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Digital Switchgear Modernization for Smart Grid Reliability in Saudi Arabia's LV/MV Electrical Networks

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***Abstract-** Saudi Arabia's distribution networks are entering a critical modernisation cycle as renewable energy growth, industrial expansion, electric mobility, urban giga-projects and customer expectations are reshaping the role of low-voltage and medium-voltage electrical infrastructure. The review evaluates the potential of digital switchgear modernisation to improve the reliability of smart grids in Saudi Arabia's LV/MV networks, by integrating interoperable protection, embedded sensing, online condition monitoring, automation, analytics, and cyber-secure operational governance. This paper reviews recent research and institutional evidence from 2020 to 2025, with a focus on medium-voltage switchgear fault detection, IEC 61850-enabled digital substations, distribution automation, predictive maintenance, smart grid cybersecurity, and Saudi energy transition priorities. The goal is to develop a practical, research-based framework for upgrading legacy switchgear to intelligent assets to support renewable integration, feeder automation, outage reduction and lifecycle asset management. The review concludes that modernisation is not simply a matter of replacing equipment. It is a comprehensive transformation that needs sensorized switchgear, standardised data models, SCADA and advanced distribution management system integration, edge analytics, workforce capability, procurement reform and cybersecurity-by-design. For Saudi Arabia, the biggest reliability gains are likely to be realised where digital switchgear is prioritised on critical industrial feeders, rapidly growing urban districts, renewable interconnection points, hospital and airport networks, desalination loads and substations exposed to high temperature, dust, humidity and load variability. The study offers a staged modernisation pathway and governance matrix to align switchgear digitalisation with Vision 2030, grid automation targets, local capability building, and sustainable energy transition outcomes.*

***Keywords:** Digital Switchgear, Smart Grid, LV/MV Networks, Saudi Arabia, IEC 61850, Condition Monitoring, Distribution Automation, Predictive Maintenance, Vision 2030*

I. INTRODUCTION

The intersection of demand growth, renewable energy deployment, industrial diversification, and investment in digital infrastructure is transforming Saudi Arabia's electricity system. Under Vision 2030, electricity networks are expected to support more renewable generation, more efficient consumption, high-reliability industrial clusters, digitally-managed cities and new strategic loads such as electrified transport, data centres, desalination and hydrogen-related infrastructure. Such changes put particular pressure on low and medium voltage networks as distribution systems are the closest to end users, i.e. they experience the immediate effects of peak demand, local faults, distributed generation, power quality disturbance and expectations of service continuity. Traditional switchgear, designed primarily for isolation and protection, cannot provide the real-time visibility, flexible operation, and predictive reliability management required by networks (Khan et al., 2023; SEC, 2025). Digital switchgear modernisation is the transformation of traditional LV/MV switchgear panels, ring main units, feeders and protection systems to data-enabled, communicative and analytically supported assets. In practical terms this means the combination of intelligent electronic devices, numerical relays, arc flash protection, partial discharge sensors, temperature sensors, circuit breaker operation counters, motorised switching, gas or vacuum monitoring, cybersecurity controls and standardised communication protocols. Rather than waiting for failure, utilities and industrial operators can monitor insulation stress, contact wear, thermal hotspots, abnormal switching behaviour and environmental exposure. The modernisation logic is thus closely related to condition-based maintenance, risk-based asset management and the feeder level automation (Alsumaidaee et al., 2022; Mortensen et al., 2024).

This issue has special significance in the Saudi context. High ambient temperatures, desert dust, coastal humidity, long feeder distances, fast growing urban districts and large industrial loads can speed the deterioration or complicate the field inspection. Meanwhile, the Kingdom is working towards national goals for renewable integration and grid automation, with Saudi Electricity Company announcing full smart metre deployment and continued distribution automation initiatives (Saudi Green Initiative, 2024; SEC, 2025). Digital switchgear can be used as the physical and information interface between power equipment and the control platform of the smart grid. It can translate hidden equipment conditions into operational intelligence and link distribution asset health to outage prevention, maintenance prioritisation, and resilience planning. This review is not only concerned with transmission-level automation but also with Saudi Arabia's LV/MV electrical networks as distribution reliability is becoming more and more important for economic diversification. A feeder interruption affecting an industrial estate, metro system, port, hospital, airport, giga-project district or petrochemical facility could have more far-reaching consequences than the immediate loss of electrical supply. Therefore, the reliability value of digital switchgear is not only the technical indicators of outage frequency and duration, but also the value of safety, productivity, customer trust, operational continuity and national development. The research problem addressed in this paper is that many modernisation programmes still treat switchgear upgrades as equipment procurement decisions, whereas smart grid reliability depends on an integrated socio-technical system. Digital devices are only valuable if they are interoperable, trusted, maintained, cyber-secure and connected to operational decision processes. Consequently, this review considers the technologies, barriers and governance requirements that can ensure that digital switchgear modernisation can provide measurable reliability benefits in Saudi LV/MV networks.

II. AIM, OBJECTIVES AND CONTRIBUTION OF THE REVIEW

This study aims to evaluate the impact of the modernisation of digital switchgear on the reliability of smart grids in the LV/MV electrical networks of Saudi Arabia and propose a structured framework for implementation. The review has five goals. It first explains the role of digital switchgear in smart distribution networks and differentiates equipment modernisation from the wider grid intelligence. Second, the book reviews recent advances in condition monitoring, fault diagnostics, protection automation, IEC 61850 communication and digital substations. Thirdly, it studies reliability challenges specific to the Saudi LV/MV networks such as climate exposure, load growth, renewable integration, industrial continuity, and skills requirements. Fourth, it identifies barriers and enablers for modernisation, including interoperability; data quality; cyber-security; legacy assets; procurement models; lifecycle costing; and local supply-chain capability. Fifth, it provides a staged pathway that can assist utilities, industrial operators and engineering consultants in planning digital switchgear upgrades. The review makes a threefold contribution. It conceptually links the modernisation of the switchgear with the reliability of the smart grid, instead of viewing it as a narrow protection upgrade. Methodologically it synthesises academic and institutional sources from 2020 to 2025 using a thematic review approach appropriate to engineering management and infrastructure policy. In practice, it provides two implementation tools: a reliability architecture figure illustrating how digital switchgear components deliver value, and a governance table summarising barriers, enablers, and recommended responses. These outputs aim to support Saudi Arabia's energy transition by helping decision makers to prioritise upgrades where they will have the greatest operational and strategic value (Rubio et al., 2025; Saudi Green Initiative, 2024).

III. REVIEW METHODOLOGY

This paper uses a structured narrative review methodology, supported by a thematic synthesis. An interdisciplinary subject like digital switchgear modernisation, which involves electrical protection, asset management, information systems, communication protocols, cybersecurity, maintenance engineering and national energy policy, is suitable for a narrative review. The goal is not to statistically synthesise one experimental variable, but to interpret how multiple strands of evidence can be combined into a practical modernisation framework for Saudi distribution networks.

The review process was fourfold. The relevant literature was initially identified through a combination of terms including medium-voltage switchgear, LV distribution automation, condition monitoring, partial discharge, digital substation, IEC 61850, smart grid reliability, predictive maintenance, digital twin, cybersecurity and Saudi Arabia smart grid from 2020 to 2025. Preference was given to peer-reviewed review articles, recent engineering studies, standards-related sources, and institutional publications that directly address distribution reliability or switchgear modernisation. Second, the selected literature was screened for relevance to the LV/MV networks and practical deployment and reliability implications. Sources that were solely about high voltage transmission and that were not relevant to distribution automation were used sparingly.

Third, the evidence was synthesised into five themes identified by the authors, namely, asset condition and fault diagnostics; protection, automation and interoperability; data platforms and analytics; cybersecurity and governance; and Saudi-specific implementation conditions. This thematic approach allows the review to link equipment-level technologies to network-level outcomes. Partial discharge monitoring is not only a diagnostic tool but also a reliability enabler when its alarms are integrated with maintenance planning and feeder criticality and risk-based replacement models (Alsumaidaee et al., 2022; Mortensen et al., 2024), for example. Fourth, results were discussed in the context of strategic assessment. The review examined how each technology or practice would enhance reliability, what barriers prevent adoption, and what governance measures would be necessary to implement. The synthesis resulting from this is presented in two tables and two figures. Table 1 presents a summary of the main review dimensions and their relevance to Saudi LV/MV systems. Barriers and enablers for deployment are described in Table 2. Figure 1 shows the architecture connecting digital switchgear to reliability outcomes, and Figure 2 shows a staged modernisation pathway. The methodology is consistent with recent review practices in engineering and sustainability research that integrate technical evidence with policy and implementation considerations (Kumar et al., 2023; Silveira et al., 2023).

IV. DIGITAL SWITCHGEAR AS A RELIABILITY PLATFORM

In LV/MV traditional networks switchgear is used as protective and switching device. It helps to isolate faults, it protects downstream equipment, it allows maintenance switching and it supports safe energization. In digital networks, the same switchgear is a platform for reliability. It senses its own state, communicates with supervisory systems, can be operated remotely, records events of disturbance, enables automated restoration, and provides data for modelling the health of the asset. This change is important because many distribution failures are preceded by detectable symptoms such as partial discharge, increased contact resistance, abnormal temperature rise, insulation degradation, excessive operating time, mechanical wear or repeated trip patterns (Alsumaidaee et al., 2022). Partial discharge monitoring is one of the most important technologies for MV switchgear, since insulation failure remains a major source of catastrophic outages. Modern sensors are able to sense electromagnetic, ultrasonic or transient earth voltage signals associated with insulation deterioration. These signals combined with machine learning or rule-based diagnostics can help with early warning and maintenance prioritisation. Recent studies highlight the potential for deep learning and smart diagnostics to classify discharge patterns and detect likely faults, but emphasise the need for clean data, validated models, and field-calibrated thresholds (Alsumaidaee et al., 2022; Nicolaou et al., 2021). Thermal monitoring has equal relevance for Saudi Arabia. High ambient temperatures and heavy summer loading can put accelerated stress on busbars, cable terminations, breakers and contact assemblies. Embedded temperature sensors, infrared windows, wireless thermal tags and continuous monitoring devices enable operators to identify abnormal heating before it leads to failure. Thermal issues in LV panels can be caused by loose connections, harmonic currents or overloaded feeders. The heating of contacts in MV switchgear may be due to mechanical or insulation

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problems. Hence continuous monitoring is more reliable than periodic inspection, as it captures dynamic load conditions that may not be evident during scheduled maintenance. Digital protection devices increase reliability by providing visibility into fault records, trip causes, breaker operations and setting changes. Numerical relays and intelligent electronic devices can record the oscillography, event sequence and disturbance information, which is helpful for engineers to analyse the faults and tune protection coordination. The presence of distributed generation in a network may destabilise the conventional assumptions of the protection due to the change in the directions and magnitude of the fault current. Properly engineered and governed digital relays, adaptive settings and communication-assisted schemes can enhance the selectivity (Rubio et al., 2025).

Modernising switchgear also enables distribution automation. Remote terminal units, intelligent feeder switches and motorised ring main units can isolate faulty sections faster and restore healthy sections quicker than manual field switching. It directly improves outage duration metrics and reduces customer impact. But automation requires dependable communication, accurate models of the network and disciplined operating procedures. A motorised switch without reliable data or command governance could create operational risk. So, the reliability advantage is down to integration of equipment, communication, control room tools and maintenance workflows.

V. SAUDI LV/MV NETWORK DRIVERS

Reliability drivers for Saudi Arabia's LV/MV networks are both global and local. The deployment of renewable energy, distributed resources, electric vehicles, battery storage, flexible demand and digital customer interfaces around the world is making distribution systems more complex. Saudi networks must support rapidly growing cities, industrial zones, giga-projects, ports, airports, desalination plants, petrochemical plants, mining regions and critical public services on a local basis. Such loads require high availability and stable power quality. Disruption of networks can have an impact on economic productivity, safety and public confidence, especially in strategic sectors aligned with Vision 2030.The Kingdom's ambitions to generate renewable energy increase the need for smart distribution infrastructure. Mentioned in Saudi Green Initiative is the Kingdom's commitment to generating 50% of power from renewable sources by 2030. Saudi Electricity Company has outlined targets for full smart metre deployment, as well as for expanding and automating the distribution network (Saudi Green Initiative, 2024; SEC, 2025). Solar output varies with weather, dust, temperature and time of day. Thus, renewable integration demands more visibility and operational flexibility. LV/MV feeders in the vicinity of renewable plants, storage systems or industrial self-generation sites may experience voltage fluctuation, reverse power flow, protection coordination issues and changing load profiles. Digital switchgear allows operators to monitor and control these conditions. Another Saudi-specific driver is environmental stress. Desert dust can also contaminate surfaces of insulation and damage ventilation. Humidity and salinity near the coast can accelerate corrosion, both west and east. High ambient temperatures can reduce the life of equipment and increase the probability of failure, especially in enclosures with limited cooling. "Heat can also increase loading stress during summer peaks of demand. Digital condition monitoring comes in handy here, as it identifies deterioration in real operating conditions, not just calendar-based maintenance. The agenda of industrial diversification also makes a better case for modernisation. Reliable MV feeders are needed in industrial clusters for motors, drives, process control systems and safety critical equipment. Short interruptions lead to production losses, restart costs or quality issues. Digital switchgear can support reliability-centered maintenance by ranking assets by condition, criticality and consequence. This is especially important for petrochemical, water, mining, logistics and manufacturing facilities where the impact of an unexpected switchgear failure can have wider repercussions for the value chain. The expectations of the customer are also changing. Smart metres and digital billing, customer portals and automated outage communication put pressure on faster restoration and greater service transparency. Distribution operators can no longer depend solely on field reports to understand outages. Newer switchgear that communicates to SCADA or advanced distribution management systems will be able to provide feeder level status and event information. When combined with smart metre outage notifications, this information allows operators to locate faults more accurately and restore service more efficiently. Digital switchgear is therefore part of a wider information ecosystem that connects network assets, control rooms and customers.

VI. INTEROPERABILITY, DATA AND AUTOMATION ARCHITECTURE

Digital switchgear modernisation is based on technical interoperability. LV/MV networks are often composed of equipment from different manufacturers and from different installation periods. “Without common data models and communication principles, modernisation can create isolated digital islands rather than a smart grid. IEC 61850 is widely discussed as a key standard for substation automation because it supports logical nodes, standardised naming, GOOSE messaging, sampled values and engineering configuration principles. Recent reviews show that IEC 61850 improves flexibility and interoperability, but requires careful engineering, testing and cybersecurity controls (Kumar et al., 2023; Silveira et al., 2023). Interoperability must be pragmatically interpreted for the Saudi LV/MV systems. Not all distribution switchgear installations require a fully digital substation architecture. Advanced IEC 61850 implementation can be justified for critical primary substations, industrial substations and renewable interconnection points. Simpler IoT gateways, remote terminal units or sensor platforms may be required for secondary substations and LV panels, that still map data into enterprise systems. The goal is to make sure that condition, protection and switching data can be trusted, stored, analysed and acted upon. The modern digital switchgear architecture consists of four layers. The first layer is the physical asset layer which contains circuit breakers, disconnectors, earthing switches, busbars, current transformers, voltage transformers, cables, relays and enclosures. The second layer is the sensing and protection layer such as partial discharge sensors, temperature sensors, pressure or gas monitoring, breaker travel measurement, arc flash detection, numerical relays and intelligent electronic devices. The third layer is the communication and control layer, covering station networks, SCADA, advanced distribution management system, time synchronisation and remote switching. The fourth layer is the analytics and governance layer, covering data historians, asset health indices, digital twins, cybersecurity monitoring, maintenance planning and executive reporting.Digital twins are becoming more and more important for distribution networks. A digital twin can merge network topology, switchgear status, operating history, loading patterns and condition indicators to simulate asset behaviour and help in maintenance decisions. Digital twins can help in voltage management, phase imbalance analysis, feeder planning and distributed resource coordination in LV networks. They can support outage simulation, protection studies and reliability-based asset management in MV networks. Recent work on low-voltage digital twins indicates the increasing importance of sensors, data processing and operational models in distribution automation (Peng et al., 2025). Automation must be kept in human control. Remote switching and self-healing schemes can reduce the duration of outages, but must be designed with operating rules, safety interlocks, cybersecurity, crew coordination and contingency procedures. Re-energizing of automated feeders shall not energise unsafe sections, conflict with maintenance permits, or compromise protection selectivity. Modernisation should therefore include re-designing of operating procedures, training, simulation and staged commissioning. Before large-scale deployment, Saudi utilities and large industrial operators can benefit from pilot projects that validate automation logic on specific feeders.

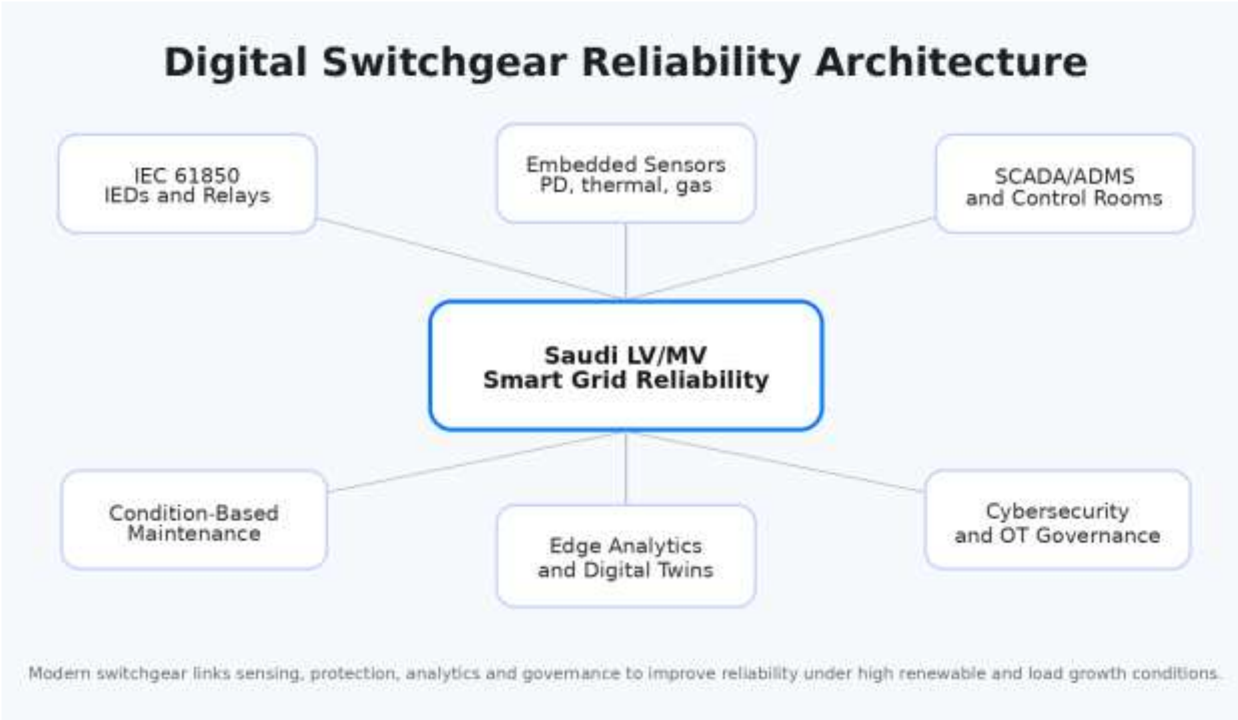

Figure 1. Digital switchgear reliability architecture for Saudi LV/MV networks.

VII. CYBERSECURITY, SAFETY AND LIFECYCLE GOVERNANCE

Digital switchgear provides new reliability benefits, but also increases the cyber-physical attack surface. The connectivity of legacy switchgear was limited externally, while modern equipment can communicate through station networks, remote access links, cloud analytics platforms and vendor maintenance channels. This brings risks of malicious commands, data manipulation, malware, time synchronisation attacks, insecure engineering laptops and compromised firmware. Systematic reviews on digitised substations highlight the importance of securing IEC 61850 communication services, protecting GOOSE and sampled value messages, and aligning cybersecurity with operational reliability (Silveira et al., 2023). Treat cybersecurity as a design requirement, not an afterthought. Key controls include network segmentation, role-based access, secure remote access, patch management, configuration baselines, logging, anomaly detection, backup engineering files, firmware governance, and incident response procedures. As switchgear is safety critical, cybersecurity decisions must consider operational continuity. Aggressive IT-style patching may not be suitable if it disrupts protection systems, and poor patch governance can leave known vulnerabilities unpatched. Therefore, a risk-based OT cybersecurity model is needed.The safety governance is equally important. Digital devices should improve safety through less manual switching, better arc-flash detection, remote isolation support and improved fault information. However, operators need to trust the information that is shown. Hazard can be created by incorrect sensor calibration, mislabelled equipment, poor data quality or communication failure. Therefore the modernisation programme must include commissioning tests, data validation, label verification, protection setting governance and maintenance of digital documentation. “Asset information should not be a records function but an operational control.Procurement logic shifts to life cycle governance. Traditional purchasing may be on initial switchgear price, but digital switchgear value is based on total lifecycle cost, spare parts, software support, cybersecurity updates, interoperability, training and data ownership. Equipment purchased without open communication capabilities could be a stranded asset. On the other hand, overly complex

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systems may not be functional if the organisation lacks the skill or capacity for maintenance. The best way is to state functional requirements: monitoring requirements, communication interfaces, data formats, cyber security controls, maintainability, environmental ratings, testing obligations and integration deliverables. Saudi Arabia has an opportunity to link the modernisation of digital switchgear to localisation. Local panels, system integration, testing services, retrofit kits, protection studies, cybersecurity assessment, sensor installation and analytics support can all be developed in domestic capability. This is in line with the broader industrial development rationale of Vision 2030. Saudi organisations can build engineering capability around standards, commissioning, data interpretation and lifecycle support, rather than depend solely on imported digital packages. Such capability is critical since reliability improvements require long-term operational excellence and not a one-time installation (Khan et al., 2023; SEC, 2025).

VIII. STRATEGIC MODERNIZATION FRAMEWORK

A practical modernisation framework for Saudi LV/MV switchgear should be progressive rather than a universal replacement. The initial phase is asset and criticality assessment. Utilities and industrial operators should determine which substations and feeders serve critical loads, have chronic failures, operate near thermal limits, connect renewable generation, or have harsh environmental exposure. This phase should incorporate maintenance history, outage records, inspection data, load growth forecasts and customer criticality. The result is a risk-ranked modernisation plan.The second phase is selective retrofitting. Not all assets need be replaced immediately. Many of the existing switchgear installations can be upgraded with partial discharge sensors, thermal monitoring, motor operators, numerical relay upgrades, arc-flash systems or communication gateways. The focus should be on retrofitting equipment that has mechanical life left but cannot be seen. The replacement should be reserved for assets with obsolete insulation, inadequate ratings, unsafe design or poor maintainability. This approach balances gains in reliability with capital discipline.The third step is system integration. Data from digital switchgear has to be delivered to the decision-making systems. For utilities, this means integrating with SCADA, outage management systems, advanced distribution management systems and asset management platforms. These can include plant electrical monitoring systems, computerised maintenance management systems, and reliability dashboards for industrial operators. Data integration should include naming standards, time synchronisation, alarm management and event classification . If it is not integrated, condition monitoring can become a passive data archive instead of a proactive reliability tool.“Fourth stage is analytics and decision intelligence. Asset health indices can include insulation condition, temperature, loading, breaker operations, fault history, age and environmental exposure. These indices should aid in maintenance scheduling, replacement planning and investment justification. Introduce predictive analytics cautiously, start with explainable models and validated thresholds. Black-box models can decrease trust if engineers don’t understand why an alarm is raised. Pilot feeders, parallel testing and comparison between algorithmic alerts and field inspection results enable Saudi organisations to gain confidence. Stage five is governance and scale-up. Standardised specifications, training modules, cybersecurity baselines and procurement templates should result from successful pilots. Governance must specify data ownership, who approves changes to protection settings, who responds to alarms, how cybersecurity incidents are handled, and how the benefits of modernisation are quantified. Key performance indicators may include outage duration, fault localisation time, percentage of monitored critical feeders, reduction of maintenance backlog, switchgear failure rate, reduction of arc-flash risk and avoided emergency replacement costs. These indicators turn modernisation from a technology programme into a reliability improvement programme.

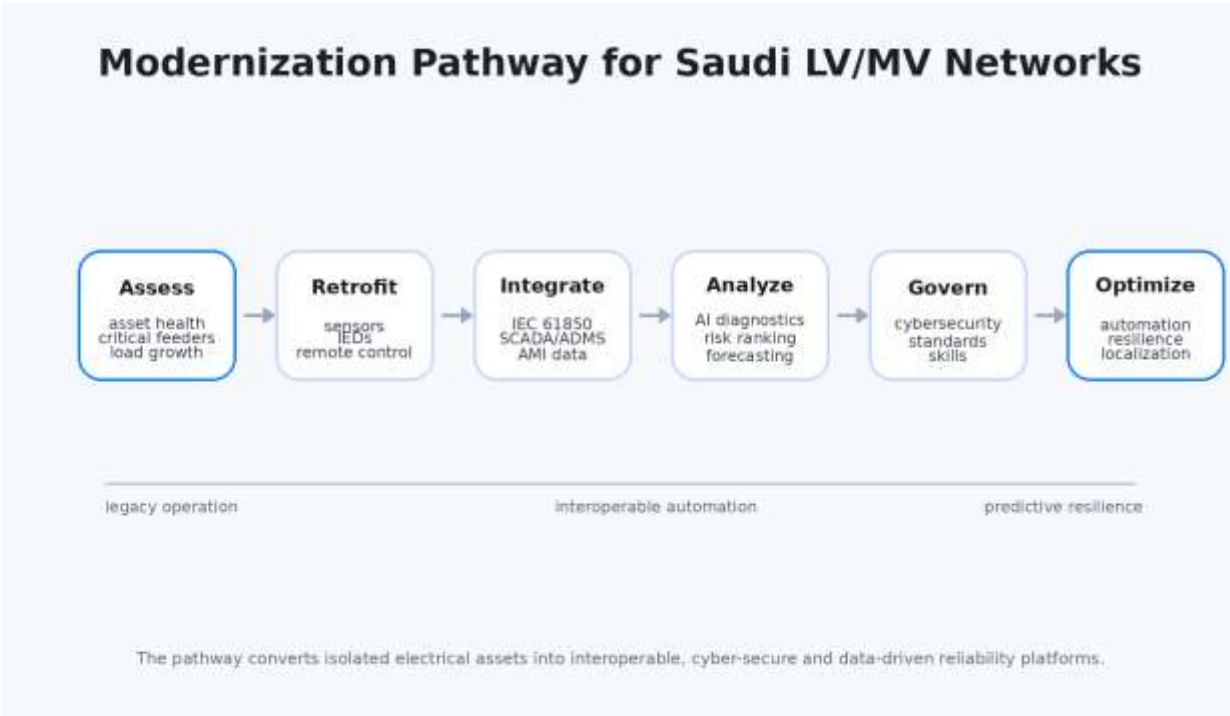

Figure 2. Staged modernization pathway from legacy switchgear to predictive smart grid reliability.

IX. DISCUSSION

The review indicates that the digital switchgear modernisation can greatly support Saudi Arabia's smart grid reliability, but only if implemented as a holistic transformation. The greatest value comes in increasing visibility over assets that were previously maintained through periodic inspection and reactive repair. In LV/MV networks many faults develop invisibly until breakdown of insulation, thermal failure or operation of protection occurs. Embedded sensing and event data can move maintenance from calendar-based activity to condition-based and risk-based decision making.

National policy and direction of infrastructure also support the Saudi modernisation case. Renewable energy targets, grid automation efforts, smart metre deployment and industrial diversification require a more observable and controllable distribution network (Saudi Green Initiative, 2024; SEC, 2025). Digital switchgear also supports energy efficiency and sustainability by minimising losses through poor connections, avoiding emergency replacements, extending asset life and improving the ability of networks to host renewable generation. These benefits align with Vision 2030, as reliable electricity is the backbone of industrial localisation, regional development and quality of life. The main risk is that implementation will be fragmented. Data structures and cybersecurity practices vary when each project chooses different vendor platforms, and that can lead to expensive complexity. So, standardisation is necessary. Saudi utilities, engineering consultants and industrial asset owners need to develop common digital switchgear specifications focusing on interoperability, lifecycle support and cyber secure integration. Standards should be flexible enough to accommodate different classes of networks but strict enough to prevent proprietary lock-in and data silos.Another important issue is the work force's ability. Digital switchgear requires engineers who know power systems, communication networks, OT cybersecurity, data analytics and maintenance planning. Training should be included in any modernisation contract. Saudi universities, technical institutes, manufacturers and utilities can cooperate to develop applied programmes on smart distribution equipment, IEC 61850 engineering, condition monitoring interpretation and cyber-physical reliability. This will ensure that modernisation is conducive to local capability, not just imported technology.

X. CONCLUSION

Modernisation of digital switchgear presents itself as a strategic approach to improve the reliability of the smart grid in Saudi Arabia's LV/MV electrical networks. The sensorized switchgear, intelligent protection, interoperable communication, remote operation, predictive maintenance, cybersecurity governance and digital twins can transform distribution assets from passive equipment to active reliability platforms, the review finds. These capabilities are particularly significant for Saudi Arabia where distribution networks must be capable of handling renewable integration, industrial growth, harsh environmental conditions and high service expectations.

The paper concludes that the priority for modernisation should be given to risk-based planning. Early attention should be given to critical feeders, industrial substations, renewable interconnection points and fast-growing urban districts. Life-cycle assessment should weigh retrofit versus replacement; data integration and cyber security should be designed in from the beginning. "The biggest benefits will come from linking digital switchgear with SCADA, asset management, maintenance planning and the development of workforce capabilities." In this sense, digital devices per se are not realising smart grid reliability. This is achieved through the creation of an operational system where trusted data, reliable equipment, skilled people and disciplined governance come together to enable the Saudi Arabia's Vision 2030 energy transformation.
This concluding synthesis reinforces that modernisation worth hinges on pragmatic engineering discipline, reliable operational data, transparent accountability, phased deployment, environmental resilience, cybersecurity assurance, lifecycle procurement, workforce training, and ongoing performance review for each chosen feeder, panel, substation and associated control platform. Future Saudi programmes should also set measurable baselines before the start of modernisation since reliability improvement cannot be demonstrated without evidence prior to upgrade. The baseline should include outage duration, switching time, recurring feeder alarms, thermal violations, partial discharge activity, protection misoperations, maintenance response time, spare-part availability, and critical customer exposure. Once baselines are established, digital switchgear data can be used to measure improvement and justify further investment. Failure mechanisms are different for desert substations, coastal substations, urban substations and industrial substations and the best projects will combine conventional equipment specifications with local engineering judgement. So, a national approach to modernisation should allow common architecture but flexible rules for deployment. For Saudi Arabia, it is important to strike this balance, as the distribution network needs to be reliable, while allowing renewable integration, industrial localisation and the service expectations of rapidly growing cities. The review also implies that smaller LV assets should not be overlooked. LV panels feed buildings, hospitals, commercial areas and industrial auxiliaries where a failure could interrupt essential services although MV switchgear receives more attention. LV monitoring, thermal sensing, power quality measurement and remote alarms can complement MV automation and provide end-to-end visibility from the primary substation down to the customer-side assets. Finally, modernisation must be viewed as a continuous learning experience. Lessons learned from each completed project should include sensor performance, communication reliability, alarm quality, operator acceptance, maintenance savings, and cybersecurity resilience. These lessons should be fed back into specifications, training and investment planning so that each new phase is more mature than the one that preceded it. This approach makes the digital switchgear modernisation a scalable capability instead of a series of one-off equipment upgrades for Saudi operating regions.

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Table 1. Review dimensions for digital switchgear modernization in Saudi LV/MV networks

Review dimension	Key focus	Reliability relevance	Saudi application
Asset condition monitoring	Partial discharge, thermal rise, breaker operation, gas/vacuum condition	Early warning of insulation, contact and mechanical defects	Critical feeders, industrial substations and harsh-weather installations
Protection and automation	Numerical relays, remote switching, feeder automation and fault records	Improves selectivity, fault isolation and restoration speed	Urban districts, renewable interconnections and industrial zones
Interoperability	IEC 61850, gateway mapping, time synchronization and naming standards	Prevents isolated digital silos and improves data trust	Multi-vendor Saudi utility and industrial networks
Analytics and maintenance	Health indices, predictive maintenance and risk-based replacement	Reduces emergency outages and prioritizes capital spending	Aging assets, high-load feeders and reliability-critical customers
Cybersecurity governance	Network segmentation, secure access, logs, firmware and incident response	Protects cyber-physical operations and switching authority	Digital substations, remote operations and vendor-connected systems

Table 2. Barriers, enablers and strategic responses for modernization

Barrier	Impact on reliability	Enabler	Strategic response
Legacy non-communicative switchgear	Limited visibility and slower fault diagnosis	Retrofit sensors and gateways	Prioritize high-risk feeders before full replacement
Vendor-specific platforms	Data silos and costly integration	Open standards and interface specifications	Require interoperable data models in procurement
Weak OT cybersecurity controls	Risk of unauthorized commands or data manipulation	IEC 62443-based governance and secure remote access	Apply segmentation, logging, roles and incident drills
Limited analytics capability	Condition data not converted into maintenance action	Asset health indices and explainable models	Train engineers and validate models through pilot projects
Harsh climate exposure	Accelerated thermal, dust and corrosion-related degradation	Environmental monitoring and ruggedized equipment	Specify thermal, humidity, dust and corrosion requirements
Capital-cost focus	Underinvestment in lifecycle value	Lifecycle costing and reliability KPIs	Measure avoided outages, faster restoration and lower emergency maintenance

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