

1 Real-Time Partial Discharge Monitoring as an Early-Warning System for Smart GIS 2 Substations in Saudi Arabia: Preventing Failures and Improving Grid Resilience.

3 Abstract

4 Gas-insulated switchgear (GIS) occupies a strategically important position in compact, high-voltage
5 substations, yet concealed insulation defects can develop before conventional protection operates.
6 Partial discharge (PD) monitoring offers a means of recognising such deterioration during service,
7 although detection alone does not establish failure imminence or guarantee outage avoidance. This
8 critical review evaluates advances published between 2020 and 2025 in electromagnetic, acoustic,
9 optical and gas-based PD sensing, alongside localisation, analytical classification and operational
10 decision support. It synthesises the evidence through an engineering chain linking physical defects,
11 trustworthy measurements, interpreted condition, intervention and electricity-service outcomes. The
12 proposed framework differentiates signal detection from defect diagnosis and separates equipment
13 reliability from system resilience. Particular consideration is given to intermittent discharges, sensor
14 ageing, domain shift between laboratories and substations, alarm governance, cybersecurity and
15 Saudi environmental and network conditions. The review argues for calibrated, multimodal
16 monitoring with uncertainty-aware alarms and documented maintenance decisions, rather than
17 unconditional reliance on automated classifications. A staged implementation and evaluation
18 framework is developed for high-value Saudi GIS assets. Evidence remains insufficient to quantify
19 nationwide avoided failures; prospective field validation and measurable service-continuity
20 indicators are therefore priorities.

21 Keywords

22 *Gas-insulated switchgear; partial discharge; condition monitoring; early warning; sensor fusion;*
23 *Saudi Arabia; substation resilience*

24 1. Introduction

25 Electricity networks increasingly depend on compact substations supporting industrial production,
26 urban transport, healthcare, communications and digitally managed buildings. Gas-insulated
27 switchgear accommodates demanding electrical duties within enclosed equipment, making it
28 attractive where land, safety and installation constraints favour small footprints. Such advantages do
29 not eliminate internal insulation vulnerability. Metallic particles, protrusions, floating electrodes,
30 contaminated spacers and imperfect interfaces can create intense local electric fields; progressive

partial discharge may damage insulation without immediately operating protection. Substation operators consequently face an asymmetry: a developing defect may be difficult to observe, whereas a mature internal failure can require extensive isolation and repair. Condition assessment literature consistently identifies the value of monitoring before breakdown, but also distinguishes useful diagnostic evidence from indiscriminate alarm accumulation [2–4].

This paper addresses an operational rather than merely algorithmic question: under which conditions can continuous PD observation improve the resilience of Saudi GIS substations? Detection systems have evolved from stand-alone instruments to connected sensor networks capable of classification, localisation and digital asset histories. Laboratory advances have been substantial, yet their contribution to avoided interruptions remains contingent on reliable signal acquisition, interpretation, maintenance response and switching flexibility. A recognised voltage waveform, for example, cannot itself determine whether a defect requires immediate isolation. Equally, a technically correct warning may provide little system benefit if repair resources or alternative supply paths are unavailable. Resilience research emphasises absorption, adaptation and restoration across interconnected infrastructure; this broader perspective is the starting point for assessing monitoring value [1].

The study aims to develop an evidence-grounded early-warning framework linking GIS dielectric assessment to operational decisions and measurable service continuity. Its objectives are to compare sensing modalities against field deployment constraints; explain how defect localisation and machine learning should handle uncertainty; define an auditable escalation sequence from observation to intervention; and identify realistic validation priorities for Saudi operators. Its contribution lies in joining engineering evidence with decision governance, rather than proposing another untested classifier. The analysis avoids assumptions that PD rate is a universal measure of remaining insulation life or that laboratory accuracy transfers unchanged between substations. Instead, it asks what each observation can justify, what remains unknown, and how the uncertainty should influence action.

2. Review design and analytical boundaries

A structured critical narrative review was selected because the research question connects heterogeneous forms of evidence: sensing experiments, laboratory classification studies, signal-propagation modelling, maintenance literature and system-level resilience concepts. The search window was restricted to publications dated 2020–2025. Targeted scholarly retrieval combined

expressions relating to gas-insulated switchgear, partial discharge, ultra-high frequency, acoustic emission, sensor fusion, insulation defects, localisation, classification, digital twins and resilience. Titles and abstracts were screened for engineering relevance; full records and persistent identifiers were checked where available. Complementary citation tracing identified methodological connections between relevant contributions. This procedure supports thematic interpretation, not a claim of exhaustive bibliometric coverage or statistical meta-analysis.

Included work had to clarify at least one link in the monitoring-to-action chain: discharge physics; measurement sensitivity; interference or propagation; defect discrimination; location estimation; sensor dependability; decision support; or infrastructure functionality. Studies of transformers or air-insulated equipment were used only when their general measurement lessons were explicitly transferable. Conference-style concepts and simulation studies were not treated as proof of substation-wide benefits. Findings were organised into physical sensing, evidence integration, warning governance and resilience evaluation. Conflicting or incomparable performance claims were interpreted in relation to data collection, defect specimens, class distribution and test conditions. There was no primary field survey, no new numerical experiment, and no access to Saudi asset-level outage histories.

A central methodological distinction concerns evidence strength. Laboratory confirmation establishes feasibility under specified conditions; operational validation establishes behaviour amid switching transients, external interference and ageing; decision validation shows whether warnings lead to appropriate maintenance; and system validation demonstrates whether interruptions are reduced or restoration improved. No tier should be substituted for another. This hierarchy also prevents inappropriate pooling of classification percentages reported on non-equivalent datasets. The attached infrastructure-resilience review informs the conceptual separation between anticipation, absorption and recovery, but does not provide GIS-specific failure probabilities or evidence of PD installations in Saudi substations [1]. Accordingly, the proposed architecture is a synthesis and prospective recommendation, not a description of a nationally implemented programme.

3. Partial discharge as an insulation warning

Partial discharge is a localised electrical event that does not fully bridge the insulation between conductors. Within a GIS enclosure, the source may be a free conductive particle, an unintended sharp feature, a floating potential, a surface imperfection or a void associated with solid insulation. Each mechanism differs in field enhancement, discharge inception, pulse repetition and sensitivity to

operating voltage. The significance of a signal therefore depends on defect type, position and progression rather than amplitude alone. Experimental analyses of pulse sequences and electrical modes indicate that even visually similar phase patterns may originate from different mechanisms [5,15,24,25]. Physical diagnosis must preserve the distinction between a repeatable defect signature and a conclusion about its remaining time to failure.

Continuous PD activity may create electromagnetic emissions, acoustic waves, optical radiation and chemical decomposition products. These channels measure different consequences of the same physical event. They also have distinct propagation paths, sampling requirements and noise environments. Pulse current techniques support electrical interpretation under controlled arrangements, while non-invasive UHF and external acoustic methods are often more practical for equipment already energised. Gas analysis integrates chemical changes over time but cannot generally timestamp the originating pulse with the precision of electromagnetic sensors [3,4,10]. Multi-physics evidence can strengthen confidence when channels agree; disagreement can also be diagnostically useful, provided differences in instrument sensitivity and signal transport are examined before declaring a fault absent.

The early-warning proposition should therefore be framed probabilistically. A detected pulse increases evidence of an electrical phenomenon, but its relationship to imminent breakdown remains conditional. Repeated patterns, verified spatial location, amplitude or count trends, operating context and corroboration can strengthen concern. Conversely, a disappearing pulse may reflect intermittent discharge, changed coupling, sensor degradation or altered network noise. Research on metallic contaminants shows why short observation windows can miss occasional events [28]. A robust system must represent both detection uncertainty and diagnostic uncertainty explicitly. A warning threshold should not be presented as a universal physical boundary separating safe from unsafe equipment, particularly when manufacturers, gas mixtures, enclosure geometry and sensor placement differ.

Table 1. Complementary sensing methods and their interpretive boundaries.

Sensing route	Primary evidence	Practical strength	Interpretive limitation
UHF	Fast electromagnetic impulses	Sensitive acquisition; localisation online potential	Geometry, attenuation and calibration dependence
Acoustic	Mechanical transients and particle movement	Non-invasive corroboration; distinct noise mechanisms	Complex sound paths and attenuation
Optical	Radiation produced by discharges	Complementary discrimination in engineered arrangements	Access, shielding and equipment constraints
Gas chemistry	Decomposition and material condition	Slower confirmation of longer-term activity	Sampling lag and background ambiguity

123

124 **4. Complementary real-time sensing technologies**

125 Ultra-high-frequency monitoring exploits the fast electromagnetic transient associated with a
126 discharge. Enclosed GIS structures provide a distinctive propagation environment in which antennas
127 or couplers can capture emissions while filtering some external disturbances. Miniaturised multi-
128 band antenna development and improved external modules illustrate efforts to balance sensitivity,
129 usable bandwidth, installation practicality and cost [7,8]. Nevertheless, reflections, attenuating
130 partitions, discontinuities and coupling variations complicate comparisons between sensor
131 amplitudes. UHF magnitude is not interchangeable with apparent charge measured through a
132 calibrated conventional circuit. Consequently, an equipment-wide sensitivity claim requires a
133 defined source location, reference injection arrangement and acceptance criterion; it cannot be
134 inferred simply because a high-frequency waveform is visible.

135 Acoustic sensing provides a complementary route through transient mechanical waves generated by
136 discharges or moving particles. Contact transducers can sometimes be installed without opening the
137 pressure envelope, an important practical advantage in operational substations. Their useful range
138 depends on enclosure geometry, mounting, propagation speed, intervening supports and acoustic
139 background. The acoustic measurement literature emphasises that differences from electrical
140 methods must be understood rather than treated as a contest yielding one universally superior sensor
141 [10]. Joint acoustic–electrical investigations show how electrical triggering and acoustic arrival

information can constrain the suspected location, but model errors in wave transmission and path choice remain material [9,11]. Sensor fusion should therefore preserve independent channels and disagreement flags instead of averaging incompatible measurements into an unexplained single score.

Optical detection can offer an additional observation channel, potentially resisting electromagnetic interference in carefully engineered arrangements. Experimental combinations of UHF and optical sensors report improved differentiation among tested defect classes [21,22]. However, optical access, shielding, calibration, insertion points and maintenance requirements determine whether laboratory performance is transferable to sealed field apparatus. In a retrofit setting, non-invasive installation should be preferred unless the operational benefits justify planned access. Chemical diagnosis, including gas decomposition analysis, offers slower complementary evidence about insulation activity and medium condition [4]. It is most informative when sampling history, temperature, gas handling and background contamination are documented; a concentration snapshot cannot automatically identify an active discharge source.

No single technology should be declared sufficient for every GIS compartment. A practical sensor plan would begin with failure consequence and access constraints, then identify locations where UHF coupling is reliable and whether acoustic confirmation can reasonably narrow uncertainty. Critical compartments may justify multiple independent sensors, while low-risk assemblies may require periodic portable inspection rather than always-on instrumentation. The architecture must include power availability, clock integrity, environmental protection and safe maintenance access. Crucially, detection capability must be reassessed after sensor replacement, enclosure work or configuration changes. Research on in-situ S-parameter comparison demonstrates that the monitoring chain itself can deteriorate, creating a false impression of stable insulation [13].

5. Localisation and interpretation of discharge evidence

Locating a defect is often more actionable than attaching a class label to a waveform. Traditional arrival-time approaches estimate source position from synchronised signals, but errors arise from multipath propagation, uncertain wave velocity, clock alignment and complex GIS geometry. Electromagnetic time reversal seeks to exploit the enclosure model, including reflections, rather than suppressing them as noise. Studies report promising localisation performance for simulated configurations, yet accuracy remains dependent on geometric fidelity and assumptions about the source [6,12]. Acoustic-electrical optimisation provides another pathway, combining electrical onset

with sound arrival and computational estimation [11]. The most useful outcome for maintenance is frequently a bounded compartment or serviceable assembly, not an unrealistically precise coordinate divorced from physical access.

Pattern recognition can reduce the interpretation burden in long monitoring streams. Pulse-sequence analysis, electromagnetic-mode features and time–frequency image methods have demonstrated that carefully selected descriptors distinguish tested defect mechanisms [5,14,15]. Yet a model optimised on a small set of artificial defects may learn the laboratory fixture, sensor response or noise spectrum rather than a transferable feature of the discharge. Comparative accuracy figures are particularly sensitive to training-test separation, whether overlapping windows share the same physical episode, and the number of genuinely independent defects. A sound review therefore reads performance alongside data provenance, not as a standalone ranking of algorithms. Confidence estimates and abstention should be retained when an event is unlike the validated training distribution.

Advanced learning methods target difficult data conditions. Zero-shot representations attempt recognition when combinations of sources have not appeared in training [16]. Synthetic minority examples and auxiliary classifiers address unbalanced collections, although generated records can also reproduce modelling assumptions [17]. Semi-supervised strategies use unlabelled signals to offset the scarcity of confirmed field defects [18,19]. Field-informed transfer learning directly addresses the distance between controlled experiments and operational apparatus; reported gains are encouraging but remain specific to the assets and datasets examined [20]. These techniques should be compared using common field-held-out protocols, event-level separation, balanced error measures and calibration rather than a single overall percentage. The relevant operational question is whether rare, consequential defects are recognised without causing an unmanageable volume of false maintenance callouts [29].

Interpretation must accommodate simultaneous sources. A single enclosure may contain multiple mechanisms, and neighbouring equipment can inject spurious energy into a monitoring chain. Digital representations have been proposed to link geometry, UHF propagation and test interpretation [27,30]. Their value depends on validated models and current as-built information. The recommended decision record should retain raw waveforms, phase context, sensor identifiers, acquisition settings, candidate source regions and competing explanations. Automatic labelling is then one layer of evidence within a supervised diagnosis process. When signals are ambiguous, resampling, portable verification or independent sensing is more defensible than a confident but unsupported defect claim.

6. A decision-oriented early-warning architecture

Figure 1 presents the proposed architecture as an evidence-preserving sequence. At the asset layer, GIS compartments carry location, voltage class, operating duty, installation history and maintenance criticality. The sensing layer acquires synchronised UHF signals and, where justified, acoustic or optical evidence, supported by self-checks of power, communication and calibration status. A signal-quality layer rejects identifiable transients and reports remaining uncertainty rather than silently deleting contested events. Feature extraction and source interpretation then estimate whether an event resembles discharge, where it may arise and how confidence changes across observation periods. This division permits operators to investigate raw evidence and separates instrument faults from insulation faults.

FROM SIGNAL TO ACTION

Quality-controlled stages for GIS partial-discharge early warning



Cross-cutting controls: traceability • calibration • uncertainty • human authorisation • cyber resilience

Figure 1. Proposed quality-controlled signal-to-action workflow for an operating GIS asset (author synthesis).

At the decision layer, the system should issue graded advisories rather than binary declarations of equipment safety. A low-confidence event may trigger extended observation; a persistent and corroborated defect may require engineering review; evidence of rapidly worsening activity in a high-consequence bay may prompt a planned contingency assessment and controlled intervention. Thresholds should incorporate asset criticality, plausible fault consequences, available switching arrangements and the credibility of the observation. Escalation authority remains with qualified engineers and dispatch personnel. The proposed workflow is not an automatic trip scheme, and it does not supersede existing protective relays. Protection clears faults after defined electrical conditions; condition monitoring supports earlier maintenance decisions and must not create new unsafe dependencies.

Data governance is integral to early warning. An event should receive a timestamp, measurement quality indicator, device-health result, model version, analyst conclusion, action owner and closure outcome. Industrial communication through an appropriately controlled substation environment can facilitate the exchange of health indicators without exposing protection functions to untrusted analytics. Remote access, network segmentation, authenticated changes and resilient local buffering deserve design review. Loss of communications should degrade monitoring availability visibly rather than be misreported as the absence of discharge. These requirements become more important as monitoring information is linked to enterprise asset management and wider infrastructure dependencies [1]. Routine audits should compare alarm records against follow-up inspection findings and actual equipment condition.

Alert thresholds should be established through staged commissioning, using known interference sources and repeatable checks of detection sensitivity. Initial operation may use conservative advisory thresholds that invite human review rather than prescriptive intervention. As verified local evidence accumulates, an operator can assess whether each threshold produces useful detections relative to workload and confirmed defects. Threshold changes must be documented with their expected consequences for missed events and false positives. A low threshold without sufficient review capacity can overwhelm engineers and erode trust; a high threshold may suppress meaningful early indications. Neither setting is inherently safer independently of the downstream response process. Evidence from intermittent discharges means that monitoring duration and event aggregation must be specified alongside amplitude criteria. Dynamic thresholds require additional safeguards against automatically learning a deteriorating equipment condition as the new normal [28].

A failure-mode review of the monitoring system should address common-cause events. The same switching operation might create electromagnetic interference, distort a waveform and disrupt a network gateway. Likewise, loss of synchronisation can corrupt localisation while leaving apparently plausible signal shapes. Operators need independent indications of acquisition health, not simply a green status attached to the analytics dashboard. Critical monitoring channels should buffer events during communication outages and reconcile records when service resumes. Remote analytics must never be placed in the essential protection path without separate safety engineering. Cybersecurity assessments should cover authorised configuration changes, tamper evidence, patch management, third-party access and restoration of known-good settings. These controls protect the

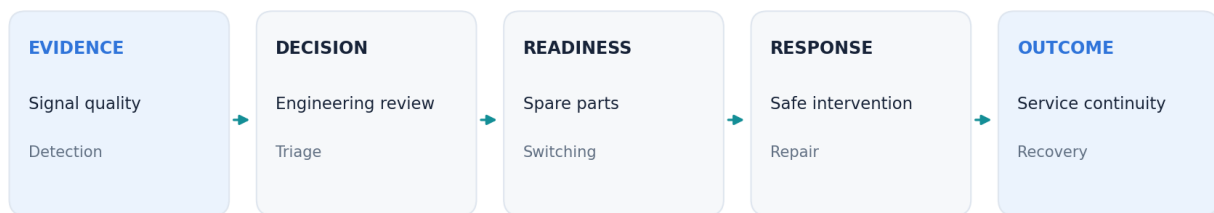
259 credibility and continuity of condition evidence, even though they do not directly alter insulation
260 behaviour [1,2].

261 7. Reliability, resilience and measurable outcomes

262 Reliability and resilience are related but distinct. Reliability concerns the likelihood of satisfactory
263 operation under specified conditions; resilience additionally considers the ability to anticipate
264 disturbances, absorb their impact, adapt and recover functionality. The attached smart-infrastructure
265 synthesis demonstrates why interconnected services make recovery and dependencies relevant
266 beyond individual component performance [1]. An early-warning system can contribute to the
267 anticipation phase by revealing credible deterioration before breakdown. Its contribution to
268 absorption and restoration is indirect: warnings only help if spares, isolation plans, switching
269 alternatives and skilled crews are available. Treating every detected PD event as a prevented
270 blackout would confuse an observation with a counterfactual outcome.

RESILIENCE DEPENDS ON THE WHOLE RESPONSE CHAIN

A conceptual model of early warning; no quantitative improvement is assumed



Weakness at any gate can prevent an accurate warning from producing a real system benefit.

271
272 *Figure 2. Conceptual chain linking diagnostic evidence to resilient service; no measured effect size*
273 *is implied.*

274 The proposed measurement hierarchy starts with monitoring validity: sensor uptime, calibration
275 performance, confirmed event capture and the proportion of alarms with traceable waveform
276 evidence. The second tier assesses diagnosis: false-positive and missed-event rates measured against
277 independently reviewed cases, uncertainty calibration, time-to-localisation and confirmation by
278 supplementary inspection. The third evaluates maintenance: elapsed time between verified warning
279 and engineering disposition, proportion of targeted inspections that find actionable defects,
280 unnecessary interventions and time needed to return equipment to service. The final tier addresses
281 system results: forced GIS outage frequency, energy not supplied, duration of interruptions,

282 successful contingency switching and restoration time. These tiers should be stratified by
 283 compartment type and operating context rather than pooled indiscriminately.

284 **Table 2. Evidence requirements for moving from measured discharge to network-level benefit.**

Validation gate	Essential records	Success indicator	Failure of interpretation
Instrument	Sensor status, clock, interference	Repeatable signal quality	Silence caused by failed sensors
Diagnosis	Waveforms, location, corroboration	Confirmed detection with calibrated uncertainty	High score for unfamiliar noise
Action	Analyst, owner, intervention	Appropriate targeted inspection	Unnecessary switching and work
Network	Outage, load, restoration	Service continuity / reduced disruption	Attributing every alert to avoided failure

285

286 A prospective evaluation should compare monitored assets with suitable historical baselines or
 287 matched assets, adjusting for equipment age, duty, preventive maintenance, network expansion and
 288 observation period. Randomised deployment may be impractical for critical substations; stepped
 289 implementation with predeclared outcomes is a realistic alternative. Investigators should record
 290 warnings that did not produce repairs alongside interventions that disclosed significant defects.
 291 Without those denominators, only successful anecdotes remain visible. Evidence of failure
 292 prevention requires an explicit causal argument, supported by inspections, operating history and
 293 credible counterfactuals, not merely the assertion that an alert preceded a scheduled maintenance
 294 visit.

295 **8. Implications for Saudi substations**

296 Saudi infrastructure presents a persuasive case for condition monitoring because high-value
 297 substations support expanding and interdependent services. Nevertheless, climatic exposure, site
 298 geography, equipment mix and organisational operating practices vary; the country should not be
 299 treated as a uniform test environment. Ambient heat, airborne dust and long-distance maintenance
 300 logistics can influence electronics, external connectors, access windows and response arrangements.
 301 These are design considerations requiring local validation rather than evidence that any particular
 302 national fleet already experiences a quantified PD failure rate. A pilot programme should establish

303 actual installed GIS types, sensor suitability, existing inspection procedures and the operational
304 consequences of outages before procurement decisions.

305 Site selection should prioritise substations where a credible failure would impose high restoration
306 costs or significant service disruption, while retaining a comparison population. Planning must
307 include heat-resistant enclosures, environmental qualification, time synchronisation, redundant data
308 storage and realistic field-calibration access. Operators should assess whether UHF sensors can be
309 fitted at inspection ports without compromising pressure containment or warranty conditions.
310 Criticality should be based on network topology, load consequences and maintenance substitutability
311 rather than simply assigning priority to the highest voltage. A high-voltage bay with ample
312 contingency can present less system consequence than a constrained connection supporting an
313 essential facility.

314 The transition to lower-impact insulating media also complicates diagnosis. Experiments on
315 alternative gas mixtures indicate that discharge signatures and domain adaptation require fresh
316 validation [23]. Accordingly, algorithms and thresholds trained on conventional equipment cannot
317 be transferred uncritically to future GIS designs. Procurement specifications should require evidence
318 of compatible sensors, access to unprocessed data, documented firmware changes and acceptance
319 tests across relevant compartments. Ownership of the data model and the ability to export event
320 records matter for long-term asset stewardship. Vendor-neutral interfaces can reduce lock-in, but
321 interoperability claims must be tested on actual equipment rather than inferred from common
322 protocol labels.

323 Evaluation economics should distinguish instrumentation expenditure from the cost of the response
324 it triggers. A monitoring contract may include engineering configuration, communications, secure
325 data storage, periodic sensitivity checks, expert review and intrusive verification after alarms. False
326 interventions can incur lost production or additional switching risk, while missed defects can
327 produce expensive failures. A defensible business case therefore compares alternative decision
328 pathways rather than simply sensor prices. Expected value calculations should use locally observed
329 defect prevalence and consequences when available, while displaying plausible uncertainty ranges
330 when data are scarce. The organisation should also value information that avoids unnecessary urgent
331 action: a well-supported low-risk diagnosis can preserve equipment availability without
332 compromising safety. Decision transparency makes these trade-offs discussable among engineering,
333 maintenance, finance and system operations teams [2,27].

An illustrative pilot workflow would begin with a baseline survey, procurement of suitably qualified sensors and a monitored commissioning period before any automated escalation is enabled. Teams would then classify environmental and switching interference, establish repeatability and reconcile sensor indications with portable measurements. In a second stage, notifications would be logged but reviewed offline to estimate workload and diagnostic credibility. Only after review could high-priority alerts enter operational procedures, with a defined engineering authority responsible for deciding whether to increase monitoring, perform targeted inspection or schedule isolation. The evaluation would retain every episode, including warnings judged benign, communication failures and maintenance visits that uncovered no defect. This design would generate field evidence needed to revise acceptance criteria responsibly, while avoiding the unsupported assertion that all recorded events imply a future breakdown.

9. Research gaps and validation priorities

The most consequential evidence gap is longitudinal prediction. Many studies classify known defect specimens or locate injected sources; relatively few follow real insulation deterioration from earliest observed activity to verified maintenance findings and post-intervention condition. The resulting uncertainty limits the credibility of forecasts of remaining service life. Future field trials should retain negative cases, document discharge intermittency and track whether corroboration improves decision quality over single-channel operation. Sensor ageing is another underexplored confounder: an apparently declining PD trend may represent equipment improvement, changing coupling or failing instrumentation [13,28]. The direction of the observed trend cannot be interpreted until channel stability is tested.

There is also a methodological gap in external validation. Diagnostic systems should be challenged using different substations, manufacturers, sensor placements, seasons and defect severities, with a clear separation between training and test assets. Rare-event false-alarm burdens should be reported per monitored bay-year, alongside recall for independently confirmed serious defects. Researchers should publish enough procedural detail to reproduce signal processing, thresholds and event definitions without disclosing sensitive substation topology. A robust benchmark needs both difficult background events and realistic examples of mixed sources; otherwise the apparent classifier advantage may disappear when an operator confronts ordinary switching noise and unfamiliar equipment [16–20,26,29].

The final research priority is human and organisational. Useful warnings require a maintained escalation roster, training in diagnostic uncertainty, documented access to specialist testing, spares strategy and coordination with dispatch. Researchers should compare how different alert explanations affect action timeliness and unnecessary outages. A clear observation accompanied by supporting evidence may be preferable to an opaque higher-confidence prediction when intervention is expensive. Decision accountability, auditability and operator confidence must be evaluated alongside accuracy. This is particularly important when remote analytics are updated frequently: a change in model version should be traceable, justified and retrospectively tested against earlier events. These safeguards connect validity to operational accountability across the asset lifecycle.

10. Discussion

The evidence favours a layered diagnostic approach rather than a simple technological hierarchy. UHF sensing offers practical opportunities for online detection, but propagation and instrument condition influence meaning. Acoustic evidence adds an independent physical channel, yet complex wave paths limit localisation confidence. Optical and chemical methods can provide corroboration, although their installation and temporal characteristics restrict universal deployment [3,4,9–11,21,22]. Machine learning can efficiently organise complex signatures, but performance measured on known laboratory defects should remain a conditional result. The strongest operational claim supported by the reviewed studies is improved capability to detect and interpret certain insulation phenomena under defined conditions; reliable prevention of grid failures still requires decision and outcome validation.

This distinction reshapes investment appraisal. Buying more sensors is not inherently equivalent to buying more resilience. Resources may be better allocated to critical compartments, calibration assurance, independent verification or repair readiness, depending on the existing constraints. Figure 2 illustrates the dependence of service benefit on the entire chain from detection to recovery. If one link fails, a sophisticated diagnostic algorithm may have little effect on customer interruption. Equally, a modest monitoring installation integrated into a mature maintenance process may deliver meaningful decisions. The proposed model therefore makes uncertain evidence visible, ties escalation to action ownership and explicitly records what happens after each warning.

Two limitations must be recognised. First, the review synthesises heterogeneous published results without conducting a harmonised performance experiment or exhaustive search; causal comparisons between techniques cannot be inferred. Second, no Saudi-specific GIS monitoring dataset was

available for external validation of thresholds, costs or avoided outages. The recommendations are consequently conditional engineering propositions rather than claims about demonstrated national performance. The most defensible next step is a governed pilot with independent fault confirmation, sensor-health checks, repeated site-level validation and predeclared reliability outcomes.

11. Conclusions

Real-time partial discharge monitoring can strengthen the anticipation function of smart GIS substations, but its value depends on more than detecting electromagnetic pulses. A credible early-warning system combines appropriately placed sensors, validated acquisition, defensible source interpretation, uncertainty-aware escalation and maintenance capability. Cross-modal confirmation and systematic sensor verification address distinct reasons for diagnostic error. Field-validated learning methods can improve pattern recognition, provided limitations from rare defects and changing operating environments remain visible. Saudi operators should evaluate such systems through staged, risk-prioritised deployments with measurable service outcomes rather than extrapolating laboratory success to prevented outages. The review advances a practical distinction between sensing performance, diagnostic credibility, maintenance action and infrastructure resilience. Future progress requires longitudinal evidence, reproducible external validation and transparent links between warning decisions and verified equipment condition.

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