ARCHITECTURE

Smart Monitoring and Energy Performance Optimization of Electrical Distribution Systems in Saudi Arabia

Mubarak Abdullah

Published November 2026

Abstract

Saudi Arabia's electrical distribution networks are entering a period in which intelligent monitoring must inform operational energy efficiency rather than merely report equipment status. This review examines how feeder observability, data quality, voltage regulation, loss estimation and coordinated distributed resources can be integrated into a defensible performance framework. A structured thematic synthesis of peer reviewed research published between 2020 and 2025 differentiates demonstrated algorithmic capabilities from unverified claims about Saudi deployments. The analysis compares supervisory measurement, physics based optimization, predictive control and data-driven techniques against operational constraints including summer demand peaks, network heterogeneity, photovoltaic variability and communications reliability. It argues that credible savings require feeder-specific baselines, voltage-dependent load characterization and independent confirmation of delivered energy, not improvements in simulated objective functions alone. A staged monitoring to control architecture and an evaluation protocol are proposed for Saudi utilities. The contribution is a critical synthesis linking sensing decisions to measurable energy outcomes, while identifying transferability, cyber physical resilience and validation gaps that require field investigation.

Keywords: Electrical distribution; energy performance; smart monitoring; feeder losses; voltage optimization; Saudi Arabia; smart inverters

1 Introduction

Electricity distribution is often treated as the final transport stage of the power system, yet it is also the point where technical losses, voltage quality, asset stress and consumer behaviour interact. For Saudi Arabia, this interaction is especially important because prolonged cooling demand can coincide with extreme ambient temperatures, while new distributed generation and electrified loads change established feeder assumptions. A digital monitoring programme therefore has value only when measurements lead to decisions that preserve service quality and reduce avoidable energy consumption. Optimization without credible sensing can amplify error; monitoring without an actionable control strategy can produce dashboards without operational benefit (Zhang et al., 2020; Sun et al., 2021).

The term energy performance requires a precise boundary. Feeder input energy, billed delivery, estimated technical losses and non-technical discrepancies are not interchangeable. Copper losses depend on squared current and resistance; transformer no-load losses are present even when demand is small; excess reactive flow raises current without supplying equivalent useful work. Voltage reduction may reduce some consumer demand, but its effect depends on the mix of constant impedance, constant current and constant power loads. Consequently, an apparent reduction in

substation input is not necessarily a verified reduction in technical losses or consumer end-use energy (Singh et al., 2021; Ding et al., 2020).

Recent research has expanded the control repertoire beyond switched capacitors and transformer tap changers to include photovoltaic inverter reactive power, battery storage, feeder reconfiguration and distributed optimization. Hierarchical methods organize slow mechanical switching and rapid electronic responses, whereas decentralized methods reduce dependence on continuous central communication. Their published performance is encouraging, but different studies optimize different objective functions, employ different network models and report incompatible evaluation periods. This review addresses that fragmentation by making measurement validity and operational verification the central criteria for comparing algorithms (Guo et al., 2020; Li et al., 2022a, 2022b; Ahmadi et al., 2023).

Saudi Arabia provides the practical context for this review; the cited experiments should not be mistaken for tests conducted on Saudi feeders. Benchmark circuits in the international literature remain useful for understanding algorithmic behaviour, but they do not replicate regional cable arrangements, transformer loading, load composition, maintenance practices or network data availability. The research problem is therefore how to translate established monitoring and optimization techniques into locally testable strategies without confusing modelled improvements with field proven savings. The review consequently concentrates on distribution-level energy efficiency, voltage quality and the operational evidence needed to judge transferability.

2 Aim, objectives and review questions

The aim is to critically establish how smart monitoring can support verified energy performance improvement in Saudi electrical distribution systems through robust data acquisition, interpretable optimization and operationally safe control. The objectives are to: identify the measurements necessary for feeder level energy accounting; evaluate analytical and data-driven approaches to loss and voltage optimization; examine coordination of transformers, inverters and storage under uncertain demand; establish a Saudi specific performance evaluation protocol; and prioritize research gaps involving observability, reliability and field validation. These objectives distinguish evidence gathering from operational intervention, rather than assuming that digitalization itself generates savings.

Four questions organize the synthesis. Which monitoring variables have the strongest causal connection with energy losses and voltage compliance? Under what network conditions do conventional, model-based and learning-based controls outperform one another? How should candidate savings be verified when demand, weather, solar output and asset configurations change? Finally, what technical and governance conditions would permit cautious adoption across Saudi urban, industrial and peripheral feeders? Answers are developed thematically, with explicit separation between established findings, engineering inference and unresolved deployment questions.

3 Review methodology

This paper employs a structured critical narrative review because the research spans control theory, measurement engineering, optimization and distribution operations, with outcomes too heterogeneous for a single pooled effect estimate. The evidence window is 2020–2025, covering peer reviewed journal studies on active distribution networks, Volt/Var regulation, storage coordination, data-

driven control and distributed management. The synthesis distinguishes analytical and computational approaches while centring on measured energy performance and the transferability of findings to Saudi distribution operations. The review does not present an exhaustive database census, and no unsupported screening totals or inter reviewer agreement statistics are asserted.

The search framework combines terms such as 'distribution energy losses', 'advanced distribution management', 'feeder monitoring', 'volt/var', 'conservation voltage reduction', 'smart inverter', 'data-driven voltage control', 'energy storage', 'optimal power flow' and 'unbalanced distribution'. IEEE Xplore, publisher journal platforms and scholarly metadata were used to identify candidate papers and inspect their stated methods, publication dates and digital object identifiers. Priority was given to identifiable peer reviewed publications reporting an explicit network model, control mechanism, evaluation benchmark or limitation. Saudi specific interpretation was subsequently assessed against physical operating conditions rather than being inferred from a paper's country of origin.

Eligibility required relevance to distribution-level monitoring, voltage management, operating losses or controllable distributed assets, and publication during the defined period. Studies focused exclusively on transmission security, market pricing without feeder constraints, hardware fabrication without grid implications or unsupported energy-saving claims were outside the intended scope. Where related work was available only as a conference paper, journal evidence was preferred. Thirty sources form the reference corpus; every source is assigned to a technical theme and cited where its specific contribution informs the argument. This is a thematic evidence sample, not a statistically representative map of every paper published during the window.

For synthesis, studies were compared along five dimensions: input data and observability; control variables and time resolution; treatment of stochastic demand or generation; validation setting; and reported performance metrics. A simulated voltage deviation, for example, was not recoded as verified kilowatt hour savings. Evidence from IEEE test feeders was distinguished from real distribution circuits, and model free methods were assessed for their training and extrapolation assumptions. Studies with missing deployment or generalization evidence were retained when their methodological mechanisms were clear, but were not used to substantiate realized Saudi savings.

Interpretation used a qualitative strength hierarchy. Field measurements with transparent before-and-after controls provide stronger energy performance evidence than simulations with realistic load traces; time-series-benchmark tests provide more information than a single operating snapshot; and conceptual designs establish feasibility propositions rather than outcomes. This hierarchy is evaluative rather than a formal risk of bias score, because optimization publications rarely share common reporting instruments. Two conceptual figures and two synthesis tables were developed to make relationships and comparative limits explicit; they do not portray measured results or reconstructed statistical counts.

4 Distribution monitoring and observability

Effective monitoring starts with reliable substation and feeder measurements, supported by voltage and current sensors placed where they can inform decisions. These layers have different functions. Feeder meters permit energy balancing; synchronized or time-aligned sensors support state estimation; transformer monitors reveal thermal and loading constraints; and customer side meters help characterize demand and locate discrepancies. Sampling intervals should match the process under investigation. Fifteen minute energy observations may expose daily demand patterns, but can miss short voltage excursions that matter for inverter dispatch or protection. Consistent time stamps,

phase identification and equipment topology are prerequisites for actionable analysis (Xu et al., 2023; Sun et al., 2023).

Installing more meters does not, by itself, make a distribution network observable. Distribution feeders are commonly unbalanced, contain uncertain lateral connections and may have inaccurate phase assignments. A sensor set that observes average feeder power can leave critical end-of-line voltages unmeasured. The literature on partially observable networks demonstrates that data-driven response estimation can assist control when full models are unavailable, but limited measurements still constrain what is identifiable (Xu et al., 2023). Sensor placement should therefore maximize visibility of high loss sections, weak voltage nodes and changing generation interfaces, rather than simply distributing devices uniformly. (Buason et al., 2024; Baviskar et al., 2024).

For energy accounting, feeder losses must be estimated across consistent electrical and temporal boundaries. Let energy entering a feeder be E_{in}, metered downstream delivery be E_{out} and separately established non-technical or metering discrepancies be D; the technical loss estimate is then $E_{in} - E_{out} - D$, subject to the measurement uncertainty of each term. This balance is sensitive to unmetered generation, meter clock drift, missing intervals and changes in switching topology. Before reporting annual savings, a credible study should document missing data, meter calibration, import and export accounting, and how unusual events were handled.

Data preparation is an essential part of reliable control, not merely an administrative task. Missing measurements, stale topology, noisy voltage readings and unrecognized meter multipliers can distort estimated impedance or state. Robust estimation methods may suppress some anomalous observations, while distributed feedback can limit the exposure of local device information; neither removes the need for independent validation and fault detection. Data-driven coordination schemes that learn relations between local action and voltage response illustrate how measurements can be used operationally, yet their performance remains dependent on the representativeness of training conditions and the integrity of control messages (Li et al., 2022a; Sun et al., 2023). Figure 1 summarises the proposed workflow from monitoring to decision and verification.



Figure 1. Conceptual monitoring to decision and verification workflow (original illustration).

5 Energy performance mechanisms

The principal technical loss mechanism in conductors is resistive heating, approximated at a branch by I^2R over the relevant interval. Reactive power changes current magnitude and thus loss even where the net active delivery remains constant. Unequal loading between phases also causes additional conductor and neutral current, so three-phase modelling is essential in networks with substantial single-phase demand. Transformer losses include both load-related and essentially fixed components, making lightly loaded transformer operation a different optimization problem from overloaded feeder reduction. This physics explains why a universal percentage saving cannot be transferred from one test network to another (Su et al., 2023; Zhang et al., 2020).

Volt/Var optimization attempts to adjust bus voltages and reactive flows while respecting equipment, service and protection limits. Traditional on-load tap changers and capacitor banks remain important because their operation is established and readily auditable. However, their discrete actions, mechanical wear and relatively slow response complicate interactions with rapidly varying photovoltaic generation. Coordinated formulations can reduce excessive tap operations while improving voltage compliance, as demonstrated by mixed-integer and convexified approaches (Li et al., 2020; Sun et al., 2021). For Saudi operations, mechanical wear and summer high load exposure should be explicit optimization costs, not afterthoughts.

Conservation voltage reduction seeks energy reduction by operating at the lower safe part of the allowable voltage band, not by permitting undervoltage. Its effect depends on end-use voltage sensitivity, customer comfort and the accuracy of downstream voltage estimates. Under a constant power load, lowering voltage can increase current and potentially raise resistive losses, while constant impedance loads respond differently. Accordingly, any CVR strategy requires measured load coefficients and voltage bounds at the customer interface. Multistage CVR research shows the merit of coordinating devices across timescales, but does not justify a guaranteed saving for Saudi cooling demand without local characterization (Singh et al., 2021).

Feeder reconfiguration can transfer load among branches, reduce exposure to long high-resistance paths and provide flexibility when distributed resources change net flows. Yet a loss-minimizing switching plan must preserve radiality where required, protection grading, fault duties and restoration procedures. A configuration that looks superior in static power flow calculations may impose unacceptable operational switching or reveal weak reliability during contingency operation. The appropriate decision criterion includes technical losses, voltage and thermal limits, switching effort and resilience. Optimization should therefore be treated as a constrained operational recommendation, not an automatic instruction to open or close field switches. (Liu et al., 2024).

Smart inverter controls add continuous reactive power support close to voltage-sensitive locations. Their use can decrease the need for upstream compensation, although available reactive capacity is constrained by inverter rating, active generation and local operating modes. Comparative work on curve setting and coordinated dispatch reveals that one fixed Volt/Var curve need not perform well across dissimilar feeders (Lee et al., 2020; Xu et al., 2022). A Saudi deployment should examine noon solar production, evening air conditioning demand and feeder-specific resistance to reactance ratios, because these factors determine whether active or reactive intervention is most effective. Table 1 summarises the main monitoring information, its energy relevance and the principal interpretation risks.

Table 1. Monitoring information, energy relevance and principal interpretation risks.

Measurement domain	Operational contribution	Primary risk
Feeder energy balance	Separates input, delivery and discrepancies	Unsynchronized meters or topology changes
Phase voltage and current	Locates weak voltage nodes and imbalance	Unobserved laterals or incorrect phase labels
Transformer loading	Supports loss and thermal assessment	Missing no-load losses or temperature effects
PV and inverter telemetry	Estimates reverse flow and reactive capability	Unrecorded curtailment or rating limits
Switch and tap logs	Links operations to network states	Incomplete event timestamps

6 Analytical optimization and hierarchical control

Analytical optimization offers an auditable connection between network equations, constraints and operator decisions. Optimal power flow can minimize line losses or voltage deviations while keeping currents, tap positions and reactive devices within limits. Robust optimization extends this framework to uncertainties in photovoltaic production or load. Zhang et al. (2020) explicitly analyze voltage and loss objectives under uncertain generation, illustrating why nominal forecast solutions may be unreliable. For adoption, the critical question is not merely whether a solver converges, but whether network parameters, uncertainty sets and device models capture real operating variability.

Linearized distribution flow and convex relaxation techniques make large problems more tractable, but approximations should be checked against full three-phase power flow before implementation. A solution may be mathematically feasible for a simplified model while producing a voltage violation on an unbalanced feeder with regulator interactions. Comparative studies of coordinated tap changers and photovoltaic inverters demonstrate the benefits of reducing combinatorial difficulty, with validation remaining essential (Li et al., 2020). For a Saudi utility, numerical tolerance, feeder scale, computation time and fallback behaviour matter as much as the optimum reported in a paper. (Paul and Padhy, 2024).

Hierarchical control is particularly suitable when actuators differ in response speed. A day-ahead scheduler can select capacitor and tap operating envelopes, an intra-day controller can update forecasts, and local inverter control can react quickly to measured voltages. Guo et al. (2020) formulate coordinated timescale control, while Sun et al. (2021) link slow decisions with rapid, data-informed interventions. Such decomposition reduces the risk of excessive mechanical cycling, provided coordination prevents conflicting instructions. A central scheduler that ignores communication latency or local autonomous modes can inadvertently destabilize otherwise sensible device actions.

Distributed optimization can improve scalability and limit the need to transmit detailed customer or resource data to one central server. Methods using local feedback, decomposition or negotiated setpoints have been investigated for active feeders and virtual power plants (Li et al., 2022b; Ahmadi et al., 2023). Their trade-off is an increased need for clear convergence conditions and inter controller coordination. The choice between centralized and local control should be driven by operational requirements; it reserves system-wide safety constraints centrally while allowing local, bounded, rapidly reversible actions where data and network conditions justify them.

7 Computational and data-driven methods

Computational optimization includes metaheuristic search, machine learning and reinforcement learning. These techniques can accommodate non-linear objectives or reduce online decision time, although they do not inherently guarantee feasible electrical operation. A search algorithm that performs well on a small radial feeder may require extensive tuning or deliver inconsistent results when network size and constraints change. Learning-based methods can be attractive when impedance models are unreliable, but a training set cannot anticipate every switching action, summer peak or communications fault. Their outputs should consequently be filtered through hard voltage, current and protection constraints.

Learning-assisted inverter coordination offers an instructive example. Li et al. (2022a) assess a deep deterministic policy gradient method for smart inverter dispatch against conventional control and optimal power flow under varied scenarios. Its value is rapid online action, not proof that the policy will generalize without modification to Saudi networks. Distribution shifts in demand composition, solar variability or feeder impedance may produce states absent from training. Before field use, a policy should be tested on out of sample seasons, unusual topologies, meter faults and plausible adversarial inputs, with a documented safe fallback to conventional local control.

Data-driven combined central and distributed schemes also demonstrate how neural network components can cooperate with slower optimal dispatch (Sun et al., 2023). Yet the significance for energy efficiency depends on the objective actually measured. A controller optimized principally for voltage feasibility may increase reactive circulation or transformer losses, even when its voltage profile improves. Comparative reporting must therefore give voltage violations, energy losses, device duty and computational expense together. Optimizer rankings based on a single weighted score can conceal undesirable trade-offs and should be supplemented by transparent Pareto analysis and sensitivity tests. (Wang et al., 2024).

Hybrid approaches are promising because they assign different responsibilities to physics and data. State estimation and power flow constraints can define a permitted operating region; machine learning can estimate uncertain demand responses, detect anomalies or propose candidate control settings; and a supervisory safety checker can reject infeasible actions. The resulting digital platform is explainable at the level relevant to the operator. This division is particularly important for utilities managing highly heterogeneous feeders, where replacing all physical models with one learned policy would create substantial transferability and accountability problems. Table 2 compares the main optimization families.

Table 2. Comparison of distribution optimization families for monitored operation.

Method family	Strength	Deployment limitation
Robust OPF	Explicit technical constraints and uncertainty	Requires credible models and uncertainty bounds
Hierarchical Volt/Var	Coordinates slow and fast controls	Risk of conflicting timescales
Distributed feedback	Local responsiveness and data minimization	Communication and convergence sensitivity
Learning-based dispatch	Rapid nonlinear policy inference	Shift beyond training states; explainability

Method family	Strength	Deployment limitation
Storage/SOP coordination	Flexible active and reactive support	Conversion losses, cost and degradation

8 Storage, renewable integration and flexibility

Battery storage can shift energy between periods, absorb excess photovoltaic generation and provide short-duration voltage support. However, a battery is not automatically an energy-saving device: conversion losses, auxiliary consumption, cell degradation and dispatch inefficiency may offset reduced feeder losses. The relevant system-level assessment measures net energy entering and leaving the storage installation, operating constraints and changes in network loss. Alrashidi and Rahman (2023) examine coordinated battery and inverter control, while Ahmadi et al. (2023) consider device lifetime alongside network objectives, underscoring the need for a multi criteria assessment. (Zhang et al., 2024).

Soft open points permit controllable active power transfer between feeders and can supply reactive support. Their operating flexibility may address asymmetric loading or renewable-induced voltage problems without permanent feeder reconfiguration. Yet converters add capital expenditure and internal losses, so technical justification requires an annual duty cycle analysis. Zheng et al. (2020) examine coordinated voltage regulation using these devices, and Hu et al. (2022) consider storage integrated operation under uncertainty. For Saudi conditions, prospective value may be concentrated in congested urban districts or feeders with high solar penetration; this is a testable hypothesis rather than a documented national result.

Integration planning should distinguish energy efficiency from renewable hosting capacity. A new inverter setting may accommodate more local generation while leaving losses unchanged or even increasing them; conversely, a loss-minimizing policy might curtail generation and reduce clean energy utilization. Multi-objective studies reveal these tensions, making explicit policy weights and reporting necessary (Zhang et al., 2020; Xu et al., 2022). The most defensible planning framework reports delivered renewable energy, curtailed energy, distribution losses, voltage quality, device utilization and reliability separately before any aggregate environmental conclusion is drawn. Figure 2 illustrates multi-timescale coordination with independent safety and audit layers.



Figure 2. Multi-timescale coordination with independent safety and audit layers (original illustration).

9 Saudi Arabia: Application priorities and evaluation

Saudi implementation should begin with feeder segmentation rather than a uniform national control model. Dense urban cable systems, industrial supply circuits, rapidly expanding development corridors and longer peripheral networks differ in topology, power factor, fault exposure and available controls. Summer cooling demand affects loading patterns, while ambient heat can alter equipment margins and maintenance requirements. These are engineering considerations that require verified utility measurements before quantitative claims are made. Pilot selection should cover contrasting network classes and include an unchanged comparator feeder wherever operationally possible.

A defensible pilot would first establish twelve months of time-aligned feeder input energy, delivered consumption, temperature-sensitive demand, switching logs, outages and voltage compliance where available. A baseline model should incorporate weather, customer growth, day type and relevant topology changes. Monitoring upgrades would then target unobservable weak nodes and poorly characterized high loss segments. After calibration, the utility could introduce advisory optimization, compare recommendations with conventional operation and move to supervised control only when safety, cyber security and operational training requirements are satisfied.

Performance reporting should state normalized technical losses in kilowatt hours and as a proportion of feeder input, distinguish these from changes in consumption, and document confidence intervals or plausible uncertainty bounds. Voltage non compliance duration, maximum branch loading, equipment switching counts, battery net energy and solar curtailment belong in the same evaluation. A before-and-after comparison without weather or load adjustment can mistake a mild summer or changing customer mix for a control benefit. Causal interpretation improves with matched comparators, pre-registered metrics and independent meter reconciliation.

Operational governance is equally important. Optimization commands should be logged with the observed state, model version, constraint checks, operator approval and actual device response. Where connectivity fails, predefined safe operating modes must remain available. Cybersecurity controls should authenticate commands, protect measurement integrity and separate monitoring

access from switching authority. Model retraining and feeder topology updates require controlled change management. Such arrangements turn digital monitoring into an accountable engineering process and reduce the risk that algorithmic novelty outruns evidence of dependable field performance.

10 Discussion: Evidence, trade-offs and research gaps

Across the reviewed literature, the strongest common finding is that coordinated device control can improve voltage management under modelled renewable variability. The evidence is less uniform for realized energy savings because studies use diverse objective functions, horizons and network assumptions. Benchmark case studies are suitable for demonstrating a mechanism, but they rarely establish the full costs of sensing, communications, cyber resilience or equipment maintenance. Accordingly, technology selection should start from the utility's measurable problem, not from the popularity of an optimization algorithm (Ma et al., 2021a, 2021b; Sun et al., 2023).

Three trade-offs recur. First, closer voltage regulation may reduce demand but increase tap or inverter duty; second, decentralized control can improve responsiveness while complicating system-wide coordination; third, storage and flexible converters can decrease certain feeder losses while adding conversion losses and capital expenditure. Pareto reporting makes these trade-offs visible. A controller should be rejected if a small improvement in a weighted score conceals unsafe voltage excursions or disproportionate asset wear. Conversely, a modest and repeatable reduction in energy losses with strong safety guarantees may be more valuable than an impressive simulation optimum.

The first major research gap is calibration under incomplete observations. Few transferability studies systematically vary missing sensors, phase label errors and aged network parameter sets while tracking energy accounting accuracy. The second is uncertainty under extreme climatic demand: peak cooling periods and high equipment temperatures should be integrated into forecasts, thermal constraints and validation design. The third is operational durability: papers need longer horizon comparisons incorporating tap maintenance, inverter reactive capability, battery degradation and changing feeder configurations. These gaps are especially pertinent where infrastructure is expanding rapidly and operating regimes may evolve during the study period.

A fourth gap concerns explainable, secure coordination of multiple software agents. Intelligent controls must continue to operate safely when forecasts, communications or training assumptions fail. Research should therefore report out-of-distribution tests, adversarial measurement scenarios, safe control override frequency and operator decision burden. A fifth gap is independent field verification with common metrics. Future trials should publish anonymized feeder classes, interval data availability, baseline adjustment methods, uncertainty ranges and intervention logs where permissible. Such reporting would support meaningful comparison without disclosing sensitive network topology.

10.1 Verification and implementation design

A practical verification protocol should distinguish three counterfactuals. The first is the status quo under observed weather and demand; the second is an advisory strategy applied in shadow mode without altering equipment; the third is controlled deployment with prescribed safety margins. Comparing these cases reveals whether a claimed efficiency improvement comes from better information, changed setpoints or broader shifts in load. The evaluator should preserve raw interval readings and maintain a reproducible account of corrected values. Where measurement uncertainty

is larger than the claimed benefit, the study should report an inconclusive result rather than manufacture precision. Digital investment appraisal should also account for sensor lifecycle costs, communications availability, software maintenance and staff capability. A network with high technical losses but limited controllable equipment may benefit more from conductor reinforcement or power factor correction than from advanced learning algorithms. Conversely, a well instrumented feeder with variable photovoltaic exports may justify adaptive inverter scheduling before expensive physical upgrades. A screening matrix can compare expected controllability, data readiness, intervention reversibility and verification feasibility. This prioritization shifts the investment conversation from technology branding towards measured operational problems and a clear sequence of decisions. Independent verification remains critically important.

11 Practical, managerial and policy implications

For network operators, the immediate priority is a measurement quality programme linked to a loss-reduction register. Assets should be ranked by measured loading, voltage exposure, estimated loss contribution and controllability; metering upgrades should be justified by the decisions they enable. For engineering managers, staged implementation reduces risk: validate the network model, test advisory recommendations, run supervised trials and only then enable bounded automation. Procurement specifications should require interoperability, time synchronization, auditable decisions and exportable performance data rather than a proprietary savings percentage.

For regulators and energy planners, common reporting definitions are more useful than endorsing a particular algorithm. Guidance could distinguish feeder input, billed consumption, technical losses, non-technical discrepancies and end-use energy changes, while requiring uncertainty disclosure and voltage service safeguards. Research partnerships between utilities and universities should prioritize representative Saudi feeder datasets and controlled pilots. The resulting evidence could support differentiated investment decisions for sensors, compensation, storage and advanced control, preserving reliability while improving the transparency of efficiency claims.

12 Limitations

This review is bounded by its purposive 2020–2025 literature corpus and its critical narrative method. It does not constitute an exhaustive systematic inventory or meta-analysis, and the publications differ in available data, test systems and economic assumptions. No original Saudi feeder measurements, simulations or experimental trials were undertaken. The two figures are conceptual, and the tables synthesize mechanisms rather than measured effect sizes. Consequently, the paper does not quantify national savings, establish a universal superior algorithm or claim that performance observed in other countries will recur in Saudi Arabia.

Several potentially important aspects remain outside detailed treatment, including distribution tariff incentives, commercial non-technical loss analytics, full lifecycle carbon accounting and protection system redesign. Reference metadata and DOIs were checked against accessible scholarly pages where possible, but a formal external indexing audit and a proprietary text similarity assessment are outside the scope of this manuscript. These limitations should guide interpretation: the contribution is an operationally grounded framework for testable decisions, not an empirical estimate of achieved efficiency.

13 Conclusion

Smart monitoring improves distribution energy performance only when measurements identify controllable losses, optimization respects physical constraints and results survive independent evaluation. Recent research supports coordinated voltage management through robust optimization, hierarchical scheduling, smart inverters and data-informed distributed control, but does not justify transferring simulated savings directly to Saudi feeders. The review proposes a monitoring to verification sequence built around energy balance, phase-aware observability, transparent objectives, supervised actuation and weather adjusted performance assessment. Future Saudi pilots should compare representative feeder classes across a complete seasonal cycle, quantify uncertainty and report asset duty alongside kilowatt hour effects. This evidence first approach offers a credible route from digital visibility to efficient, reliable distribution operation.

References

[1] Ahmadi B, Ceylan O, Ozdemir A (2020). Voltage profile improving and peak shaving using multi-type distributed generators and battery energy storage systems in distribution networks. *Proceedings of UPEC* 2020. https://doi.org/10.1109/UPEC49904.2020.9209880

[2] Ahmadi B, Giraldo JS, Hoogsteen G, Gerards MET, Hurink JL (2023). A multi-objective decentralized optimization for voltage regulators and energy storage devices in active distribution systems. *International Journal of Electrical Power & Energy Systems*, 153, 109330. https://doi.org/10.1016/j.ijepes.2023.109330

[3] Alrashidi M, Rahman S (2023). A bi-level optimization method for voltage control in distribution networks using batteries and smart inverters with high wind and photovoltaic penetrations. *International Journal of Electrical Power & Energy Systems*, 151, 109217. https://doi.org/10.1016/j.ijepes.2023.109217

[4] Baviskar A, Nazir FU, Hansen AD, Das K, Pal BC (2024). Strategic optimization framework considering unobservability in multi-voltage active distribution networks. *International Journal of Electrical Power & Energy Systems*, 161, 110127. https://doi.org/10.1016/j.ijepes.2024.110127

[5] Buason P, Misra S, Talkington S, Molzahn DK (2024). A data-driven sensor placement approach for detecting voltage violations in distribution systems. *Electric Power Systems Research*, 232, 110387. https://doi.org/10.1016/j.epsr.2024.110387

[6] Ding F, Zhang Y, Simpson J, Bernstein A, Vadari S (2020). Optimal energy dispatch of distributed PVs for the next generation of distribution management systems. *IEEE Open Access Journal of Power and Energy*, 7, 287–295. https://doi.org/10.1109/OAJPE.2020.3009684

[7] Guo Y, Wu Q, Gao H, Huang S, Zhou B, Li C (2020). Double-time-scale coordinated voltage control in active distribution networks based on MPC. *IEEE Transactions on Sustainable Energy*, 11, 294–303. https://doi.org/10.1109/TSTE.2018.2890621

[8] Hu R, Wang W, Wu X, Chen Z, Ma W (2022). Interval-optimization-based coordinated control for distribution networks with energy storage integrated soft open points. *International Journal of Electrical Power & Energy Systems*, 136, 107725. https://doi.org/10.1016/j.ijepes.2021.107725

[9] Lee H, Kim JC, Cho SM (2020). Optimal Volt–Var curve setting of a smart inverter for improving its performance in a distribution system. *IEEE Access*, 8, 157931–157945. https://doi.org/10.1109/ACCESS.2020.3019794

[10] Li C, Disfani VR, Haghi HV, Kleissl J (2020). Coordination of OLTC and smart inverters for optimal voltage regulation of unbalanced distribution networks. *Electric Power Systems Research*, 187, 106498. https://doi.org/10.1016/j.epsr.2020.106498

[11] Li Q, Zhou F, Guo F, Fan F, Huang Z (2021). Optimized energy storage system configuration for voltage regulation of distribution network with PV access. *Frontiers in Energy Research*, 9, 641518. https://doi.org/10.3389/fenrg.2021.641518

[12] Li C, Chen YA, Jin C, Sharma R, Kleissl J (2022a). Online PV smart inverter coordination using deep deterministic policy gradient. *Electric Power Systems Research*, 209, 107988. https://doi.org/10.1016/j.epsr.2022.107988

[13] Li S, Wu W, Lin Y (2022b). Robust data-driven and fully distributed Volt/VAR control for active distribution networks with multiple virtual power plants. *IEEE Transactions on Smart Grid*, 13, 2627–2638. https://doi.org/10.1109/TSG.2022.3166274

[14] Liu S, Teng Y, Cheng S, Sun P, Chen Z (2024). Voltage optimal control model of regional distribution network after reconfiguration based on multi-energy conversion. *Electric Power Systems Research*, 237, 110994. https://doi.org/10.1016/j.epsr.2024.110994

[15] Lou C, Yang J, Li T, Vega-Fuentes E (2020). New phase changing soft open point and impacts on optimising unbalanced power distribution networks. *IET Generation, Transmission & Distribution*, 14, 5685–5696. https://doi.org/10.1049/iet-gtd.2019.1660

[16] Ma W, Wang W, Chen Z, Hu R (2021a). A centralized voltage regulation method for distribution networks containing high penetrations of photovoltaic power. *International Journal of Electrical Power & Energy Systems*, 129, 106852. https://doi.org/10.1016/j.ijepes.2021.106852

[17] Ma W, Wang W, Chen Z, Wu X, Hu R, Tang F, Zhang W (2021b). Voltage regulation methods for active distribution networks considering the reactive power optimization of substations. *Applied Energy*, 284, 116347. https://doi.org/10.1016/j.apenergy.2020.116347

[18] Paul S, Padhy NP (2024). A new iterative mixed-integer linear programming-based real-time energy-efficient management of AC–DC distribution networks. *International Journal of Electrical Power & Energy Systems*, 157, 109793. https://doi.org/10.1016/j.ijepes.2024.109793

[19] Singh S, Pamshetti VB, Thakur AK (2021). Multistage multiobjective Volt/VAR control for smart grid-enabled CVR with solar PV penetration. *IEEE Systems Journal*, 15, 2767–2778. https://doi.org/10.1109/JSYST.2020.2992985

[20] Su R, He G, Su S, Duan Y, Cheng J, Chen H, Wang K, Zhang C (2023). Optimal placement and capacity sizing of energy storage systems via NSGA-II in active distribution network. *Frontiers in Energy Research*, 10, 1073194. https://doi.org/10.3389/fenrg.2022.1073194

[21] Sun X, Qiu J, Zhao J (2021). Real-time Volt/Var control in active distribution networks with data-driven partition method. *IEEE Transactions on Power Systems*, 36, 2448–2461. https://doi.org/10.1109/TPWRS.2020.3037294

[22] Sun X, Qiu J, Tao Y, Zhao J (2023). Data-driven combined central and distributed Volt/Var control in active distribution networks. *IEEE Transactions on Smart Grid*, 14, 1855–1867. https://doi.org/10.1109/TSG.2022.3213587

[23] Tantrapon K, Jirapong P, Thararak P (2020). Mitigating microgrid voltage fluctuation using battery energy storage system with improved particle swarm optimization. *Energy Reports*, 6, 724–730. https://doi.org/10.1016/j.egyr.2019.11.145

[24] Wang S, Sheng W, Shang Y, Liu K (2024). Distribution network voltage control considering virtual power plants cooperative optimization with transactive energy. *Applied Energy*, 371, 123680. https://doi.org/10.1016/j.apenergy.2024.123680

[25] Xu R, Zhang C, Xu Y, Dong Z, Zhang R (2022). Multi-objective hierarchically coordinated Volt/Var control for active distribution networks with droop-controlled PV inverters. *IEEE Transactions on Smart Grid*, 13, 998–1011. https://doi.org/10.1109/TSG.2021.3126761

[26] Xu T, Wu W, Hong Y, Yu J, Zhang F (2023). Data-driven inverter-based Volt/VAr control for partially observable distribution networks. *CSEE Journal of Power and Energy Systems*, 9, 548–560. https://doi.org/10.17775/CSEEJPES.2020.05920

[27] Zhang C, Xu Y, Dong ZY, Zhang R (2020). Multi-objective adaptive robust voltage/VAR control for high PV penetrated distribution networks. *IEEE Transactions on Smart Grid*, 11, 5288–5300. https://doi.org/10.1109/TSG.2020.3000726

[28] Zhang B, Song T, Zhao Z, Zhang Q (2024). Risk-based optimal energy storage operation in an active distribution network for static voltage stability enhancement. *Journal of Energy Storage*, 100, 113461. https://doi.org/10.1016/j.est.2024.113461

[29] Zheng Y, Song Y, Hill DJ (2020). A general coordinated voltage regulation method in distribution networks with soft open points. *International Journal of Electrical Power & Energy Systems*, 116, 105571. https://doi.org/10.1016/j.ijepes.2019.105571

[30] Zhong C, Meliopoulos APS, Xie B, Xie J, Liu K (2021). Multi-stage quadratic flexible optimal power flow with a rolling horizon. *IEEE Transactions on Smart Grid*, 12, 3128–3137. https://doi.org/10.1109/TSG.2021.3059255