

Partial Discharge Monitoring in Power Transformers Using Ultra High Frequency Techniques

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ABSTRACT

Partial discharge is a localized electrical phenomenon that can indicate developing insulation defects in power transformers. Reliable monitoring is valuable because insulation deterioration may progress while the transformer remains in service. This review examines ultra high frequency detection of partial discharge, with emphasis on sensor installation, electromagnetic propagation, signal acquisition, calibration, and integration with complementary diagnostic methods. A structured narrative synthesis of the literature addresses the physical basis of detection and the practical factors governing monitoring performance. The reviewed work supports UHF sensing as a useful approach for online monitoring, particularly when the transformer tank attenuates external electromagnetic interference. However, sensitivity depends on the discharge location, propagation path, antenna response, installation geometry, and acquisition chain. UHF amplitude is not automatically equivalent to apparent charge, and immunity to interference is not absolute. Drain-valve and dielectric-window sensors offer different installation opportunities, while synchronized high-frequency electrical and acoustic measurements can strengthen interpretation. The discussion develops a practical framework for commissioning, event validation, trend analysis, and maintenance escalation without treating proposed procedures as experimentally demonstrated results. UHF monitoring is most defensible as part of a calibrated, asset-specific diagnostic system that combines reliable signal capture with contextual evidence and engineering judgment.

Keywords: partial discharge; power transformer; ultra high frequency; online monitoring; insulation diagnostics

1. INTRODUCTION

Power transformers provide voltage conversion within electric power systems, and deterioration of their insulation can threaten continuity of supply. Insulating oil, solid insulation, bushings, and winding structures experience electrical, thermal, mechanical, and environmental stresses over their service life. Partial discharge (PD) is one observable consequence of localized electrical stress. Detecting PD does not by itself establish the remaining lifetime of a transformer, but it can provide evidence that warrants investigation before a defect develops into more extensive damage [1], [2].

Unlike complete breakdown, a partial discharge does not bridge the entire insulation between conductors. Its short current pulse can produce electromagnetic radiation, acoustic emissions, and chemical changes. Different monitoring methods observe different consequences of this event, so their readings need not be numerically interchangeable. The ultra high frequency (UHF) method detects the electromagnetic component rather than directly measuring apparent charge at the equipment terminals [1], [3].

Early transformer-specific work established that UHF monitoring requires attention to both the sensor interface and the interpretation of signals propagating inside the tank. Judd, Yang, and Hunter described external sensors coupled through dielectric windows and examined how electromagnetic propagation could support source localization [6]. This history is important because a UHF detector is not simply an antenna placed near equipment: the measurement depends on how radiation leaves the discharge region, travels through the transformer, and reaches an accessible sensing interface. A suitable installation must therefore be evaluated as part of the transformer structure rather than as an isolated electronic component.

Sensor development introduces a further design problem. The review by Chai, Phung, and Mitchell compares UHF sensing approaches for power-system equipment, including their antenna

configurations, bandwidths, and physical dimensions [7]. These characteristics provide a useful basis for comparing candidate sensors, but they do not constitute a single performance ranking for all transformers. In this review, their relevance is interpreted in terms of installation constraints: an electrically promising antenna must also fit the available interface and operate within the measurement chain. Consequently, sensor selection should begin with the intended equipment and diagnostic objective, followed by an assessment of the frequency response that the installation can actually deliver.

The frequency range used for monitoring also deserves explicit consideration. Tenbohlen et al. examined laboratory literature and practical transformer measurements and found substantial variation in the spectra recorded across cases [8]. Approximately 400–900 MHz was a common region of signal power in their practical examples; this observation is not a universal passband requirement or a guarantee that every defect will be detectable in that interval. Their findings motivate an asset-specific approach to bandwidth selection. For the present review, the central implication is that a nominal UHF specification should not replace an examination of sensor response, receiver settings, and the propagation conditions of the transformer being monitored.

These studies frame a practical gap between demonstrating that a pulse can be detected and establishing what that pulse means for insulation condition. The present synthesis addresses this gap by connecting physical detection, instrument response, and diagnostic interpretation. It asks whether a recorded change is consistent with discharge activity, whether the measurement configuration could explain that change, and what further evidence would be required before acting on it. These are analytical questions proposed for this review, not a validated decision algorithm. Keeping them separate helps avoid treating sensitivity, source identification, and maintenance urgency as equivalent outcomes.

This review considers how that distinction affects sensor selection, interpretation, and maintenance decisions. It retains the emphasis on transformer UHF monitoring while expanding the discussion of measurement uncertainty and field deployment. The aim is to explain when UHF evidence is useful, what limits its reliability, and how it can be combined with other diagnostics. No new transformer experiment, detection-accuracy benchmark, or field failure prediction is claimed.

2. REVIEW APPROACH AND EVIDENCE SCOPE

2.1 Research Questions and Selection Logic

The review uses a structured narrative approach organized around two central questions: what constitutes partial discharge, and how UHF detection works in a transformer. These questions are extended analytically to include sensor placement, acquisition constraints, and the interpretation of online measurements. The purpose is comparative technical synthesis rather than a statistical meta-analysis or an exhaustive census of the literature.

The literature search used Google Scholar and combinations of terms such as partial discharge monitoring, PD detection, ultra high frequency, and UHF method. English- and Indonesian-language studies on transformer PD were considered relevant. The synthesis prioritizes studies addressing UHF sensing, propagation, calibration, online architecture, or complementary interpretation. General PD discussions are used for context, not as evidence that a particular UHF system achieves a stated performance level.

Table 1. Review questions and evidence required

Question	Review focus	Evidence sought
RQ1	Physical meaning of PD	Localized discharge mechanisms and observable signals
RQ2	UHF measurement principle	Antenna response, propagation, coupling and acquisition

Question	Review focus	Evidence sought
RQ3	Reliable online interpretation	Calibration, interference checks and complementary measurements

2.2 Evidence Extraction and Interpretation

Each study is considered in terms of its equipment context, measured quantity, sensor interface, acquisition method, and diagnostic objective. Sensor-development work is distinguished from field measurements and calibration proposals. A laboratory antenna demonstration, for example, supports feasibility under its test conditions; it does not establish equivalent sensitivity at every location inside a full-scale transformer. Likewise, a field case demonstrates practical relevance without proving that the same alarm threshold applies to other assets [1]-[5].

The core technical evidence includes: intelligent sensor development [1], an operating-transformer case study [2], a calibration proposal [3], transfer-function evaluation [4], and a multimodal online system [5]. Their differing objectives are retained in the synthesis. No journal-quartile ranking or pooled performance score is used to imply that the studies are directly comparable. Instead, each contribution is related to the measurement problem it addresses, including the distinction between detecting a signal, characterizing a channel, and interpreting equipment condition. Three supporting publications extend the introduction with historical transformer sensing, comparative sensor design, and practical frequency-range evidence [6]-[8]. This expanded selection remains a narrative synthesis rather than an exhaustive systematic review.

2.3 Boundaries of the Synthesis

The analysis is qualitative because a harmonized dataset of sensitivity, false-alarm rate, and localization error is not available across the reviewed work. The commissioning and validation procedures developed later are proposals derived from the measurement issues, not procedures tested by this review. Distinguishing reported findings from proposed practice is necessary when the discussion is used to guide further research or equipment evaluation.

3. PHYSICAL BASIS OF UHF DETECTION

3.1 From a Local Discharge to a Measured Signal

A PD event begins in a localized region where the electrical stress is sufficient to initiate discharge. Its rapid current change excites electromagnetic fields that can propagate through the transformer interior. The UHF designation commonly refers to 300 MHz to 3 GHz, but a practical monitoring system captures only the portion supported by its antenna, coupler, cable, filter, and receiver. A detector specified up to a particular upper frequency therefore does not measure all radiation produced by every defect [1].

The signal reaching a sensor has already been modified by the transformer. Windings, the core, tank surfaces, oil, and insulating structures introduce attenuation, reflections, resonances, and obstructed paths. A measured waveform is consequently a combination of the discharge excitation and the transfer characteristics of the installation. Promwong and Tiengthong examine this transfer-function perspective, which helps explain why apparently similar events can produce different signals at different sensor locations [4].

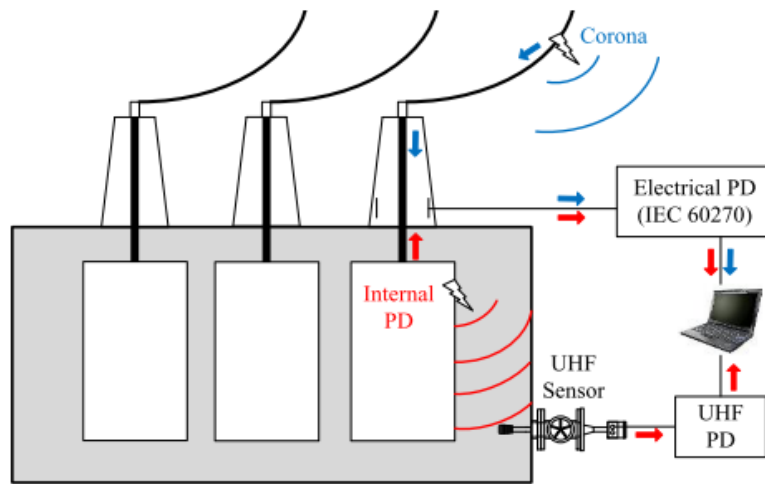


Figure 1. Internal and external discharge signal paths in transformer measurements, signal-path illustration attributed to Siegel et al. [3].

3.2 Shielding Is Helpful but Not Absolute

Figure 1 distinguishes an internal discharge from external corona and shows the separate electrical and UHF measurement paths. A conducting tank can attenuate external electromagnetic interference, making internal UHF sensing attractive in noisy locations. However, openings, sensor interfaces, wiring, grounding conditions, and nearby radio transmitters can still affect the measurement. Shielding should therefore be verified in the installed arrangement rather than assumed from the presence of a metal enclosure.

The practical implication is that a large pulse is not automatically an internal insulation defect, and a weak pulse does not establish harmlessness. A distant or screened defect may couple weakly to one sensor. Interpretation should consider the noise floor, channel sensitivity, repeated occurrence, phase relationship where available, and agreement with independent measurements. Absence of detected UHF activity only describes the observation interval and sensitivity achieved; it is not proof that the entire insulation system is defect-free.

4. SENSOR DESIGN AND INSTALLATION

4.1 Antenna Response and Mechanical Interfaces

The antenna converts an incident electromagnetic field into a receiver signal. Its bandwidth, frequency-dependent sensitivity, matching, orientation, and mounting arrangement all affect what is recorded. A compact antenna may be convenient to install, but physical size alone does not establish its suitability. Figure 2 illustrates an example antenna; the marked dimensions describe that example and are not a universal transformer-sensor specification [1].

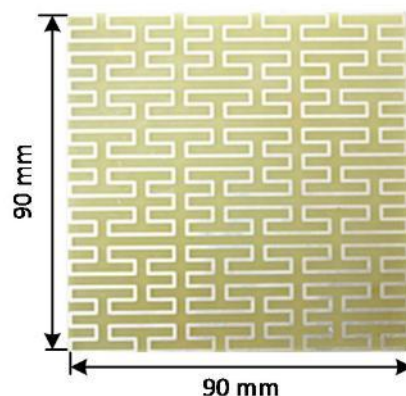


Figure 2. Illustrated UHF antenna with 90 mm by 90 mm dimensions, antenna example discussed in connection with Li et al. [1].

Drain-valve sensors access the transformer interior through a compatible valve interface. Their performance depends on valve geometry, insertion position, oil compatibility, and the relationship between the antenna and nearby metalwork. A dielectric-window sensor couples through an electrically insulating aperture in the tank and may remain outside the oil. Its response depends on window properties and the surrounding flange and housing. These are alternative interfaces, not interchangeable installations with identical sensitivity [3].

4.2 Placement and Coverage

Sensor placement should be evaluated against the internal structure and probable propagation paths. Two sensors on opposite sides may provide complementary observations, but sensor count alone does not guarantee complete coverage or three-dimensional localization. Obstructed paths and reflections can make a nearby source appear weaker than a more distant one. Where localization is an objective, placement must also support time synchronization and sufficiently distinct arrival information.

Installation must preserve the transformer's sealing, mechanical integrity, insulation clearances, and approved operating conditions. The dielectric-window concept should not be interpreted as an instruction to drill an operating tank or weld the polymer itself. Any new aperture or valve modification requires manufacturer-approved engineering and appropriate outage procedures. Before deployment, the selected sensor, interface, cable, and receiver should be documented as one measurement channel so that later changes do not invalidate the baseline.

4.3 Comparing Installation Options

A useful selection process considers accessibility, existing approved ports, expected coverage, environmental protection, calibration repeatability, and serviceability. Retrofitting may favor an available compatible valve, whereas a new transformer may accommodate planned windows. The preferred option is the one whose installed performance and integrity can be demonstrated for the asset, rather than the option with the broadest nominal antenna bandwidth alone.

5. ONLINE ACQUISITION AND SIGNAL PROCESSING

5.1 Measurement Chain and System Architecture

An online UHF channel typically contains a sensor, analog conditioning, acquisition electronics, event processing, and communication to a monitoring server. Li et al. discuss an intelligent sensor approach, while Sikorski et al. describe a system combining high-frequency electrical, UHF, and acoustic observations [1], [5]. Figure 3 shows an example of the latter architecture. Its product labels identify an example system rather than mandatory equipment for all installations.

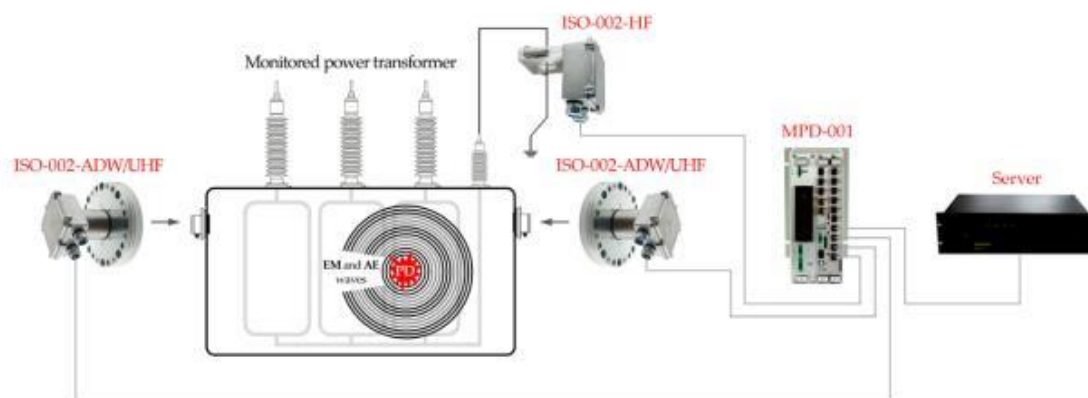


Figure 3. Example online architecture combining HF, UHF and acoustic-emission measurements with a data concentrator and server; architecture attributed to Sikorski et al. [5].

The measurement chain must preserve information relevant to its diagnostic purpose. Gain should reveal weak pulses without saturating on larger events. Filtering should reject unwanted bands while retaining useful discharge content. Time stamps allow comparison between channels, and an

appropriate phase reference supports phase-resolved analysis in AC operation. Fiber-optic communication can reduce conductive coupling along a data link, but it cannot correct interference already captured at the sensor or poor timing within the acquisition system.

5.2 Acquisition Tradeoffs

Direct waveform recording offers detailed pulse information but places substantial demands on bandwidth, sampling, storage, and processing. The sampling requirement depends on the analog frequency range and the acquisition architecture; not every UHF monitor must digitize the complete radio-frequency band directly. Envelope detection or frequency conversion can reduce the data rate, but may discard information needed for fine arrival-time analysis. The acquisition method should therefore follow the intended task: event trending, classification, or localization [1].

Continuous monitoring also requires a strategy for event bursts. Recording only pulses above a fixed threshold can miss weaker activity when noise rises, while a very low threshold can overwhelm storage with interference. Event counters, summary features, and selected waveform retention provide a practical compromise. The system should record dropped events, clipping, channel outages, and threshold changes so that a decrease in recorded activity is not mistaken for improved insulation condition.

5.3 Preserving Diagnostic Context

Relevant context includes operating voltage, load, sensor identity, gain, filter settings, time reference, and maintenance history. Keeping these attributes with the signal makes comparisons more defensible. Raw waveform examples should remain available for reviewing disputed alarms, even if routine displays show only trends. A monitoring dashboard should distinguish equipment condition indicators from measurement-system health, because both can change independently.

6. INTERPRETATION AND COMPLEMENTARY METHODS

6.1 Phase Resolved Patterns and Event Validation

Phase-resolved partial-discharge analysis organizes events relative to an AC cycle, commonly using pulse magnitude and occurrence count. Such patterns can help distinguish recurring activity from unrelated events, but their meaning depends on the phase reference and measurement channel. In UHF monitoring, the magnitude axis represents a receiver-derived quantity unless a justified conversion is available. It should not be relabeled as apparent charge merely because the plot resembles an electrical PD display.

Pattern interpretation should use repeated observations and operating context. Switching interference may produce structured signals, and simultaneous defects can create overlapping patterns. A classifier should therefore be treated as a decision aid rather than a conclusive defect diagnosis. Representative waveform review, cross-channel agreement, and inspection evidence improve confidence. The reviewed literature supports combining information, but it does not provide a universal classification accuracy applicable to every transformer [2], [5].

Table 2. Complementary diagnostic roles

Method	Useful evidence	Main interpretation limit
UHF sensing	Fast electromagnetic events and internal activity trends	Coupling, propagation and interference influence amplitude
Electrical PD	Calibrated terminal response where applicable	External interference and coupling require careful control
Acoustic emission	Mechanical-wave evidence and location support	Attenuation, structural paths and mechanical noise
Oil gas analysis	Chemical evidence of developing faults	Different time response and limited direct localization

6.2 Comparison Without Assuming Universal Superiority

The methods in Table 2 observe different physical consequences and are therefore complementary. UHF can perform well where conventional electrical measurements face strong interference, but electrical methods are not inherently unusable online. Their suitability depends on coupling, noise management, and the measurement objective. Similarly, acoustic measurements may help investigate location while being less responsive to some weak or screened sources. A defensible comparison specifies the test conditions and the information each method supplies.

Multi-sensor coincidence is useful when the channels have different noise mechanisms. An electromagnetic event accompanied by a plausible acoustic response is more informative than either signal alone, provided propagation delays are considered. Absence of a corresponding acoustic pulse does not automatically reject a UHF event because the acoustic path may be strongly attenuated. Agreement increases confidence; disagreement should trigger investigation rather than an automatic majority vote [5].

6.3 Trends and Maintenance Decisions

Trend analysis should compare like-for-like operating conditions and stable instrument settings. Rising event rate or amplitude may justify further review, but neither directly predicts time to failure. Decisions should account for persistence, supporting evidence, transformer criticality, and inspection history. UHF findings can help prioritize diagnostic work while avoiding unsupported claims that a single pulse magnitude requires immediate replacement of the transformer.

7. CALIBRATION VALIDATION AND RESEARCH GAPS

7.1 Calibration and Sensitivity Verification

Calibration addresses the response of the measurement chain; sensitivity verification asks whether relevant signals can be detected in the installed arrangement. These are related but different questions. Siegel et al. propose accounting for sensor sensitivity and recorder characteristics to improve comparability [3]. Such work supports disciplined channel characterization. It does not establish a universal conversion from UHF voltage to apparent charge for arbitrary sources inside arbitrary transformers.

The distinction matters because the unknown propagation path remains part of the measurement. A reproducible injected signal can test connectivity and channel response without reproducing every possible internal defect. Commissioning records should therefore identify the injection arrangement, frequency content, instrument configuration, observed response, and limitations of the test. Repeating the same procedure after sensor replacement or receiver changes can reveal measurement drift that would otherwise be confused with a change in PD activity.

7.2 Proposed Validation Programme

A practical validation programme should separate controlled source tests from field demonstrations. Controlled experiments can vary the source position, sensor interface, interference level, and acquisition settings while holding other conditions constant. Field testing then examines whether the resulting interpretation survives realistic transformer geometry, operational variability, and environmental noise. These stages are proposed extensions of the review; no experimental outcomes are assigned to them.

Performance should be reported using clearly defined measures. Detection probability requires a known event reference; false-alarm rate requires a stated observation interval and interference scenario. Signal-to-noise ratio should identify the amplitude or power definition and bandwidth used. Localization error requires independent knowledge of the source position. For classifiers, the validation split should separate independent equipment or test sessions where feasible, because highly similar pulses from one recording can otherwise inflate apparent generalization.

For continuous monitoring, operational metrics are also important. Channel availability, event loss during bursts, alarm latency, synchronization stability, and the proportion of alarms reviewed by

specialists describe whether the system remains usable outside the laboratory. A system can produce a clean example waveform yet be unsuitable for long-term monitoring if it loses timing, saturates frequently, or does not distinguish sensor failure from quiet equipment. These outcomes should be evaluated alongside signal-level performance.

7.3 Limitations and Future Work

The present synthesis is limited by heterogeneous equipment, a small purposively selected evidence base, and limited cross-study comparability. There is no common dataset from which to calculate a pooled UHF advantage or a universal alarm threshold. Future reviews should publish complete queries, screening records, and study-quality criteria, while future experiments should report the installed transfer path and acquisition settings in enough detail to support comparison.

Priority research directions include repeatable installed-sensitivity checks, sensor-placement studies that consider internal obstructions, multimodal timing validation, and classifiers tested across independent transformers. Practical value will depend on reducing uncertainty as well as improving sensitivity. Linking UHF evidence to inspected defects and documented maintenance outcomes would provide stronger support for operational decisions than additional isolated demonstrations of detectable laboratory pulses.

8. CONCLUSION AND RECOMMENDATIONS

UHF sensing is a useful method for observing electromagnetic emissions associated with partial discharge in power transformers. The reviewed work connects compact sensors, transformer propagation, calibration, and online multimodal monitoring. Its principal attraction is the opportunity to detect internal activity with reduced exposure to some external interference, particularly when coupling through a well-designed tank interface. That advantage is conditional rather than absolute.

Reliable interpretation requires the entire measurement chain to be considered. Antenna response, mounting geometry, internal obstructions, receiver settings, and synchronization can all change the recorded signal. UHF magnitude should not be assumed to equal apparent charge, and non-detection should not be interpreted as proof of healthy insulation. Sensor coverage and sensitivity must be evaluated for the installation, while uncertainty remains explicit in the diagnosis.

For deployment, an asset-specific baseline should be established and retained with configuration records. Repeated events should be assessed alongside phase information, complementary measurements, and operating conditions. Alarm escalation should support specialist review and proportionate maintenance action rather than automatically translating a single threshold crossing into a failure prediction. Future work should emphasize reproducible validation and field-confirmed outcomes so that improvements in signal detection lead to more defensible transformer-condition decisions.

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