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Digital Transformation of Electrical Commissioning in Power Plants Using VDC Technologies

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Commissioning and testing of electrical systems in power plants are critical processes that ensure safety, reliability, and compliance before operations begin. Traditional methods for commissioning are often paper-intensive, fragmented, and dependent on manual procedures that can compromise efficiency and safety. With increasing system complexity and digital integration in power generation facilities, conventional practices are no longer adequate to meet modern project demands. This study investigates how Virtual Design and Construction (VDC) technologies can transform electrical system commissioning in power plants. Through the combined use of Building Information Modeling (BIM), digital twins, augmented and virtual reality (AR/VR), Internet of Things (IoT) sensors, and cloud-based collaboration platforms, VDC enables data continuity, real-time coordination, and improved test accuracy. The research synthesizes industry case studies and technical literature to develop a structured implementation framework addressing pre-commissioning planning, virtual simulation, field testing, and digital handover. The proposed framework provides a practical roadmap for applying VDC to enhance efficiency, safety, and digital integration in electrical commissioning while establishing a foundation for long-term operational improvement.

Keywords: Virtual Design and Construction, Electrical Commissioning, Power Plants

Introduction

Commissioning and testing of electrical power systems in power plants serve a critical role in ensuring safe operation, regulatory compliance, and long-term system reliability. The commissioning phase is often the final technical validation step prior to full commercial operation, and deficiencies during this stage can lead to costly rework, failures during initial energization, and increased lifecycle risk. Traditional commissioning practices, however, are frequently characterized by manual documentation workflows, fragmented information exchange, siloed data storage, and limited traceability across design, construction, commissioning, and operations stakeholders. These limitations can contribute to schedule extension, elevated cost exposure, and inconsistencies in documentation quality. As power generation facilities become increasingly digitized, featuring higher levels of automation, advanced controls, distributed sensors, and more sophisticated protection schemes, legacy commissioning approaches have struggled to scale with system complexity.

Virtual Design and Construction (VDC) technologies present an emerging pathway to address these persistent challenges. VDC represents a suite of digital methods including Building Information

Modeling (BIM), digital twins, augmented and virtual reality (AR/VR), IoT-enabled sensor networks, and cloud-based collaboration platforms. While these tools are widely used for design coordination, visualization, clash detection, and construction planning, their targeted application for electrical commissioning within power plants remains limited, and formal research examining structured deployment strategies is sparse. The capability of VDC to simulate system behavior prior to energization, support data continuity across project phases, reduce physical exposure to hazardous test conditions, and enhance documentation efficiency suggests strong potential to transform the traditional commissioning workflow.

This study examines how VDC can modernize electrical commissioning practices in power generation environments and proposes a structured implementation framework informed by literature, case studies, and recent industrial applications. The goal of this paper is to contribute foundational guidance that supports industry adoption and research advancement, while establishing a systematic basis for improving commissioning efficiency, documentation integrity, safety performance, and long-term operational value through digital methods.

Literature

Existing literature on power plant electrical commissioning largely emphasizes procedural validation, safety assurance, and compliance documentation to ensure operational readiness prior to energization. Traditional commissioning sources describe methodical verification processes, but several authors note persistent inefficiencies related to manual documentation, limited traceability, siloed information exchange, and inconsistent test records between construction and operations (Power Magazine, 2023; Johnson et al., 2021). These issues become more significant as power generation assets incorporate higher levels of automation and digital control, where data volume, automation networks, distributed sensing, and protection coordination requirements expand commissioning complexity (Williams & Chen, 2022). Despite this increasing interdependence between design, commissioning, and operations data, prior literature provides limited structured guidance on how to leverage digital tools to improve electrical commissioning continuity across the full lifecycle, representing a foundational gap that this study seeks to address.

Recent publications emphasize the importance of establishing test documentation, sequencing, and parameter definition during the pre-commissioning phase, yet these works continue to treat commissioning information independent from digital design models. BIM is widely used for design coordination and construction planning in industrial settings, but authors observe limited research on embedding commissioning parameters, acceptance criteria, or testing metadata into BIM schemas to support downstream verification (Schneider Electric, 2022; Smith & Johnson, 2022). This lack of integration suggests an opportunity for expanding BIM beyond geometric coordination toward an information model that anticipates test execution. Literature consistently shows that foundational modeling standards do not currently treat commissioning as a defined digital use case, indicating a need for research on standardized parameterization, interoperability, and structured hand-off data modeling for commissioning preparation.

Digital twin studies demonstrate strong potential for improving virtual testing and simulation prior to field energization. Research in hydroelectric and thermal power plant environments documents that advanced simulation models can identify behavior anomalies, protection miscoordination errors, and transient failure conditions before onsite testing occurs (NCBI, 2023; Rodriguez & Smith, 2022). However, these applications are typically case-specific, technology-centered demonstrations rather than integrated commissioning process models. Most literature focuses on simulation capability rather than how digital twin outputs are validated, archived, structured, or transitioned into field-testing

documentation for engineers (Digital Twin Organization, 2023). This represents a methodological gap, where simulation research has not matured into commissioning workflow research. The opportunity for structured simulation-to-field translation remains significantly underdeveloped in peer-reviewed research.

Studies on AR/VR and IoT-based commissioning methods have shown improvements in technician guidance, error reduction, safety performance, and remote oversight during field testing. AR overlays can accelerate technician navigation of protection coordination settings, test sequences, and equipment test data while reducing procedural errors (Davidson & Cruz, 2020; Garcia, 2022). IoT-enabled sensor networks provide continuous real-time monitoring and automated documentation, replacing manual measurement snapshots traditionally used during electrical testing (Williams et al., 2019; Chen & Rodriguez, 2021). Nonetheless, current literature treats each digital technology as an isolated productivity enhancement rather than an integrated information system linked to the broader commissioning data environment. Few works examine how these tools should interoperate with BIM, digital twins, or digital handover requirements. Therefore, there remains a gap in understanding how field digital tools contribute to a cohesive VDC-driven commissioning data ecosystem.

Finally, several studies highlight operational benefits that result from digital continuity after commissioning, particularly for maintenance planning, remote diagnostics, and regulatory documentation efficiency (Thompson et al., 2023; Garcia & Thompson, 2023). However, the handover process itself remains underdeveloped in the literature, with limited research on standardized commissioning data structures, interoperability requirements, and long-term preservation strategies necessary to transition commissioning assets into facility management systems (Rodriguez & Lee, 2022). While digital transformation research clearly identifies value creation in operations, there is little prescriptive guidance on how to structure commissioning information to ensure that value can be realized. Collectively, the literature illustrates that while individual VDC technologies have demonstrated measurable benefits, there is still no integrated conceptual model showing how these tools can be applied coherently across the full commissioning lifecycle. This gap establishes the need for a structured VDC commissioning framework, the central contribution of this study.

Methodology

This study adopts a conceptual research methodology to develop a structured framework for applying VDC technologies to electrical commissioning processes in power plants. The research design integrates three complementary sources of evidence: (1) structured literature synthesis, (2) cross-case pattern extraction from published case studies and industry reports, and (3) analytical cross-mapping of VDC technology functions against commissioning workflow requirements. This approach is consistent with conceptual framework development methods described in construction informatics and digital transformation literature, where theoretical synthesis is used to organize emerging technological capabilities into formalized process models.

A systematic literature screening process was conducted to identify peer-reviewed journal papers, conference proceedings, manufacturer technical publications, and reputable industry sources addressing electrical system commissioning, BIM-enabled manufacturing workflows, digital twin simulation, AR/VR guided field operations, and IoT-enabled monitoring. Sources were reviewed to extract recurring challenges, common process steps, and capability themes within contemporary commissioning practice. Literature was then coded into four commissioning lifecycle phases: pre-commissioning preparation, virtual simulation and testing, field execution support, and digital handover and operational transition. This phase-based structure provided an organizing foundation for

evaluating where VDC interventions align most directly with commissioning tasks and decision points.

Technology capability mapping was performed to align digital technology characteristics to commissioning requirements identified through the synthesis. For example, BIM parameterization was linked to pre-commissioning and test definition requirements, digital twins were aligned with virtual validation and scenario exploration, IoT sensors were mapped to real-time monitoring and field data acquisition functions, and cloud platforms were aligned to documentation, storage, and collaboration needs. Case study evidence reported in academic and industrial publications was then reviewed to support or challenge these alignments. These cases were used as secondary data validation of applicability and outcomes reported in practice but were not treated as primary empirical testing.

The outcome of this methodological process is a structured framework establishing specific VDC contributions across the commissioning lifecycle. This approach supports generalizable conceptualization while grounding development in empirical evidence published in the field. The methodology therefore produces an academically defensible basis for proposing a VDC-enabled commissioning model while enabling future researchers to conduct empirical validation and measurement studies that extend the framework into quantitative evaluation.

Proposed VDC Framework for Electrical Commissioning

Pre-Commissioning Preparation

The foundation of VDC-enabled commissioning begins during pre-commissioning, where information modeling decisions directly influence downstream test efficiency and verification accuracy. VDC implementation at this early stage requires the development of BIM models that include commissioning-relevant data parameters such as equipment test requirements, acceptance criteria, protective relay settings, test voltage levels, operational tolerances, and regulatory compliance attributes (Schneider Electric, 2022; Smith & Johnson, 2022). Literature indicates that commissioning performance is significantly constrained when these parameters are defined only during field testing rather than within digital design artifacts (Williams & Chen, 2022). Establishing commissioning attributes in BIM during design also aligns with recommendations in digital asset modeling literature because it enables model-based traceability throughout the project. This early integration supports enhanced documentation consistency, standardizes information structure, and reduces manual coordination complexity.

Operationally, organizations implementing VDC should develop commissioning-specific BIM execution plan addendums that define test information parameters, exchange formats, and role-based data delivery responsibilities before construction begins (Robinson & Lee, 2023). Integrating such plans with digital asset management platforms further enables technicians to access all specifications and manufacturer records from mobile devices in the field (Kumar et al., 2022). This approach reduces time spent searching for documents, enhances information continuity between design and commissioning, and reduces early-stage errors associated with manual test planning. Establishing commissioning intent during pre-design allows project teams to shift documentation load earlier in the project lifecycle, producing measurable reductions in rework and schedule disruption.

Virtual Simulation and Testing

Digital twins enable virtual simulation of electrical systems prior to energization, supporting validation of test procedures, operational sequencing, and coordination logic in a risk-free environment (Williams & Chen, 2022). Prior research demonstrates that simulation-based commissioning can detect miscoordination faults and failure modes that conventional field tests often fail to identify (Johnson et al., 2021; NCBI, 2023). Digital twins therefore enable systematic evaluation of hazardous or difficult-to-test operating scenarios and can accelerate fault finding significantly prior to field mobilization. This aligns with recent research advocating simulation-supported commissioning methods to reduce physical test exposure and improve operator preparation (Digital Twin Organization, 2023). From a VDC perspective, virtual simulation becomes an intermediate verification environment linking design intent to physical implementation and serves as an early validation stage before live equipment testing begins.

In application, virtual simulation environments should be directly connected to digital test procedure repositories, enabling technicians to rehearse steps virtually using equipment-specific models and system configurations. Virtual testing environments can also be used to pre-generate expected outcome data to support automated field test comparison later (Rodriguez & Smith, 2022). Field deployment readiness is improved when commissioning personnel enter live testing environments already familiar with component behavior and expected parameter ranges (Thompson, 2023). Integrating simulation feedback into commissioning documentation closes the loop between digital and physical testing and reduces the cognitive load required during energization activities. This approach produces safer, more efficient commissioning execution by enabling early-stage digital learning, validation, and procedural rehearsal.

Field Testing Support

Field commissioning activities benefit from AR-enabled guidance tools that provide real-time overlays of procedures, wiring diagrams, relay settings, and connection information directly within the physical environment (Davidson & Cruz, 2020; Garcia, 2022). Research demonstrates that AR-based instruction significantly reduces procedural errors, documentation inaccuracies, and test sequencing mistakes (Martinez et al., 2021). IoT-enabled monitoring further enhances field testing performance by generating continuous real-time data streams instead of reliance on point-in-time diagnostic readings (Williams et al., 2019; Chen & Rodriguez, 2021). These technologies strengthen commissioning test reliability by improving the accuracy of measurements and enabling remote oversight from subject matter experts not present on site (Nguyen & Peterson, 2022). VDC strengthens collective decision-making by providing multi-modal visibility into real conditions.

Operationally, VDC-based field support should enable collaborative problem-solving during test execution via cloud-linked platforms that unify data entry, test results, and anomaly reporting. Mobile devices, tablets, and AR headsets reduce friction associated with documentation and ensure that field observations feed the same information ecosystem used during design and simulation (Kumar & Williams, 2023). Unified data pathways eliminate transcription errors and reduce unnecessary manual task transitions, enabling commissioning technicians to remain focused on physical test activity rather than administrative documentation. These integrated systems support predictive responses to emerging test anomalies and reduce troubleshooting delays.

Commissioning Data Management

Commissioning produces large volumes of structured and unstructured data originating from sensors, digital logs, test instruments, model outputs, and procedural documentation. VDC-based environments provide mechanisms for structuring, storing, and processing this information so that it

becomes a persistent operational asset rather than ephemeral short-term documentation. Machine learning-based anomaly detection can identify deviations from expected performance trends and automatically flag potential failure patterns, enhancing quality assurance and enabling higher levels of automation in test verification. Integrating commissioning documentation with BIM models allows stakeholders to visualize test results in spatial context and reinforces spatial reasoning and problem localization. This aligns with emerging recommendations in digital construction literature which suggests commissioning data must be treated as high-value structured information rather than disposable supporting material.

To operationalize this within VDC-enabled commissioning, organizations should adopt formal data schemas and interoperability formats to enable seamless transition of commissioning data into operational systems and facility management workflows (Williams, 2023). Data models should be standardized at the outset of commissioning planning to ensure test results can be archived, accessed, and analyzed consistently for the operational life of the facility (Rodriguez & Lee, 2022). This conceptual reframing of commissioning documentation as an operational knowledge product rather than a commissioning-only deliverable supports long-term value realization and reduces information loss at project handover.

Digital Handover and Operation Transition

Digital handover represents the culmination of VDC-enabled commissioning where digital test results, system models, operational setpoints, and maintenance requirements are transferred to operations teams as structured, navigable, and integrated information (Garcia & Thompson, 2023; Martinez et al., 2022). VDC continuity improves operations onboarding speed, reduces mean-time-to-repair (MTTR), and enhances regulatory documentation readiness during initial plant operations (Thompson et al., 2023). This stage benefits significantly from structured digital repositories because operators require accessible, indexed, and validated information sources to maintain system reliability and performance. The deeper the integration between commissioning data and asset management systems, the greater the return realized during operational life (Williams, 2023).

In practice, successful digital handover depends on establishing standardized documentation formats, interoperability requirements, and access protocols early in the commissioning cycle (Rodriguez et al., 2023). These standards should be developed collaboratively with plant operators to ensure relevance and usability to future operations workflows. Data transition into building automation systems and digital condition monitoring infrastructure should occur automatically rather than being manually assembled post commissioning. When commissioning data is structured as a long-term asset, VDC enables extended operational value capture long after start-up completion.

The proposed VDC commissioning framework highlights how digital methods can systematically address long-standing inefficiencies in electrical commissioning environments. By aligning BIM parameterization, digital twin simulation, sensor-based field validation, and structured data management with commissioning workflow phases, the framework demonstrates a pathway for strengthening data continuity, test reliability, and commissioning scalability. This aligns with prior findings that digital integration improves information flow between project phases and creates measurable performance advantages (Richardson et al., 2021; Thompson et al., 2023). Advancing commissioning into a model-based verification environment supports proactive risk control rather than reactive troubleshooting approaches that historically characterize power plant startup and testing. This shift positions VDC commissioning as both a technical and procedural modernization of legacy practice.

From an industry adoption standpoint, the consolidated literature reviewed and cross-mapping analysis suggest significant potential for quantifiable value realization. Multiple studies report reductions in commissioning duration (20–30%), documentation workload (60–65%), anomaly response time (40%), and commissioning-related design change costs (35%), while also demonstrating safety incident reductions of approximately 40% (Martinez et al., 2022; Thompson et al., 2023). These results collectively indicate that industry investment in VDC commissioning carries potential for high compound benefit across schedule, cost, safety, and operational readiness. The challenge moving forward involves standardization and implementation maturity: VDC commissioning benefits are clearest where data models, interoperability rules, and information handover formats are defined consistently. This creates an important future research agenda that examines empirical validation, cost-performance modeling, and post-handover operational return.

Conclusion

This study proposes a VDC-enabled commissioning framework to strengthen digital continuity, improve test reliability, and support safer and more efficient electrical commissioning for power generation facilities. While existing literature and reported industrial case implementations demonstrate significant potential value in reduced commissioning duration, improved documentation quality, and lower safety exposure, the empirical maturity of VDC-supported commissioning remains limited. The next stage of research should pursue structured measurement studies to validate the framework's performance across multiple facility types, commissioning team structures, electrical system configurations, and technology deployment scenarios. Quantitative benchmarking studies comparing VDC-enabled commissioning projects against conventional practice would support clearer economic performance modeling and decision-making for future adopters.

Additional research is needed to standardize commissioning parameter definitions and digital interoperability requirements across BIM schemas, digital twin simulation environments, IoT sensor platforms, and asset management systems. Establishing formal data exchange standards for commissioning would support consistent modeling implementation and reduce the reliance on custom integration during project delivery. Future research should further explore advanced automation, including AI-based anomaly detection, automated test sequence generation, and self-validating digital handover packages capable of integrating directly into plant operations and maintenance platforms. These efforts will help transition VDC-enabled commissioning from early-stage practice to a mature, repeatable digital delivery model.

While this study establishes a structured conceptual framework for applying Virtual Design and Construction technologies to electrical commissioning in power plants, several important areas remain the focus of ongoing and future research. Planned work includes empirical validation of the proposed framework through real-world pilot implementations and detailed case studies to evaluate practical applicability across different power generation contexts. Future studies will also investigate comparative benchmarking between conventional commissioning approaches and VDC-enabled commissioning, with emphasis on quantifying impacts on schedule, cost, documentation effort, change orders, and safety performance. In addition, ongoing research efforts will examine the additional modeling effort, data authoring requirements, and implementation costs associated with commissioning-oriented BIM and digital twin development, with particular attention to current industry norms where electrical conduit and wiring are not typically modeled in detail. These studies will support rigorous cost-benefit and return-on-investment analyses to clarify when and where increased digital modeling effort is justified. Collectively, this future work will extend the conceptual framework presented here into empirically validated, implementation-ready guidance for industry adoption.

In conclusion, VDC technologies provide a viable pathway for modernizing electrical commissioning workflows in power plants by integrating design intent, simulation capability, field execution support, and long-term operational information continuity. By establishing commissioning as a structured digital lifecycle process rather than a field documentation exercise, the proposed framework supports increased efficiency, enhanced test quality, and long-term value capture. Continued research, standardization, and empirical validation will be required to accelerate widespread adoption and fully realize the benefits of VDC-enabled commissioning across the power generation sector.

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