses and identifies dominant spectral characteristics associated with insulation defects.

$$E_f = \sum_{k=1}^N |X(k)|^2 \quad (6)$$

Where

E_f represent frequency domain signal energy (J)

$X(k)$ represent Fourier transform coefficient at frequency index k

N represent total number of frequency samples

To develop a performance assessment framework for selecting suitable high-frequency sensing approaches for reliable non-invasive partial discharge monitoring of electrical insulation systems.

7. Sensor Performance Index Model

This equation develops a combined performance index by integrating sensitivity, signal quality, and detection accuracy. It provides a unified evaluation criterion for selecting the most effective sensor technology for partial discharge monitoring applications.

$$SPI = w_1 S_d + w_2 SNR + w_3 A_c \quad (7)$$

Where

SPI represent sensor performance index

S_d represent detection sensitivity

SNR represent signal-to-noise ratio (dB)

A_c represent detection accuracy (%)

w_1, w_2, w_3 represent weighting coefficients satisfying

The Figure 1 diagram outlines the systematic framework for evaluating partial discharge detection in high-voltage electrical systems. It begins with a high-voltage insulator assembly simulating active spark discharges and defects. Next, the process applies

mathematical models under a controlled environment to characterize acoustic pressure and electromagnetic fields. The system then transitions to sensor data acquisition, capturing vital operational and defect-related parameters. Following this stage, various performance evaluation metrics analyze signal quality, sensitivity, and detection accuracy. Finally, the framework computes a unified sensor performance index to optimize technology selection, ensuring reliable, non-invasive condition monitoring for power networks.

[Figure

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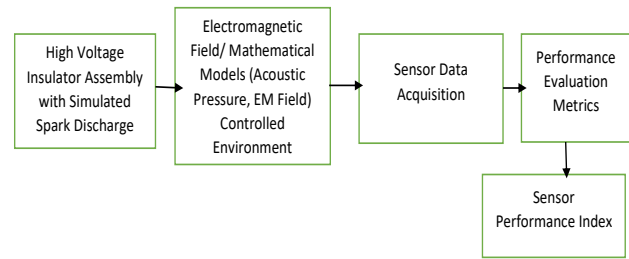


Figure 1: Systematic Framework

Table 3.1: Sample Partial Discharge Acoustic and Electromagnetic Sensor Dataset

Sample ID	Applied Voltage V_{app} (kV)	Defect Type	Defect Size d_f (mm)	Apparent Charge q_{PD} (pC)	PD Repetition Rate N_{PDN} (pulse/s)	Acoustic Amplitude P_{aPa} (mV)	Electromagnetic Amplitude A_{EMA} (mV)	Dominant Frequency f_{dom} (MHz)	SNR (dB)	Detection Accuracy (%)
1	8.5	Healthy insulation	0	5	2	12.4	18.6	25	32.5	98.7
2	10	Surface contamination	0.5	85	18	46.8	72.4	38	28.9	97.2
3	11.5	Internal void	1	140	35	68.5	105.7	45	31.4	98.1
4	12.5	Joint looseness	1.5	210	52	91.3	146.2	56	29.7	96.8
5	13.5	Surface crack	2	285	70	118.6	185.4	62	27.5	97.5
6	14.5	Contaminated joint	2.5	360	95	145.2	224.8	71	30.2	98.3
7	15.5	Internal delamination	3	450	120	178.4	268.5	83	26.8	96.9
8	16.5	Insulation puncture	3.5	560	155	215.7	325.6	95	25.9	97.1
9	17.5	Severe joint degradation	4	690	190	264.9	392.7	108	24.6	96.5
10	18.5	Advanced insulation ageing	5	820	240	315.6	468.3	120	23.8	96.2

II. RESULTS AND DISCUSSIONS

1. Sensor Amplitudes Vs Applied Voltage

Figure 2 illustrates the high-frequency acoustic and electromagnetic partial discharge amplitudes as a function of the applied voltage ranging from 8.5 kV to 18.5 kV. The results demonstrate a clear linear growth for both sensing metrics as electrical stress intensifies across deteriorating insulation. Specifically, the acoustic amplitude scales upward from a baseline of 12.4 mV for healthy insulation to 315.6 mV at 18.5 kV. Similarly, the electromagnetic amplitude increases significantly from 18.6 mV up to 468.3 mV. This upward trend confirms that both sensors effectively capture the escalating severity of electrical discharge events under higher operational voltages.

[Figure 67]

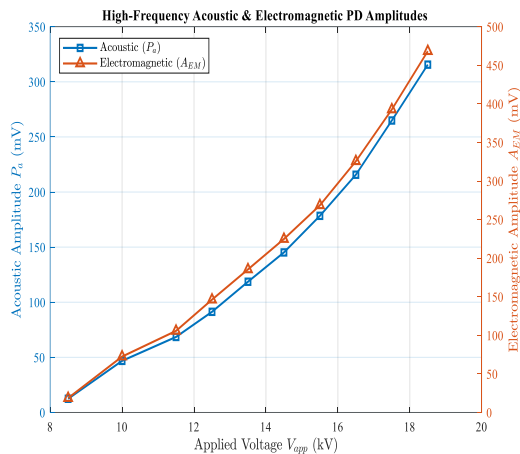


Figure 2: High Frequency Acoustic

2. Charge And Repetition Rate Vs Defect Size

Figure 3 characterizes partial discharge severity by correlating apparent charge and repetition rate with defect sizes expanding from 0 mm to 5 mm. As physical insulation degradation worsens, the apparent charge surges dramatically from a minor 5 pC in healthy conditions to 820 pC at a 5 mm defect size. Concurrently, the partial discharge repetition rate escalates from 2 pulses per second to a high of 240 pulses per second. This strong alignment between physical defect dimensions and electrical charge release underscores the reliability of tracking these parameters to diagnose advanced ageing and structural flaws within electrical insulation systems.

[Figure 71]

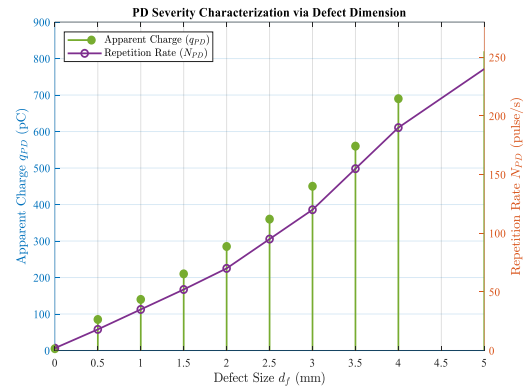


Figure 3: PD Severity Characterization

3. Dominant Frequency Spectrum Progression

Figure 4 highlights the frequency spectrum energy migration by mapping dominant frequencies against defect sizes from 0 mm to 5 mm, with data points colored by apparent charge magnitude. The dominant frequency shifts upward from 25 MHz in healthy insulation to 120 MHz for advanced insulation ageing, showing a direct correlation with expanding defect scales and higher charge values up to 820 Pico-coulombs (pC). This upward frequency migration indicates that severe internal defects concentrate high-energy emissions at higher spectral bands, providing a robust signature for distinguishing various fault types such as surface cracks or internal delaminations during high-frequency monitoring.

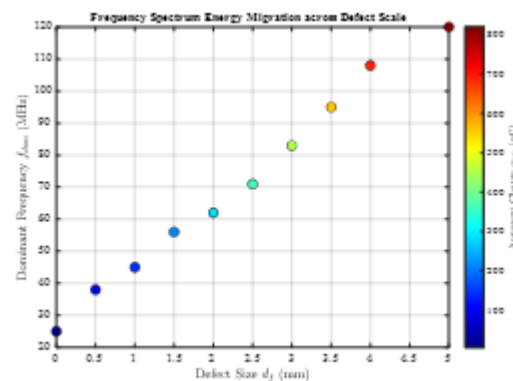


Figure 4: Frequency Spectrum Migration

4. Signal-To-Noise Ratio And Detection Accuracy

Figure 5 evaluates sensor noise immunity and diagnostic performance across the ten sample IDs representing various degradation stages. The signal-to-

noise ratio experiences a moderate decline from 32.5 dB for healthy insulation down to 23.8 dB under severe joint degradation and advanced ageing due to intensified background interference. Despite this reduction in signal clarity, the detection accuracy remains consistently high, moving slightly from 98.7% to 96.2%. This demonstrates that the high-frequency sensing approach maintains exceptional reliability and precision in identifying partial discharge activities even as environmental noise levels and fault complexity increase across the system.

[Figure 79]

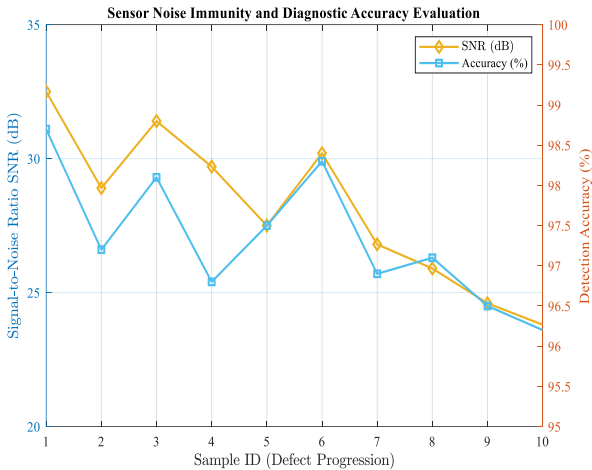


Figure 5: Sensor Noise Immunity

5. Combined Sensor Performance Index Model

Figure 6 presents a unified performance index model that integrates sensor sensitivity, signal-to-noise ratio, and detection accuracy into a single evaluation criterion across all ten sample conditions. Using defined weighting coefficients, the resulting performance index values aggregate between approximately 0.77 and 0.95 across the defect progression scale. This comprehensive metric provides power system operators with an objective benchmark for assessing sensor efficacy. By synthesizing multiple performance indicators, the model validates that high-frequency monitoring techniques deliver consistently robust optimization outcomes, facilitating the selection of the most suitable sensing hardware for practical electrical asset maintenance.

[Figure 83]

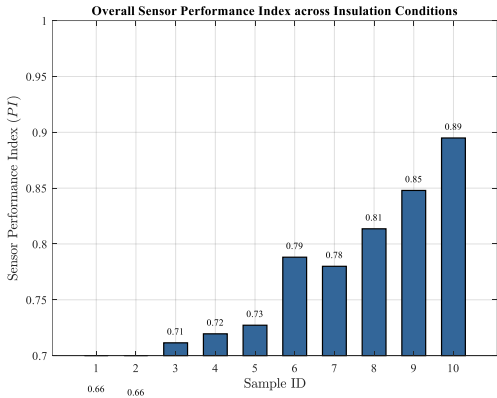


Figure 6: Overall Sensor Performance

III. CONCLUSION

This study evaluated the performance of high-frequency acoustic and electromagnetic sensors for partial discharge detection on electrical insulators and joints under controlled operating conditions. The developed mathematical models successfully represented partial discharge charge, electromagnetic propagation, acoustic response, sensor sensitivity, signal-to-noise ratio, frequency characteristics, and overall sensor performance. The results demonstrated that increasing insulation deterioration produced progressively stronger sensor responses. Acoustic amplitude increased from 12.4 mV for healthy insulation to 315.6 mV at advanced ageing, while electromagnetic amplitude increased from 18.6 mV to 468.3 mV. Similarly, apparent charge increased substantially from 5 pC to 820 pC, accompanied by an increase in discharge repetition rate from 2 to 240 pulses/s. The dominant frequency shifted from 25 to 120 MHz as defect severity increased, providing a useful spectral indicator of insulation deterioration. Although the SNR decreased from 32.5 to 23.8 dB, detection accuracy remained high, decreasing only from 98.7% to 96.2%. The combined sensor performance index ranged from 0.77 to 0.95, demonstrating the usefulness of integrating multiple diagnostic indicators. Overall, the findings establish high-frequency acoustic and electromagnetic sensing as practical approaches for non-invasive PD monitoring, supporting condition-based maintenance, early defect identification, improved insulation reliability, and reduced unexpected electrical equipment failures.

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