

Digital Metrology Framework for Improving Quality Control in High-Voltage Substation and Transmission Line Projects in Saudi Arabia

Abstract

The critical measurements for high-voltage substation and transmission-line projects are dimensional, electrical, geospatial, thermal, mechanical and documentary. Their reliability directly impacts safety, commissioning, asset performance and contractual acceptance. However, the current quality-control practices often treat measurements as isolated inspection records, but not as traceable electronic evidence with design tolerances, calibration status, uncertainty, location, responsible personnel, and corrective actions. The review synthesises recent research on digital metrology, machine-readable calibration, sensor networks, digital substations, point-cloud inspection, unmanned aerial systems, building-information-model-based quality control, and digital twins, to propose an integrated framework for high-voltage projects in Saudi Arabia. The proposed framework links calibrated field instruments and sensors to a regulated measurement-data layer, automated conformity rules, spatial models, and project-level quality decisions. Critical analysis shows that digitalisation improves repeatability and traceability only when measurement uncertainty, synchronisation, metadata integrity, interoperability and calibration provenance are explicitly preserved. The biggest opportunities in substations are in digitally traceable testing of protection, current and voltage measurements, equipment alignment, grounding, and commissioning evidence. UAV photogrammetry, LiDAR, thermal imaging and point-cloud comparison can be used to extend quality verification for transmission lines over corridors, towers, conductors, insulators, clearances and foundations. Saudi projects need a metrology-first digital architecture, not a technology-first approach, says the review. Every automated inspection result must remain linked to an identifiable measurand, a calibrated measurement chain, an uncertainty statement, acceptance criteria and auditable evidence.

Keywords: Digital metrology, High voltage substation, Transmission line, Quality control, Measurement uncertainty, Calibration, Digital twin, UAV, LiDAR, Saudi Arabia

1. Introduction

Saudi Arabia is undergoing rapid expansion and modernisation of its electricity infrastructure, as well as increasing the digital intensity of grid planning, operation and construction. The

deployment of smart grids, integration of renewables, automated substations and data-centric asset management underline the need to replace scattered inspection records with reliable digital measurement systems [29,30]. In high voltage projects, digitisation is of value only if the underlying measurements remain technically defensible. Digitally stored values can still be wrong due to instrument drift, inappropriate measurement range, inadequate sampling, coordinate registration error, environmental influences, operator technique, or loss of calibration provenance. Digital quality control should therefore be based on the fundamental concepts of metrology: traceability, stated uncertainty, repeatability, comparability and fitness for purpose, using automation and connected data. Digital metrology is not just electronic recordkeeping. Research on heterogeneous sensor networks has shown that networked measurements require explicit calibration and uncertainty information to fuse data to be comparable and reproducible [1]. Digital Calibration Certificates (DCCs) extend this logic by making calibration information machine-readable and thus reusable in industrial workflows [2-4]. Measurement quality should be carried through processing with the data, not just to the final report, as demonstrated by traceable sensor-network calibration [5] and uncertainty-aware data pipelines [6]. These principles are very applicable to substations and transmission lines where engineering decisions are increasingly being made based on measurements from total stations, GNSS, laser scanners, current and voltage transformers, protection test sets, thermal cameras, torque tools, drones, LiDAR, environmental sensors and intelligent electronic devices. Research into construction quality has revealed that the use of BIM-linked inspection, RFID, computer vision and point clouds can enhance defect localisation and reduce the requirement for subjective manual inspections [11-17]. UAV and LiDAR methods provide repeatable access to conductors, towers, insulators and right-of-way geometry within transmission corridors [18-24]. Research on digital substation also suggests that sampled values, process bus architectures and communications performance may be used for accurate testing, but they also can bring new data-quality and synchronisation issues to the table [25,26]. Digital twins connect models with live or as-built measurements, but real-world demonstrations show that imperfect models and measurement uncertainty can have material impact on outputs [27,28]. The basic problem is that these research streams are commonly treated as separate. The metrology literature is about reliable measurement infrastructure; construction informatics is about spatial quality and workflow; power-system research is about equipment behaviour and operational data; and UAV literature is

about inspection automation. All four are necessary for high voltage project quality. Accordingly, this review develops an integrated digital metrology framework for substation and transmission-line projects in Saudi Arabia with a focus on construction and commissioning quality and not routine operational maintenance. The intended contribution is a measurement-governance architecture that transforms field observations into traceable, spatially referenced, uncertainty-aware and auditable quality evidence.

2. Aim of the study

This paper presents a new approach to developing an integrated digital metrology framework based on recent peer-reviewed evidence. This framework can be applied to improve quality control for high-voltage substation and transmission-line projects in Saudi Arabia by integrating calibrated measurement systems, spatial digital models, automated acceptance logic, and auditable project-quality records. In the study, a conscious differentiation is made between a metrology framework and a generic digital-twin or inspection platform. The central question is whether every digital quality decision can be traced back to a valid measurand, a calibrated instrument or sensor chain, documented uncertainty, applicable tolerance and controlled data transformation.

3. Research Objectives

The review has five aims. First, the metrological requirements for digitised quality-control measurements are specified, i.e. traceability, uncertainty, calibration status, synchronisation and machine-readable meta-data. Second, it evaluates digital inspection technologies for substation civil, electrical, mechanical, protection and commissioning activities. Thirdly, it evaluates UAV, LiDAR, imaging and point-cloud methods for verification of transmission-line geometry and component quality. Fourth, it synthesises how BIM, digital twins, and structured quality data can link measurements to design intent and acceptance criteria. Fifth, it offers a model for implementation and governance that is specific to Saudi project conditions, with special attention to interoperability, robustness in tough environments, contractor control, and evidence for owner acceptance and lifecycle handover.

4. Questions for Research

The synthesis is guided by four questions: RQ1. What metrological controls are needed to get trustworthy digital quality evidence in high-voltage projects? RQ2: Which digital measurement technologies offer the best quality-control value across substations and transmission lines? RQ3: How to combine spatial models, calibration data, uncertainty and acceptance rules so that automated findings are auditable? RQ4: What technical, organisational and policy measures are needed for practical adoption in Saudi Arabian electricity projects?

5. Review Methodology

The research question covers topics from metrology, electrical engineering, construction informatics, remote sensing and asset digitalisation. Hence, a structured integrative review design was used. The search logic was designed to prioritise peer-reviewed journal and conference literature primarily published from 2020 to 2025. The core database families were Scopus- and Web of Science-indexed sources, with access available on publisher platforms, IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, Frontiers, and subject-specific journal portals. The search strings combined terms such as “digital metrology”, “metrological traceability”, “measurement uncertainty”, “digital calibration certificate”, “digital substation”, “IEC 61850 sampled values”, “construction quality inspection”, “BIM point cloud”, “laser scanning quality control”, “UAV transmission line inspection”, “LiDAR power line”, “insulator defect detection”, “digital twin power system” and “Saudi Arabia smart grid”. The inclusion criteria required a clear link to measurement quality, calibration, digital inspection, spatial conformance, high voltage assets, transmission inspection, digital substations, or digital twin data fidelity. Studies were excluded if they were not peer-reviewed marketing materials, lacked sufficient methodological detail to support synthesis, or were unrelated low-voltage consumer applications or purely algorithmic results without a plausible quality-control or measurement pathway. Both review and original-research papers were kept because the former indicates the maturity of the technology and the latter demonstrates practical limitations. The paper provided by the user was only a benchmark of academic writing and structure, and was not used in the present synthesis. Screening was qualitative, not based on fictitious counts. We searched candidate studies for

relevance, recency, publication venue, DOI validity and the relation between measured data and engineering decisions. Quality appraisal covered whether calibration or uncertainty was discussed, whether experimental or field conditions were described, whether validation data were reported, whether model-data alignment was discussed and whether limitations were acknowledged. The synthesis then clustered evidence into five themes: metrological trust infrastructure; substation measurement and commissioning; spatial construction quality; transmission-line remote inspection; and digital-twin integration.

Meta-analysis was not performed due to heterogeneity of reported outcomes including dimensional error, classification accuracy, localisation performance, latency, uncertainty, workflow efficiency and interoperability. Instead, a critical narrative synthesis was used to compare mechanisms, assumptions and implications for deployment. Methodological limitations include differences in voltage level, project phase, sensor accuracy, test environment and geographical context. Most of the available studies were not conducted on the Saudi high-voltage construction sites. Therefore, the recommendations are given as transferable engineering principles rather than claims of local performance.

6. Thematic Literature review and critical analysis

6.1 Digital quality as a basis of metrological reliability

The digitalisation does not replace metrological control. According to Eichstädt and Ludwig [1], sensor fusion without calibration, uncertainty and SI traceability can create seemingly rich data that are not reliably comparable. DCC research takes this a step further by converting the calibration evidence from static documents into machine-readable structures [2-4]. Industry demonstrations show that digital calibration data can be directly fed into asset and quality systems [7-10] thus reducing transcription errors and allowing software to determine if a measurement device was calibrated at the time a reading was taken. This principle should apply to laboratory instruments and to field devices such as insulation testers, micro-ohmmeters, relay test sets, torque tools, total stations, GNSS receivers, thermal cameras, clamp metres, earth-resistance testers and laser scanners for high-voltage projects. What's crucial is that the uncertainty must travel with the data. Prato et al [5] implemented a traceable method for a

network of digital accelerometers. Dorst et al. [6] propagated the uncertainty from the calibration through an automated data-processing pipeline. Their impact on project quality is significant: derived values, such as conductor sag, busbar offset, equipment verticality, clearance, phase-angle error, or thermal-anomaly severity, should not be assumed to be exact simply because software calculated them. The acceptance logic should compare the measured result and its uncertainty to the specification limits. If the uncertainty is large compared with the tolerance, the proper result may be “indeterminate, remeasure” rather than automatically passing or failing. Machine-readable calibration also leads to better governance. DCC architectures [2-4,7-10] allow for unique instrument identification, calibration date, result, uncertainty and digital integrity. For instance, a Saudi owner might require contractors to upload calibration metadata before the inspection forms could be activated. The system can prevent the use of expired equipment; flag instruments being used outside of their calibrated range and carry the certificate reference with every quality record. This would turn calibration from an occasional audit document into an active quality-control rule.

6.2 Digital metrology for substation construction and commissioning

The quality of a substation is a sum of geometric, mechanical, civil, electrical, protection and communication measurement. Traditionally, these domains are divided into different checklists. Digital metrology, in contrast, could provide a common evidence layer. Spatial methods can compare installed equipment, structures, trenches, foundations, bus supports, cable routes and clearances against coordinated design models. Studies on BIM-RFID have shown the advantages of linking physical elements with digital records and defects [11]. Image-based BIM inspections have shown the spatial localisation of identified defects in the project model [12]. Point-cloud studies are based on a more solid geometric basis, as they measure the as-built surface rather than photographs only [13-17].

Laser scanning can check foundation level, gantry geometry, phase spacing, equipment centerlines and bus alignment for substation primary equipment. But, raw point-cloud accuracy does not translate into measurement uncertainty. The error is attributed to scanner calibration,

target geometry, incidence angle, registration control, atmospheric conditions and coordinate transformations. So the most useful workflow is not “scan and compare”, but “calibrate, register, quantify uncertainty, compare against tolerance, then preserve evidence”. Point-cloud-to-BIM research [14,15] confirms that model registration is central to inspection performance; weak alignment can cause automated deviation maps to generate false defects. Dense scanning can also increase inspection coverage according to construction studies [13,16,17] but automated decisions still depend on segmentation and geometric assumptions. And then there is the layer of electrical commissioning that is added. In a digital substation, many of the analogue secondary circuits are replaced with sampled values and network messages. Tobar-Rosero et al. [25] showed that the process-bus protection testing can be performed with acceptable timing, but the communication traffic, the merging units and the interoperability should be taken into consideration. Saleh et al. [26] specifically assessed the quality of sampled-value data and concluded that digitised current and voltage streams can preserve relay performance when the measurement and communications chain is properly controlled. For project quality, the metrology record should therefore include time synchronisation, sampling configuration, instrument-transformer or sensor accuracy, merging-unit identity, network conditions, test-set traceability, firmware/configuration version and the protection setting under test.

This approach changes the nature of the inspection record. Instead of saving a relay test result as a separate PDF, it should be stored as a structured measurement object, including the injected quantities, measured operating time, permissible tolerance, uncertainty, associated IED and bay, configuration checksum, calibration identifiers, tester identity and corrective action history. This data model allows traceability through factory acceptance, site acceptance, commissioning and future troubleshooting.

6.3 Spatial quality control of transmission line construction

Transmission line quality is spatially distributed, and therefore subject to remote measurement. UAV-LiDAR research has shown that it is possible to capture corridor geometry and support automated power-line inspection [18]. At the same time, broader reviews illustrate the increasing use of UAVs for mitigating exposure, increasing coverage, and standardising inspection [19,20].

Methods from close-range UAV [21] and deep-learning extraction of single conductors from laser-scanning point clouds [22] show the increasing automation of the acquisition process. The most valuable use of construction quality is not just defect recognition but geometric conformance. A digital metrology workflow can verify tower location, verticality, cross-arm geometry, conductor attachment points, span geometry, clearance envelopes, foundation coordinates, and potentially sag profiles. The measured entities can be related to design alignment, approved profile data and geodetic control. The point-cloud model then becomes an auditable as-built measurement surface not a visualisation artefact. Repeated surveys can document progressive erection quality and systematic deviations before energization. Insulator image-based inspection shows its potential and limits. While Transformer-based and deep learning methods can detect insulator defects from UAV images [23,24], classification confidence is not a metrological result per se. The detection results are affected by image resolution, angle of view, illumination, dust, background complexity, label quality and domain shift. A robust quality framework should therefore distinguish between “algorithmic indication” and “verified nonconformity.” The former calls for targeted review or measurement; the latter requires confirmation against defined acceptance criteria. This distinction is important in Saudi conditions where dust, high solar loading, haze and high temperatures can change optical and thermal signatures.

6.4 Integration of measurements with digital twins and quality decisions

Digital twins are valuable because they link models and field data, but trust in them depends on both. Digital-twin architecture for real-time monitoring and diagnostics is presented by Xiong et al. [27], and Deakin et al. [28] demonstrate in an operational network context that imperfect measurement data and model uncertainty have a material effect on twin outputs. This is directly related to project quality: a digital twin should not obscure the pedigree of its measurements. Each data object shall maintain provenance, timestamp, coordinate reference, instrument identity, calibration status, uncertainty, processing history and approval status. Saudi smart-grid research highlights the strategic role of digital information and communication infrastructure [29,30]. In practice, this means that the data on construction quality should be designed for use throughout the life cycle. When a substation or line is handed over, the owner should receive not

only drawings and test reports, but a validated digital quality baseline. Verified coordinates, equipment identifiers, commissioning results linked to the calibration, scanned geometry, accepted deviations, unresolved concessions and configuration records. This baseline can then seed operation and maintenance digital twins without requiring the owner to rebuild asset truth from unstructured documents. The proposed architecture is shown in Figure 1. The acquisition layer is comprised of measurement devices and remote sensors; metrological trust is built through calibration and uncertainty metadata; spatial and asset models provide context for results; automated rules assess conformity; and governed workflows manage review, corrective action, acceptance, and handover. The architecture is designed to be deliberately closed-loop, with a failure or indeterminate result leading to a corrective action and a remeasurement using the same traceable data structure.

6.5 Acceptance Logic, Measurement Life Cycle and Evidence Integrity

A useful framework must be able to manage the whole measurement lifecycle, not only the field instrument. Before acquisition, the project shall specify the measurand, target tolerance, required uncertainty, reference system, environmental limits, sampling plan and acceptance rule. During acquisition, the system has to tag the result with the instrument identifier, calibration status, operator, time, asset, location and method. Keep a log of all transformations applied during processing, such as filtering, coordinate transformation, point-cloud registration, image enhancement, thermal correction, algorithmic classification, software version, and parameters used. When accepting, compare the result with the contractual limit using a decision rule that avoids false confidence when uncertainty straddles the boundary. Once accepted, the original measurement, processed result, reviewer action and any concession should be kept associated. This lifecycle is important because high voltage quality records typically pass through a number of systems. For example, a survey measurement can be exported from a total station, transformed into a project coordinate system, imported into BIM, compared with a design object, and summarised in a PDF report. Each transfer can cause loss of metadata. A similar problem occurs when relay-test software exports only a pass/fail report without preserving injected values, sampling settings, or device configuration. Digital metrology does this by building provenance into the result itself. The DCC concepts demonstrate that the calibration information can be

expressed in a machine-readable form [2-4,7-10]. The same principle applies to construction and commissioning measurements. Acceptance logic should also be based on risk. A small dimensional deviation in a non-critical support may require a routine review. However, a similar relative deviation in phase spacing, minimum electrical clearance, current-transformer polarity or protection timing can be of much greater consequence. Therefore, the digital rule engine should classify measurands by consequence, and require tighter uncertainty ratios, independent verification, or witness points for safety-critical items. This prevents automation from reducing engineering significance to a common check list.

6.6 Conditions for Saudi implementation

Saudi deployment requires special attention to environmental, scale and organisational interfaces. The large transmission corridors offer strong value for UAV and LiDAR coverage but the long distances also result in increased reliance on geodetic control, GNSS integrity, battery logistics and consistent acquisition procedures. Substation projects often include a mix of international OEM equipment and local civil and electrical construction, making interoperable identifiers and standardised data structures important for linking factory records, site measurements and final asset registers. The smart-grid development of the Kingdom creates a favourable digital environment [29,30], but project-quality systems should not assume that operational digitalisation automatically ensures the quality of construction data. The harshness of the environmental conditions strongly argues for explicit measurement metadata. Temperature influences instruments and materials, dust can obscure optical targets and insulator surfaces, solar radiation can complicate thermal interpretation, and atmospheric conditions can affect long-range optical observations. Instead of setting generic confidence thresholds, the Saudi pilot projects should set validated operating envelopes for each sensor and algorithm. Any data recorded outside of those envelopes should be flagged for confirmation, not accepted blindly. A practical national approach would start with a controlled set of critical quality use cases: substation foundation and equipment geometry, grounding measurements, protection commissioning, tower geometry, conductor clearance, and UAV-based visual inspection. There are a number of projects that could pilot standard data templates and uncertainty rules before broader mandates. Such a staged approach would allow owners to measure benefits, identify

integration problems, train contractors and laboratories, and refine specifications without
subjecting project delivery to immature automation. Figure 2 shows this sequence as a closed-
loop digital quality workflow from planning to handover.
Another requirement is version control of design tolerances. Quality decisions could be voided if
a drawing, protection setting, tower schedule or approved material changes following
measurement. The framework should therefore associate each inspection with the revision of the
requirement against which it was judged. Where a revision is the subject of a governing revision,
the records should be re-evaluated and/or put in review automatically. This is especially true in
fast-track projects where construction, engineering clarification and commissioning overlap.
Electronic signatures and role-based approval can preserve accountability, but technical
governance must be separate from simple access control. The system also needs to retain rejected
and superseded results, instead of overwriting them, as trend information can show recurring
problems with artistry, survey or calibration. Finally, dashboards should present pass rates, but
also uncertainty margins, remeasurement frequency, overdue calibration exposure and the share
of automated findings validated by engineers. These indicators are a more meaningful measure
of digital quality-system maturity than the total volume of data collected across all active
projects

Proposed digital metrology architecture for high-voltage project quality control

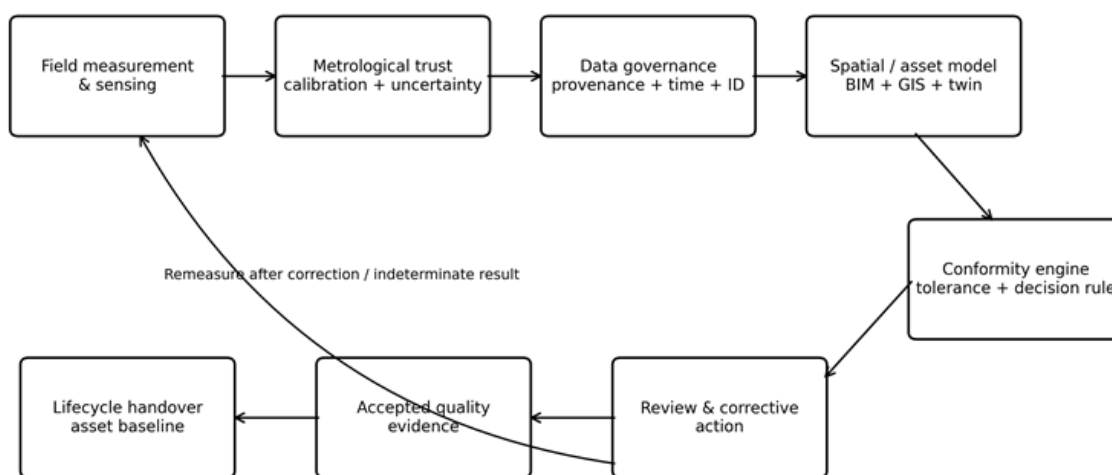


Figure 1. Proposed digital metrology architecture for high-voltage project quality control.

Closed-loop measurement and acceptance workflow

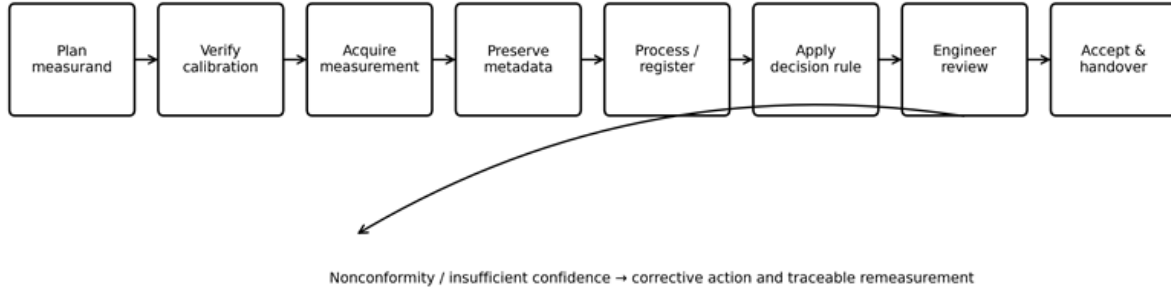


Figure 2. Closed-loop measurement and acceptance workflow from planning to lifecycle handover.

Domain	Representative measurands / evidence	Digital method	Required metrological control
Substation civil & geometry	Foundation level, equipment centerline, verticality, clearance, trench and gantry geometry	Total station, GNSS, laser scanning, point-cloud/BIM comparison	Survey control, scanner calibration, registration residuals, coordinate-system integrity, uncertainty vs tolerance
Primary electrical installation	Bus alignment, phase spacing, torque, contact resistance, grounding resistance, insulation values	Digital test instruments linked to asset IDs	Instrument calibration, range suitability, environmental correction, test method and timestamp
Protection & digital substation	Injected current/voltage, relay operate time, sampled values, GOOSE timing, settings	Relay test set, process-bus capture, structured commissioning records	Time synchronization, merging-unit identity, sampling configuration, firmware/settings version, uncertainty
Transmission structures	Tower position/verticality, foundation coordinates, attachment geometry, corridor clearance	UAV photogrammetry, GNSS, LiDAR point clouds	Geodetic control, sensor calibration, registration, flight conditions, accuracy statement
Conductors & insulators	Sag/clearance, conductor geometry, visible/thermal component condition	LiDAR, RGB/thermal UAV imagery, AI-assisted inspection	Resolution and range limits, environmental envelope, algorithm confidence separated from verified

			nonconformity
--	--	--	---------------

344

345

346

Table 1. Digital measurement domains and required quality controls.

UNDER PEER REVIEW IN IJAR

Maturity stage	Primary capability	Minimum governance requirement	Indicative outcome
1. Controlled measurement	Standard measurands and approved methods	Instrument register, calibration validity, defined tolerances and uncertainty targets	Comparable measurements across contractors
2. Digital evidence	Structured field capture and machine-readable calibration links	Unique asset/instrument IDs, timestamps, provenance and immutable source records	Reduced transcription loss and stronger auditability
3. Model integration	BIM/GIS/asset-register linkage with point clouds and test data	Coordinate/reference control, revision control, validated registration	Spatially contextualized quality decisions
4. Automated conformity	Rule-based screening and uncertainty-aware decision logic	Approved rule library, guard bands, exception workflow, human review thresholds	Faster and more consistent nonconformity detection
5. Lifecycle twin	Validated quality baseline supports operations and analytics	Handover schema, configuration governance, data-quality KPIs, change management	Reusable asset truth for maintenance and future upgrades

Table 2. Implementation maturity model for digital metrology in high-voltage projects.

7.Discussion literature leads to a clear conclusion: the main advantage of digital quality control is not only faster data collection, but the possibility of making measurements connected, comparable, searchable and auditable. Construction informatics studies show that BIM and point clouds can localise deviations [11-17]. Power-line research shows scalable remote acquisition [18-24]. The metrology studies add the missing requirement: measurements must be traceable and have an uncertainty [1-10]. Then studies on digital substations and digital twins reveal why timing, interoperability, model fidelity and data quality matter when decisions are automated [25-30]. The framework is especially applicable for Saudi high voltage projects where project portfolios can involve multiple EPC contractors, testing laboratories, OEMs, survey teams and subcontractors working over large geographical areas. In these cases, the inconsistency of measurement techniques can be as significant as the measured defect. You can reduce that inconsistency with a standardised digital metrology layer that defines the measurand, method, instrument class, calibration evidence, sampling or survey procedure, acceptance tolerance and required uncertainty before you start the work. The framework also shifts quality assurance from checking documents to governing data. Often the current practice is to check if a calibration certificate is available and if a report is signed. A digital approach can confirm the exact instrument was valid at the time of measurement, the instrument range was appropriate, the operator used the approved method, the measurement was spatially associated with the correct asset, and the acceptance rule was consistently applied. This is a stronger indication of owner acceptance and dispute resolution. However, automation must be selective. When control networks and registration quality are known, high confidence geometric checks such as tower coordinates or equipment offsets can be automatically screened. “Until performance is demonstrated for the specific site conditions, computer-vision indications should continue to be review-assisted. Protection and electrical test data can be automatically validated against numerical limits, but engineering review is still required when results are close to limits, configurations have been changed or materiality of any uncertainty. Thus, the framework provides for automatic triage and consistency, without eliminating professional judgement. Table 1 shows the main measurement domains and their digital-quality controls. Table 2 translates the evidence into a maturity model for implementation. They demonstrate that the order of technology deployment should be: (i) measurement governance; (ii) calibration and data capture;

(iii) spatial/model integration; (iv) conformity automation; and (v) predictive digital-twin functions, when data quality is demonstrably stable.

8. Research Gaps and Future Research Directions

There are several gaps. First, there is little published evidence of end-to-end digital metrology for high voltage construction projects. Existing studies usually optimise one stage – calibration, scanning, vision, relay testing, or digital-twin analytics – but do not validate the complete chain from instrument to acceptance decision. Future field tests should quantify the degree of uncertainty propagation through acquisition, registration, processing and rule-based conformity. Secondly, validation is limited and Saudi specific. Algorithms trained on temperate or visually clean environments may degrade under dust, glare, heat shimmer, high surface temperatures, and long distance atmospheric effects. Research should define rules for environmental correction and confidence in UAV imagery, thermal measurements, GNSS and LiDAR applicable to representative Kingdom conditions. Third, the interoperability between calibration systems, common data environments, BIM/GIS platforms, protection-test software and owner asset registers is still immature. Future work should include defining a vendor-neutral measurement schema with measurand, unit, uncertainty, calibration reference, location, asset identifier, timestamp, method, tolerance and approval state. DCC concepts provide a solid basis [2-10] but need to be extended to be specific to the construction and the grid. Fourth, acceptance rules should be defined in an uncertainty-aware manner. Most automated construction-quality research compares a measured deviation directly to a tolerance. In future systems, there should be guard bands or decision rules that consider measurement uncertainty, particularly where tolerances are tight or rework is expensive. Finally, research should look at lifecycle value. A controlled digital quality baseline may reduce future survey, troubleshooting, outage and maintenance effort. However, the economic case for the Saudi transmission and substation portfolios has not been quantified. Longitudinal studies should compare rework, commissioning delays, nonconformity closure time, claim frequency and handover completeness between conventional and digital-metrology-enabled projects.

9. Implications for Practice, Management and Policy

As a matter of practice, owners should specify a Measurement and Digital Quality Plan at tender stage. The plan shall define the critical measurands, the required accuracy and uncertainty, the approved methods, instrument classes, calibration data formats, coordinate systems, file naming conventions, asset identifiers and digital acceptance rules. “Once construction starts, contractors should not be able to pick incompatible measurement conventions. Managerially, responsibility for measurement integrity should be clear. The Survey, electrical testing, quality, BIM/GIS, and commissioning teams often report through separate lines. Master data, calibration rules, coordinate reference systems, instrument registers, uncertainty requirements and integration with the common data environment can be controlled by a governance board, or digital metrology lead at the project level. Quality dashboards need to differentiate measured non-conformities, algorithmic alerts, indeterminate results, concessions and closed corrective actions. At policy level, large transmission and substation programmes could require calibration evidence in machine-readable form and structured test results for critical measurements. Owner specifications should also require minimum metadata for UAV and laser-scanning surveys including ground control, registration residuals, sensor calibration, acquisition conditions and accuracy statements. For digital substations, the commissioning specifications should maintain the sampled-value configuration, time synchronisation, network state, firmware versions and device identities with the test results. The short-term goal should not be a fully autonomous digital twin. It has to be a trustworthy digital chain of custody. When that chain is solid, you can layer in advanced analytics without eroding confidence in the measurements that inform those analytics.

10. Limitations

The multidisciplinary nature of the evidence and the lack of a large body of Saudi field studies specifically on digital metrology in high-voltage construction are constraints on this review. Different sensors, accuracy metrics, datasets, voltage levels and validation conditions used in the included studies do not allow for quantitative pooling. Some digital-metrology publications describe industrial manufacturing rather than power infrastructure. They were included because the principles of traceability, machine-readable calibration and uncertainty propagation are directly transferable, but implementation details need to be adapted. Similarly, UAV and deep-learning studies demonstrate technical capability, but do not, in and of themselves, demonstrate contractual suitability for project acceptance. Thus, the proposed framework should be validated with controlled pilot projects before being used as a mandatory acceptance mechanism.

11. Conclusion

Digital transformation can improve the quality of high-voltage projects significantly, but only if it improves the measurement chain and does not obscure it. The evidence reviewed here shows complementary advances in machine-readable calibration, traceable sensor networks, uncertainty-aware data processing, BIM and point-cloud quality inspection, UAV and LiDAR transmission-line surveying, digital substations and digital twins. Together they provide a pragmatic path from discrete inspection records to controlled digital quality evidence . The proposed framework relies on a concept of metrological trust. Each critical result shall be associated with a defined measurand, calibrated device or sensor chain, uncertainty statement, asset and location, acceptance criterion, and immutable processing history. Substation applications are geometric verification, primary-equipment alignment, grounding and electrical tests, protection and sampled value commissioning and structured handover Transmission-line applications include tower and foundation geometry, verification of conductor and clearance, point-cloud as-built comparison, and risk-based UAV inspection. Automated analytics can improve coverage and consistency, but the confidence scores are not to be confused with verified measurements.

A phased approach is recommended for Saudi Arabia, starting with the standardisation of measurement governance and digital calibration, followed by the integration of spatial and commissioning data, automation of conformity checks, and finally the construction of lifecycle digital twins on top of the validated quality baseline. This chain connects digital ambition with engineering accountability. The outcome is a traceable decision architecture that reduces rework, improves commissioning evidence, enhances handover quality and gives asset owners a defensible digital representation of what was actually built and tested, not just a paperless inspection process.

References

1. Eichstädt, S., & Ludwig, B. (2020). Metrology for heterogeneous sensor networks and Industry 4.0. *Automatisierungstechnik*, 68(6), 459–464. <https://doi.org/10.1515/auto-2020-0059>

2. Gadelrab, M. S., & Abouhogail, R. A. (2021). Towards a new generation of digital calibration certificate: Analysis and survey. *Measurement*, 181, 109611. <https://doi.org/10.1016/j.measurement.2021.109611>
3. Basic, N., & Grasso Toro, F. (2021). PDF/A-3 solution for digital calibration certificates. *Measurement: Sensors*, 18, 100282. <https://doi.org/10.1016/j.measen.2021.100282>
4. Hackel, S., Härtig, F., Schrader, T., Scheibner, A., Loewe, J., Doering, L., Gloger, B., Jagieniak, J., Hutzschenreuter, D., & Öktem, G. S. (2021). The fundamental architecture of the DCC. *Measurement: Sensors*, 18, 100354. <https://doi.org/10.1016/j.measen.2021.100354>
5. Prato, A., Mazzoleni, F., D'Emilia, G., Gaspari, A., Natale, E., & Schiavi, A. (2021). Metrological traceability of a digital 3-axis MEMS accelerometers sensor network. *Measurement*, 184, 109925. <https://doi.org/10.1016/j.measurement.2021.109925>
6. Dorst, T., Gruber, M., Seeger, B., Vedurmudi, A. P., Schneider, T., Eichstädt, S., & Schütze, A. (2022). Uncertainty-aware data pipeline of calibrated MEMS sensors used for machine learning. *Measurement: Sensors*, 22, 100376. <https://doi.org/10.1016/j.measen.2022.100376>
7. Nummiliukki, J., Saxholm, S., Kärkkäinen, A., & Koskinen, S. (2023). Digital Calibration Certificate in an industrial application. *Acta IMEKO*, 12(1). <https://doi.org/10.21014/actaimeko.v12i1.1402>
8. Mustapää, T., Koskinen, S., Sundfors, M., Jonsson, J., Riska, K., Löytynoja, L., & Broo, J.-A. (2024). Enabling the use of digital calibration certificates in industrial calibration management systems. *Journal of Sensors and Sensor Systems*, 13, 71–82. <https://doi.org/10.5194/jsss-13-71-2024>
9. Engel, T., & Popescu, A. (2025). GEMIMEG – Digitalization of calibration processes in metrology. *Measurement: Sensors*, 38, 101474. <https://doi.org/10.1016/j.measen.2024.101474>
10. Janzen, K., & Heißelmann, D. (2025). Development of digital calibration certificates for coordinate metrology applications. *Measurement: Sensors*, 38, 101478. <https://doi.org/10.1016/j.measen.2024.101478>
11. Huo, H., Ji, Y., Xie, K., & Lu, Y. (2023). Design and application of intelligent construction quality inspection system based on BIM-RFID. *Advances in Civil Engineering*, 2023, 5638265. <https://doi.org/10.1155/2023/5638265>

12. Ma, G., Wu, M., Wu, Z., & Yang, W. (2021). Single-shot multibox detector- and building information modeling-based quality inspection model for construction projects. *Journal of Building Engineering*, 38, 102216. <https://doi.org/10.1016/j.jobbe.2021.102216>
13. Liu, Z., Liu, Z., & Sun, Z. (2024). Massive point cloud processing for efficient construction quality inspection and control. *Sensors*, 24(21), 6806. <https://doi.org/10.3390/s24216806>
14. Tan, Y., Chen, L., Huang, M., Li, J., & Zhang, G. (2024). Automated geometric quality inspection for modular boxes using BIM and LiDAR. *Automation in Construction*, 165, 105474. <https://doi.org/10.1016/j.autcon.2024.105474>
15. Liu, H., Liu, D., & Chen, J. (2024). Depth-informed point cloud-to-BIM registration for construction inspection using augmented reality. *Advanced Engineering Informatics*, 62, 102867. <https://doi.org/10.1016/j.aei.2024.102867>
16. Polat, H., & Ali, N. M. (2023). A case study of quality control application with BIM-laser scanning collaboration in building construction process. *Eastern-European Journal of Enterprise Technologies*, 5(2(125)), 56–66. <https://doi.org/10.15587/1729-4061.2023.289987>
17. Wu, K., Prieto, S. A., Mengiste, E., & García de Soto, B. (2024). Automated quality inspection of formwork systems using 3D point cloud data. *Buildings*, 14(4), 1177. <https://doi.org/10.3390/buildings14041177>
18. Guan, H., Sun, X., Su, Y., Hu, T., Wang, H., Wang, H., Peng, C., & Guo, Q. (2021). UAV-lidar aids automatic intelligent powerline inspection. *International Journal of Electrical Power & Energy Systems*, 130, 106987. <https://doi.org/10.1016/j.ijepes.2021.106987>
19. Li, X., Li, Z., Wang, H., & Li, W. (2021). Unmanned aerial vehicle for transmission line inspection: Status, standardization, and perspectives. *Frontiers in Energy Research*, 9, 713634. <https://doi.org/10.3389/fenrg.2021.713634>
20. Ahmed, F., Mohanta, J. C., & Keshari, A. (2024). Power transmission line inspections: Methods, challenges, current status and usage of unmanned aerial systems. *Journal of Intelligent & Robotic Systems*, 110, 54. <https://doi.org/10.1007/s10846-024-02061-y>
21. Wang, Q., Wang, W., Li, Z., Namiki, A., & Suzuki, S. (2023). Close-range transmission line inspection method for low-cost UAV: Design and implementation. *Remote Sensing*, 15(19), 4841. <https://doi.org/10.3390/rs15194841>

22. Zhu, S., Li, Q., Zhao, J., Zhang, C., Zhao, G., Li, L., Chen, Z., & Chen, Y. (2024). A deep-learning-based method for extracting an arbitrary number of individual power lines from UAV-mounted laser scanning point clouds. *Remote Sensing*, 16(2), 393. <https://doi.org/10.3390/rs16020393>
23. Cheng, Y., & Liu, D. (2022). An image-based deep learning approach with improved DETR for power line insulator defect detection. *Journal of Sensors*, 2022, 6703864. <https://doi.org/10.1155/2022/6703864>
24. Ahmed, M. F., Mohanta, J. C., & Sanyal, A. (2022). Inspection and identification of transmission line insulator breakdown based on deep learning using aerial images. *Electric Power Systems Research*, 211, 108199. <https://doi.org/10.1016/j.epsr.2022.108199>
25. Tobar-Rosero, O. A., Candelo-Becerra, J. E., & Zapata, G. (2022). Performance analysis of overcurrent protection in a digital substation with process bus. *Sustainability*, 14(13), 7958. <https://doi.org/10.3390/su14137958>
26. Saleh, S. A., Ozkop, E., Al-Durra, A., Hill, T., Meng, J., & Valdes, M. E. (2023). Effects of sampled-values data quality on responses of time-frequency based digital relays. *IEEE Transactions on Industry Applications*, 59(5), 5443–5452. <https://doi.org/10.1109/TIA.2023.3287811>
27. Xiong, J., Ye, H., Pei, W., Kong, L., Huo, Q., & Han, Y. (2022). A monitoring and diagnostics method based on FPGA-digital twin for power electronic transformer. *Electric Power Systems Research*, 210, 108111. <https://doi.org/10.1016/j.epsr.2022.108111>
28. Deakin, M., Vanin, M., Fan, Z., & Van Hertem, D. (2024). Smart energy network digital twins: Findings from a UK-based demonstrator project. *International Journal of Electrical Power & Energy Systems*, 162, 110302. <https://doi.org/10.1016/j.ijepes.2024.110302>
29. Khan, K. A., Quamar, M. M., Al-Qahtani, F. H., Asif, M., Alqahtani, M., & Khalid, M. (2023). Smart grid infrastructure and renewable energy deployment: A conceptual review of Saudi Arabia. *Energy Strategy Reviews*, 50, 101247. <https://doi.org/10.1016/j.esr.2023.101247>
30. Alharbey, R., Shafiq, A., Daud, A., Dawood, H., Bukhari, A., & Alshemaimri, B. (2024). Digital twin technology for enhanced smart grid performance: Integrating sustainability,

569 security, and efficiency. Frontiers in Energy Research, 12, 1397748.
570 <https://doi.org/10.3389/fenrg.2024.1397748>

571

UNDER PEER REVIEW IN IJAR