Predictive Maintenance and Reliability-Centred Asset Management for Resilient Industrial Infrastructure in Saudi Arabia: A Framework for Transformers, Switchgear and High-Voltage Electrical Systems.

Abstract

Industrial electricity networks depend on transformers, switchgear and associated high-voltage apparatus whose failures can propagate from individual defects to prolonged production interruptions. This critical review evaluates how predictive diagnostics can be coupled with reliability-centred asset management to strengthen infrastructure resilience in Saudi Arabia. Thirty DOI-traceable studies published during 2020–2025 were selected through a structured, purposive examination of transformer condition assessment, partial-discharge sensing, circuit-breaker diagnostics, maintenance optimisation and grid transition. Evidence was synthesised by failure mechanism, measurement maturity, decision relevance and transferability to industrial substations. Transformer literature offers comparatively mature dissolved-gas, thermal and health-index approaches, although diagnostic ambiguity and poorly calibrated remaining-life estimates persist. Switchgear research demonstrates promising acoustic, electromagnetic and data-driven detection but often relies on laboratory defects or sparsely labelled field observations. Across asset classes, prognostic accuracy alone does not establish maintenance value: network topology, safety consequences, outage windows, spares and recovery capability determine which intervention is justified. An integrated, human-governed framework is proposed linking condition evidence, uncertainty-aware failure-mode assessment, consequence modelling, constrained work planning and post-intervention learning. Saudi-specific application requires attention to high ambient temperatures, dust exposure, expanding electrification and renewable integration without presuming that evidence from other networks transfers unchanged. The review contributes an actionable decision architecture and a validation agenda rather than untested claims of national performance improvement.

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Keywords: predictive maintenance; reliability-centred maintenance; power transformer; gas-insulated switchgear; high-voltage infrastructure; Saudi Arabia; asset resilience

1. Introduction

Reliable electrical infrastructure is an operational precondition for industrial expansion. A transformer failure can remove a major supply pathway; a failed circuit breaker can prevent fault isolation; and an undetected insulation defect can evolve into a safety incident. Consequently, maintenance policy must address both deterioration inside components and the system consequences of losing their functions. Scheduled servicing alone cannot distinguish equipment facing accelerated degradation from assets operating safely despite age. Equally, machine-learning alarms have limited value when they do not alter an approved engineering decision [1–3].

The literature on transformer diagnostics has expanded from conventional dissolved-gas interpretation to combinations of chemical, thermal and historical evidence [4–11]. Parallel research investigates partial discharge, switching mechanisms and signal classification in gas-insulated apparatus [12–22]. These developments improve visibility into particular failure modes, yet they do not automatically identify the most consequential asset, reserve a feasible outage or secure replacement components. Reliability-centred maintenance provides a separate decision logic: start from the function required, identify functional failures and choose defensible tasks according to their consequences [23,24]. Predictive analytics should inform that logic rather than displace it.

Saudi Arabia presents a meaningful context for this integration. Industrial clusters, large development projects and evolving electricity architectures place heterogeneous demands on substations, including fluctuating loading and continuity requirements. Research on Saudi smart-grid development highlights the importance of integration, flexibility and infrastructure readiness [28,29]. These findings create a rationale for locally validated maintenance strategies; they do not demonstrate that a single predictive model can be deployed nationally. Ambient heat, airborne contamination and regional differences in industrial criticality also suggest that condition baselines and outage consequences will vary between sites [8,30].

The aim of this review is to construct a technically specific framework that connects equipment-level prognostics with risk-informed, reliability-centred asset decisions for resilient industrial electrical systems. Four objectives guide the synthesis: assess the diagnostic evidence for transformers and switchgear; identify where prognostic uncertainty undermines maintenance planning; formalise a multi-asset decision pathway based on function and consequence; and define validation requirements for Saudi industrial deployment. The central argument is that infrastructure resilience depends on converting credible warnings into coordinated actions while retaining the capacity to absorb, isolate and recover from unavoidable failures.

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2. Review design and evidence appraisal

This study adopts a structured critical narrative review, suitable for integrating heterogeneous diagnostic experiments, reviews and maintenance optimisation models. It does not claim an exhaustive census of publications, independent dual screening or a pooled quantitative effect estimate. Source discovery combined targeted searches of scholarly and publisher records with backward examination of relevant technical concepts. Search expressions connected “power transformer”, “gas-insulated switchgear”, “circuit breaker” and “high voltage” to “condition monitoring”, “partial discharge”, “dissolved gas”, “health index”, “reliability-centred maintenance”, “asset management” and “resilience”. An additional search strand addressed Saudi smart-grid development and weather-related reliability.

Eligibility was restricted to research and review articles published from 2020 through 2025 with identifiable DOIs, a clear relationship to electrical equipment or transferable maintenance decision methods, and sufficient methodological detail to support critical interpretation. The final purposive sample comprises 30 studies, not 30 independent field trials. Broad industrial-maintenance reviews were retained only to inform system architecture and explainability; evidence on lower-voltage distribution equipment was treated as transferable theory, not direct proof for transmission-class apparatus [1–3,23–27]. Articles outside the time window, unsupported promotional claims and papers without traceable bibliographic identity were excluded from the cited synthesis.

For each study, extraction focused on equipment, failure mechanism, sensing modality, learning or reliability method, validation environment, reported outcome and operational limitation. Findings were organised into transformer, switchgear, decision-optimisation and Saudi-context domains. Claims were weighted qualitatively: long-duration field measurements offer stronger deployment evidence than a laboratory fault library, while simulations are informative about decision logic rather than measured savings. Because datasets and failure definitions differ, classification scores were not averaged across studies. No fictitious screening counts, pooled accuracy figures or Saudi failure statistics are presented.

The resulting evidence is interpreted through a common question: does the proposed technique produce information that could change a maintenance intervention without adding unacceptable safety or operational risk? Table 1 provides an asset-centred comparison of available signals. The synthesis then examines how those signals can support consequence-sensitive decisions. Bibliographic details and DOI identifiers were checked against accessible publisher or scholarly records; this check is distinct from a similarity-index test of the manuscript.

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The appraisal also distinguished evidence for detection, prognosis and action effectiveness. A sensor paper can establish that a signature is measurable without showing its relation to future equipment failure. A prognostic study can estimate risk without demonstrating that an available repair changes that risk. A maintenance optimisation simulation may illustrate a superior scheduling policy without proving equivalent gains on a real industrial site. Recording these inferential boundaries avoids treating adjacent claims as interchangeable. Studies were assessed for time separation between training and testing, physical verification of fault labels, representation of normal operating variability and discussion of uncertainty. Where such details were unavailable, the corresponding implications were described as possibilities rather than established field capabilities.

3. Transformer deterioration, diagnostics and prognostics

Power transformers exhibit interacting electrical, chemical, thermal and mechanical ageing processes. Insulation deterioration is particularly consequential because oil and cellulosic paper form a coupled dielectric and cooling system. Dissolved-gas analysis identifies compounds associated with overheating and discharge phenomena, but interpretation is complicated by mixed defects, sampling effects, gas migration and decision boundaries. Wani and colleagues showed that intelligent combinations may mitigate unresolved traditional diagnostic cases, while Nanfak and colleagues emphasised that technically impressive models are often difficult to reproduce consistently [4,5]. Consequently, an automated gas classification should be interpreted as evidence for investigation, not as an unconditional command to remove a transformer from service.

The health-index literature combines diagnostic indicators into a common condition score. Guo and Guo incorporated operating history with measurements to prevent a test-only index from ignoring exposure and age [7]. Zahra and colleagues reviewed conventional and learning-based approaches, identifying the attraction of wider condition information alongside difficulties in consistency and lifespan estimation [6]. An index can aid fleet ranking, but numerical aggregation may conceal a single critical defect if favourable indicators dilute an abnormal test. Engineering governance therefore requires component-level red flags, documented weights, uncertainty bands and the ability to challenge a composite result. Replacement timing should reflect consequence as well as condition: Zuñiga and colleagues explicitly combined health information with risk in an optimisation methodology [11].

Thermal state is another distinct evidence stream. Hot-spot temperature influences paper degradation and can reveal loading or cooling abnormalities. Doolgindachbaporn and colleagues

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trained data-driven thermal models using measurements from nine transformers, including ambient and weather inputs, and compared predictions with established thermal formulations [8]. Their approach supports residual-based anomaly detection, yet an unusual residual can arise from sensor bias, cooling changes or genuinely abnormal internal heating. Interpretation therefore depends on data quality, equipment operating state and inspection feedback. In hot industrial environments, a model developed elsewhere needs recalibration before its thresholds can support Saudi operating decisions.

Mechanical deformation and winding displacement require complementary tests. Frequency-response analysis detects changes in transformer transfer characteristics but does not uniquely identify the corresponding physical defect. Faiz and colleagues reviewed numerical indices, modelling and artificial-intelligence interpretation, underscoring the difficulty of associating signature changes with specific causes [9]. This reinforces a multi-evidence principle: dissolved gas, moisture, thermal residuals, electrical tests and repair history should be reconciled rather than compressed prematurely into a single machine-learning output.

Remaining useful life is more demanding than current-state classification. Forecasting a failure horizon requires explicit assumptions about stress exposure, intervention history, competing failure modes and what constitutes terminal failure. An apparent decline in estimated life must not be equated with a known replacement date. Acikgoz and colleagues examined dataset balance and model comparison in gas-based fault classification, demonstrating why headline predictive performance needs methodological scrutiny [10]. For industrial assets with sparse failures, calibrated hazard ranges and defensible maintenance triggers are more operationally useful than an unjustifiably precise life estimate.

Transformer ancillary systems deserve explicit attention because the main tank does not capture every source of operational vulnerability. On-load tap changers experience contact wear, switching stress and mechanism faults; pumps, fans and coolers can lose performance independently of winding insulation. A fleet programme that monitors gas concentrations but ignores cooler availability may misattribute a thermal excursion to core degradation. Likewise, a healthy insulation index says little about whether an alarm relay, auxiliary supply or tap-drive motor will operate when demanded. A practical transformer record should associate each diagnostic observation with a functional subsystem and a specific action, preserving the distinction between identifying damage, restoring a supporting function and replacing a life-limited component.

Table 1. Asset-specific diagnostic evidence, inferential limits and corresponding maintenance responses. Author synthesis of [4–22].

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Asset / functional concern	Condition evidence	What it can reveal	Main interpretive limitation	Action pathway
Oil-immersed transformer / insulation	DGA, moisture, oil tests	Thermal or electrical fault indicators	Mixed faults and sampling uncertainty	Confirm trend; test; manage exposure
Transformer / cooling and ageing	Hot-spot, load, ambient, fan and pump data	Thermal stress and cooling deviation	Temperature residual is not a failure clock	Inspect auxiliaries; adjust loading
Transformer / winding integrity	Frequency-response testing	Possible mechanical deformation	Signature is not uniquely diagnostic	Compare baseline; engineering inspection
Gas-insulated switchgear / dielectric system	UHF, acoustic, TEV, gas by-products	Partial-discharge activity and possible location	External interference and sensor position	Verify defect; schedule controlled test
Circuit breaker / interruption	Vibration, timing, trip current, contact tests	Mechanism or operating abnormalities	Signature does not prove interrupting capability	Functional test; repair; safety escalation

4. Switchgear and circuit-breaker condition intelligence

Switchgear combines dielectric barriers, switching contacts, operating mechanisms, seals and protection interfaces. Its dominant observable signatures differ from those of oil-filled transformers. Partial discharge can indicate insulation defects in gas-insulated switchgear, but detection sensitivity depends on defect geometry, sensor position, interference and operating conditions. Mahdi and colleagues reviewed the relationship between gas decomposition products and discharge activity, while Zohrevand and colleagues investigated electromagnetic time reversal as a localisation method [12,13]. Neither finding eliminates the need for equipment-specific discrimination between external noise and internal degradation.

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Ultra-high-frequency and associated electromagnetic sensors provide fast access to discharge signatures, and acoustic measurements can complement their location or discrimination performance. Shu and colleagues reported a low-noise UHF detection module evaluated with simulated discharges and a real switchgear installation [14]. Mier and colleagues distinguished discharge from interference by combining electric and magnetic observations [19]. Han and colleagues developed a transient-earth-voltage and ultrasonic sensing arrangement for detection, diagnosis and localisation [20]. Collectively, these studies suggest that sensor architecture and interference management are as important as downstream classification algorithms. Field validation must therefore cover electromagnetic interference, sensor ageing and installation constraints, not merely clean laboratory recordings.

The machine-learning literature explores limited labels, overlapping defects and privacy constraints. Wang and colleagues investigated federated deep learning to learn from distributed datasets without transferring raw data [15]. Their later few-shot work used metric-based learning to recognise discharge patterns with restricted examples [16]. Yan and colleagues explored federated meta-learning, while Yang and colleagues examined semi-supervised classification when labelled instances are scarce [17,18]. These approaches address practical constraints, but model transfer can fail when new apparatus designs, grounding arrangements or sensors change the signal distribution. Training partitions must be separated by asset or site rather than allowing nearly identical recordings from one experiment into both training and test sets.

Other studies offer signal-processing alternatives. Sun and colleagues coupled decomposition with optimised support-vector classification for partial-discharge signals [21]. Such controlled comparisons are useful for algorithm selection, yet their demonstrated classification performance cannot stand in for an estimate of future arc risk or required outage urgency. Circuit-breaker mechanics add a different problem: vibration patterns can indicate deterioration in actuation assemblies. A 2024 multimodal fault-diagnosis study illustrates the promise of vibration-based mechanism assessment [22]. Engineering interpretation still needs operating-time tests, trip-coil current, contact resistance, duty history and maintenance findings where available.

For high-voltage switchgear, a defensible alert pathway should progress from signal validation to suspected mechanism, confidence assessment, failure consequence and inspection planning. Protective device testing and safety-critical switching operations cannot be delegated to a statistical classifier. The preferred outcome is a traceable diagnostic case that helps authorised engineers decide whether to monitor, test under controlled conditions, schedule an outage or escalate immediately.

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A further complication is the difference between condition sensing and protection assurance. A breaker might show acceptable vibration traces yet fail an independent trip-circuit supervision test. Conversely, an unusual mechanical signature may reflect a harmless configuration difference rather than reduced interrupting capability. This asymmetry means that mandatory timing, contact and protective-function tests retain their role even after advanced sensing is installed. Diagnostic models should be calibrated by breaker type, interrupting duty and maintenance state; historical switching counts must not be assumed to measure contact damage linearly. For gas-insulated equipment, any environmental implications of insulating-gas handling also belong in work planning, but must not override immediate electrical safety requirements.

5. From prediction to reliability-centred decisions

The distinction between prediction and maintenance optimisation is fundamental. A model that assigns a high probability of defect to a redundant transformer may indicate a lower near-term operational priority than a moderate-confidence warning on the only supply breaker for a critical process. Reliability-centred analysis begins with required function, functional failure and effects at asset and network levels. Moradi-Sarvestani and colleagues formulated feeder criticality, failure-mode prioritisation and maintenance selection as linked decisions; Wang and colleagues extended virtual-age concepts to represent the different effects of individual tasks [23,24]. Their distribution-level findings support the logic of task-specific risk reduction, although voltage class and site consequences still require local engineering adjustment.

A proposed decision model distinguishes probability, consequence and intervention effectiveness. For asset i and failure mode m, conditional risk can be represented conceptually as the estimated likelihood of failure within a planning interval multiplied by its consequence under a particular network configuration. Consequence should include personnel safety, expected interrupted production, environmental harm, equipment damage and time to restore function. This is a prioritisation expression, not a claim that dissimilar harms can always be valued precisely in money. Mandatory safety limits and statutory requirements remain constraints, not items to be traded against lower maintenance expenditure.

Maintenance actions must be mapped to the degradation mechanism they can influence. Oil sampling may reduce uncertainty without reversing insulation ageing; a cooling-system repair may lower future thermal stress; contact adjustment may restore switching functionality; and asset replacement changes the underlying exposure and inventory requirement. A virtual-age reduction should only be applied when technical evidence justifies it. If monitoring detects a worsening hazard but no available intervention alters that hazard, the plan may require additional

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redundancy, operating restrictions or accelerated capital renewal rather than more frequent measurements [24].

Network-aware optimisation then compares action bundles under practical constraints. Relevant variables include available outage windows, spare transformers, lifting equipment, switching sequences, isolation permits, crew qualifications and contingency supplies. Mirshekali and colleagues demonstrate the value of reliability-aware multi-objective asset decisions, while Mortensen and colleagues show why digitally enabled maintenance must connect sensing with the full planning workflow [25,3]. Objective functions can combine expected loss, lifecycle cost and restoration readiness, but decisions should report trade-offs rather than conceal them behind a single opaque score.

Reliability is only one element of resilience. A highly reliable component may still form an unacceptable single point of failure. Conversely, sectionalisation, alternative feeds, isolation procedures and spares can contain the impact of a component fault. The framework in Figure 1 therefore treats diagnosis, criticality, intervention and recovery as separate linked stages. It recommends explicit escalation thresholds, an auditable engineering sign-off and feedback after every completed intervention.

Decision makers should also test sensitivity to uncertain assumptions. A maintenance choice that appears optimal only when an unverified failure probability is treated as exact is too fragile for high-consequence electrical service. Scenario analysis can compare conservative, central and adverse failure estimates while varying production-loss consequences and spare-delivery times. A robust plan may favour targeted testing when the ranking changes across scenarios, or favour rapid replacement when one credible scenario exceeds a defined safety limit. Reporting the decision boundary is valuable: it explains what new evidence would justify changing the recommendation. Such sensitivity studies are especially relevant where historical outages are few and consequences are site-specific.

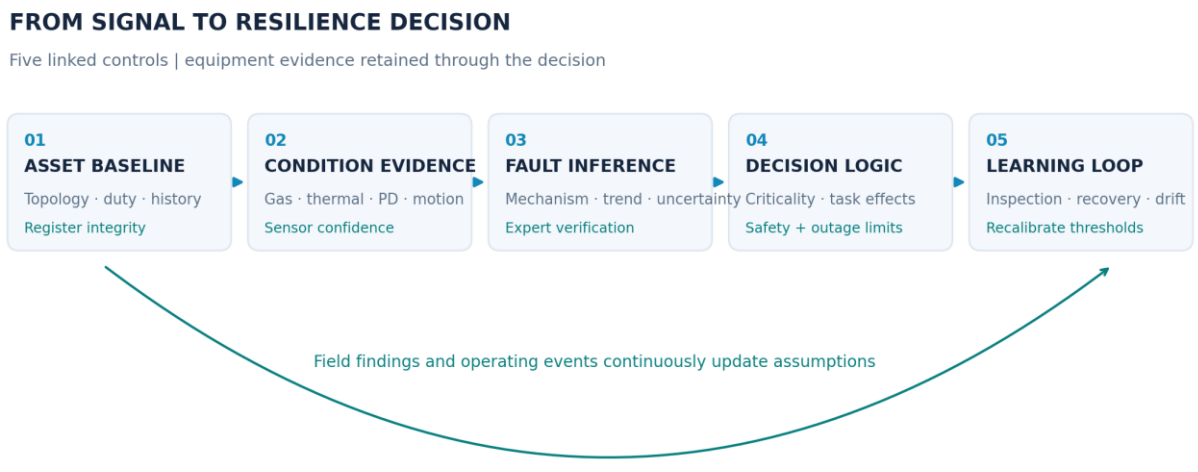

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Figure 1. Proposed condition-to-decision architecture for industrial electrical assets. Original conceptual figure.

6. An integrated resilience-oriented asset framework

The proposed architecture has five layers. The first is a trusted asset register containing nameplate ratings, topology, protection settings, commissioning tests, maintenance records and ownership. Inconsistently labelled feeders or missing equipment histories can produce more decision error than an imperfect predictive algorithm. The second layer acquires condition evidence at the correct frequency: online gas and temperature trends for selected transformers, periodic dielectric testing, partial-discharge recordings and breaker mechanical signatures. Data lineage, calibration date and sensor health accompany every observation.

The third layer generates diagnostic hypotheses and quantified uncertainty. Physics-guided residuals provide a baseline where failure examples are rare; transparent statistical models may outperform highly parameterised networks when datasets are small. Explainable predictive-maintenance research identifies the importance of making model limitations understandable to engineers [26]. A useful alarm states the suspected defect, supporting evidence, alternative explanations, data confidence and the next discriminating test. Classification outputs should remain separate from reliability parameters whenever the empirical link between defect class and failure frequency is unknown.

The fourth layer translates uncertain evidence into risk-ranked tasks. A joint engineering and operations review evaluates the required electrical function, network alternatives, exposure window and effects of available interventions. A task is selected only when it can feasibly reduce risk or improve knowledge enough to influence a later decision. The fifth layer records executed work, inspection discoveries, near misses and subsequent sensor behaviour. Post-maintenance measurements provide an essential test of causal assumptions: if the alarm persists after a purported corrective task, the diagnosis or expected task effect must be reconsidered.

This design separates automated support from accountable authority. A prediction engine may flag a suspected overheating condition; it cannot independently authorise switching, isolation or work on energised high-voltage plant. Role-based access, change management and independent protection-system verification are necessary controls. An adversarial or malfunctioning data feed could trigger unnecessary outages or conceal developing hazards. Segmentation between monitoring systems and protection/control functions, secure time synchronisation and retained manual operating procedures help reduce that exposure.

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Figure 2 extends the workflow into a resilience cycle. Prevention comprises condition assessment and corrective action; absorption relies on protection coordination and redundancy; recovery requires safe restoration, spare capacity and rehearsed switching procedures; adaptation uses event evidence to revise thresholds and maintenance policy. Each capability has measurable outputs. Suggested measures include unplanned outage hours attributable to tracked assets, forecast calibration, missed critical defects, mean restoration duration, scheduled versus emergency work, and the proportion of alerts that generate a justified action. These measures must be audited together because suppressing alarms can make a dashboard look better without making equipment safer.

Model oversight is particularly important where historical failure events are scarce. Cross-validation within recordings can exaggerate real-world generalisation if samples from the same transformer or test campaign appear in both folds. External validation should hold out complete assets, time periods and sites; drift monitoring should test whether temperatures, loading patterns or sensors have changed. Hoffmann and Lasch's survey of data-driven maintenance reinforces the broader distinction between algorithmic advances and deployable industrial systems [27]. An operational pilot should report false-positive work orders and missed consequential defects alongside conventional classification measures.

Governance also needs a controlled path for exceptions. During commissioning, temporary loading, emergency backfeeding or sensor replacement, normal model assumptions may be violated. The system should mark observations from these periods, record who authorised any temporary threshold change, and require expiry or review of overrides. Alert suppression must have a reason and end date; otherwise persistent defects can disappear from management attention. Versioned equipment configuration, model parameters and inspection outcomes allow an analyst to reconstruct why a decision was made months earlier. This audit trail is essential for learning from near misses, reconciling disagreements between maintenance and operations, and distinguishing model drift from a real physical change.

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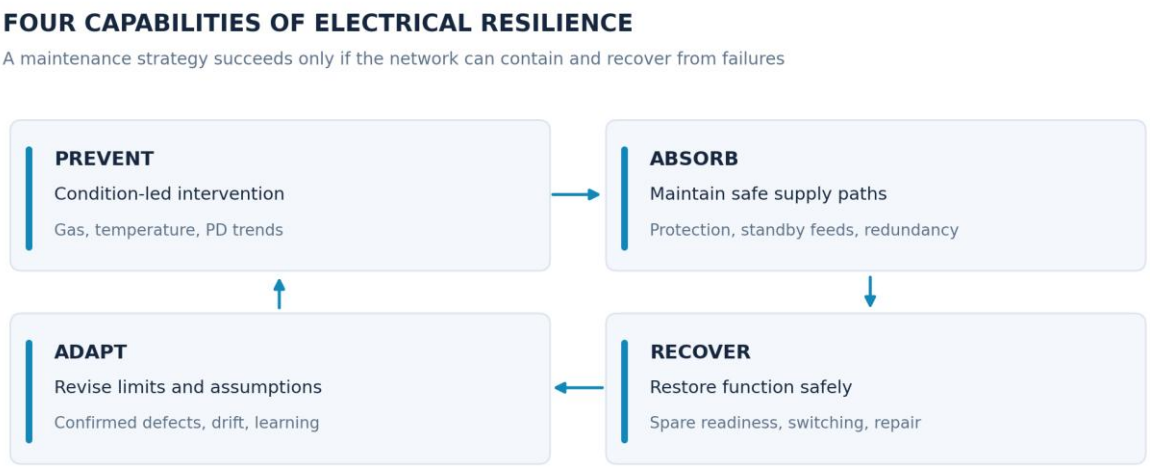

Figure 2. Resilience capabilities and their operational maintenance interfaces. Original conceptual figure.

7. Saudi Arabian application and implementation

The Saudi setting shapes both equipment stress and the economic consequences of electricity interruption. Research on the Kingdom's smart-grid transition outlines requirements for distributed generation, communications and flexible power-system operation [28]. A broader review of renewable integration identifies standardisation, interoperability and system security as practical dependencies [29]. Neither source supplies a national high-voltage transformer failure database, so local design assumptions must be separated from measured Saudi evidence. A review intended for industrial deployment must resist substituting international fault rates for site-specific experience.

High ambient temperature changes cooling margins and the interpretation of transformer thermal measurements. Dust and contamination can increase the maintenance importance of exposed insulators, enclosure integrity and filtration, although severity depends on local equipment design and cleaning history. Variation in industrial activity also affects consequence: a refinery process interruption, a remote mining feeder and a redundant urban substation cannot be prioritised using the same generic cost of lost load. Weather-aware reliability research indicates why exposure belongs in failure modelling instead of being regarded as a constant [30].

A staged pilot should begin with a clearly bounded network: for example, one industrial receiving substation and its critical downstream switchgear. The asset team would validate records, review failure modes, baseline existing alarms and document protection boundaries before adding sensors. Selected transformer units could receive integrated gas, thermal and maintenance-history assessment; priority switchgear panels could receive periodic partial-

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discharge measurements and mechanism testing. Baseline data should span operating variation before thresholds are used for consequential decisions. Where data are sparse, expert-reviewed rules provide a safer initial reference than a complex model trained on unrelated equipment.

Pilot evaluation should compare the new decision process with a predefined baseline, not simply count how many sensors were installed. Suitable outcomes include whether emergent defects were identified earlier, whether work orders addressed confirmed mechanisms, the proportion of planned outages that remained within their windows, and the restoration readiness of critical electrical paths. Safety events and near misses should be tracked separately from cost. A before-and-after comparison requires caution because asset replacement, demand variation and major network upgrades can change failure exposure independently of maintenance practice.

Institutional arrangements matter equally. Reliability engineers establish failure modes; electrical operations personnel evaluate switching feasibility; maintenance planners validate crew and spare availability; cybersecurity teams protect data pathways; and management approves risk appetite. Cross-functional review prevents a high-scoring algorithm from creating a work order that cannot be safely executed. Capacity building should include fault interpretation, model uncertainty, high-voltage permit controls and the ability to challenge automated recommendations. This combination is more defensible than promising guaranteed reductions in downtime or asset replacement expenditure.

A useful implementation sequence separates readiness from automation. During preparation, engineers should catalogue criticality and establish a trustworthy equipment hierarchy. During observation, they should collect matched sensor and inspection evidence while leaving existing protection and maintenance schedules intact. During supervised decision support, proposed interventions should be compared with decisions that experienced personnel would have made without the model. Only after stable performance across seasonal and operational variation should work-order integration be considered. Procurement documents can then specify sensor reliability, data export, ownership, cybersecurity and calibration requirements rather than rewarding proprietary prediction scores alone. This sequence also creates opportunities for local engineering skills development and vendor accountability.

Table 2. Proposed pilot verification matrix for high-voltage asset management. Normative framework; not observed Saudi outcomes.

Validation domain	Required evidence	Failure criterion / guardrail	Responsible function

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Validation domain	Required evidence	Failure criterion / guardrail	Responsible function
Signal validity	Sensor calibration, noise testing, installation log	Unresolved interference or missing traceability	Condition monitoring
Predictive credibility	Asset-held-out tests, probability calibration, drift checks	Leakage between training and evaluation sites	Reliability engineering
Engineering utility	Alarm review, confirmed faults, action changes	Model flags without a defensible maintenance response	Electrical asset owner
Safety and protection	Permit, switching, trip and interlock testing	Any compromise of mandatory protective functions	Electrical operations
Resilience performance	Restoration drills, spare readiness, interruption records	Recovery pathway untested under contingency	Operations and planning
Governance and security	Access audit, model change log, cyber review	Undocumented override or unowned data feed	Asset governance / cyber team

8. Evidence limitations and research priorities

The reviewed evidence contains several recurring weaknesses. Diagnostic experiments frequently compare algorithms against a fixed labelled dataset without measuring how the result changes when deployed at another substation. Test laboratories create informative defect signatures but cannot reproduce the full mixture of operating stresses, sensor interference and maintenance practices. Transformer health indices are sensitive to feature weights and missing tests, while failure labels may conflate a repairable anomaly with end-of-life deterioration [5,6,10]. These problems limit the precision of estimated remaining life and the portability of any universal intervention threshold.

First, longitudinal field studies should join condition history, verified defect findings, interventions and subsequent operation at the same asset level. Stable identifiers and standardised failure definitions would allow comparison without revealing commercially

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sensitive details. Second, risk models should incorporate calibrated probabilities and scenario-based consequences while keeping uncertainty visible. Third, maintenance-effect models should distinguish inspection, repair, refurbishment and replacement, since their effects on hazard and knowledge are not equivalent. Fourth, prospective trials should evaluate decision utility against existing engineering practice, rather than selecting an algorithm solely by classification accuracy.

An important research opportunity lies in joint modelling of transformer and switchgear dependencies. Condition problems rarely respect departmental boundaries: a deteriorating transformer can change loading elsewhere, while an unavailable breaker can remove the isolation option required to repair that transformer. Interdependent scenarios could be assessed through fault trees, network simulations and restoration exercises, with the boundaries of any model stated explicitly. However, digital representations must be updated after switching changes and physical modifications or their apparently precise predictions may be misleading.

Finally, studies designed for Saudi applications should report geography, asset voltage, duty, thermal exposure, maintenance history and validation setting. This metadata would permit evaluation of whether a prediction model remains credible across facilities with different dust burdens, industrial loads and redundancy arrangements. Publishing negative or inconclusive pilot outcomes is valuable: knowledge that a sensor adds little decision value under particular conditions prevents unnecessary capital spending. The framework is therefore a falsifiable implementation proposal, not an empirically validated national performance claim.

Publication bias may favour successful fault-detection experiments. Future evaluations should preregister decision thresholds, disclose missed diagnoses, and report whether alerts changed work safely, while protecting sensitive industrial operating information.

9. Conclusions

Evidence from 2020–2025 shows substantial progress in detecting transformer insulation and thermal anomalies, classifying switchgear discharge signatures and analysing mechanical faults. Nevertheless, the strongest predictive output is not automatically the best maintenance decision. Site-specific consequence, intervention effectiveness, outage constraints and restoration arrangements mediate its value. This review accordingly proposes a five-layer framework that joins trustworthy data, interpretable diagnosis, uncertainty-aware criticality, feasible work selection and operational learning.

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For Saudi industrial infrastructure, implementation should start with bounded pilots, explicit baselines, local stress calibration and high-voltage safety governance. Future research must demonstrate transferable performance using independent sites and report missed defects, unnecessary interventions and resilience measures alongside algorithmic accuracy. The practical contribution is a defensible route from condition evidence to system continuity, while the central limitation remains the absence of prospective Saudi field validation. These conclusions support informed investment and testing; they do not imply that the proposed architecture has already reduced outages or achieved a measured reliability improvement.

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