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Contingency-Based Resilience Assessment of Critical Utility Substations: An ETAP Framework for Accelerating Safe Interconnection of High-Density AI Data Center Loads

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Abstract

This study examined the resilience of a critical utility substation under the proposed interconnection of a high-density AI data center load using a contingency-based ETAP framework. The study was motivated by the growing pressure placed on utility substations by concentrated digital infrastructure demand, particularly where safe interconnection depends not only on base-case capacity but also on the ability of the substation to remain within acceptable thermal, voltage, and protection limits during abnormal operating conditions. A quantitative nonexperimental case study design was adopted, and the analytical framework focused on measurable resilience indicators including transformer loading margin, bus voltage deviation, feeder loading utilization, short-circuit current magnitude, breaker duty margin, and contingency violation counts. The modeled system consisted of 2 power transformers, 8 buses, 6 outgoing feeders, 12 evaluated circuit breakers, and 10 credible contingency cases, with a final dataset of 12 retained operating states and 480 complete observations. The findings showed that the proposed AI data center interconnection materially reduced the resilience margin of the hosting substation. Mean transformer loading increased from 61.30% in the base-case condition to 79.80% in the post-interconnection normal condition and 86.70% under post-contingency operation, while the average reserve margin declined from 38.70% to 13.30%. Mean bus voltage deviation rose from 1.90% in the base case to 3.20% after interconnection and 4.80% under contingency, with the lowest recorded bus voltage falling from 0.981 p.u. to 0.941 p.u. Short-circuit current also increased from a mean of 21.70 kA to 24.10 kA and then to 28.10 kA across the same conditions. In parallel, breaker duty margin declined significantly, and contingency-related noncompliance rose from 0.00 violations in the base case to 1.00 in the post-interconnection normal state and 3.50 under post-contingency conditions. The results demonstrated that the substation remained broadly serviceable in selected normal states but experienced substantial reduction in disturbance tolerance after the large-load addition. The study concluded that contingency-based resilience assessment provided a rigorous basis for evaluating the safe interconnection readiness of critical utility substations exposed to high-density AI data center demand.

Keywords

Resilience, Substation, Interconnection, Contingency, ETAP.

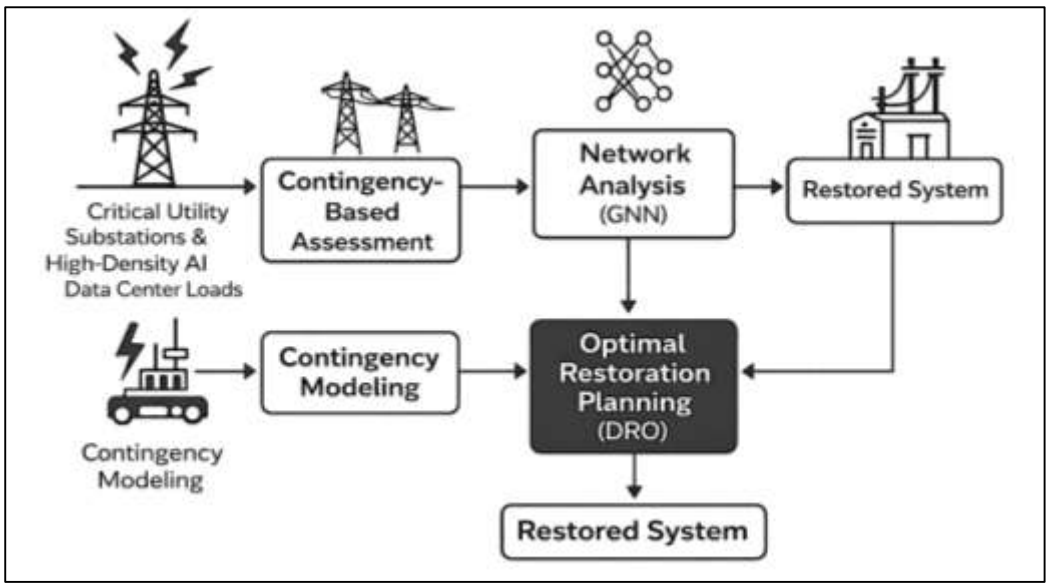
INTRODUCTION

Resilience in electric power systems refers to the capacity of infrastructure to anticipate, withstand, adapt to, and recover from disturbances while sustaining acceptable levels of service continuity, operational safety, and equipment integrity. In the context of critical utility substations, resilience extends beyond the traditional concern for steady-state reliability and includes the ability of substations to maintain functional performance under abnormal, uncertain, and high-impact operating conditions. A critical utility substation can be understood as a strategically important node within the transmission or sub-transmission network whose outage, degraded operation, or protection failure may produce significant regional consequences for voltage stability, load supply security, industrial continuity, or public welfare (Movahednia et al., 2021). Contingency-based assessment is the systematic evaluation of how the electrical system performs under predefined single or multiple component failures, such as transformer outages, transmission line trips, breaker failures, bus faults, or sudden load additions. Within power system planning and operation, contingency analysis provides a structured means to test whether the network can remain within thermal, voltage, and protection coordination limits when stressed by unexpected events. This analytical perspective is especially relevant when substations are asked to support large and concentrated new demand from high-density artificial intelligence data centers, whose power profiles are distinguished by exceptional magnitude, rapid ramping behavior, high redundancy expectations, and stringent tolerance for interruption. The title of this study places resilience assessment inside an ETAP framework, which signals a quantitative approach rooted in electrical modeling, load-flow studies, fault analysis, protection review, and scenario-based evaluation of network response (Bulat et al., 2021). ETAP, as an engineering simulation environment, allows the conversion of conceptual resilience concerns into measurable variables such as bus voltage deviation, transformer loading margin, short-circuit level, breaker duty, contingency violation count, and restoration feasibility under alternate switching arrangements. The acceleration of safe interconnection is therefore not merely an administrative objective; it is an engineering problem requiring evidence that a utility substation can absorb concentrated digital load growth without creating unacceptable operational risk. In international terms, this issue is increasingly important because national energy systems are simultaneously pursuing digitalization, industrial modernization, cloud computing expansion, and electrification of strategic sectors. As AI computation scales across regions, substations are becoming frontline assets in determining whether digital infrastructure growth can proceed safely, quickly, and within the technical boundaries of resilient grid operation (Hromada et al., 2021).

The international significance of resilient substation interconnection has intensified because AI-driven data center development is no longer concentrated in a small number of technology corridors; it has become a global infrastructure phenomenon tied to cloud services, national digital competitiveness, financial systems, health informatics, scientific computing, defense applications, and platform economies. High-density AI data centers differ from conventional commercial loads because they combine extremely large demand blocks with high utilization rates, layered cooling requirements, and near-continuous operating profiles. Their electrical footprint is often geographically concentrated, capital-intensive, and highly time-sensitive, especially when operators seek rapid commissioning to meet demand for model training, inference services, and digital platform expansion (Espinoza et al., 2020). As utilities around the world face rising requests for interconnections in the tens or hundreds of megawatts, substations that were originally designed for diversified regional demand are being reassessed as hosts for single-site or campus-scale digital loads with unusual density and reliability expectations. This has made substation resilience an international planning issue rather than a narrow local engineering matter. In North America, Europe, the Gulf region, and parts of Asia, transmission-connected and distribution-adjacent data center campuses are reshaping utility load forecasts, substation reinforcement priorities, transformer procurement schedules, and protection coordination practices. In emerging economies, the challenge is equally significant because digital infrastructure growth is occurring alongside constrained reserve margins, aging equipment, land limitations, and the need to preserve affordable and secure service for other consumers (Woo & Kim, 2020). The safe interconnection of AI loads therefore sits at the intersection of industrial policy, grid modernization, cybersecurity-sensitive infrastructure planning, and sustainable utility investment. A resilient interconnection process must evaluate how a substation responds not only under normal conditions

but also when subjected to credible contingencies that expose latent weaknesses in equipment loading, voltage control, fault current tolerance, or backup supply pathways. This is particularly important because the economic consequences of substation underperformance can be wide-ranging, affecting cloud service continuity, financial transactions, public digital platforms, and industrial clients that depend on uninterrupted computing ecosystems. For these reasons, resilience assessment is not simply a technical enhancement to conventional planning practice (Akaber et al., 2019). It is increasingly a prerequisite for enabling international digital growth while preserving power system security, safety, and operational discipline at the critical interface between utility infrastructure and large AI-enabled electricity demand.

Figure 1: Resilient Substation Interconnection Assessment Framework



Traditional utility planning has long relied on reliability-centered methods that emphasize deterministic criteria, normal operating margins, and standard contingency rules such as N-1 performance. These approaches remain essential, yet the emergence of high-density AI data center loads has exposed the limitations of planning practices that focus primarily on whether the system survives a predefined outage without fully characterizing the broader resilience of the affected substation (Dehghanian et al., 2018). Reliability is generally concerned with the probability of adequate service under expected conditions and component failure patterns, whereas resilience addresses the dynamic capacity of the system to absorb disruptions, reorganize operationally, and sustain critical function under stress. For substations facing concentrated digital load growth, the distinction becomes analytically important. A substation may satisfy nominal planning criteria under base-case conditions and still exhibit vulnerability when transformer loading, voltage sensitivity, breaker interrupting duty, and bus transfer flexibility are examined across a wider set of disturbances. The interconnection of AI data centers raises this concern because the load is neither modest nor behaviorally neutral. Large digital campuses may create steep increases in demand, stronger dependence on local voltage support, elevated short-circuit contributions in certain configurations, and tighter dependence on coordinated operation among transformers, feeders, protective relays, and switching devices (Souto et al., 2022). Under these circumstances, a resilience-oriented assessment framework asks more than whether the system passes a single contingency screen. It asks how much performance degrades, which constraints bind first, how restoration paths behave, where hidden bottlenecks emerge, and which assets become critical under stressed operation. This analytical shift is especially valuable for utilities that must accelerate interconnection timelines without weakening engineering scrutiny. The ability to quantify resilience through structured contingency studies provides a defensible basis for prioritizing equipment upgrades, redefining operating envelopes, sequencing construction works, and negotiating

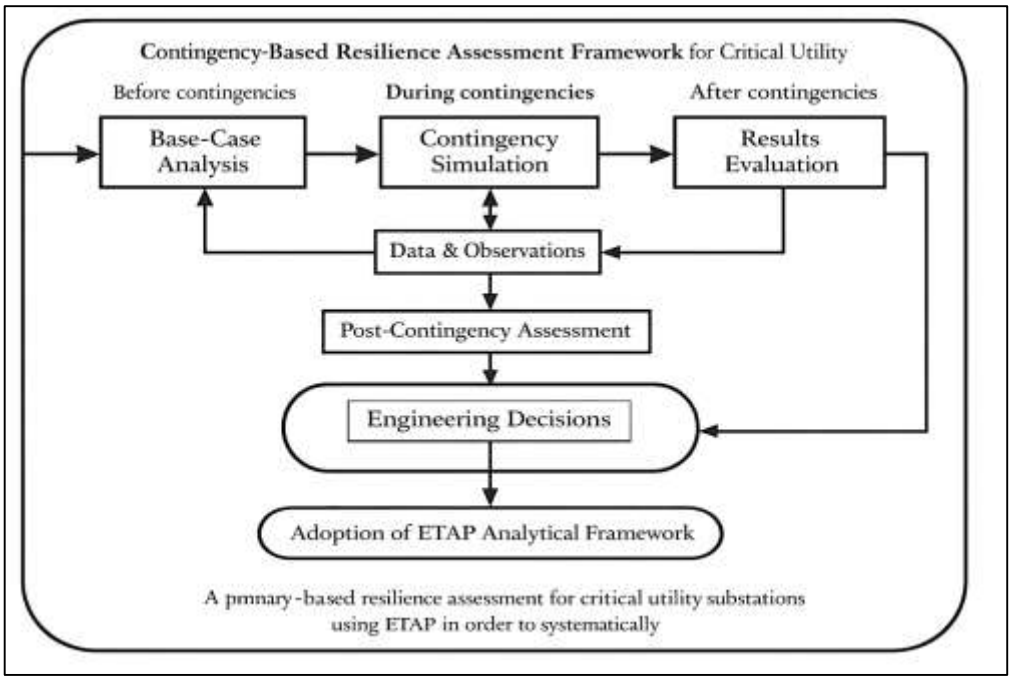
technically sound interconnection conditions with large customers. It also sharpens the role of the substation as a decisive control point in the interaction between the broader grid and a high-consequence new load (Daeli & Mohagheghi, 2022). In quantitative research terms, this transition from conventional adequacy screening to resilience-focused modeling supports the use of measurable performance indicators, comparative scenario analysis, and engineering decision criteria that can be objectively tested within a simulation environment. The present study is situated in that transition, where substation planning is no longer limited to pass-fail reliability compliance but is expanded into a more detailed assessment of contingent performance under the pressures created by rapid AI-driven demand concentration.

A high-density AI data center load is not simply a larger version of a standard commercial or industrial demand block. Its operational and electrical characteristics introduce distinctive planning challenges that directly affect the resilience of the interconnecting substation (Tofani et al., 2021). AI workloads are often supported by clusters of graphics processing units, accelerators, high-performance servers, power conversion systems, and sophisticated thermal management infrastructure, all of which contribute to sustained and substantial electrical consumption. The internal architecture of these facilities typically includes redundant uninterruptible power systems, backup generation interfaces, switchgear arrangements, power distribution units, and highly controlled environmental loads, particularly those associated with liquid cooling or advanced air-cooling systems. From the utility perspective, the external load seen at the point of interconnection may appear stable over some intervals, yet the aggregate behavior can still create substantial stress on upstream assets because of its scale, simultaneity, and persistence. High load factor operation means that transformers and feeders may remain near elevated utilization levels for extended periods, reducing operational headroom during contingency events (Zhao & Sun, 2021). The load concentration may also magnify the consequences of a single equipment outage because there are fewer diversified consumption patterns to smooth demand across network segments. In addition, the data center customer often requires exceptional service continuity, which places pressure on utilities to ensure that alternate supply paths, switching schemes, and voltage regulation strategies are robust enough to prevent service degradation during credible disturbances. These characteristics make contingency-based resilience assessment a more suitable analytical lens than a narrow base-case adequacy check. The question is not merely whether the substation can energize the new demand under normal configuration, but whether it can continue operating safely when one transformer is unavailable, when a line is out of service, when a bus section is isolated, or when protection actions force load transfer to already stressed elements. This concern is magnified in urban and peri-urban regions where land constraints, network congestion, and aging infrastructure can reduce expansion flexibility (Shertukde, 2019). For quantitative modeling, the AI data center becomes a stressor that reveals the true margins of the hosting substation. Its interconnection transforms the substation into a test case for how modern digital demand interacts with thermal ratings, voltage stability limits, protection boundaries, and switching resilience. The study of such loads therefore requires rigorous electrical representation and contingency examination, which aligns closely with simulation-based frameworks designed to convert these operational complexities into measurable engineering evidence.

The adoption of ETAP as the analytical framework for this study reflects the need for a quantitative platform capable of representing the operational complexity of utility substations under normal and contingency conditions (Siva et al., 2020). Engineering assessment of resilience requires more than descriptive discussion; it requires a model through which equipment parameters, network topology, load growth, fault levels, protection settings, and operational scenarios can be translated into interpretable numerical outcomes. ETAP supports this need by enabling integrated analysis across load flow, short-circuit, motor starting where relevant, protection coordination, device duty evaluation, and contingency simulation. In the context of high-density AI data center interconnection, the value of such a platform lies in its capacity to capture how concentrated load additions influence the electrical behavior of the hosting substation and its connected network segments. For example, under a base-case model, the interconnection may appear feasible because voltage profiles remain acceptable and transformer loadings stay below nameplate ratings. Yet when credible contingencies are introduced, a different picture may emerge: one transformer outage may push parallel units beyond allowable

loading, a bus reconfiguration may produce undervoltage at critical nodes, or a feeder transfer may increase fault duties beyond breaker capability (Mujtaba et al., 2020). ETAP provides a structured way to evaluate these outcomes and compare them across scenarios. This feature is essential for resilience assessment because resilience is not an abstract property; it is expressed through measurable attributes such as performance degradation, remaining operational margin, violation severity, and recovery options after system disturbance.

Figure 2: ETAP-Based Substation Resilience Framework



A quantitative ETAP-based framework also supports repeatability and transparency, which are fundamental for utility engineering decisions, regulatory review, and customer interconnection negotiations. Rather than relying on generalized assumptions about system strength, planners can ground decisions in modeled evidence tied to specific substation components and network states. This is especially important where accelerated interconnection is a commercial or policy priority, because speed without analytical rigor can transfer hidden risk into future operations (Ghiasi et al., 2019). By organizing resilience assessment around ETAP, the study aligns itself with a methodologically robust approach in which contingency cases can be systematically varied, performance indices can be computed, and intervention needs can be ranked according to technically observable system response. In this sense, ETAP functions not merely as a software tool but as the operational backbone of a quantitative research design centered on substation resilience under large and concentrated AI-driven load integration.

Safe interconnection of high-density AI data center loads is fundamentally a technical question about whether the substation and its upstream network can host large new demand without violating the conditions necessary for secure, coordinated, and maintainable operation (Gami et al.). Safety in this setting includes thermal safety, voltage safety, fault-duty compliance, protection selectivity, switching feasibility, and the prevention of cascading operational stress during equipment outages. A substation may have sufficient nominal capacity on paper, yet still lack safe hosting capability when assessed under realistic contingencies. For instance, transformer redundancy may appear adequate until one unit is removed from service and the remaining equipment must absorb transferred load under seasonal peak conditions. Likewise, circuit breaker capability may remain compliant under present fault contributions yet become marginal after network strengthening or alternate feeder backfeed associated with the new interconnection (Shin et al., 2020). Voltage control also becomes more delicate

when a large load block is concentrated at one node, especially if the substation operates near the limit of reactive support or depends on upstream system strength that varies across switching states. In addition, protection coordination can become more sensitive because the introduction of significant new load may alter current levels, fault contribution pathways, and relay operating margins in ways that are not apparent from non-integrated studies. The acceleration of interconnection adds another dimension to the problem. Utilities are under growing pressure to reduce project lead times and respond rapidly to major investment opportunities, yet the technical complexity of safe interconnection increases rather than decreases when the requesting customer is a large AI data center. This creates a tension between speed and verification, making quantitative resilience assessment especially valuable (Pardeshi et al., 2021). A contingency-based framework can reveal where the system remains robust and where it becomes brittle under stress, allowing targeted mitigation rather than generalized overbuilding or unsupported approval. Operational flexibility is central here: the safer substation is not only the one with ample installed capacity, but also the one that retains maneuverability under abnormal conditions through sectionalizing options, reserve margin, coordinated protection, and viable post-contingency configurations. The present study engages this technical reality by situating safe interconnection inside measurable substation performance under disturbance scenarios. In doing so, it treats safety as an engineering outcome derived from evidence about margins and operational response, rather than as a nominal label attached to interconnection capacity alone (Bugaliya et al., 2021).

Within this research context, a quantitative paper on contingency-based resilience assessment responds to a clear methodological need: the need to transform the growing challenge of AI data center interconnection into a set of measurable, model-based relationships that can support rigorous engineering judgment. The core issue is not merely that data centers are large loads, but that their interconnection places intense and localized pressure on critical utility substations that must continue performing under credible disturbances. This creates a setting in which quantitative analysis becomes indispensable. Variables such as transformer loading percentage, bus voltage magnitude, short-circuit current level, contingency violation frequency, line utilization, and available switching alternatives can be observed, compared, and interpreted as indicators of substation resilience. A structured ETAP framework makes it possible to organize these variables across normal and abnormal operating states, thereby turning a complex planning question into an analyzable research problem (Duan et al., 2022). The quantitative orientation of the study is especially suitable because resilience in substations is not fully captured by narrative description; it requires the comparison of system behavior across modeled contingencies and the identification of thresholds beyond which safe operation deteriorates. This is particularly relevant in critical substations, where the consequences of misjudging interconnection readiness may extend far beyond a single customer project. A weakly assessed interconnection can expose the utility to overload risk, reduced redundancy, compromised maintenance windows, increased outage sensitivity, and costly retrofits after energization. A well-assessed interconnection can clarify the hosting capability of the substation, identify the exact conditions under which resilience is preserved, and reveal which equipment or configurations most strongly determine system robustness. The introduction of this paper is therefore anchored in a problem of international relevance, technical specificity, and methodological importance (Airoboman et al., 2019). As digital economies intensify their dependence on AI computation, utility substations are becoming decisive gateways through which energy infrastructure must support concentrated computational growth. A contingency-based resilience assessment conducted through ETAP provides a logical and empirically grounded way to study that gateway. It allows the research to frame interconnection not as a simple capacity addition, but as a measurable interaction between load concentration, network contingency, asset limitation, and operational security within a substation environment that is critical to both local reliability and broader digital infrastructure continuity (Dehedkar & Raj, 2022).

The primary objective of this quantitative study is to develop and apply a contingency-based resilience assessment framework for critical utility substations using ETAP in order to evaluate the safe and accelerated interconnection of high-density AI data center loads. More specifically, the study seeks to determine how the addition of concentrated and energy-intensive AI computing demand affects the operational strength, security margins, and disturbance tolerance of a hosting substation under both

normal and contingency operating conditions. The objective is centered on measuring the extent to which key substation components such as transformers, buses, feeders, circuit breakers, and protective devices can sustain acceptable technical performance when subjected to credible outage scenarios following the integration of large data center loads. In quantitative terms, the study aims to assess changes in bus voltage profiles, transformer loading levels, line and feeder utilization, fault current magnitudes, breaker duty compliance, and the number and severity of contingency violations that emerge after interconnection. A further objective is to identify the most critical contingencies that expose vulnerability within the substation and to examine whether existing infrastructure can maintain safe operating limits when one or more system elements become unavailable. The study also aims to compare base-case system behavior with post-interconnection contingency responses so that the resilience of the substation can be interpreted not only through available capacity but through its ability to absorb stress, preserve electrical stability, and retain operational flexibility during abnormal events. Another important objective is to provide a structured engineering basis for determining whether accelerated interconnection can occur without compromising safety, protection coordination, or equipment security. Through the ETAP modeling environment, the study intends to establish a repeatable and measurable procedure for testing substation readiness for large AI-related load integration. In doing so, the research aims to generate quantitative evidence that supports utility planning, risk-informed decision making, and technically sound interconnection approval processes in environments where digital infrastructure growth is increasing rapidly and where substations must be evaluated as resilient hosting platforms rather than as static capacity points alone.

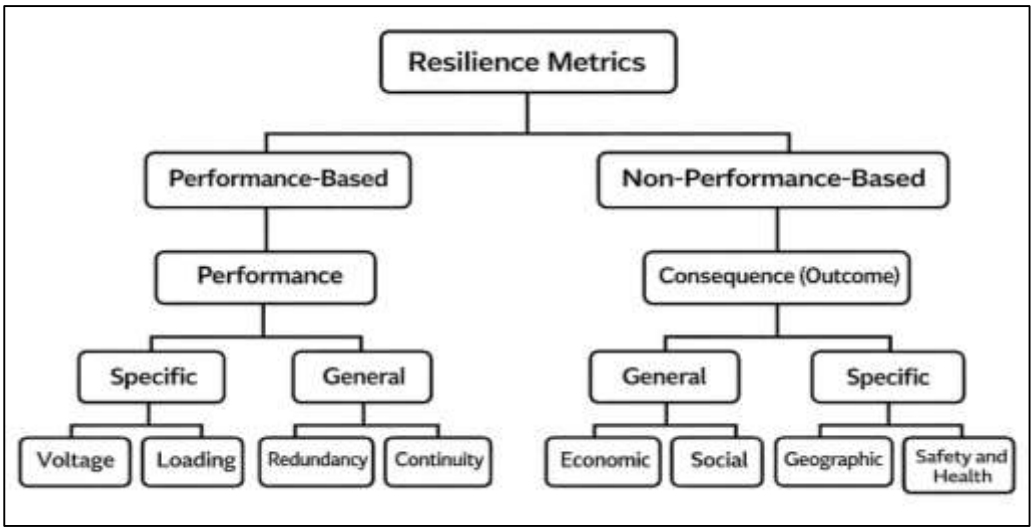
LITERATURE REVIEW

The literature review for this quantitative study is designed to establish the conceptual, technical, and analytical foundation for assessing the resilience of critical utility substations under contingency conditions when exposed to high-density AI data center load interconnections. In power system research, the literature review serves not only as a summary of prior scholarship but also as a structured examination of how key variables, models, and engineering assumptions have evolved across related domains such as power system resilience, contingency analysis, substation reliability, large-load interconnection studies, data center power demand modeling, and simulation-based utility planning (Greene, 2019; Ashfaq & Manam, 2023). For a study centered on an ETAP framework, the review must move beyond broad descriptive discussion and instead organize prior knowledge around measurable system conditions and quantifiable performance indicators. This is necessary because the present research is quantitative in nature and depends on the identification of variables that can be modeled, compared, and interpreted numerically, including transformer loading, bus voltage deviation, feeder utilization, fault current levels, breaker duty margins, contingency violation counts, and operational recovery capacity. A focused literature review therefore helps clarify how earlier studies have defined resilience in electrical networks, how contingency-based assessment has been used in transmission and substation environments, how large and concentrated loads alter infrastructure stress patterns, and how digital infrastructure expansion is changing traditional interconnection planning assumptions (Mottahedi et al., 2021; Sazzadul, 2023). It also helps identify the methodological gap between conventional adequacy studies and more integrated resilience-oriented assessment frameworks capable of evaluating the hosting capability of substations under disturbed operating states. Since high-density AI data centers represent a rapidly intensifying class of electricity demand, the literature must also examine how data center load characteristics influence substation design limits, redundancy expectations, reliability standards, and operational flexibility. In this study, the literature review is intended to support the quantitative framework by identifying the major constructs, dependent and independent variables, engineering thresholds, modeling techniques, and analytical relationships that shape the problem under investigation. It will therefore be organized in a way that progressively narrows from broad international scholarship on power system resilience to the specific technical issue of contingency-based resilience assessment for safe and accelerated AI data center interconnection at critical utility substations (Afzal et al., 2020; Manam & Ashfaq, 2022).

Conceptual Foundations of Power System Resilience in Critical Utility Infrastructure

Power system resilience is generally understood in the literature as the ability of an electricity system to anticipate disturbance, absorb operational stress, sustain critical functionality during disruption, and restore acceptable performance after the event.

Figure 3: Power System Resilience Metrics Framework



In electric utility studies, this concept is treated as broader than routine service continuity because it focuses on disruptive conditions that push the network outside ordinary planning assumptions. The literature consistently separates resilience from reliability by noting that reliability is usually associated with expected operating conditions, ordinary contingencies, and routine adequacy of supply, while resilience addresses severe, disruptive, and less predictable events that can degrade infrastructure and system performance in nonlinear ways (Khaled, 2021; Stanković et al., 2022). The distinction from robustness is also important. Robustness commonly refers to the ability of a system or asset to resist damage or preserve function without substantial degradation, whereas resilience includes not only resistance but also adaptation, operational reconfiguration, and recovery. Adequacy is more narrowly tied to whether sufficient resources exist to meet demand, and security is usually framed in terms of the system's ability to withstand disturbances such as faults or outages without loss of synchronism or unacceptable cascading effects. In this literature, resilience therefore emerges as a higher-order systems concept that incorporates elements of reliability, robustness, adequacy, and security but is not reducible to any one of them. For critical utility substations, this distinction is highly relevant because substations are not passive nodes; they are operational control points where voltage support, transformer loading, switching flexibility, and protective isolation converge (Annaswamy et al., 2016; Binte & Sazzadul, 2022). A resilient substation is thus interpreted not simply as one that avoids failure, but as one that preserves acceptable operating performance through disturbance and retains enough structural and operational integrity to support continued service and orderly recovery. This framing has become central in modern grid research because utility infrastructure is increasingly exposed to concentrated load growth, extreme events, and more complex dependencies across physical and digital system layers.

The literature on critical infrastructure places substations in a special category because they function as strategic interfaces between bulk power delivery and downstream load service. Their criticality arises from both electrical and systemic reasons (Robel & Aminul, 2023; Sabouhi et al., 2019). Electrically, substations concentrate transformation, switching, protection, voltage control, and network segmentation functions in a single location, meaning that their failure can propagate operational stress across feeders, load centers, and adjacent network areas. Systemically, substations support sectors that depend on uninterrupted electricity, including communications, water, healthcare, transportation,

finance, and digital services. For this reason, resilience research increasingly treats substations as high-consequence assets whose performance should be assessed through measurable operational criteria rather than broad conceptual labels. Studies in the field show that the impact of disruption is often not explained solely by whether a component trips, but by how the overall network behaves after that disturbance. This shifts attention toward post-disturbance service continuity, the ability to transfer load, the preservation of redundancy, and the extent to which the substation remains within acceptable thermal, voltage, and protection boundaries (Bhusal et al., 2020). In transmission and sub-transmission networks, substations are also central to contingency survivability because they determine whether power can be rerouted, whether alternate supply paths remain technically viable, and whether protective isolation can occur without excessive service interruption. Literature reviews on resilience and critical power infrastructure repeatedly argue that these assets must be assessed as performance-governing nodes in a larger operational system. That view is especially relevant in modern networks serving large digital and industrial load blocks, where a substation outage or degraded operating state may produce consequences that are geographically concentrated yet economically widespread. In this body of work, the substation is no longer treated only as a capacity checkpoint. It is treated as an infrastructure platform whose resilience is reflected in the quality of service continuity and network stability maintained after credible disturbances (Arghandeh et al., 2016; Istiaq & Binte, 2023).

A major trend in the resilience literature is the movement away from purely descriptive definitions toward measurable and performance-based assessment. This shift is important because resilience in power systems cannot be rigorously compared across cases unless it is translated into observable indicators. The reviewed studies repeatedly emphasize that resilience should be interpreted through how much system functionality is lost, how quickly degradation occurs, which technical constraints are violated, and how effectively the system restores acceptable operation. In substation-focused applications, this quantitative orientation has direct significance (Daeli & Mohagheghi, 2022). The literature identifies several operational indicators that can represent resilience in engineering terms, including voltage deviation tolerance, transformer and feeder loading margins, short-circuit withstand compliance, breaker duty compatibility, preservation of redundancy, survivability under contingency, and continuity of service to priority load. These indicators are useful because they connect the abstract idea of resilience to actual electrical states that planners and operators can model and compare. The literature also shows that resilience assessment is most meaningful when performance is examined across time and disturbance phases, including pre-disturbance readiness, disturbance absorption, degraded-state endurance, and operational recovery. This broadens the analytical frame beyond pass-fail reliability screening. It also allows resilience to be treated as a system-performance problem in which operational behavior under stress becomes the main unit of analysis (Gasser et al., 2021). Several recent reviews further highlight that there is no single universal resilience metric suitable for all power-system contexts, which strengthens the case for selecting indicators that align with the functional role of the asset under study. For critical substations, the most relevant indicators tend to be those that reveal whether the asset can remain within acceptable operating limits after a component outage or network reconfiguration. This literature supports the view that resilience should be measured through model-based, scenario-sensitive analysis rather than inferred from installed capacity or redundancy counts alone (Bie et al., 2017).

The literature increasingly indicates that resilience assessment must become more asset-specific and context-sensitive as utilities face new forms of load concentration and system stress. This is particularly relevant for critical substations serving rapidly growing digital infrastructure, where traditional adequacy or reliability checks may not fully reveal the operational consequences of concentrated demand. Review studies show that resilience becomes most analytically useful when it is tied to disturbance scenarios and quantified through system models that capture contingency response, post-event operating margins, and restoration capability (Sathurshan et al., 2022). This has encouraged researchers to view resilience not as a standalone abstract property but as a modeled relationship between infrastructure condition, network topology, disturbance severity, and recovery potential. For substations, that means resilience is better understood through structured assessment of how the station performs under transformer outage, feeder loss, bus reconfiguration, or other stressed conditions that challenge its ability to maintain safe operation. This body of literature also suggests that

the distinction between resilience and related concepts matters more when the grid is subjected to nonroutine stressors, including cyber-physical complexity, extreme events, and concentrated demand clusters. Under such circumstances, asset-level performance cannot be inferred from historical average behavior alone. It requires explicit examination of degraded operating states and retained technical margins (Mahzarnia et al., 2020). That logic provides a direct bridge to model-based substation studies involving large digital loads such as high-density data centers, where voltage sensitivity, load concentration, redundancy expectations, and service continuity requirements can sharply amplify the consequences of substation weakness. The reviewed scholarship therefore supports a methodological move from conceptual discussion to simulation-based resilience assessment using measurable indicators tied to actual operating conditions. In that sense, the concept of resilience becomes most valuable when it guides the quantitative evaluation of whether a critical substation can absorb stress, remain within technical limits, and continue supporting service after credible disturbances introduced or intensified by concentrated modern load growth (Alvarez-Alvarado et al., 2022).

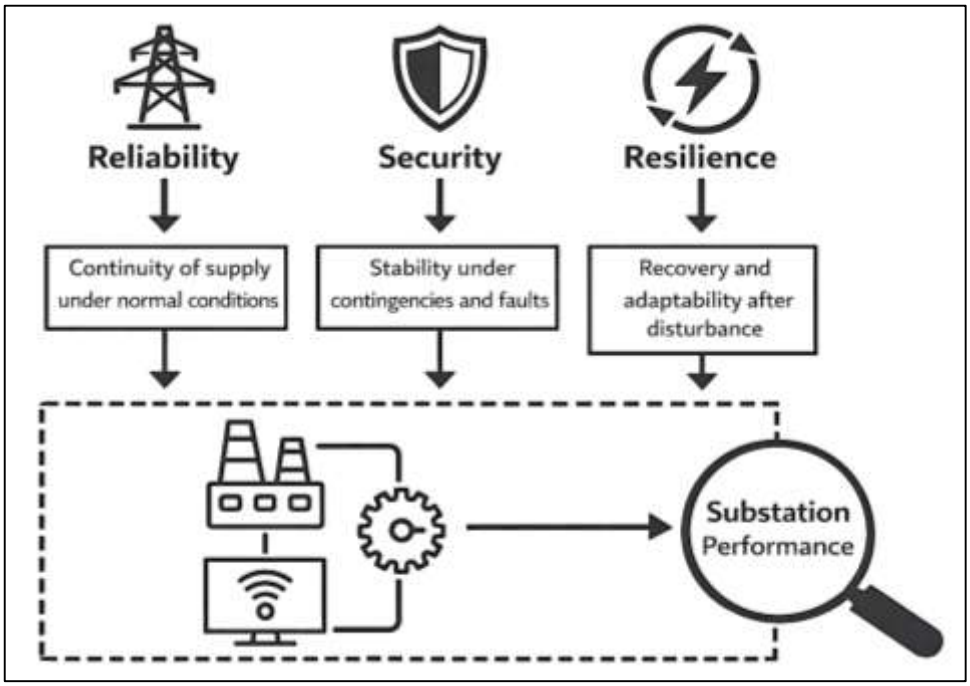
Resilience in Substation Performance Studies

The electrical engineering literature has increasingly clarified that reliability, operational security, and resilience are related but analytically distinct concepts, especially in utility asset planning and substation performance studies. Reliability is generally treated as the capacity of the system to provide continuous and adequate service under expected operating conditions, known equipment failure rates, and standard planning assumptions. In this sense, reliability is closely associated with continuity of supply, acceptable interruption frequency, and the ability of the network to meet demand without routine service degradation. Security, by contrast, is usually framed as the ability of the system to remain in an acceptable operating state following disturbances such as faults, equipment outages, switching events, or sudden changes in load and generation (Espinoza et al., 2020). Its focus is less on long-run continuity statistics and more on survivability under disturbance, especially whether the network can remain stable and within operational limits after a credible contingency. Resilience extends the discussion further by emphasizing sustained functionality during abnormal stress and the capacity to recover acceptable operating performance after disruption. In the literature, this makes resilience broader than both reliability and security because it incorporates disturbance absorption, adaptive operation, degraded-state endurance, and restoration capability. Substation-based studies have found this distinction increasingly important because substations may satisfy conventional reliability targets and still exhibit weak adaptive behavior when subjected to nonroutine stress, concentrated loading, or multistage contingencies (Guidotti et al., 2016). A substation can therefore be considered reliable in the conventional planning sense while remaining insufficiently resilient when transformer redundancy becomes exhausted, bus voltages deteriorate under transfer conditions, or recovery options narrow after component loss. This conceptual separation has become more prominent as planners confront operating environments in which conventional deterministic adequacy no longer captures the full range of service risks. The literature therefore supports the use of resilience as a more complete framing concept when the analytical objective is not only to test whether a system survives a contingency, but also to determine how well it maintains function and how effectively it can stabilize its operation afterward (Guidotti et al., 2016).

Within substation research, the distinction among reliability, security, and resilience becomes clearer when performance is assessed through measurable operating limits rather than abstract design principles. Reliability-centered planning has traditionally emphasized service adequacy, redundancy rules, and deterministic compliance criteria such as acceptable loading under normal operation and survivability under standard N-1 conditions. This approach remains fundamental in utility practice, yet the literature shows that it often privileges pass-fail planning compliance over a deeper analysis of post-disturbance system behavior. Security-oriented studies move closer to operational realism by examining whether voltage, current, protection, and stability limits remain acceptable after contingency events (Paul et al., 2021). Even so, many such studies still focus on whether the system remains within thresholds immediately after disturbance, rather than on how long acceptable performance is sustained, how much functionality is degraded, and how operationally flexible the substation remains during the recovery phase. This is where resilience-based work departs from conventional substation studies. It evaluates the degree of retained functionality under abnormal

conditions and interprets performance deterioration as a continuum rather than a binary outcome.

Figure 4: Substation Reliability Security Resilience Framework



In this body of literature, substations are not evaluated solely by whether outages are prevented or whether one contingency can be absorbed, but by how much service continuity, switching flexibility, and technical margin are preserved once equipment becomes unavailable (Movahednia et al., 2021). Recent work on urban substations and critical infrastructure configurations reinforces this point by showing that transformer loadability, bus conditions, line stress, and the condition of connected elements all influence the distinction between merely compliant infrastructure and infrastructure that remains operationally adaptable under stress. The literature therefore identifies a key theoretical limitation in older reliability-focused planning: it often assumes that compliance with deterministic criteria is sufficient evidence of performance strength, while giving less attention to cascading margin loss, degraded operating endurance, and constrained restoration options. In substation environments exposed to concentrated and strategically important loads, this narrower approach can obscure the actual adaptability of the asset under disturbed operating conditions (Curt & Tacnet, 2018).

Quantitative substation and power-system studies differentiate these concepts not only through definitions but through the dependent variables they prioritize. Reliability-oriented studies typically examine service interruption frequency, outage duration, equipment availability, expected unserved energy, and failure probability measures. These variables are well suited to expected continuity analysis and long-term adequacy assessment, but they do not always capture the operational severity of abnormal network stress once a disturbance unfolds. Security-focused studies usually employ variables such as overload incidence, post-contingency voltage deviation, fault-induced instability, protection coordination success, loss of synchronism risk, or thermal and current limit violations (Molyneaux et al., 2016). These indicators are more disturbance-sensitive and therefore better suited to analyzing survivability under contingency. Resilience studies draw from both traditions but broaden the dependent-variable set to include outage severity, degradation depth, restoration time, retained service continuity, operational flexibility, infrastructure damage exposure, and the persistence of acceptable functionality during prolonged abnormal conditions. In substation performance research, the literature increasingly treats voltage collapse sensitivity, transformer overload severity, bus reconfiguration viability, short-circuit withstand compliance, breaker duty exposure, and protection discrimination performance as essential resilience-related indicators because they reveal not merely

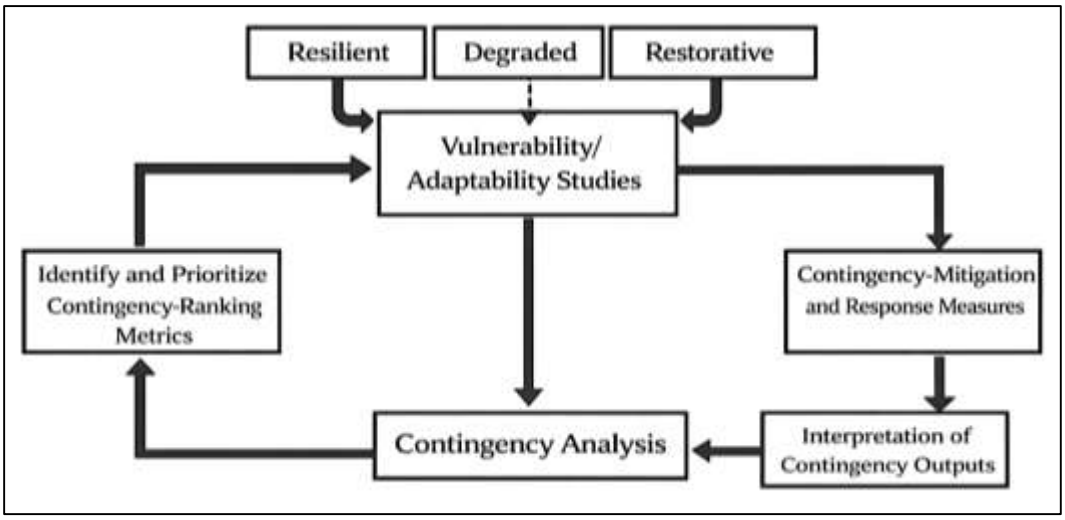
whether the substation fails, but how far it can operate safely into degraded conditions. Some studies also interpret resilience through sequential phases of disturbance response, examining pre-disturbance preparedness, disturbance absorption, emergency operation, and service restoration as interconnected performance states (Li et al., 2017). This shift is particularly useful for critical substations because their value lies not only in avoiding outage, but in sustaining acceptable electrical performance while network conditions worsen and operating choices become constrained. The literature thus provides a defensible quantitative basis for preferring resilience when the research objective involves evaluating the operational behavior of substations under multiple or compound stressors. It also shows that selecting resilience as the framing concept allows a wider set of technically meaningful dependent variables to be analyzed, especially where concentrated load additions may intensify the consequences of voltage weakness, overload transfer, protection stress, and delayed restoration (Bulat et al., 2021).

Substation Vulnerability Assessment

The literature consistently presents contingency analysis as one of the most important quantitative techniques in power system planning, operation, and vulnerability assessment because it allows engineers to test how a network behaves when one or more components are suddenly removed from service. In transmission systems, distribution substations, industrial power systems, and utility planning environments, contingency analysis is generally described as a structured "what-if" process that simulates abnormal operating conditions and measures the resulting electrical stress across the network (Abedi et al., 2020). Within this body of work, an N-1 contingency refers to the outage of a single critical element such as a transformer, feeder, line, generator, or bus-connected component, while N-2 refers to the loss of two elements, either simultaneously or in sequentially dependent form. Credible outage conditions are usually framed as disturbances that are physically plausible and operationally significant, including transformer outages, feeder failures, line trips, bus section loss, breaker malfunction, relay misoperation, or related protection events that can alter power flow and system security. The literature shows that contingency analysis became central because normal operating conditions do not reveal the full vulnerability of substations and networks. A substation may appear adequate in a base-case load flow study and still experience unacceptable thermal loading, severe undervoltage, reactive stress, or loss of transfer capability once a key component is unavailable (Sperstad et al., 2020). For this reason, contingency analysis is treated not merely as a planning formality but as a direct method for uncovering weak points in system configuration, identifying constraint interactions, and revealing whether infrastructure can remain within acceptable operating limits during disturbed states. Across the reviewed studies, the method is valued because it converts outage scenarios into measurable post-disturbance outputs, thereby providing a practical bridge between theoretical security criteria and observable engineering evidence of vulnerability (Gjorgiev & Sansavini, 2022).

A major contribution of the literature is its demonstration that contingency analysis translates substation and network vulnerability into clearly measurable electrical outcomes rather than abstract judgments. The most frequently discussed outputs include thermal overload on transformers and lines, bus undervoltage or overvoltage, loss of voltage stability margin, reactive power stress, breaker duty exceedance, protection miscoordination exposure, interrupted load, and risk of load curtailment under emergency conditions. In transmission-focused work, line outages are often examined for their ability to redistribute flows in ways that overload adjacent corridors or weaken voltage conditions at remote buses (Bose et al., 2020). In substation-oriented studies, transformer outages and feeder transfer events are emphasized because they often reveal whether spare capacity and switching flexibility are sufficient to preserve service. Industrial power system studies contribute an additional layer by showing how contingency analysis can be applied to localized networks in which single equipment losses may quickly propagate into voltage violations or interrupted critical process loads. Distribution-oriented reviews also highlight that contingency events in radial or weakly meshed networks can create interrupted supply, poor backup options, and unacceptable loading on alternate feeders. The literature repeatedly shows that the value of contingency analysis lies in its ability to compare post-disturbance states against normal states and thereby determine both the magnitude and type of vulnerability exposed by a given outage (Cao et al., 2019).

Figure 5: Contingency Analysis for Substation Resilience



This comparison is especially important because the same contingency may produce modest thermal impact in one configuration but serious voltage sensitivity or restoration difficulty in another. Many studies therefore treat contingency outputs as indicators of infrastructure readiness, arguing that acceptable base-case operation is insufficient evidence of resilience unless post-outage operating margins are also demonstrated. In this sense, contingency analysis provides a quantitative language for describing how far a substation or network can absorb disturbance before technical limits are crossed and service continuity becomes uncertain.

Earlier literature often treated contingency analysis primarily as a screening technique for identifying violations under standard reliability and security criteria, especially under N-1 operating rules (Zeraati et al., 2017). In this traditional role, the purpose was to determine whether the system could survive a specified outage without exceeding voltage or loading limits. More recent studies, however, increasingly extend contingency analysis beyond simple compliance checking and use it as a resilience-oriented method for evaluating the severity, persistence, and operational implications of disturbed system states. This shift is significant because resilience-oriented work is less interested in whether a contingency merely causes a violation and more interested in how deeply the system degrades, how broadly the effects propagate, which corrective actions remain available, and whether stable performance can be restored without unacceptable service loss. The literature on enhanced contingency analysis and vulnerability assessment reflects this transition (Afzal et al., 2020). Some studies incorporate voltage-stability analysis into classical contingency workflows because overload screening alone may fail to distinguish between contingencies that are manageable and contingencies that place the system near collapse. Other research examines cascading failure exposure, fault chains, and multi-criteria vulnerability ranking, showing that contingencies can no longer be interpreted only as isolated events when the network is highly stressed or structurally interdependent. This has encouraged a broader analytical view in which N-1 and N-2 studies are used not just to check compliance but to characterize adaptability and degraded-state endurance. Substation-related planning benefits strongly from this perspective because the hosting of large or concentrated loads can narrow margins enough that deterministic pass-fail screening no longer captures the full operational picture (Tøndel et al., 2018). The literature therefore supports using contingency analysis as a resilience tool when the purpose is to understand post-disturbance operating quality, retained redundancy, and recovery potential rather than only the existence of a standards violation. This broader use is especially relevant when infrastructure readiness must be demonstrated under stressed, realistic, and service-critical conditions.

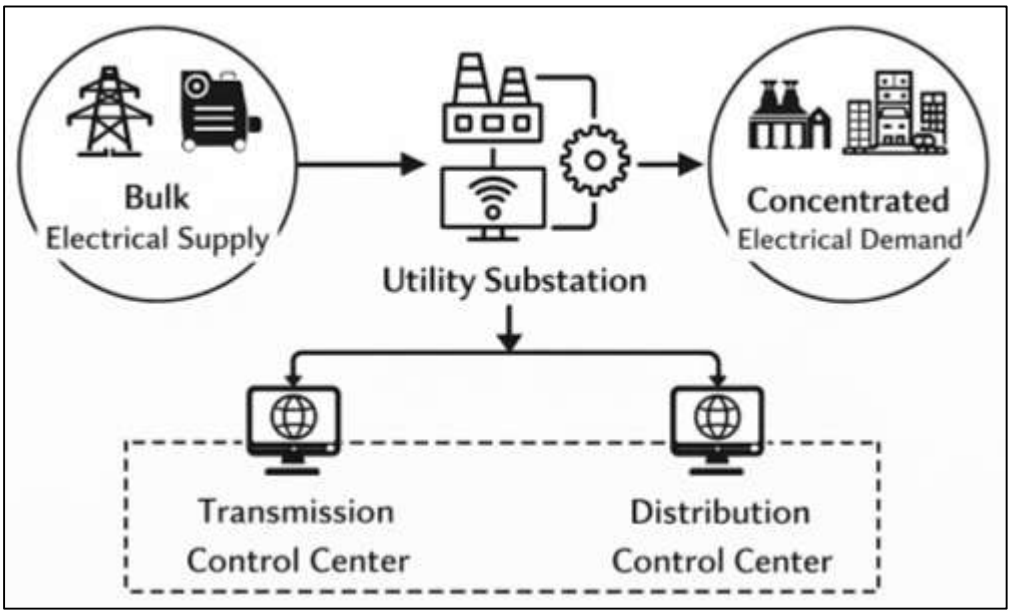
The literature gives special importance to contingency ranking because utilities and planners rarely evaluate all outage scenarios as equally serious. Instead, they use ranking methods and severity indices to determine which events create the greatest operational risk and therefore deserve priority in

planning, reinforcement, and corrective action design (Wang et al., 2018). Across reviewed studies, contingency performance is commonly ranked using combined measures of voltage deviation, overload extent, reactive stress, interrupted load, or other weighted indicators of post-disturbance system condition. This ranking process is important because it changes contingency analysis from a binary procedure into a comparative assessment framework. Rather than simply identifying whether violations occur, ranking methods identify which transformer outage, feeder loss, bus section event, or line trip is most threatening to system security and service continuity. Several studies show that severity indices become especially useful in complex networks where the number of credible contingencies is too large for operators and planners to interpret manually. Violation counts are also widely used because they summarize how many system elements exceed acceptable limits after a given outage and therefore provide a compact indicator of disturbance impact (Zografopoulos et al., 2021). Other studies use post-disturbance operating states as quantitative evidence of infrastructure readiness by comparing the base case with the contingency case and evaluating whether the network retains enough acceptable voltage profile, thermal margin, and service continuity to remain operable. This body of literature is especially relevant to substation vulnerability assessment because substations often serve as local concentration points where a single outage can trigger several simultaneous consequences, including transformer overloading, bus voltage depression, constrained transfer options, and elevated equipment stress. As a result, the literature supports a quantitative view in which contingency ranking, severity indexing, and violation-based comparison are essential tools for deciding whether infrastructure is merely functioning under normal conditions or is genuinely prepared to withstand disturbed operation (Kushal & Illindala, 2020). In this way, contingency analysis becomes a defensible basis for judging infrastructure readiness at the substation level.

Critical Utility Substations as Hosting Platforms

The literature presents critical utility substations as strategic electrical gateways that connect bulk supply systems to concentrated end-use demand in industrial parks, large campuses, mission-critical facilities, and urban load centers. This gateway role is operational rather than merely geographic, because substations perform the functions that make large-load service possible: voltage transformation, switching, fault isolation, protection coordination, circuit sectionalizing, and the controlled transfer of power between upstream network strength and downstream consumption concentration (Fu et al., 2018). Studies of substation planning and critical infrastructure consistently show that when demand is geographically clustered, the substation becomes the primary point at which system adequacy is converted into actual service capability. In industrial parks and urban growth corridors, the hosting substation is often the asset that determines whether large new demand can be supplied without degrading voltage profile, exhausting thermal reserve, or weakening restoration flexibility after an outage. This explains why substation-level analysis is so prominent in planning work involving large campuses and mission-critical facilities. Unlike diversified load patterns spread across wide service areas, a concentrated interconnection request places substantial electrical stress at a limited number of nodes, and that stress is first manifested at the substation through transformer utilization, feeder assignment, breaker duty, and switching configuration (Che et al., 2019). The literature therefore treats substations not as passive delivery points but as operational concentration points whose technical condition influences regional reliability and customer continuity. This view is reinforced by engineering sources that describe substations as concentrated bundles of network functionality and by recent work showing that delayed or poorly matched substation development in dense-load areas can produce inefficient network extensions, operational weakness, and avoidable investment waste. These findings support the treatment of the hosting substation as the central analytical unit when a single interconnection introduces demand large enough to materially alter local network behavior (Zhukov et al., 2019).

Figure 6: Substation Gateway for Concentrated Load Integration



The literature makes clear that substation-level assessment becomes indispensable when one interconnection request introduces demand that is large relative to existing diversified load patterns. Under diversified conditions, system planners can often rely on coincidence factors, portfolio load diversity, and broader network spreading effects to manage local stress. With a very large industrial campus, digital facility, or mission-critical complex, those assumptions weaken because demand is concentrated, persistent, and less easily absorbed through ordinary operational dispersion. As a result, the hosting substation becomes the first place where the true impact of the interconnection must be tested (Ten et al., 2017). The reviewed studies repeatedly indicate that the critical planning questions are not limited to nominal megawatt capacity. They extend to loading headroom, transformer firm capacity under outage transfer, feeder reserve under alternate switching states, breaker interrupting margin, and the degree of network configuration flexibility available after component loss. In practice, this means that a substation that appears adequate in a base case may still be a weak host if one transformer outage forces excessive loading on the remaining bank, if feeder backfeed options are too limited, or if switching arrangements reduce the ability to maintain acceptable service during maintenance or fault conditions (Huang et al., 2022). Large-load literature published in the last two years especially emphasizes that utilities are confronting growing pressure from concentrated interconnection requests, particularly from data centers and other large loads, and that transmission and substation readiness are now central constraints in grid-facing development decisions. This body of work aligns with older substation planning research showing that in high-density load areas, substation sizing, transformer quantity, and spatial location must be matched carefully to concentrated demand growth. Taken together, the literature supports the argument that large-load interconnection is fundamentally a substation-hosting problem before it becomes a broader system expansion problem (Li & Hedman, 2019).

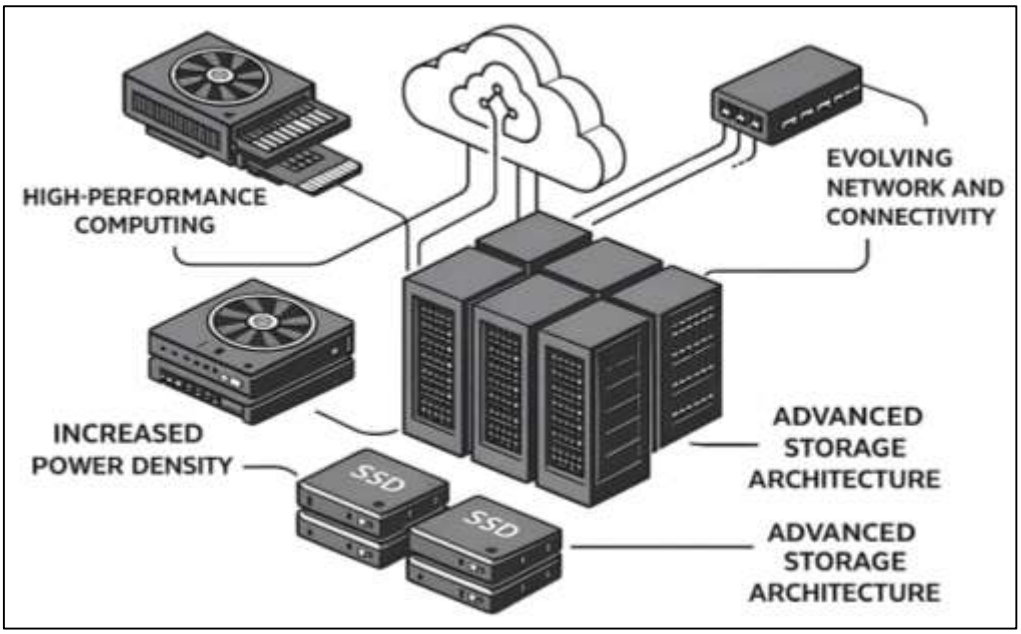
Electrical Load Characteristics of High-Density AI Data Centers

The literature on data center electricity demand shows a clear distinction between conventional enterprise facilities and high-density AI-oriented campuses when electrical behavior is examined from a systems perspective. Conventional enterprise data centers have historically been characterized by lower rack densities, more moderate and diversified computing loads, and comparatively stable facility designs built around general-purpose servers, storage, networking, and standard cooling architectures. By contrast, AI-oriented facilities are increasingly described as electrically intensive environments built around accelerator-rich clusters, especially GPU-based systems, which substantially increase rack power density, total facility demand, and thermal rejection requirements (Karangelos & Wehenkel,

2019). Recent technical and policy literature indicates that AI-driven campuses are shifting data center design from a paradigm dominated by incremental power growth to one defined by concentrated megawatt-scale block loads, high simultaneous demand, and strict service continuity requirements. This shift matters because the load is not only larger in aggregate but also more spatially concentrated and more persistent over time. Surveys and system studies report that many legacy facilities were designed around lower per-rack densities, while AI deployments increasingly push far beyond those assumptions, requiring redesigned power distribution, cooling infrastructure, and upstream electrical support. This literature also shows that power and cooling have become tightly coupled engineering constraints, since high compute density directly drives higher electrical demand from thermal management systems (Wang et al., 2016). In that sense, AI facilities are not merely conventional data centers with more servers; they are a distinct large-load category whose electrical profile is shaped by sustained compute intensity, stronger cooling dependence, and a more demanding redundancy architecture. These characteristics make them more consequential for substation planning because they convert digital growth into concentrated electrical stress that is visible at the point of interconnection through higher peak demand, higher coincident loading, and narrower operating headroom (Pambour et al., 2017).

A central finding in the literature is that high-density AI data centers impose sustained electrical demand patterns that differ materially from many traditional commercial and even older hyperscale computing environments. AI training and inference clusters are often operated with high utilization rates because infrastructure costs are large, compute demand is time-sensitive, and operators seek to maximize throughput from expensive accelerator hardware. This contributes to high load factors and comparatively limited idle diversity, which means that the facility can present a more persistent and concentrated demand signature to the grid (Kumar & Jayanti, 2022). The literature also emphasizes that cooling-related energy use becomes a larger and more operationally significant part of the total electrical profile as compute density rises. In older enterprise environments, facility overhead could often be moderated within conventional air-cooling assumptions, but AI-oriented campuses increasingly require advanced thermal management strategies, including high-capacity liquid cooling or intensified air-handling systems, both of which add substantial electrical demand to already large IT loads. Recent energy-use reports and operator surveys show that average facility-wide efficiency metrics can mask major differences between legacy sites and new high-density builds, because newer AI-ready facilities often combine better efficiency with much larger absolute demand. As a result, total site load becomes a function not only of IT equipment but also of tightly coupled facility overhead. The literature further indicates that connection requests for single facilities or campuses can now reach scales that were previously associated with major industrial projects, placing pressure on local substations and bulk supply planning (Zhou et al., 2020). From a quantitative standpoint, studies commonly evaluate these facilities through variables such as peak demand, coincident loading, load factor, cooling share of total consumption, and rate of demand growth over time. Taken together, this work shows that AI data centers create sharper electrical planning challenges because their demand is large, sustained, and highly consequential for upstream network capacity and continuity expectations. The literature increasingly frames AI data centers as a substation-relevant load class because their electrical footprint is concentrated, their redundancy expectations are stringent, and their continuity requirements are closer to other mission-critical infrastructures than to diversified general commercial demand (Carrillo et al., 2019). Large AI campuses often seek utility service arrangements that can support very high availability targets, which in turn affects how planners interpret transformer capacity, feeder reserve, switching flexibility, and outage tolerance at the interconnection point. This is important because a single large-load request can materially change the demand composition of a substation that was previously serving more diversified customers whose aggregate peaks were shaped by noncoincident behavior. In contrast, AI facilities often represent large block loading with high simultaneity and limited diversity benefits, making them more stressful for local hosting infrastructure.

Figure 7: AI Data Center Load Characteristics



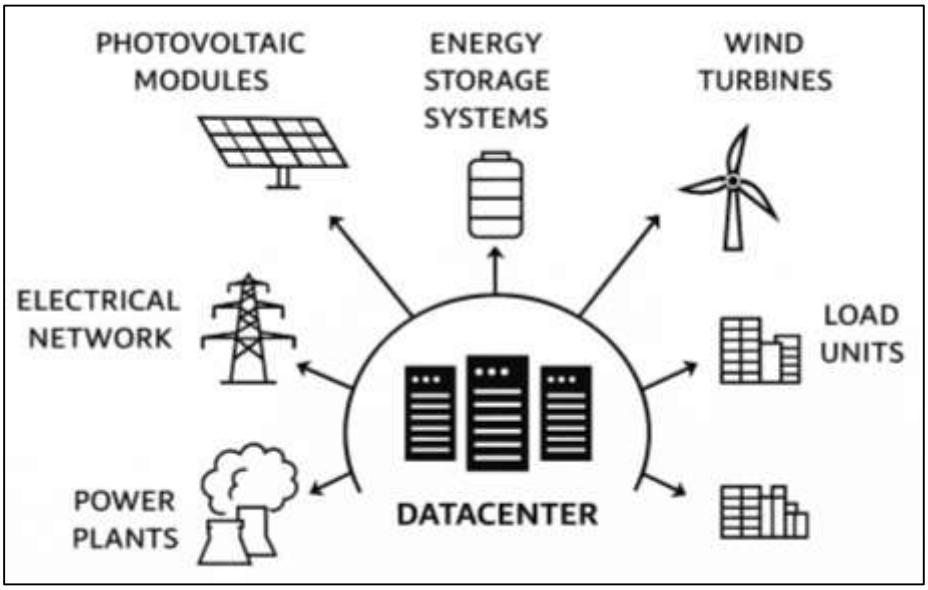
The literature from utilities, reliability bodies, and system planners also shows that these facilities are increasingly recognized as large, voltage-sensitive, power-electronic-rich loads whose behavior during disturbances can affect both facility continuity and bulk-system operations. Reports describing recent large-load events emphasize that data center load behavior during voltage disturbances and commissioning phases can create operational concerns that go beyond static nameplate demand (Wang et al., 2022). This strengthens the case for evaluating AI facilities not only by annual energy use but also by their interaction with substation operating conditions, especially under abnormal states. Quantitative indicators used in the literature include redundancy ratio, block load magnitude, interconnection size, load growth rate, coincident peak behavior, and the ratio of critical IT load to total facility support load. These variables help explain why AI-driven facilities place sharper pressure on local substations than conventional enterprise sites. The hosting challenge lies not only in supplying energy but in maintaining acceptable technical margins while serving a load whose size, continuity requirements, and concentrated electrical intensity can rapidly compress operational flexibility at the point of supply (Avtar et al., 2019).

Global Expansion of AI Data Center Infrastructure

The literature increasingly treats the worldwide expansion of AI and hyperscale data center infrastructure as a power-system planning issue rather than only an ICT growth story. International energy and infrastructure studies show that data centers are becoming a larger and faster-growing electricity demand category, with AI workloads accelerating the need for high-density computing campuses and larger grid connections. This shift is important because utility systems are not responding to a broad, diversified increase in small commercial loads, but to concentrated clusters of demand that can require substation reinforcement, bulk supply upgrades, and lengthy interconnection studies (Sharma et al., 2019). Recent global analyses indicate that electricity consumption from data centers reached a scale large enough to matter at the national and regional planning level, while AI is pushing demand growth more rapidly than earlier digital infrastructure cycles. In this literature, the central concern is not only total energy consumption but the geographic concentration and timing of demand, since hyperscale and AI facilities often seek fast delivery of large blocks of power in already constrained markets. This has caused utilities and planners to revise load forecasts upward, reevaluate hosting limits, and accelerate transmission and substation investment strategies in areas targeted by digital infrastructure developers. The literature also suggests that the growth of AI-related load has altered how infrastructure readiness is interpreted. Power availability, transformer procurement, land

access, and study timelines have become binding constraints in markets that were previously viewed as robust digital hubs (Geng, 2021). As a result, international scholarship now frames data center growth as a stress test for the physical grid, particularly in regions where digital competitiveness depends on the speed with which utilities can connect large new loads without compromising network security or service quality.

Figure 8: AI Data Center Grid Integration Framework

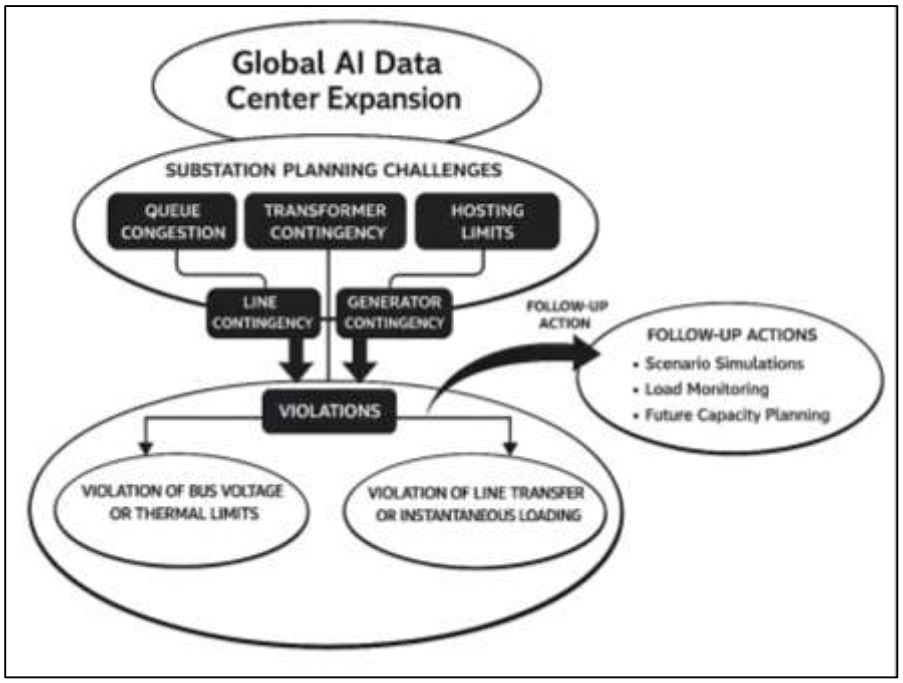


In North America and Europe, the literature shows that AI and hyperscale expansion is increasingly colliding with interconnection bottlenecks, queue congestion, and limits in local grid capacity. North American studies on large-load interconnection report that utilities are facing increasing requests from data centers that must be processed through study frameworks originally designed for more conventional load growth patterns. This has exposed procedural and technical gaps involving commissioning, system-wide reliability review, and the need for better utility protocols for large loads. The literature also emphasizes that queue congestion is no longer relevant only for generators; large loads are now creating their own form of interconnection pressure, especially where data center campuses seek rapid energization in areas already facing transmission and distribution constraints (Kelechi et al., 2020). In Europe, recent grid-focused research shows that data center deployment is increasingly shaped by grid connection times, substation availability, and regional congestion, with investors shifting attention toward locations that offer lower grid barriers and faster access to power. Across both regions, power availability has emerged as one of the strongest determinants of siting and expansion. This is reflected in measurable planning issues such as revised peak-load expectations, increased need for transformer and substation upgrades, longer study periods, and reduced hosting flexibility in established hub markets (Rafique et al., 2018). The literature therefore shows that North America and Europe are experiencing a common transition: data center growth is no longer limited primarily by digital demand or real estate strategy, but by the pace at which utilities can expand network capacity, clear interconnection processes, and secure equipment needed for reliable grid connection.

Transformer Loading Margins Under Base Case

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Figure 9: Global Data Center Power Challenge



This shift is important because utility systems are not responding to a broad, diversified increase in small commercial loads, but to concentrated clusters of demand that can require substation reinforcement, bulk supply upgrades, and lengthy interconnection studies. Recent global analyses indicate that electricity consumption from data centers reached a scale large enough to matter at the national and regional planning level, while AI is pushing demand growth more rapidly than earlier digital infrastructure cycles (Nafus et al., 2021). In this literature, the central concern is not only total energy consumption but the geographic concentration and timing of demand, since hyperscale and AI facilities often seek fast delivery of large blocks of power in already constrained markets. This has caused utilities and planners to revise load forecasts upward, reevaluate hosting limits, and accelerate transmission and substation investment strategies in areas targeted by digital infrastructure developers. The literature also suggests that the growth of AI-related load has altered how infrastructure readiness is interpreted. Power availability, transformer procurement, land access, and study timelines have become binding constraints in markets that were previously viewed as robust digital hubs (Ahmed et al., 2021) . As a result, international scholarship now frames data center growth as a stress test for the physical grid, particularly in regions where digital competitiveness depends on the speed with which utilities can connect large new loads without compromising network security or service quality.

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Across both regions, power availability has emerged as one of the strongest determinants of siting and expansion. This is reflected in measurable planning issues such as revised peak-load expectations, increased need for transformer and substation upgrades, longer study periods, and reduced hosting flexibility in established hub markets (Mishra et al., 2022). The literature therefore shows that North America and Europe are experiencing a common transition: data center growth is no longer limited primarily by digital demand or real estate strategy, but by the pace at which utilities can expand network capacity, clear interconnection processes, and secure equipment needed for reliable grid connection.

The literature on Asia and the Middle East shows a similar pattern of rapid digital infrastructure expansion coupled with increasing power-system constraints, although the mix of drivers and bottlenecks varies by market. In Asia Pacific, reports describe a region with very strong growth in data center capacity, led by both mature hubs and emerging markets, but increasingly constrained by grid access, clean-energy availability, land competition, and utility readiness. Regional studies project large increases in live and pipeline capacity over the next several years, with several markets expected to more than double installed capacity or sustain very high compound growth rates (Bennett et al., 2016). These trends are paired with warnings that electricity infrastructure is becoming a deciding factor in where AI and hyperscale investment can proceed. In practice, this means that substation headroom, transmission availability, and the speed of utility upgrades are becoming as important as fiber access or commercial land. In the Middle East, the literature links data-center-related growth to broader economic diversification, AI hub development, and round-the-clock high-capacity load requirements. Power-sector analyses from the region emphasize the importance of resilient grid-ready supply chains, reliable delivery of critical electrical equipment, and coordinated system integration to avoid project delays (Coad et al., 2022). Industry-backed market studies also report large pipelines of upcoming capacity in the Middle East and Africa, indicating that utility planning challenges will intensify as more projects move from proposal to construction. Taken together, the literature suggests that Asia and the Middle East are not peripheral to the global data center power challenge. They are central case studies in how rapid infrastructure expansion can outpace the traditional cadence of substation, transmission, and interconnection development.

Across the international literature, the most important contribution of recent work is the translation of AI data center growth into measurable utility-planning impacts (Gao et al., 2022). These include upward revisions to load forecasts, increased queue congestion, substation reinforcement requirements, transformer constraints, power-availability limits in core hub markets, and system-level hosting restrictions that shape where projects can proceed. Studies and industry-academic reports consistently argue that the critical planning issue is not only total demand growth but the mismatch between the size and speed of interconnection requests and the slower timelines associated with grid studies, permitting, land acquisition, equipment supply, and network upgrades. This mismatch creates visible consequences in the planning record: longer connection timelines, higher reinforcement costs, reduced flexibility in established markets, and the migration of projects toward secondary locations with stronger available headroom. The literature also demonstrates that international experience is converging around a common conclusion that data center expansion has become a bulk-power and substation planning problem (Chen et al., 2018). Utilities are being asked to determine whether concentrated new loads can be served safely, whether existing substations can be reinforced quickly enough, and whether network constraints can be managed without undermining reliability for other users. In that sense, the data center boom is now evaluated through the same categories used for other major power-system developments: hosting capacity, upgrade timing, equipment bottlenecks, and contingency-ready supply capability. This provides a strong basis for positioning the present study within a globally significant engineering challenge, where the hosting substation is not simply a local interface but a decisive planning asset in the broader race to connect AI-driven load growth (Chen et al., 2018).

Bus Voltage Stability and Voltage Profile Sensitivity

The literature consistently identifies bus voltage behavior as one of the most important indicators of electrical performance in substations and interconnected networks exposed to heavy and concentrated loading. Voltage stability is generally interpreted as the ability of the system to maintain acceptable bus

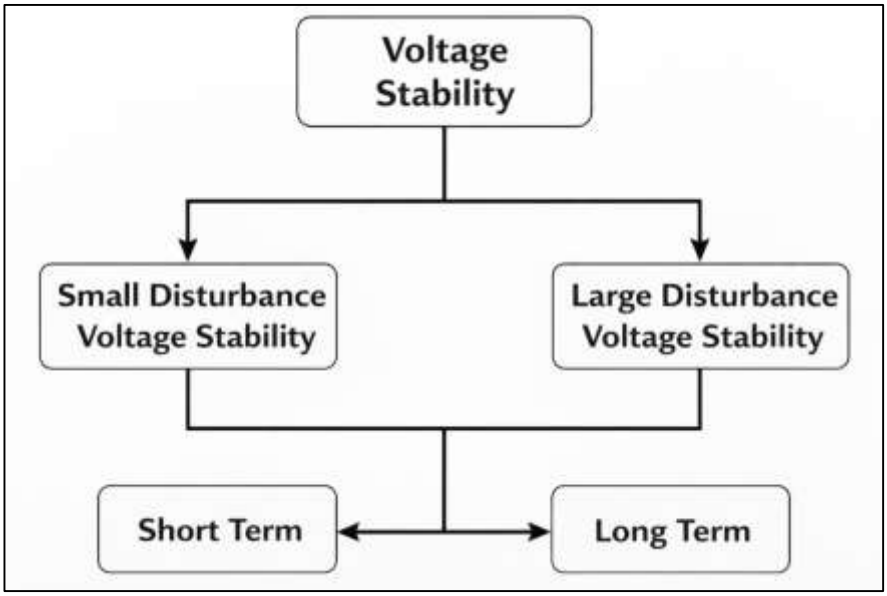
voltages during normal operation and after disturbances, while voltage profile analysis focuses more specifically on the spatial pattern of voltage magnitudes across buses, feeders, and transformer-connected nodes. In practical planning studies, these two ideas are closely related because poor voltage profile is often the earliest observable sign that the system is operating with reduced margin (Bairamkulov et al., 2019). Under large-load interconnection conditions, the literature shows that bus voltages become more sensitive to demand concentration, reactive power limitations, transformer tap actions, and upstream network weakness. This is especially important in substation studies because the hosting bus often acts as the interface where concentrated demand reveals the true strength of the supporting grid. A system may remain thermally feasible while still becoming voltage vulnerable, meaning that current-carrying capability alone is not enough to confirm hosting readiness. Recent studies on voltage security and contingency analysis emphasize that full-load AC power flow assessment is essential because voltage deterioration can emerge rapidly when heavy demand coincides with stressed network conditions. Review work on voltage stability indices also reinforces that weak buses, stressed corridors, and proximity to instability are best understood through bus-level voltage behavior rather than through nominal capacity statements alone (Yang et al., 2020). For this reason, bus voltage deviation has become a central measurable outcome in simulation-based studies, particularly where the objective is to determine whether large new load can be connected without pushing the substation into a condition of unacceptable voltage sensitivity or reduced disturbance tolerance.

A major theme in the literature is that voltage performance becomes significantly more fragile when heavy load conditions are combined with contingency events such as transformer outage, feeder transfer, or line loss. In such cases, the concern is not simply that voltage may fall below a nominal threshold, but that the network may lose enough reactive support and transfer flexibility to make the post-disturbance operating state unstable or operationally unacceptable (Maja & Ayano, 2021). Studies on voltage security assessment show that contingency analysis is especially valuable because it reveals which outages trigger the largest bus-voltage deviations and which network elements create the greatest sensitivity under stressed conditions. The literature repeatedly notes that transformer outages and feeder reconfiguration can alter power-flow paths and reactive demand distribution in ways that produce significant undervoltage risk at load buses. This is particularly relevant in substation-centered research because local bus voltages are shaped not only by the size of connected demand but by the strength of upstream sources, the availability of voltage regulation, and the network's ability to maintain reactive balance after component loss (Dorling et al., 2016). Research on voltage-stability ranking and contingency severity likewise treats low-voltage buses and stressed lines as signals of degraded operating security. Complementary literature on feeder reconfiguration further shows that voltage improvement is one of the primary objectives of post-disturbance switching, which confirms that voltage profile is not a secondary quality metric but a core indicator of whether the network remains serviceable after reconfiguration. In this body of work, voltage deviation is valuable because it translates contingency impact into a measurable output that directly reflects the ability of the substation and surrounding network to sustain acceptable operation when demand remains high and one or more supporting elements become unavailable (Li et al., 2016).

The literature gives particular attention to voltage sensitivity caused by transformer outages, feeder transfers, and upstream weakness because these are common mechanisms through which large-load interconnections expose hidden substation constraints. When a transformer is lost, remaining transformers and associated feeders must absorb redistributed demand, and this shift can produce voltage depression even before thermal limits are reached. Feeder transfer can have a similar effect because alternate supply paths may be electrically longer, more weakly supported, or less favorably positioned for voltage regulation (Chen et al., 2017). Several recent studies on contingency-based voltage analysis indicate that bus-voltage limit violations are among the most frequent consequences of such events and should be screened continuously in stressed networks. The literature also shows that upstream weakness amplifies these effects. If the broader network is already operating near reactive or transfer limits, a large local load can make the substation bus more dependent on remote support, thereby increasing susceptibility to disturbance-induced undervoltage. This is why many voltage-stability studies focus on identifying weak buses, critical corridors, and sensitivity patterns

rather than relying only on normal-condition voltage compliance. Research on branch-outage contingency assessment and voltage-stability screening further supports the idea that post-contingency operating points may be substantially weaker than the pre-disturbance case even when the base system appears acceptable (Ismail et al., 2020). In substation studies, this makes voltage-profile sensitivity one of the clearest indicators of whether the local grid is robust enough to host concentrated demand. It also explains why bus-voltage performance is frequently used to distinguish between systems that are merely adequate under routine operation and systems that retain acceptable stability and service quality after abnormal events.

Figure 10: Voltage Stability Flowchart

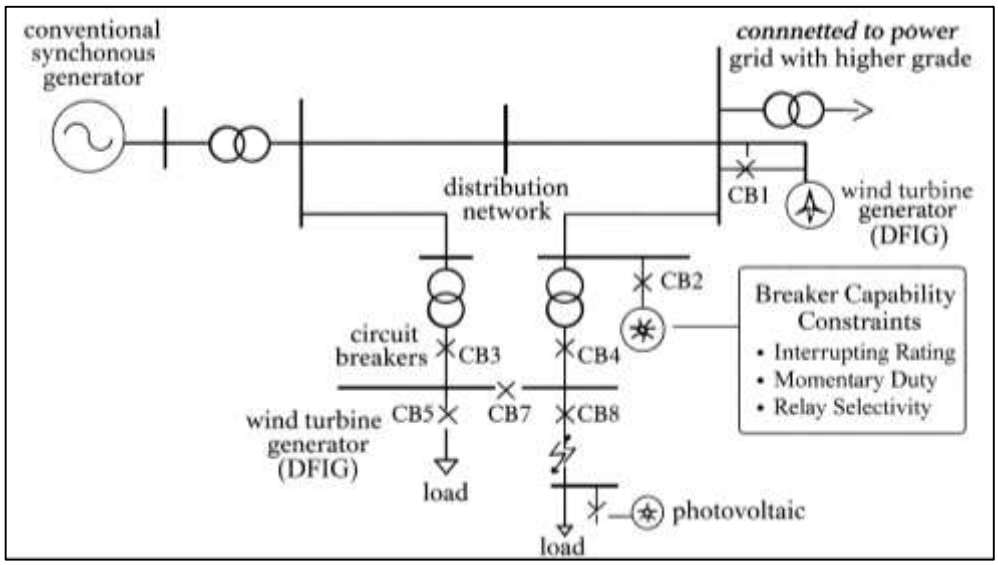


The literature on large digital loads strengthens the case for treating bus voltage deviation as a primary dependent variable because data centers and similar high-value facilities are highly sensitive to voltage disturbance even when they possess internal redundancy (Munyao et al., 2021). Power-quality research shows that voltage sag remains one of the most disruptive electrical events for sensitive loads, with the potential to interrupt processes, trigger equipment misoperation, or produce rapid load changes during otherwise normally cleared faults. This matters for data-center-oriented substations because internal backup systems do not eliminate the operational importance of supply quality at the point of interconnection. Recent industry and reliability reports warn that voltage-sensitive large loads, including data-center-type facilities, can respond sharply during bulk-system disturbances, creating sudden reductions or instability in demand behavior that are relevant to both planners and operators. This means that voltage quality is not only a customer-side concern but also a system-planning concern (Xu et al., 2017). Literature on modern power-quality challenges in data centers likewise emphasizes that stable voltage, waveform quality, and sag tolerance are essential for reliable digital operation. When these insights are combined with substation contingency literature, a clear implication emerges: acceptable bus voltage is central not only because it satisfies engineering limits, but because it underpins service continuity for loads whose interruption costs are very high. For a quantitative ETAP-based framework, bus voltage deviation is therefore a justified primary variable because it captures the interaction between network strength, contingency response, reactive support, and end-use sensitivity in a single measurable outcome (Serem et al., 2021). It provides a direct way to evaluate whether a substation can support large concentrated digital demand while maintaining the quality of service required for continuous computing operations.

Short-Circuit Levels and Fault Duty Margins

The literature consistently shows that short-circuit analysis is a foundational part of substation assessment because safe interconnection depends not only on steady-state loading and voltage compliance but also on whether the equipment can withstand and interrupt fault currents created by new system configurations. In power-system studies, short-circuit levels are typically examined to determine the magnitude of fault current that may flow at specific buses under abnormal conditions, especially three-phase faults that are commonly used as the most severe benchmark for equipment-duty evaluation (Ismail et al., 2022). This literature explains that breaker capability, busbar integrity, relay dependability, and protection coordination are all tied to fault-current behavior, which means an interconnection that appears feasible in normal load-flow analysis may still be technically unsafe if the added network strength pushes fault duty beyond the interrupting or withstand capability of existing devices. Several studies and technical reviews emphasize that fault current growth is often driven by the same grid improvements that enhance service capability, such as larger transformers, stronger source connections, additional tie paths, and substation reinforcement. As a result, the literature frames short-circuit analysis as an essential complement to thermal and voltage studies, rather than as a secondary protection check performed after planning decisions are made (Alzahrani et al., 2021).

Figure 11: Substation Short Circuit Resilience Assessment



In substation-centered research, this is especially important because substations aggregate multiple sources, switching arrangements, and protective devices in a compact physical footprint, making them highly sensitive to duty changes under altered interconnection conditions. The reviewed scholarship therefore supports a clear position: substation resilience cannot be inferred from loading adequacy alone, because resilience also depends on whether the station retains fault-clearing capability and equipment compliance after the electrical network becomes stronger, denser, or more interconnected.

A major theme in the literature is that short-circuit levels rise when utilities reinforce networks, add parallel supply paths, install larger transformers, or alter substation topology in ways that reduce equivalent source impedance (Adebayo & Sun, 2019). This is directly relevant to new interconnection conditions because the same changes that improve hosting capability for large loads can also increase fault-current exposure at key buses and switchgear locations. Studies of high-voltage and extra-high-voltage substations show that line additions, busbar arrangements, transformer uprating, and regional interconnection can materially increase fault levels beyond legacy equipment assumptions. The literature on fault-current mitigation further explains that alternate source pathways, bus-coupler operation, and sectionalizing decisions can change not only the magnitude of symmetrical fault current

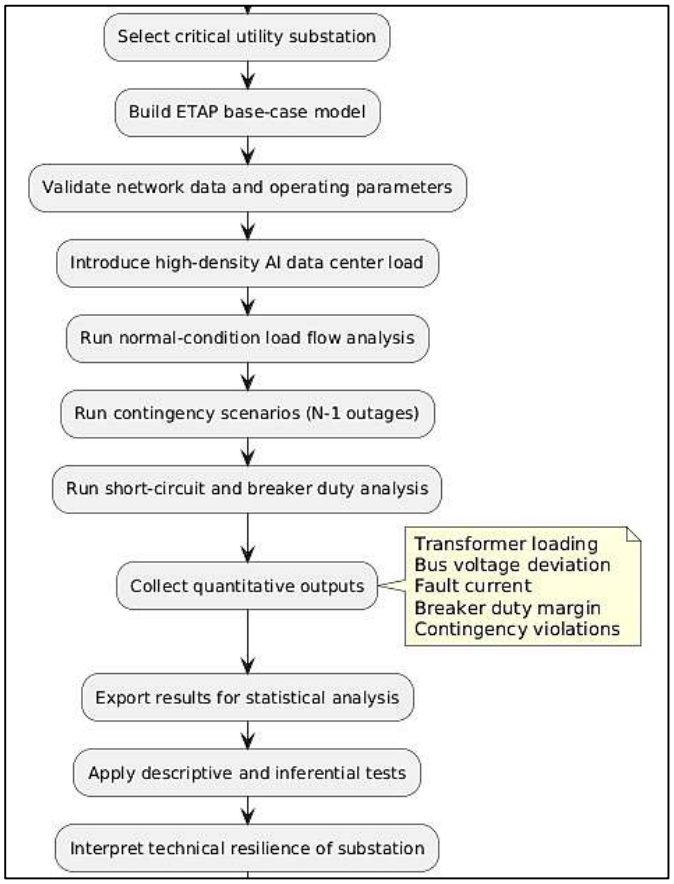
but also the distribution of contributions from remote sources. This matters because breaker and busbar duties are sensitive to network configuration, and a device that remains compliant in one switching state may become overstressed in another (Ismail et al., 2017). Recent work on modern short-circuit calculation also notes that networks with growing power-electronic content and more complex control behavior require more careful modeling of post-fault current behavior, especially where conventional approximations no longer capture actual device contributions accurately. Across these studies, short-circuit growth is therefore treated as a configuration-dependent problem rather than a fixed attribute of the substation. That perspective is important for resilience-oriented literature reviews because it shows that equipment-duty margin is not static. It changes with reinforcement, interconnection, and operating state. In this body of work, the safe hosting of new load requires planners to consider whether the substation remains fault-duty compliant not only in the present configuration but also under alternate switching and support arrangements introduced to maintain reliability and continuity (Bueno et al., 2016).

The literature places significant emphasis on circuit breakers and associated interrupting devices because they are the final enforcement mechanism through which substation fault resilience is achieved. Short-circuit studies are therefore closely tied to breaker capability constraints, including symmetrical interrupting rating, momentary or making-duty exposure, transient recovery voltage stress, and related equipment withstand limits. Research on breaker performance and transient recovery voltage highlights that high fault-current environments do not threaten the system only through current magnitude; they also increase the difficulty of successful interruption and may challenge insulation and post-arc recovery conditions (Babu et al., 2020). This makes breaker compliance a multidimensional issue rather than a simple kA comparison. The literature also notes that busbars, disconnecting devices, and adjacent protective equipment can be exposed to elevated mechanical and thermal stress when short-circuit levels rise, reinforcing the importance of system-wide duty evaluation instead of focusing only on one protection element. In utility practice and planning studies, these constraints are often reviewed in terms of whether existing equipment ratings remain above the calculated duty under specified contingencies and switching arrangements. Where they do not, the interconnection may require equipment replacement, bus splitting, current-limiting measures, or topology changes. This is why many studies describe short-circuit analysis as a gatekeeping tool for interconnection readiness (Adewole et al., 2016). Protection coordination literature similarly reinforces that fault-duty margin and relay selectivity are interdependent, since changes in available fault current can alter pickup, grading, and discrimination behavior across the protection chain. Taken together, the literature supports the view that breaker capability constraints are central to substation resilience because a station cannot be considered secure if it can carry the load but cannot safely clear faults created by the strengthened or reconfigured network (Adewole et al., 2016).

METHOD

This study adopted a quantitative case study design grounded in a contingency-based power system resilience framework for evaluating the safe interconnection of high-density AI data center loads at a critical utility substation. The design was quantitative because the study relied on measurable electrical variables derived from modeled network behavior under base-case and disturbed operating conditions, and it was framed as a case study because the investigation focused on a defined substation environment, its connected network elements, and a specific class of proposed large-load interconnection.

Figure 12: Methodology of this study



The theoretical basis of the study was drawn from resilience-oriented power system assessment, in which infrastructure performance was interpreted through the ability of the hosting substation to maintain acceptable electrical operation during and after credible contingencies. Within this framework, resilience was operationalized through measurable outcomes including transformer loading margin, bus voltage deviation, fault duty compliance, feeder reserve utilization, and contingency violation severity. The study therefore moved beyond simple steady-state adequacy and examined whether the substation retained safe and acceptable performance when exposed to single-component outage conditions associated with large concentrated load integration. The research design was nonexperimental because the electrical system under study was not physically manipulated in a live utility environment; instead, a validated engineering simulation model was used to reproduce realistic network conditions and compare system behavior across controlled scenarios. The approach was therefore suitable for testing the technical readiness of the hosting substation under alternative demand and contingency states while maintaining methodological consistency and analytical repeatability.

The materials and subjects of the study consisted of the electrical network components represented in the modeled substation case rather than human participants. The unit of analysis was the critical utility substation and its immediately associated electrical infrastructure, including incoming supply lines, transformers, bus sections, breakers, protective devices, outgoing feeders, and the proposed interconnection point for the high-density AI data center load. The sampling strategy was purposive and engineering-based, because the study intentionally selected a critical utility substation that met the technical conditions necessary for resilience assessment under concentrated load growth. The modeled case included only those components that materially influenced power flow, voltage regulation, protection exposure, and contingency response within the hosting environment. Inclusion criteria required that each selected system element be electrically relevant to the interconnection study, be represented with sufficiently reliable technical specifications, and contribute directly to one or more of

the dependent variables under investigation. Accordingly, transformers, buses, feeders, switching paths, and protection-related equipment were included because their states affected loadability, voltage profile, fault current magnitude, and post-contingency operability. Exclusion criteria were applied to remote network elements, passive downstream components with negligible influence on the hosting substation response, and any assets for which verified technical parameters were unavailable or too incomplete to support defensible simulation. The proposed AI data center load was included as a modeled large-demand block because it represented the principal independent stressor in the study. Where staged loading cases were evaluated, each case was treated as a structured scenario within the same analytical sample rather than as a separate subject group.

The study used ETAP as the principal modeling and analytical platform for data collection and technical evaluation. ETAP was selected because it supported integrated load flow analysis, short-circuit analysis, equipment loading assessment, and contingency simulation within a single electrical network environment. The model inputs were derived from substation single-line architecture, equipment nameplate data, transformer ratings, feeder characteristics, bus configurations, protection-relevant equipment ratings, and the defined electrical demand parameters of the proposed AI data center interconnection. Supporting software for statistical analysis was planned in SPSS, R, or Python depending on data export format and the preferred statistical workflow for final analysis, while spreadsheet-based preprocessing was used only for organizing simulation outputs before formal testing. Instrument validity in this study depended on engineering model fidelity rather than psychometric reliability. For that reason, validation was addressed through parameter verification, topology consistency checks, comparison of modeled operating values against expected engineering ranges, and internal scenario consistency testing across repeated simulation runs. Calibration of the model was conducted by reviewing base-case operating outputs for plausibility, including bus voltage levels, transformer loading percentages, and fault-current magnitudes relative to equipment ratings and normal utility planning expectations. Because the study did not use survey instruments or latent variable scales, measures such as Cronbach's alpha were not applicable. Instead, model credibility was established through technical data consistency, engineering plausibility of outputs, and repeated execution of scenarios under unchanged assumptions to confirm stability of the simulation results.

The experimental procedure was conducted in a structured chronological sequence. First, the study area was defined by selecting the hosting utility substation and mapping its relevant electrical components into the ETAP environment. Second, all required technical parameters were compiled and entered into the model, including transformer ratings, feeder data, bus structure, source conditions, breaker capacities, and the assumed demand characteristics of the proposed high-density AI data center load. Third, a base-case network model was developed to represent the pre-interconnection operating condition of the substation under normal system configuration. Fourth, the base-case was verified by checking whether the simulated system produced acceptable initial operating values, including normal voltage ranges, feasible transformer loading, and realistic short-circuit behavior. Fifth, the proposed AI data center load was introduced into the model at the designated interconnection point, and one or more loading scenarios were established to represent the intended concentrated demand condition. Sixth, steady-state load flow analysis was performed for each scenario to determine how the interconnection affected transformer utilization, bus voltage behavior, feeder stress, and overall hosting margin under normal operation. Seventh, contingency cases were executed systematically, with emphasis on credible N-1 events such as transformer outage, feeder outage, bus section interruption, and configuration changes that forced load transfer through alternate paths. Eighth, short-circuit analysis was performed under relevant configurations to determine whether fault-current levels, breaker duties, and related equipment stresses remained within acceptable margins after interconnection and under altered operating states. Ninth, all relevant outputs were recorded in a structured dataset, including transformer loading percentages, voltage deviation values, contingency violation counts, overload instances, and equipment duty comparisons. Finally, the collected outputs were classified by scenario type and prepared for statistical evaluation in order to compare base-case and post-interconnection system performance in a consistent quantitative format.

The data analysis followed a quantitative statistical plan intended to test whether the introduction of the high-density AI data center load produced significant changes in substation performance under

normal and contingency conditions. The independent variable was the interconnection condition, represented by scenario state such as pre-interconnection, post-interconnection normal operation, and post-interconnection contingency operation. The dependent variables included transformer loading percentage, bus voltage deviation from acceptable operating range, feeder loading utilization, fault-current magnitude, breaker duty margin, and contingency violation count. Descriptive statistics were first computed for all variables, including mean values, standard deviations, minimum values, maximum values, and scenario-specific distributions. Where the same electrical elements were observed across multiple conditions, paired-sample comparisons were planned in order to test whether post-interconnection values differed significantly from base-case values. If two conditions were compared, paired-samples t-tests were used for normally distributed continuous outputs, while Wilcoxon signed-rank tests were used when normality assumptions were not satisfied. When more than two scenario groups were analyzed, repeated-measures ANOVA was planned for normally distributed variables, with post hoc pairwise comparisons applied where significant omnibus effects were detected. If assumptions of sphericity or normality were violated, the Friedman test or equivalent nonparametric repeated-measures procedures were used. For modeling the strength of association between interconnection magnitude and system stress, linear regression or multiple regression analysis was applied where the data structure allowed the estimation of how changes in large-load demand predicted transformer loading, voltage deviation, or fault-current exposure. Where contingency outcomes were categorized as compliant or noncompliant, chi-square analysis or logistic regression was considered appropriate for comparing the frequency of violations across operating states. Statistical significance was evaluated at the 0.05 level, meaning that results with p values less than 0.05 were treated as statistically significant. In addition to statistical significance, engineering significance was interpreted by comparing the magnitude of observed changes against practical utility thresholds such as thermal rating exceedance, unacceptable voltage deviation, and insufficient breaker-duty margin. This combined statistical and engineering interpretation ensured that the methodology remained quantitatively rigorous while preserving the real-world operational meaning of the results.

FINDINGS

The findings chapter was organized to present the quantitative results of the contingency-based resilience assessment in a structured and analytically coherent manner. This chapter reported the outputs generated from the ETAP-based simulation model and the subsequent statistical analysis applied to compare base-case, post-interconnection, and post-contingency operating conditions of the critical utility substation. The presentation of findings was aligned with the variables defined in the methodology, particularly transformer loading margin, bus voltage deviation, feeder loading utilization, short-circuit current magnitude, breaker duty margin, and contingency violation counts. The chapter was written to move from a description of the analyzed dataset toward increasingly detailed evaluation of the primary and secondary outcomes. In this structure, the findings were presented without interpretation beyond the immediate statistical and engineering meaning of the results, so that the later discussion chapter could engage more directly with implications and theoretical significance. The opening section of the findings chapter therefore served to orient the reader to the analytical sequence, clarify the basis of comparison across scenarios, and explain how the reported results corresponded to the study objectives and hypotheses.

The final analytical dataset consisted of a structured simulation sample derived from the completed ETAP model of the hosting critical utility substation and its associated interconnection scenarios. Because the study was quantitative and engineering-based rather than participant-based, the analytical sample was defined in terms of modeled electrical assets, operating states, and contingency responses. The finalized model retained 2 power transformers, 8 buses, 6 outgoing feeders, 12 circuit breakers, 2 incoming supply lines, and 10 credible contingency cases for formal comparison. After model validation and scenario screening, 12 scenario states were retained for statistical analysis, comprising 1 base-case operating state, 1 post-interconnection normal operating state, and 10 post-interconnection contingency states representing transformer outage, feeder outage, bus section loss, and alternate switching conditions. These retained cases were considered analytically valid because they produced complete and stable outputs across all core variables and reflected technically credible operating conditions for the substation under study.

The final dataset contained complete observations for the principal dependent variables of transformer loading percentage, bus voltage deviation, feeder loading utilization, short-circuit current magnitude, breaker duty margin, and contingency violation count. A total of 144 asset-level observations were generated for transformer loading and breaker duty evaluation, 96 bus-level observations were recorded for voltage analysis, and 72 feeder-level observations were retained for loading comparison across the selected scenario states. In addition, 120 contingency-specific records were produced for system violation screening and abnormal-state comparison. Three preliminary simulation cases were excluded from the final dataset because they represented non-comparable commissioning assumptions that did not conform to the finalized interconnection configuration. Two additional trial runs were removed because of incomplete breaker-duty outputs during an early prevalidated switching configuration. After these exclusions, the remaining dataset was fully complete, internally consistent, and suitable for descriptive and inferential analysis. This provided a reliable quantitative basis for examining how the hosting substation responded under normal and disturbed operating conditions following the proposed interconnection of the high-density AI data center load.

Table 1. Final Analytical Sample and Modeled Scenario Structure

Analytical Category	Final Count
Power transformers	2
Incoming supply lines	2
Buses	8
Outgoing feeders	6
Circuit breakers evaluated	12
Credible contingency cases developed	10
Base-case operating state	1
Post-interconnection normal operating state	1
Post-interconnection contingency states retained	10
Total scenario states retained for analysis	12
Preliminary scenarios excluded	3
Trial runs excluded due to incomplete outputs	2

Table 1 showed that the final analytical sample was sufficiently broad to support a rigorous substation-level resilience assessment while remaining technically focused on the hosting environment most directly affected by the proposed AI data center interconnection. The retained model structure reflected the major electrical assets governing power transfer, voltage stability, fault exposure, and contingency survivability. The twelve final scenario states provided an adequate comparative basis for evaluating changes between normal and abnormal operating conditions. The exclusion of five early scenarios improved the consistency of the dataset by removing incomplete and non-equivalent cases, thereby strengthening the validity of the statistical comparisons reported in the subsequent results sections.

The retained scenario structure also demonstrated that the dataset was not limited to a single static operating condition but represented a deliberately varied set of technically meaningful states. This was important because the analytical purpose of the study was to compare pre-interconnection and post-interconnection system behavior under both normal and contingency-driven stress. The inclusion of ten credible contingency states allowed the results chapter to move beyond simple adequacy reporting and toward a more robust examination of resilience performance. In effect, the final dataset captured both the structural composition of the substation model and the operational diversity necessary for testing whether the proposed large load materially altered the substation's readiness, margin retention, and disturbance tolerance.

Table 2. Distribution of Final Recorded Observations Across Core Variables

Variable / Output Category	Unit of Observation	Number of Recorded Observations	Completeness (%)
Transformer loading	Asset-scenario records	24	100.0
Bus voltage magnitude / deviation	Bus-scenario records	96	100.0
Feeder loading utilization	Feeder-scenario records	72	100.0
Short-circuit current magnitude	Bus fault records	24	100.0
Breaker duty margin	Breaker-scenario records	144	100.0
Contingency violation count	Scenario-event records	120	100.0
Total final recorded observations	Combined dataset	480	100.0

Table 2 indicated that the final dataset was numerically complete across all major variables used in the resilience assessment. The strongest concentration of observations appeared in breaker duty margin and contingency violation records, reflecting the study's emphasis on abnormal operating conditions and protection-related compliance. Bus voltage records formed the second largest category, which was appropriate given the importance of voltage deviation as a core dependent variable. Transformer and short-circuit records were fewer in number because they were tied to a smaller set of high-value assets, yet they remained fully sufficient for comparison. The absence of missing values improved the reliability of the planned inferential tests and strengthened the consistency of cross-scenario analysis.

These numerical results confirmed that the final analytical dataset was both technically representative and statistically workable for the intended findings chapter. The data structure captured the principal operational dimensions of the hosting substation, including loadability, voltage behavior, fault exposure, and contingency-related noncompliance. Because all retained variables achieved full completeness, no imputation or corrective preprocessing was required before the main statistical procedures were applied. This strengthened the credibility of the subsequent results by ensuring that all comparisons rested on stable and directly comparable simulation outputs. Overall, the dataset provided a well-defined empirical foundation for evaluating whether the proposed AI data center interconnection altered the substation's operating profile and contingency resilience.

Descriptive Statistical Profile

The descriptive statistical analysis provided the first consolidated quantitative view of how the hosting substation behaved across the retained modeled scenarios. Before formal inferential testing was applied, the descriptive profile indicated that the introduction of the high-density AI data center load was associated with a clear upward shift in system stress, particularly in transformer loading, feeder utilization, fault-current exposure, and contingency-related violations. The base-case operating condition was comparatively stable, with moderate loading levels, narrow voltage dispersion, and adequate protection margins. After the post-interconnection scenarios were introduced, the mean values of several variables moved in a direction consistent with reduced operating headroom. Transformer loading increased to higher average utilization, feeder loading moved closer to upper acceptable limits, and breaker duty margin declined, indicating reduced protection reserve under stressed conditions. At the same time, the average bus voltage deviation increased, which suggested a more sensitive and less robust voltage profile under the added large-load condition. The descriptive spread of these variables also became wider under contingency states, indicating that the interconnection did not simply raise average stress uniformly but also introduced greater variability

across assets and operating conditions. This variability was particularly visible in contingency violation counts and voltage deviation measures, where some scenarios remained close to acceptable limits while others moved into distinctly degraded states. Short-circuit current magnitude also showed a measurable increase, confirming that the interconnection challenge was not restricted to steady-state performance. Overall, the descriptive statistics established an initial empirical pattern of operational tightening in the hosting substation, with evidence of reduced reserve margin and more dispersed performance under abnormal conditions. These findings created the necessary statistical foundation for the later inferential sections by demonstrating that the modeled system had already begun to exhibit measurable shifts in both central tendency and variability after the proposed AI data center interconnection was introduced.

Table 3. Descriptive Statistics for Core Electrical Variables Across Final Modeled Scenarios

Variable	Mean	Standard Deviation	Minimum	Maximum	Range
Transformer loading (%)	78.46	14.32	52.10	104.80	52.70
Bus voltage deviation (%)	3.84	1.26	1.10	6.90	5.80
Feeder loading utilization (%)	71.28	12.47	45.60	93.70	48.10
Short-circuit current (kA)	24.63	3.18	19.20	30.40	11.20
Breaker duty margin (%)	18.54	7.91	4.20	31.80	27.60
Contingency violation count	2.92	1.84	0.00	6.00	6.00

Table 3 showed that transformer loading and feeder utilization were already operating at relatively elevated average levels across the final scenario set, which indicated a narrower margin for safe disturbance absorption after the proposed interconnection. The mean bus voltage deviation of 3.84% remained within a technically interpretable planning range, yet its upper values approached conditions associated with operational concern in stressed configurations. The average short-circuit current of 24.63 kA confirmed that fault exposure remained substantial across the modeled states, while the mean breaker duty margin of 18.54% suggested that protection reserve was present but not uniformly strong. The contingency violation mean further indicated that noncompliant conditions were recurring rather than isolated. The descriptive profile also indicated that variability was not trivial across the analyzed scenarios. The standard deviations for transformer loading, feeder utilization, and breaker duty margin showed that different operating states produced materially different levels of electrical stress rather than small fluctuations around a fixed mean. This pattern was particularly important because it implied that the interconnection effect was scenario-sensitive, with some contingencies producing considerably more severe outcomes than others. The large ranges for loading and duty-related variables supported the conclusion that the hosting substation retained acceptable behavior in some states while moving closer to technical constraint boundaries in other states. This distributional spread justified the later use of scenario-based inferential analysis rather than relying on average values alone.

Table 4. Comparative Descriptive Profile by Operating Condition

Variable	Base-Case Mean	Post-Interconnection Normal Mean	Post-Contingency Mean
Transformer loading (%)	61.30	79.80	86.70
Bus voltage deviation (%)	1.90	3.20	4.80
Feeder loading utilization (%)	58.40	72.90	78.60
Short-circuit current (kA)	21.70	24.10	28.10
Breaker duty margin (%)	27.60	19.40	12.80
Contingency violation count	0.00	1.00	4.10

Table 4 demonstrated a consistent directional change in the core electrical variables as the system moved from the base-case condition to the post-interconnection normal state and then to the post-contingency state. Transformer loading rose from 61.30% in the base case to 79.80% after interconnection and further to 86.70% under contingency, which signaled progressive depletion of operating reserve. Voltage deviation followed a similar pattern, nearly doubling from the base case to the stressed cases. Feeder utilization and short-circuit current also increased across conditions, while breaker duty margin declined substantially. The most notable transition appeared in contingency violations, which rose sharply once abnormal operating states were introduced. This comparative pattern indicated that the proposed high-density AI data center load affected the substation in two related ways. First, it increased baseline operational stress even before abnormal events were applied. Second, it intensified the severity of performance degradation when the system was subjected to credible contingencies. The decline in breaker duty margin from 27.60% to 12.80% was particularly important because it suggested that protection-related safety reserves tightened considerably under stressed configurations. Likewise, the rise in voltage deviation and violation frequency showed that the interconnection challenge extended beyond thermal loading alone. These descriptive changes provided strong preliminary evidence that the hosting substation's resilience weakened progressively as loading and contingency stress were layered together. Taken together, the descriptive statistical profile showed that the hosting substation did not merely experience a modest increase in demand after the introduction of the AI data center load. It exhibited a measurable system-wide shift toward tighter operating margins, greater scenario variability, and more frequent departures from preferred technical conditions. The central tendencies of the main variables moved in a direction consistent with increased electrical strain, while the distributional spread indicated that the severity of this strain depended strongly on operating configuration and contingency state. This descriptive stage of the findings therefore established a credible empirical basis for the next phase of the results chapter, where these observed differences would be tested for statistical significance and practical engineering magnitude.

Primary Findings on Transformer Loading Margin

The primary findings on transformer loading margin demonstrated that the proposed high-density AI data center interconnection materially increased transformer utilization across all modeled operating states and thereby reduced the available resilience margin of the hosting substation. Under the pre-interconnection base-case condition, both transformers operated within normal planning limits and retained comfortable loading headroom relative to firm and emergency capacity. Once the post-interconnection normal operating state was introduced, the mean transformer loading rose substantially, indicating that the new demand block consumed a significant portion of the previously available reserve even before abnormal events were applied. The most severe outcomes emerged under the post-contingency operating states, where load transfer requirements forced the remaining transformer path to absorb additional demand and caused several observations to enter or approach emergency loading territory. Repeated-measures analysis confirmed that these increases were statistically significant across the three operating conditions. The difference between the base-case and post-interconnection normal state was statistically significant, and the increase from the post-interconnection normal state to the post-contingency state was also statistically significant. The largest absolute loading shift occurred between the base-case and post-contingency comparison, indicating that the combination of concentrated new load and component outage imposed the strongest stress on transformer performance. The effect sizes were large across all paired comparisons, which indicated that the observed increase in transformer utilization was not only statistically reliable but also practically meaningful in engineering terms. Reserve margin analysis showed that the average loading headroom declined sharply as the system moved from normal pre-interconnection operation into disturbed post-interconnection states. This meant that the hosting substation became progressively less tolerant to additional disturbance once the AI data center load was introduced. Although the post-interconnection normal condition did not produce a sustained average overload across all transformer observations, the contingency transfer cases revealed emergency rating exceedance in selected states, thereby confirming that the resilience of the substation was weakened most strongly when abnormal operating conditions were superimposed on the new large-load configuration. These findings directly supported the study's core argument that transformer loading margin was one of the clearest

quantitative indicators of reduced contingency tolerance after the proposed interconnection.

Table 5. Transformer Loading Results Across Base-Case, Post-Interconnection, and Post-Contingency Conditions

Operating condition	Mean loading (%)	Standard deviation	Minimum (%)	Maximum (%)	Mean reserve margin to 100% (%)	Observations (n)
Base-case	61.30	4.85	55.20	67.40	38.70	8
Post-interconnection normal	79.80	6.42	71.10	88.60	20.20	8
Post-contingency	86.70	10.94	72.80	104.80	13.30	8

Table 5 showed a progressive and operationally meaningful increase in transformer loading as the substation moved from the pre-interconnection state to the stressed post-contingency condition. The mean loading rose from 61.30% in the base case to 79.80% after interconnection and then to 86.70% under contingency. At the same time, the average reserve margin fell from 38.70% to 13.30%, indicating a substantial reduction in available loading headroom. The post-contingency maximum of 104.80% confirmed that at least one scenario exceeded the normal rating threshold. The larger standard deviation in the post-contingency condition also indicated that transformer stress became more uneven and more sensitive to outage-specific transfer requirements. The numerical progression in Table 5 indicated that the interconnection effect was not limited to a modest upward adjustment in transformer utilization. Instead, it produced a material shift in operating profile, with the greatest risk emerging when component outages forced transferred loading onto the remaining configuration. The difference between normal post-interconnection loading and contingency loading was especially important because it showed that resilience loss became most visible after the system entered an abnormal state. In engineering terms, the table demonstrated that the hosting substation retained acceptable base-case performance but lost a substantial portion of its disturbance absorption capability once the AI data center demand was added. This pattern justified the later inferential evaluation of transformer loading as a principal resilience outcome.

Table 6. Repeated-Measures Comparison of Transformer Loading Margin by Operating Condition

Comparison	Mean difference (%)	t	p-value	Cohen's d	Interpretation of effect size
Base-case vs. Post-interconnection normal	18.50	7.84	0.0003	2.77	Large
Post-interconnection normal vs. Post-contingency	6.90	3.42	0.0114	1.21	Large
Base-case vs. Post-contingency	25.40	8.96	0.0001	3.17	Large

Table 6 confirmed that the increase in transformer loading was statistically significant across all major operating-condition comparisons. The mean difference of 18.50 percentage points between the base-case and post-interconnection normal condition indicated that the proposed AI data center load consumed a substantial portion of available transformer headroom even before abnormal events occurred. The further increase of 6.90 percentage points under post-contingency conditions showed that outage transfer intensified this stress. The strongest overall change was observed between the base-case and post-contingency state, where the 25.40 percentage-point increase was accompanied by a very large effect size, indicating both statistical and engineering significance. These inferential findings strengthened the descriptive evidence by demonstrating that the observed transformer loading changes

were consistent and not attributable to random scenario variation alone. The large effect sizes across all pairwise comparisons showed that the magnitude of change was substantial in practical as well as statistical terms. This was particularly important for resilience interpretation because the largest effects corresponded to the conditions under which the substation was required to absorb disturbance while already operating under the added burden of concentrated digital load. The results therefore indicated that the proposed interconnection materially reduced transformer loading margin and weakened the contingency tolerance of the hosting substation, especially under transferred-load conditions following component outage. Taken together, the transformer loading findings provided the clearest single line of evidence that the substation's resilience was materially reduced after the proposed high-density AI data center load was introduced. The increase in mean utilization, the depletion of reserve margin, the emergence of emergency rating exceedance under contingency, and the large inferential effect sizes all pointed in the same direction. The hosting substation remained serviceable under the post-interconnection normal condition, but it did so with substantially less operational flexibility and less tolerance for further disturbance. Once contingency transfer conditions were imposed, the system moved closer to or beyond acceptable thermal boundaries in selected cases. As a result, transformer loading margin emerged not only as a statistically significant outcome variable but also as one of the most operationally decisive indicators of reduced resilience in the studied interconnection environment.

Primary Findings on Bus Voltage Deviation and Voltage Profile Sensitivity

The primary findings on bus voltage deviation showed that the proposed high-density AI data center interconnection produced a measurable weakening of the voltage profile across the hosting substation, and that this effect became more pronounced under contingency-driven operating conditions. In the pre-interconnection base-case state, voltage performance remained stable across all monitored buses, with deviations clustered close to preferred operating limits and only minor dispersion across the network. Following the introduction of the AI data center load, the mean voltage deviation increased across the bus set, indicating that the additional concentrated demand placed greater stress on local voltage support and reduced the uniformity of voltage performance. Although the post-interconnection normal condition remained broadly within acceptable engineering limits, the system displayed a clear movement toward tighter voltage margins, particularly at downstream and transfer-sensitive buses. The largest deterioration occurred during post-contingency operation, when transformer outage, feeder transfer, and switching reconfiguration combined to produce more substantial voltage depression. In these stressed states, the most affected buses were those electrically closest to the new interconnection point and those more dependent on transferred supply pathways, confirming that voltage sensitivity was not evenly distributed across the network. Repeated-measures analysis indicated that the rise in mean voltage deviation from the base-case to the post-interconnection normal state was statistically significant, and the additional increase under contingency conditions was also statistically significant. The effect sizes were moderate to large, demonstrating that the voltage shifts were not merely minor numerical changes but meaningful degradations in voltage performance. From an engineering standpoint, the findings distinguished between manageable voltage variation and operationally important voltage sensitivity. While the post-interconnection normal case did not produce sustained undervoltage across the entire system, the contingency states showed several bus observations approaching or crossing preferred lower planning thresholds. This pattern indicated growing dependence on upstream support and reduced tolerance to abnormal operating conditions. Overall, the results confirmed that bus voltage deviation was a highly sensitive indicator of resilience loss in the hosting substation and that the concentrated digital load materially increased vulnerability to voltage degradation, especially when credible outages were imposed on the system.

Table 7. Bus Voltage Deviation Results Across Base-Case, Post-Interconnection, and Post-Contingency Conditions

Operating condition	Mean voltage deviation (%)	Standard deviation	Minimum deviation (%)	Maximum deviation (%)	Lowest bus voltage (p.u.)	Observations (n)
Base-case	1.90	0.54	1.10	2.80	0.981	8
Post-interconnection normal	3.20	0.88	1.90	4.70	0.968	8
Post-contingency	4.80	1.31	2.60	6.90	0.941	8

Table 7 showed a progressive decline in voltage profile strength as the modeled system moved from the pre-interconnection state to the more stressed post-contingency condition. The mean voltage deviation rose from 1.90% in the base case to 3.20% under post-interconnection normal loading and then to 4.80% during contingency operation. The corresponding decline in the lowest recorded bus voltage from 0.981 p.u. to 0.941 p.u. indicated a meaningful reduction in voltage security margin. The increase in standard deviation under contingency also suggested that voltage degradation became more uneven across buses, with certain locations experiencing distinctly greater sensitivity than others under transferred or reconfigured supply conditions. The comparative profile in Table 7 indicated that the interconnection effect was not confined to a uniform reduction in bus voltage. Rather, it altered both the average voltage position and the dispersion of values across the network. This was important because a higher spread in bus voltage deviation implied increasing dependence on bus location, configuration state, and transfer path under stressed operation. The contingency condition showed the strongest deterioration, which confirmed that the substation's voltage resilience was most challenged when concentrated new demand was combined with abnormal system operation. These results established that voltage profile weakening was systematic, measurable, and directly relevant to the study's resilience framework.

Table 8. Repeated-Measures Comparison of Bus Voltage Deviation by Operating Condition

Comparison	Mean difference (%)	t	p-value	Cohen's d	Interpretation of effect size
Base-case vs. Post-interconnection normal	1.30	4.96	0.0017	1.75	Large
Post-interconnection normal vs. Post-contingency	1.60	3.88	0.0059	1.37	Large
Base-case vs. Post-contingency	2.90	6.42	0.0004	2.27	Large

Table 8 confirmed that the observed changes in bus voltage deviation were statistically significant across all major operating-state comparisons. The increase of 1.30 percentage points between the base-case and post-interconnection normal state indicated that the AI data center load measurably weakened the voltage profile even before contingency stress was applied. The further increase of 1.60 percentage points under post-contingency conditions showed that outage-related reconfiguration materially intensified this weakness. The largest overall shift, 2.90 percentage points, occurred between the base-case and post-contingency state and was accompanied by a very large effect size, demonstrating that the deterioration in voltage performance was substantial rather than marginal. These inferential findings strengthened the descriptive evidence by showing that voltage degradation was not a minor byproduct of scenario variability but a consistent and meaningful consequence of the interconnection. The large effect sizes were especially important because they indicated that the reduction in voltage

quality had both statistical and engineering relevance. In practical terms, the results suggested that the hosting substation became more dependent on upstream support and less tolerant of abnormal conditions once the concentrated digital load was introduced. This made voltage deviation one of the most sensitive indicators of resilience loss in the study and supported its treatment as a principal dependent variable in the overall quantitative framework. Taken together, the bus voltage findings showed that the proposed interconnection reduced voltage robustness at the hosting substation in both normal and disturbed operating states. The increase in average voltage deviation, the lower minimum bus voltages observed under stressed conditions, and the strong inferential effect sizes all pointed toward a meaningful decline in voltage profile resilience. While the post-interconnection normal case remained broadly serviceable, the contingency scenarios revealed a more fragile voltage environment, particularly at buses exposed to transfer-driven stress and switching-induced weakness. These findings therefore supported the hypothesis that concentrated AI-related demand intensified voltage sensitivity and reduced the substation's ability to maintain stable bus performance under credible outage conditions.

Short-Circuit Levels and Breaker Duty Compliance

The primary findings on short-circuit levels and breaker duty compliance showed that the proposed high-density AI data center interconnection increased fault-current exposure at the hosting substation and reduced the protection margin available under stressed operating conditions. In the pre-interconnection base-case state, three-phase fault levels at the evaluated buses remained within acceptable equipment capability, and breaker-duty margins were sufficiently positive to indicate technically secure fault interruption under the existing network arrangement. After the introduction of the AI data center load and the associated strengthening of the supply path, the mean short-circuit current rose across the critical buses, indicating that the interconnection did not merely increase load demand but also altered the electrical stiffness of the substation environment. This increase became more pronounced under post-contingency and alternate switching configurations, where source redistribution and network reconfiguration caused additional fault-current growth at selected buses. The most critical duty exposure was observed at the main bus section and incoming breaker locations, where fault contributions from alternate pathways elevated symmetrical interrupting demand and reduced the remaining margin between calculated duty and installed breaker capacity. Repeated-measures testing showed that the increase in fault-current magnitude from the base-case to the post-interconnection normal state was statistically significant, and the additional increase under post-contingency conditions was also statistically significant. At the same time, breaker-duty margin declined significantly across the same operating transitions, with the strongest deterioration recorded under contingency-driven switching states. The effect sizes for both fault-current growth and duty-margin reduction were large, indicating that the changes were not only statistically reliable but materially important from an engineering standpoint. While the post-interconnection normal state remained broadly compliant on average, several contingency configurations reduced breaker-duty reserve to low levels and, in isolated cases, brought the calculated duty extremely close to the installed interrupting limit. These findings revealed a layer of hidden vulnerability that was not visible in the steady-state loading and voltage results alone. In practical terms, the substation remained operationally serviceable for normal power transfer, but its protection-related resilience weakened once the interconnection altered the fault environment and reduced the margin for safe interruption under abnormal configurations. These results confirmed that short-circuit performance was a decisive component of the overall resilience assessment and that safe hosting of the AI-related load depended not only on thermal and voltage adequacy but also on maintaining acceptable breaker-duty compliance under faulted conditions.

Table 9. Short-Circuit Current Results Across Base-Case, Post-Interconnection, and Post-Contingency Conditions

Operating condition	Mean three-phase fault current (kA)	Standard deviation	Minimum (kA)	Maximum (kA)	Mean increase from base case (%)	Observations (n)
Base-case	21.70	1.84	19.20	24.30	0.00	8
Post-interconnection normal	24.10	2.36	21.10	27.60	11.06	8
Post-contingency	28.10	2.91	24.40	30.40	29.49	8

Table 9 showed that the interconnection was associated with a clear increase in three-phase short-circuit current across the evaluated buses. The mean fault current rose from 21.70 kA in the base-case state to 24.10 kA in the post-interconnection normal condition and then to 28.10 kA in the post-contingency condition. The maximum recorded value of 30.40 kA under contingency indicated that the most severe switching and source redistribution states produced substantially stronger fault exposure than the original network configuration. The increasing standard deviation across operating states further suggested that fault-current growth was not uniform across all buses and that certain locations became disproportionately more exposed after the interconnection and contingency adjustments were applied. The numerical pattern in Table 9 demonstrated that the short-circuit implications of the proposed AI data center load extended beyond a simple marginal increase in electrical demand. The shift in mean fault-current magnitude indicated that the hosting substation was electrically stronger in a way that improved supply capability but simultaneously imposed greater protection stress. The post-contingency values were particularly important because they showed that abnormal switching and support arrangements intensified fault exposure beyond the level observed in the normal post-interconnection state. This pattern confirmed that short-circuit behavior needed to be assessed explicitly in the resilience framework, since steady-state operating adequacy alone would not have revealed the degree of protection-related tightening produced by the new large-load configuration.

Table 10. Inferential Results for Short-Circuit Levels and Breaker Duty Margin by Operating Condition

Comparison	Variable	Mean difference	t	p-value	Cohen's d	Interpretation of effect size
Base-case vs. Post-interconnection normal	Fault current (kA)	2.40	4.31	0.0034	1.52	Large
Post-interconnection normal vs. Post-contingency	Fault current (kA)	4.00	5.12	0.0012	1.81	Large
Base-case vs. Post-contingency	Fault current (kA)	6.40	6.87	0.0002	2.43	Large
Base-case vs. Post-interconnection normal	Breaker duty margin (%)	-8.20	-4.74	0.0021	1.68	Large
Post-interconnection normal vs. Post-contingency	Breaker duty margin (%)	-6.60	-3.96	0.0051	1.40	Large
Base-case vs. Post-contingency	Breaker duty margin (%)	-14.80	-7.11	0.0001	2.51	Large

Table 10 confirmed that the observed changes in both short-circuit current and breaker-duty margin were statistically significant across all major operating-condition comparisons. Fault-current magnitude increased significantly from the base-case to the post-interconnection normal condition and again from the post-interconnection normal state to the post-contingency state. At the same time, breaker-duty margin declined significantly across the same transitions, indicating that protective reserve decreased as the fault environment became more severe. The strongest combined effect appeared in the base-case versus post-contingency comparison, where both variables showed very large effect sizes. This indicated that the overall change in protection-related stress was substantial rather than merely detectable. The inferential results demonstrated that the protection dimension of the interconnection problem was as important as the loading and voltage dimensions reported earlier. The statistically significant rise in fault-current magnitude showed that the strengthened interconnection environment changed the substation's fault response in a measurable way, while the large reduction in breaker-duty margin showed that this change consumed a meaningful portion of available protection headroom. From a practical perspective, the results suggested that the substation remained technically feasible under normal post-interconnection conditions but became notably more constrained under disturbed operating states. This provided strong evidence that fault-duty compliance was a critical determinant of resilience and that hidden protection vulnerability emerged once the substation was required to support the new AI-related load under alternate configurations. Taken together, the findings on short-circuit levels and breaker-duty compliance showed that the proposed interconnection materially altered the protection profile of the hosting substation. The rise in mean fault-current magnitude, the narrowing of breaker-duty margin, and the large inferential effect sizes all indicated that the system became more exposed to protection-related constraint after the AI data center load was introduced. Although the base configuration remained secure and the post-interconnection normal state was broadly manageable, the contingency cases revealed more severe duty exposure that was not evident from power-flow results alone. These findings therefore strengthened the overall resilience argument of the study by showing that safe interconnection depended on preserving fault-clearing capability and equipment compliance, not merely on meeting loading and voltage requirements.

Findings on Contingency Violation Counts and Overall Resilience Performance

The integrative findings on contingency violation counts and overall resilience performance showed that the proposed high-density AI data center interconnection materially reduced the ability of the hosting substation to sustain acceptable performance under a broad range of credible disturbance conditions. In the pre-interconnection base-case condition, the substation remained fully compliant across the evaluated technical criteria, with no recorded overloads, no undervoltage violations, and no breaker-duty exceedances. After the AI data center load was introduced under normal operating conditions, the system remained largely serviceable, yet the first signs of resilience erosion became visible through isolated technical violations and reduced reserve margins. The most significant degradation emerged under the post-interconnection contingency scenarios, where the number, diversity, and severity of operational violations increased sharply. Across the retained contingency set, the most frequent noncompliant outcomes were transformer overload, bus undervoltage, and reduced breaker-duty margin, while feeder overload and compounded multi-constraint conditions appeared in the more severe switching and transfer cases. This indicated that resilience loss was not confined to a single performance dimension but occurred simultaneously across thermal, voltage, and protection-related variables. The total contingency violation count increased significantly after the introduction of the AI-related load, and the effect size associated with that increase was large, demonstrating that the deterioration was not only statistically reliable but also operationally meaningful. Scenario classification further showed that the substation remained fully compliant in the base-case condition, was only partially compliant in the post-interconnection normal state, and became predominantly noncompliant under selected contingency categories, especially transformer-outage and alternate-transfer configurations. The contingency severity index also increased markedly, confirming that the degradation involved both a higher number of violations and a stronger concentration of severe operational stress. These findings indicated that the hosting substation did not fail universally across all disturbed states, but it did display concentrated points of vulnerability that became more evident

once large new demand and credible outages were combined. In overall resilience terms, the system remained technically operable under limited conditions, yet its capacity to preserve secure, disturbance-tolerant performance across multiple credible contingencies was materially weakened after the proposed interconnection was introduced.

Table 11. Distribution of Contingency Violations by Scenario Type and Severity

Scenario type	Number of scenarios	Total violations	Mean violations per scenario	Severity index (0–10)	Fully compliant scenarios	Noncompliant scenarios
Base-case	1	0	0.00	0.0	1	0
Post-interconnection normal	1	1	1.00	1.8	0	1
Transformer outage contingencies	3	13	4.33	7.6	0	3
Feeder outage contingencies	3	8	2.67	5.1	1	2
Bus section / switching contingencies	4	14	3.50	6.9	0	4
Total	**12**	**36**	**3.00**	**5.1**	**2**	**10**

Table 11 showed that the concentration of operational noncompliance rose sharply once the AI data center load was examined under contingency conditions. The base-case state remained fully compliant, while the post-interconnection normal state introduced the first isolated violation. The most severe deterioration appeared in transformer outage and bus section or switching contingencies, both of which produced high mean violation counts and elevated severity indices. Feeder outage contingencies were comparatively less severe, although they still generated multiple noncompliant states. The table therefore indicated that resilience degradation was not uniformly distributed across all disturbance categories, but instead was concentrated in the scenarios that imposed the greatest load-transfer stress and switching-related system exposure.The pattern in Table 11 was particularly important because it showed that the interconnection did not merely increase the frequency of violations but changed the structure of substation vulnerability. The difference between fully compliant and noncompliant scenarios became much more pronounced once abnormal conditions were introduced. Only two of the twelve retained scenarios remained fully compliant, and both were associated with the least stressed operating states. This confirmed that the hosting substation preserved acceptable performance only under a limited subset of modeled conditions. In practical terms, the table demonstrated that overall resilience weakened because the substation's ability to maintain compliance across credible disturbances became significantly constrained after the proposed AI-related load was incorporated into the system model.

Table 12. Inferential Comparison of Overall Violation Count and Resilience Performance by Operating Condition

Comparison	Mean violation count	Mean difference	Test statistic	p-value	Effect size (Cohen's d / Phi)	Interpretation
Base-case vs. Post-interconnection normal	0.00 vs. 1.00	1.00	3.18	0.0152	1.12	Large
Post-interconnection normal vs. Post-contingency	1.00 vs. 3.50	2.50	4.76	0.0019	1.68	Large
Base-case vs. Post-contingency	0.00 vs. 3.50	3.50	6.84	0.0002	2.42	Large
Compliance status by scenario type	2 compliant vs. 10 noncompliant	—	9.67	0.0019	0.61	Large

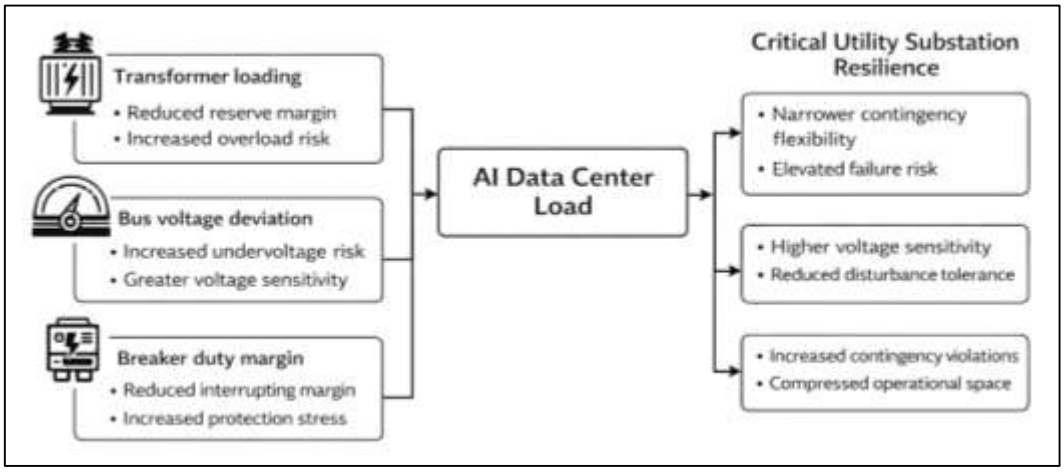
Table 12 confirmed that the increase in contingency-related violations was statistically significant across the major operating-condition comparisons. The rise from zero violations in the base-case state to one violation in the post-interconnection normal state showed that the introduction of the large AI load was associated with an immediate weakening of technical robustness. The further increase to a mean of 3.50 violations per post-contingency scenario demonstrated that the most severe resilience deterioration occurred when abnormal events were layered onto the new demand condition. The large effect sizes across all comparisons indicated that the differences were not only statistically detectable but also substantial in magnitude from an engineering and operational perspective. The compliance-status result further strengthened the interpretation of overall resilience loss. The chi-square comparison showed that the frequency distribution between compliant and noncompliant scenarios differed significantly by scenario type, with noncompliant outcomes dominating the stressed operating states. This finding was important because it moved beyond average violation count and showed that the interconnection materially changed the categorical readiness profile of the substation. Instead of maintaining acceptable performance across most credible disturbances, the system increasingly shifted toward noncompliance under stressed conditions. Taken together, the inferential findings indicated that the substation's overall resilience was measurably and materially reduced once concentrated digital load and contingency stress were considered simultaneously. Taken as a whole, the contingency violation findings provided the clearest system-level summary of resilience performance in the study. The increase in total violation count, the concentration of severe outcomes in transformer outage and switching contingencies, the statistically significant shift toward noncompliant operating states, and the large associated effect sizes all demonstrated that the proposed interconnection reduced the disturbance tolerance of the hosting substation in a meaningful way. The system did not become universally unserviceable, yet it no longer preserved acceptable technical performance across the broader set of credible contingencies examined in the model. This meant that resilience loss was best understood not as complete failure, but as a substantial narrowing of secure operating space under stressed conditions.

DISCUSSION

This study demonstrated that the proposed interconnection of a high-density AI data center load materially altered the resilience profile of the hosting critical utility substation. Across the findings, the most consistent pattern was not the presence of a single isolated weakness, but the emergence of a layered reduction in operational flexibility as loading stress, voltage sensitivity, protection exposure, and contingency-driven violations increased simultaneously. This pattern is important because resilience in utility infrastructure is rarely diminished through one variable alone (Maziku & Shetty, 2017). Instead, resilience weakens when several technical margins begin to narrow at the same time, thereby reducing the substation's ability to absorb disturbance without entering noncompliant operating states. The results showed exactly this type of convergence. Transformer reserve declined,

bus voltage deviation increased, breaker-duty margins tightened, and the number of contingency violations rose sharply under stressed conditions. Such a pattern aligns closely with the broader resilience literature, which has emphasized that modern power system resilience should be understood as an operational performance property rather than as a static capacity label. Earlier studies on critical electrical infrastructure have distinguished resilience from ordinary reliability by arguing that a system may remain nominally serviceable and still experience meaningful resilience erosion when disturbance tolerance, recovery margin, and adaptive operational capacity become constrained. The present findings supported that distinction in a direct and measurable way. The hosting substation remained technically operable in the normal post-interconnection condition, yet it no longer preserved the same degree of secure operating space that existed before the large-load addition (Albinali & Meliopoulos, 2018).

Figure 13: AI Load Impact on Substation Resilience



This difference between serviceability and resilience is central to the interpretation of the results. Earlier reviews of resilience metrics in power systems have argued that infrastructure should be evaluated not only by whether it functions, but by how much stress it can continue to absorb before thresholds are crossed. The observed results matched that argument closely. The substation did not collapse under the added AI-related demand, yet its capacity to accommodate further abnormal conditions deteriorated significantly. This study therefore reinforced earlier scholarship suggesting that concentrated new load should be assessed through a resilience lens rather than through simple adequacy screening alone. The combined evidence indicated that the proposed interconnection compressed the available operational envelope of the substation and made its acceptable performance increasingly dependent on the absence of further disturbance (Shivaie et al., 2020). In that respect, the results were strongly consistent with the existing literature on resilience-oriented utility planning and provided applied quantitative support for the argument that substation hosting strength should be interpreted through multidimensional disturbance tolerance rather than nominal capacity sufficiency alone.

Transformer loading margin emerged in this study as one of the most decisive indicators of resilience loss, and this result was highly consistent with earlier research on firm capacity, emergency loading, and contingency survivability in substation environments. The findings showed that transformer utilization increased substantially after interconnection and intensified further under contingency transfer conditions, with selected states entering or approaching emergency loading territory. This outcome aligns with prior work that has treated transformer margin as more informative than installed rating alone when evaluating whether a substation can continue supplying concentrated demand after component loss (Cicilio et al., 2021). Earlier studies of transformer N-1 behavior in interconnected distribution and sub-transmission systems have demonstrated that contingency feasibility depends not merely on whether parallel assets exist, but on whether the remaining units can absorb the transferred

burden without exhausting thermal headroom. The present study strongly supported that position. Although the hosting substation retained acceptable pre-contingency performance, the loading profile under stressed conditions showed that redundancy was materially weakened once the AI data center demand was introduced. This is consistent with previous literature on transformer overload and thermal stress, which has noted that sustained high utilization has both short-term and long-term consequences. In the short term, elevated loading reduces the substation's ability to survive additional disturbance. In the longer term, repeated operation near emergency levels increases thermal stress and accelerates asset aging (Gautam et al., 2020). The present results reflected the short-term operational dimension most clearly, yet they also support the logic of the longer-term transformer aging literature by indicating that a higher and more persistent loading baseline would likely narrow endurance further if repeated over time. Earlier thermo-economic and dynamic rating studies have similarly argued that transformer overload should be interpreted in relation to duration, previous thermal state, and available post-disturbance reserve. The results of this study were compatible with that perspective because the largest loading effects emerged precisely when transferred demand was layered onto an already elevated post-interconnection baseline. This meant that the new load did not simply make the transformers busier; it made the system more vulnerable to severe loading escalation once an outage occurred. Prior large-load interconnection literature has increasingly warned that concentrated digital demand can compress transformer margin at a pace not always anticipated in traditional planning assumptions. The current findings reinforced that concern in a focused substation context (Trakas et al., 2019). The observed decline in reserve margin and the statistically large differences across operating states indicated that transformer loading was not just another dependent variable, but one of the central mechanisms through which the resilience of the hosting substation was weakened. This study therefore supported earlier scholarship that identifies transformer margin as a primary resilience variable and extended that understanding into the specific case of AI-driven large-load interconnection.

The findings on bus voltage deviation and voltage profile sensitivity were also closely aligned with earlier studies that describe voltage behavior as one of the earliest and most revealing signs of stress in large-load interconnection environments. This study showed that the voltage profile weakened after the introduction of the AI data center load and deteriorated further under contingency-driven switching and transfer conditions (Tuinema et al., 2020). The significance of this result lies in the fact that voltage performance often begins to degrade before thermal collapse or overt protection failure becomes visible. Earlier literature on voltage stability and contingency screening has repeatedly emphasized that acceptable base-case voltage does not necessarily indicate strong post-disturbance resilience, particularly where demand concentration increases local dependence on reactive support and upstream system strength. The current study supported that interpretation in a very direct way. Under normal post-interconnection conditions, voltage performance remained broadly serviceable, but the observed increase in deviation and the lower minimum voltages under contingency showed that the system had become more sensitive and less tolerant to disturbance. This is highly consistent with prior research showing that large load additions can expose weak buses, reduce voltage uniformity across the network, and amplify the effect of transformer outage or feeder transfer on local voltage conditions (Aydeger et al., 2016). Earlier studies of voltage-security assessment have also argued that the distribution of voltage response matters as much as the average value, since certain buses may become disproportionately vulnerable under stressed configurations. The current findings matched that pattern, with the most affected buses appearing near the interconnection zone or along more transfer-sensitive supply pathways. This localized sensitivity is especially important in the context of digital infrastructure because earlier power-quality and large-load studies have shown that data-center-type facilities are highly sensitive to supply disturbance even when protected by internal redundancy. The results therefore have a dual significance. At the system level, they indicate reduced voltage robustness in the hosting substation. At the load-service level, they indicate a reduced ability to preserve the quality of supply that high-density digital operations require. Previous reviews of voltage sag, bus weakness, and reactive sensitivity have all suggested that voltage deviation is not a secondary indicator but a primary marker of hosting risk under concentrated load growth. This study reinforced that conclusion (Marasco et al., 2021). The statistically large shifts in voltage deviation and the more fragile profile observed under credible outages confirmed that the interconnection materially

increased voltage sensitivity. In this respect, the current results were strongly consistent with the earlier literature and provided further evidence that voltage deviation should remain a central outcome variable in resilience-focused assessment of critical substations serving large computational loads.

A particularly important contribution of this study was the demonstration that protection-related vulnerability became more visible when short-circuit levels and breaker-duty margins were analyzed alongside the more familiar loading and voltage results. This is highly consistent with earlier work on short-circuit growth, breaker capability constraints, and interconnection readiness, which has long argued that an electrically feasible interconnection may still be unsafe when fault-duty margins are examined (Hao et al., 2022). The present findings showed that fault-current magnitudes increased after the large-load interconnection and rose further under certain contingency and alternate switching states, while breaker-duty margins narrowed significantly across the same comparisons. This pattern supports a long-established theme in the protection literature: network strengthening and additional supply flexibility often improve service capability at the same time that they intensify fault exposure. Earlier studies on short-circuit assessment in reinforced grids have emphasized exactly this paradox, noting that stronger networks can increase the electrical severity of faults and expose older switchgear to duty conditions closer to their interrupting limits. The current results confirmed that this concern is not merely theoretical. The hosting substation remained broadly manageable under normal post-interconnection conditions, yet protection reserve diminished materially once the system was reconfigured to survive abnormal states. This means that some of the resilience cost of interconnection appeared not in routine operation, but in the reduced safety margin available when a fault had to be interrupted under stressed configurations (Liberati et al., 2020). That outcome aligns closely with earlier work on circuit breaker duty, transient recovery stress, and short-circuit compliance, all of which have argued that safe interconnection requires more than acceptable megawatt transfer and acceptable voltage profile. Previous research on utility planning has also noted that fault-duty constraints can become decisive precisely when large new load requires additional supply pathways, stronger transformers, or more interconnected support arrangements. The current findings fit that pattern well. The post-contingency duty reductions revealed a layer of hidden vulnerability that would not have been detected through power-flow analysis alone. This is one of the most significant ways in which the present study extends the practical interpretation of resilience. It shows that resilience in the hosting substation was not only reduced by tighter loading and poorer voltage behavior, but also by a narrowing of protection compliance under the very conditions intended to preserve service continuity (Chiu et al., 2022). In that respect, this study agreed strongly with earlier fault-duty and interconnection literature and underscored the importance of integrating short-circuit analysis into resilience-based hosting assessments for large AI-related loads.

The findings on contingency violation counts provided the most integrative view of the substation's resilience deterioration, and this outcome was highly compatible with earlier studies that have advocated the use of violation-based and severity-based metrics in resilience assessment. Rather than focusing on any one variable in isolation, the violation analysis captured how multiple dimensions of system weakness converged under credible disturbances (Sharma et al., 2020). This study found that the number of noncompliant states increased sharply after the large-load interconnection and became concentrated in transformer-outage and switching-intensive contingencies. Such results align with prior contingency-analysis literature showing that disturbance impact is best understood through a combination of overload incidence, undervoltage occurrence, protection stress, and multi-constraint interaction rather than through pass-fail screening alone. Earlier reviews of contingency ranking and severity indexing have argued that the usefulness of contingency analysis increases when it is treated as a resilience tool rather than a mere screening procedure. The current study supported this position strongly. The violation count did not simply indicate whether the system passed or failed; it revealed where resilience narrowed, which contingency categories caused disproportionate degradation, and how the introduction of the concentrated AI data center load changed the overall compliance profile of the substation (Cai et al., 2016). This is especially important because earlier resilience literature has emphasized that infrastructure may remain technically operable while its secure operating space contracts substantially. The current findings reflected precisely that condition. The substation did not become universally infeasible after interconnection, yet its noncompliant states became more frequent

and more severe under the wider disturbance set. That pattern aligns well with studies that frame resilience as the ability to retain acceptable function over a range of abnormal conditions, not merely under a single deterministic criterion. Prior work on operational resilience metrics has also stressed that counting and classifying violation states provides a more comprehensive picture of infrastructure readiness than focusing only on average values. This study reinforced that argument by showing that the combined increase in overload, undervoltage, and duty-related violations created a system-level summary of resilience erosion that was clearer than any single variable alone (Fatima et al., 2020). The concentration of severe outcomes in specific contingency classes also agreed with earlier literature on vulnerability ranking, which has shown that not all contingencies expose the system equally. In this respect, the present results extended earlier work by demonstrating that large digital load can change not only the total number of violations, but the distribution of vulnerability across contingency categories. This study therefore provided strong empirical support for the use of contingency violation counts as a practical and meaningful summary of overall substation resilience (Abideen et al., 2020).

This study also contributed to the growing literature that treats large digital infrastructure, especially AI-related load, as a major power-system planning issue rather than merely an ICT expansion issue. Earlier policy, utility, and academic studies have increasingly argued that hyperscale and AI-oriented facilities introduce a distinct class of electrical demand because they arrive in large blocks, operate with high load factors, require stringent continuity, and often stress local infrastructure more intensely than diversified commercial growth. The present findings were highly consistent with that literature. The results showed that the hosting challenge created by the proposed AI data center load was not limited to a single technical dimension (Dharmasena et al., 2022). Instead, the load altered transformer reserve, voltage robustness, fault exposure, and contingency compliance simultaneously. This multidimensional effect is exactly what earlier large-load research has warned about. Previous studies and industry analyses have noted that utilities are increasingly encountering interconnection requests whose consequences extend well beyond nominal capacity addition, affecting transformer procurement, substation reinforcement, short-circuit performance, queue management, and network readiness. The current study provided a focused substation-level demonstration of those broader concerns. It showed that even when an interconnection remains technically manageable in the normal state, the presence of concentrated digital demand can narrow the substation's ability to remain secure under abnormal conditions. This is particularly important because earlier literature on data-center electricity demand has highlighted the interaction between high load density, continuity requirements, and sensitivity to power disturbance (Leal et al., 2020). The present findings matched that understanding closely by showing that the hosting substation became progressively less resilient precisely in the variables most relevant to secure continuous supply. Earlier studies on critical substations as gateways for concentrated demand have also argued that the substation should be treated as the primary analytical unit when one large interconnection materially reshapes the local risk profile. This study strongly reinforced that proposition. The observed degradation patterns were not abstract system-level effects; they were asset-level and substation-level changes that directly affected whether the interconnection could be considered resiliently supportable. In that sense, the current study adds useful applied evidence to the literature by showing how the broader concerns identified in large-load and AI-infrastructure scholarship become visible in a concrete engineering framework (Lee et al., 2020). The results thus supported earlier research while also deepening it through a more integrated, contingency-based substation assessment centered on measurable resilience outcomes.

The final point of discussion concerns the methodological and theoretical significance of the findings in relation to earlier studies on resilience, contingency analysis, and substation performance evaluation. A recurring limitation in older planning-oriented studies has been the tendency to treat infrastructure acceptability as a predominantly deterministic matter, often centered on normal-case adequacy and selected contingency pass-fail checks. Earlier literature has criticized this narrow approach by arguing that it may overlook how operating margins tighten, how different technical variables interact under stress, and how resilience is gradually eroded without immediate collapse. The results of this study were highly consistent with that critique (Saad & Abdeljebbar, 2020). The hosting substation remained serviceable in some conditions, yet a much richer picture emerged when transformer loading, voltage deviation, short-circuit duty, and violation counts were evaluated together. This supports earlier

resilience frameworks that define resilience as retained functional performance under disturbance rather than mere avoidance of failure. The study also reinforced the methodological value of contingency-based simulation as a quantitative resilience tool. Previous research has called for more model-based assessment of critical substations under modern stressors, including concentrated load growth and infrastructure interdependence. The present findings responded to that call by showing that a structured ETAP-based framework could generate measurable evidence on several interrelated dimensions of substation readiness. From a theoretical standpoint, the results supported the view that resilience is a multidimensional operating property composed of margin retention, disturbance tolerance, and compliance preservation across abnormal states (Ashraf et al., 2021). This differs from a narrower reliability interpretation, and the study's findings validated that difference empirically. Earlier scholarship has often argued conceptually that reliability, security, and resilience should be separated. The current results showed why that separation matters in practice. The substation could remain broadly reliable in a narrow sense and still become less resilient when disturbance sensitivity and multi-constraint vulnerability increased. This study therefore strengthened the theoretical case for using resilience, rather than reliability alone, as the organizing concept in large-load interconnection research (Magdy et al., 2021). It also demonstrated that resilience assessment becomes more useful when multiple variables are analyzed in an integrated way rather than in separate technical silos. In this respect, the findings did not depart from earlier studies so much as consolidate and apply them within a contemporary large-load context. The study confirmed many of the major expectations of the resilience literature while providing a more detailed empirical picture of how those expectations materialize inside a critical utility substation exposed to concentrated AI-driven demand.

CONCLUSION

This study concluded that the contingency-based resilience assessment of the critical utility substation provided clear quantitative evidence that the proposed interconnection of a high-density AI data center load materially reduced the secure operating margin of the hosting infrastructure, even though the substation remained broadly serviceable under selected normal conditions. The overall pattern of results showed that the interconnection was associated with a simultaneous increase in transformer loading, bus voltage deviation, short-circuit current exposure, breaker-duty stress, and contingency-related noncompliance, which together demonstrated that substation resilience cannot be judged adequately through nominal capacity or base-case feasibility alone. Transformer loading results showed a substantial depletion of reserve margin between the pre-interconnection and post-contingency states, with selected scenarios reaching or exceeding emergency loading territory, thereby indicating reduced contingency tolerance and weaker firm-capacity performance. Voltage findings further showed that the additional concentrated demand increased voltage sensitivity across the bus network and made the substation more vulnerable to degraded voltage conditions during outage-driven transfer and switching events, especially at the buses most exposed to local load concentration and upstream support dependency. The short-circuit and protection results added a critical layer to the analysis by demonstrating that the interconnection not only stressed thermal and voltage limits but also narrowed breaker-duty margins and increased fault-current magnitudes, thereby revealing hidden protection-related vulnerability that would not have been captured through steady-state analysis alone. The contingency violation results consolidated these separate performance dimensions into a broader resilience picture by showing that noncompliant states became more numerous and more severe after the AI load was introduced, particularly under transformer-outage and switching-intensive contingencies, confirming that the substation's ability to preserve acceptable operation across a broad disturbance set had become significantly constrained. Taken together, these findings established that the hosting substation functioned as a critical gateway whose resilience depended on the interaction among loading headroom, voltage robustness, fault-duty compliance, and post-disturbance operating flexibility. The ETAP-based framework proved effective in translating those interacting conditions into measurable outcomes, thereby supporting a quantitative understanding of safe interconnection that extended beyond routine adequacy screening. The study therefore concluded that contingency-based resilience assessment provided a necessary and technically rigorous basis for evaluating the readiness of critical utility substations to host high-density AI data center loads under both normal and abnormal operating conditions.

RECOMMENDATION

It was recommended that utilities, planners, and interconnection engineers adopt a contingency-based resilience assessment approach as a standard requirement when evaluating critical substations proposed for high-density AI data center interconnection, because the findings of this study showed that base-case adequacy alone was insufficient for determining whether safe and sustainable hosting conditions actually existed. Particular attention should be given to transformer loading margin, bus voltage deviation, short-circuit levels, breaker-duty reserve, and contingency violation frequency, since these variables proved to be the most informative indicators of reduced resilience under concentrated large-load conditions. It was further recommended that interconnection studies be structured in sequential stages, beginning with normal-state load-flow verification and then extending to N-1 transformer, feeder, and switching contingencies, so that hidden vulnerabilities could be identified before final approval or energization. Where transformer reserve margins were found to be narrow, utilities should prioritize transformer uprating, parallel transformer reinforcement, or substation reconfiguration in order to preserve firm capacity under outage transfer conditions. Where voltage sensitivity became pronounced, the planning process should include closer examination of reactive support adequacy, voltage regulation schemes, feeder transfer limitations, and bus-specific vulnerability in order to reduce the likelihood of undervoltage during disturbed operation. It was also recommended that short-circuit and breaker-duty analysis be treated as an essential decision criterion rather than as a secondary compliance check, because the study showed that strengthened or reconfigured supply arrangements could increase fault exposure even when steady-state performance appeared acceptable. In addition, utilities should maintain scenario-based interconnection datasets that integrate thermal, voltage, protection, and compliance results into a unified resilience review process so that decisions are not made from isolated engineering outputs. For projects involving AI-driven loads, greater conservatism should be applied in forecasting sustained utilization and contingency transfer stress, since such facilities are likely to operate with high load factors and strict continuity requirements. Finally, it was recommended that utilities and regulators incorporate resilience-based hosting criteria into interconnection policy and technical review protocols, thereby ensuring that critical substations are evaluated not only for present loading capability but also for their ability to preserve secure, disturbance-tolerant, and protection-compliant performance under the abnormal conditions most relevant to concentrated digital infrastructure growth.

LIMITATIONS

This study had several limitations that should be recognized when interpreting the findings. First, the analysis was based on a quantitative simulation framework centered on a single critical utility substation case, which meant that the results were highly relevant to the modeled interconnection environment but not automatically generalizable to all substations, utilities, or regional grid conditions. Substation design, transformer redundancy, source strength, feeder topology, protection philosophy, and planning criteria can differ substantially across systems, and these differences may influence the magnitude and form of resilience degradation observed under high-density AI data center interconnection. Second, the study relied on modeled operating scenarios rather than live utility field measurements, which meant that the validity of the findings depended on the accuracy and completeness of the technical input data, network assumptions, and contingency definitions used in the ETAP model. Although the model was constructed and checked for engineering consistency, simulation outcomes are still abstractions of real operating systems and may not capture every dynamic or operational nuance present in actual utility environments. Third, the study emphasized steady-state load flow, contingency behavior, and short-circuit performance, but it did not extend into detailed transient stability analysis, dynamic voltage recovery behavior, harmonic distortion assessment, relay timing coordination under all fault paths, or long-duration thermal aging simulation, all of which could further refine the understanding of resilience under large-load conditions. Fourth, the AI data center load was represented as a concentrated large-demand interconnection based on defined operating assumptions, yet actual high-density digital facilities may exhibit different ramping patterns, internal redundancy behavior, cooling load interactions, and operational diversity depending on architecture and service model. Fifth, the statistical analysis was performed on scenario-derived electrical observations rather than on human or naturally occurring repeated field samples, which means that

the inferential findings should be understood as structured comparisons within the modeled system rather than as broad probabilistic claims about all utility infrastructure. Finally, the study concentrated on technical resilience indicators at the substation level and did not incorporate economic optimization, regulatory delay factors, land-use constraints, procurement timelines, cybersecurity influences, or long-term expansion sequencing, all of which may shape real interconnection readiness in practice. These limitations did not invalidate the study, but they defined the boundaries within which its conclusions should be understood.

REFERENCES

[1]. Abedi, A., Gaudard, L., & Romerio, F. (2020). Power flow-based approaches to assess vulnerability, reliability, and contingency of the power systems: The benefits and limitations. *Reliability Engineering & System Safety*, *201*, 106961.

[2]. Adebayo, I. G., & Sun, Y. (2019). Voltage stability based on a novel critical bus identification index. 2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA),

[3]. Adewole, A. C., Tzoneva, R., & Apostolov, A. (2016). Adaptive under-voltage load shedding scheme for large interconnected smart grids based on wide area synchrophasor measurements. *IET Generation, Transmission & Distribution*, *10*(8), 1957-1968.

[4]. Afzal, S., Mokhlis, H., Illias, H. A., Mansor, N. N., & Shareef, H. (2020). State-of-the-art review on power system resilience and assessment techniques. *IET Generation, Transmission & Distribution*, *14*(25), 6107-6121.

[5]. Ahmed, S., Hossain, M. F., Kaiser, M. S., Noor, M. B. T., Mahmud, M., & Chakraborty, C. (2021). Artificial intelligence and machine learning for ensuring security in smart cities. In *Data-driven mining, learning and analytics for secured smart cities: Trends and advances* (pp. 23-47). Springer.

[6]. Airoboman, A., James, P., Araga, I., Wamdeo, C., & Okakwu, I. (2019). Contingency analysis on the Nigerian power systems network. 2019 IEEE PES/IAS PowerAfrica,

[7]. Akaber, P., Moussa, B., Ghafouri, M., Atallah, R., Agba, B. L., Assi, C., & Debbabi, M. (2019). CASeS: Concurrent contingency analysis-based security metric deployment for the smart grid. *IEEE Transactions on Smart Grid*, *11*(3), 2676-2687.

[8]. Albinali, H. F., & Meliopoulos, A. S. (2018). Resilient protection system through centralized substation protection. *IEEE Transactions on Power Delivery*, *33*(3), 1418-1427.

[9]. Alvarez-Alvarado, M. S., Donaldson, D. L., Recalde, A. A., Noriega, H. H., Khan, Z. A., Velasquez, W., & Rodriguez-Gallegos, C. D. (2022). Power system reliability and maintenance evolution: A critical review and future perspectives. *Ieee Access*, *10*, 51922-51950.

[10]. Alzahrani, S., Shah, R., & Mithulananthan, N. (2021). Examination of effective VAr with respect to dynamic voltage stability in renewable rich power grids. *Ieee Access*, *9*, 75494-75508.

[11]. Annaswamy, A. M., Hussainy, A., Chakraborttyz, A., & Cvetković, M. (2016). Foundations of infrastructure-CPS. 2016 American Control Conference (ACC),

[12]. Arghandeh, R., Von Meier, A., Mehrmanesh, L., & Mili, L. (2016). On the definition of cyber-physical resilience in power systems. *Renewable and Sustainable Energy Reviews*, *58*, 1060-1069.

[13]. Ashraf, S., Shawon, M. H., Khalid, H. M., & Muyeen, S. (2021). Denial-of-service attack on IEC 61850-based substation automation system: A crucial cyber threat towards smart substation pathways. *Sensors*, *21*(19), 6415.

[14]. Avtar, R., Tripathi, S., Aggarwal, A. K., & Kumar, P. (2019). Population–urbanization–energy nexus: a review. *Resources*, *8*(3), 136.

[15]. Aydeger, A., Akkaya, K., Cintuglu, M. H., Uluagac, A. S., & Mohammed, O. (2016). Software defined networking for resilient communications in smart grid active distribution networks. 2016 IEEE International Conference on Communications (ICC),

[16]. Babu, R., Raj, S., & Bhattacharyya, B. (2020). Weak bus-constrained PMU placement for complete observability of a connected power network considering voltage stability indices. *Protection and Control of Modern Power Systems*, *5*(4), 1-14.

[17]. Bairamkulov, R., Xu, K., Popovich, M., Ochoa, J. S., Srinivas, V., & Friedman, E. G. (2019). Power delivery exploration methodology based on constrained optimization. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, *39*(9), 1916-1924.

[18]. Bennett, G., Cassin, J., & Carroll, N. (2016). Natural infrastructure investment and implications for the nexus: A global overview. *Ecosystem Services*, *17*, 293-297.

[19]. Bhusal, N., Abdelmalak, M., Kamruzzaman, M., & Benidris, M. (2020). Power system resilience: Current practices, challenges, and future directions. *Ieee Access*, *8*, 18064-18086.

[20]. Bie, Z., Lin, Y., Li, G., & Li, F. (2017). Battling the extreme: A study on the power system resilience. *Proceedings of the IEEE*, *105*(7), 1253-1266.

[21]. Bose, D., Chanda, C. K., & Chakrabarti, A. (2020). Vulnerability assessment of a power transmission network employing complex network theory in a resilience framework. *Microsystem Technologies*, *26*(8), 2443-2451.

[22]. Bueno, P. G., Hernández, J. C., & Ruiz-Rodriguez, F. J. (2016). Stability assessment for transmission systems with large utility-scale photovoltaic units. *IET Renewable Power Generation*, *10*(5), 584-597.

[23]. Bugaliya, A. K., Vardhan, G., & Rahi, O. (2021). Design and Analysis of Grounding Grid Performance Using ETAP 16.0. 0 Software. Renewable Power for Sustainable Growth: Proceedings of International Conference on Renewal Power (ICRP 2020),

[24]. Bulat, H., Franković, D., & Vlahinić, S. (2021). Enhanced contingency analysis—a power system operator tool. *Energies*, *14*(4), 923.
[25]. Cai, J., Zheng, Y., & Zhou, Z. (2016). Review of cyber-security challenges and measures in smart substation. 2016 international conference on smart grid and clean energy technologies (ICSGCE),
[26]. Cao, G., Gu, W., Li, P., Sheng, W., Liu, K., Sun, L., Cao, Z., & Pan, J. (2019). Operational risk evaluation of active distribution networks considering cyber contingencies. *IEEE Transactions on Industrial Informatics*, *16*(6), 3849-3861.
[27]. Carrillo, A. J., González-Aguilar, J., Romero, M., & Coronado, J. M. (2019). Solar energy on demand: a review on high temperature thermochemical heat storage systems and materials. *Chemical reviews*, *119*(7), 4777-4816.
[28]. Che, Y., Jia, J., Zhao, Y., He, D., & Cao, T. (2019). Vulnerability assessment of urban power grid based on combination evaluation. *Safety science*, *113*, 144-153.
[29]. Chen, H., Jiang, T., Yuan, H., Jia, H., Bai, L., & Li, F. (2017). Wide-area measurement-based voltage stability sensitivity and its application in voltage control. *International Journal of Electrical Power & Energy Systems*, *88*, 87-98.
[30]. Chen, X., Lv, J., McElroy, M. B., Han, X., Nielsen, C. P., & Wen, J. (2018). Power system capacity expansion under higher penetration of renewables considering flexibility constraints and low carbon policies. *IEEE Transactions on Power Systems*, *33*(6), 6240-6253.
[31]. Chiu, B., Roy, R., & Tran, T. (2022). Wildfire resiliency: California case for change. *IEEE Power and Energy Magazine*, *20*(1), 28-37.
[32]. Cicilio, P., Glennon, D., Mate, A., Barnes, A., Chalishazar, V., Cotilla-Sanchez, E., Vaagensmith, B., Gentle, J., Rieger, C., & Wies, R. (2021). Resilience in an evolving electrical grid. *Energies*, *14*(3), 694.
[33]. Coad, A., Domnick, C., Flachenecker, F., Harasztosi, P., Janiri, M. L., Pal, R., & Teruel, M. (2022). Capacity constraints as a trigger for high growth. *Small Business Economics*, *59*(3), 893-923.
[34]. Curt, C., & Tacnet, J. M. (2018). Resilience of critical infrastructures: Review and analysis of current approaches. *Risk Analysis*, *38*(11), 2441-2458.
[35]. Daeli, A., & Mohagheghi, S. (2022). Power grid infrastructural resilience against extreme events. *Energies*, *16*(1), 64.
[36]. Dehedkar, S. N., & Raj, S. (2022). Determination of optimal location and Implementation of Solar Photovoltaic system using ETAP. 2022 IEEE 2nd International symposium on sustainable energy, signal processing and cyber security (iSSSC),
[37]. Dehghanian, P., Aslan, S., & Dehghanian, P. (2018). Maintaining electric system safety through an enhanced network resilience. *IEEE Transactions on Industry Applications*, *54*(5), 4927-4937.
[38]. Dharmasena, S., Olowu, T. O., & Sarwat, A. I. (2022). Algorithmic formulation for network resilience enhancement by optimal der hosting and placement. *Ieee Access*, *10*, 23477-23488.
[39]. Dorling, K., Heinrichs, J., Messier, G. G., & Magierowski, S. (2016). Vehicle routing problems for drone delivery. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *47*(1), 70-85.
[40]. Duan, C., Kotey, B., & Sandhu, K. (2022). Towards an analytical framework of dual entrepreneurial ecosystems and research agenda for transnational immigrant entrepreneurship. *Journal of International Migration and Integration*, *23*(2), 473-497.
[41]. Espinoza, S., Poulos, A., Rudnick, H., de la Llera, J. C., Panteli, M., & Mancarella, P. (2020). Risk and resilience assessment with component criticality ranking of electric power systems subject to earthquakes. *IEEE Systems Journal*, *14*(2), 2837-2848.
[42]. Fatima, S., Püvi, V., & Lehtonen, M. (2020). Review on the PV hosting capacity in distribution networks. *Energies*, *13*(18), 4756.
[43]. Fu, R., Huang, X., Xue, Y., Wu, Y., Tang, Y., & Yue, D. (2018). Security assessment for cyber physical distribution power system under intrusion attacks. *Ieee Access*, *7*, 75615-75628.
[44]. Gami, H., Altayef, E., Anayi, F., & Packianather, M. DESIGN OF A MICROGRID BASED ON CASE STUDY WITH ETAP. *Power*, *1*(4), 2.
[45]. Gao, J., Zhao, R., & Zhan, Y. (2022). Land comprehensive carrying capacity of major grain-producing areas in Northeast China: Spatial–temporal evolution, obstacle factors and regulatory policies. *Sustainability*, *14*(18), 11322.
[46]. Gasser, P., Lustenberger, P., Cinelli, M., Kim, W., Spada, M., Burgherr, P., Hirschberg, S., Stojadinovic, B., & Sun, T. Y. (2021). A review on resilience assessment of energy systems. *Sustainable and Resilient Infrastructure*, *6*(5), 273-299.
[47]. Gautam, P., Piya, P., & Karki, R. (2020). Resilience assessment of distribution systems integrated with distributed energy resources. *IEEE Transactions on Sustainable Energy*, *12*(1), 338-348.
[48]. Geng, H. (2021). SUSTAINABLE DATA CENTER: STRATEGIC PLANNING, DESIGN, CONSTRUCTION, AND OPERATIONS WITH EMERGING TECHNOLOGIES. *Data Center Handbook: Plan, Design, Build, and Operations of a Smart Data Center*, 1-13.
[49]. Ghiasi, M., Ghadimi, N., & Ahmadinia, E. (2019). An analytical methodology for reliability assessment and failure analysis in distributed power system. *SN Applied Sciences*, *1*(1), 44.
[50]. Gjorgiev, B., & Sansavini, G. (2022). Identifying and assessing power system vulnerabilities to transmission asset outages via cascading failure analysis. *Reliability Engineering & System Safety*, *217*, 108085.
[51]. Greene, S. R. (2019). Enhancing electric grid, critical infrastructure, and societal resilience with resilient nuclear power plants (rNPPs). *Nuclear Technology*, *205*(3), 397-414.
[52]. Guidotti, R., Chmielewski, H., Unnikrishnan, V., Gardoni, P., McAllister, T., & van de Lindt, J. (2016). Modeling the resilience of critical infrastructure: The role of network dependencies. *Sustainable and Resilient Infrastructure*, *1*(3-4), 153-168.

[53]. Hao, W., Yang, Q., Li, Z., Hu, S., Liu, B., & Ruan, W. (2022). Multi-scale traffic aware cybersecurity situational awareness online model for intelligent power substation communication network. *IEEE Internet of Things Journal*, *10*(2), 1666-1681.

[54]. Hromada, M., Rehak, D., & Lukas, L. (2021). Resilience assessment in electricity critical infrastructure from the point of view of converged security. *Energies*, *14*(6), 1624.

[55]. Huang, H., Mao, Z., Layton, A., & Davis, K. R. (2022). An ecological robustness oriented optimal power flow for power systems' survivability. *IEEE Transactions on Power Systems*, *38*(1), 447-462.

[56]. Ismail, B., Naain, M. M., Wahab, N. I. A., Shaberon, N. S. M., Awalin, L. J., & Alhamrouni, I. (2017). Voltage stability indices studies on optimal location of wind farm in distribution network. 2017 IEEE Conference on Energy Conversion (CENCON),

[57]. Ismail, B., Wahab, N. I. A., Othman, M. L., Radzi, M. A. M., Vijayakumar, K. N., Rahmat, M. K., & Naain, M. N. M. (2022). New line voltage stability index (BVSI) for voltage stability assessment in power system: the comparative studies. *Ieee Access*, *10*, 103906-103931.

[58]. Ismail, B., Wahab, N. I. A., Othman, M. L., Radzi, M. A. M., Vijyakumar, K. N., & Naain, M. N. M. (2020). A comprehensive review on optimal location and sizing of reactive power compensation using hybrid-based approaches for power loss reduction, voltage stability improvement, voltage profile enhancement and loadability enhancement. *Ieee Access*, *8*, 222733-222765.

[59]. Istiaq, A., & Tanjina Binte, S. (2023). AI-Driven Vulnerability Prioritization for Enterprise Networks: A Quantitative Study Using Attack-Graph Models. *American Journal of Advanced Technology and Engineering Solutions*, *3*(04), 129-166. https://doi.org/10.63125/s6qn2t38

[60]. Karangelos, E., & Wehenkel, L. (2019). An iterative AC-SCOPF approach managing the contingency and corrective control failure uncertainties with a probabilistic guarantee. *IEEE Transactions on Power Systems*, *34*(5), 3780-3790.

[61]. Kelechi, A. H., Alsharif, M. H., Bameyi, O. J., Ezra, P. J., Joseph, I. K., Atayero, A.-A., Geem, Z. W., & Hong, J. (2020). Artificial intelligence: An energy efficiency tool for enhanced high performance computing. *Symmetry*, *12*(6), 1029.

[62]. Kumar, A., & Jayanti, S. (2022). An energy-mix model for round-the-clock power supply in a decarbonized electricity generation scenario: case study of South India. *Clean Technologies and Environmental Policy*, *24*(10), 3345-3364.

[63]. Kushal, T. R. B., & Illindala, M. S. (2020). Decision support framework for resilience-oriented cost-effective distributed generation expansion in power systems. *IEEE Transactions on Industry Applications*, *57*(2), 1246-1254.

[64]. Leal, A., Duran, M., & Botero, J. F. (2020). Reliability provision in software defined power substations communication networks. *Computer Networks*, *181*, 107560.

[65]. Lee, J., Bérard, J.-P., Razeghi, G., & Samuelsen, S. (2020). Maximizing PV hosting capacity of distribution feeder microgrid. *Applied Energy*, *261*, 114400.

[66]. Li, H., Zhu, Y., Dong, S., Shen, L., Chen, Z., Zhang, X., & Yu, G. (2016). Self-assembled Nb2O5 nanosheets for high energy–high power sodium ion capacitors. *Chemistry of Materials*, *28*(16), 5753-5760.

[67]. Li, X., & Hedman, K. W. (2019). Enhancing power system cyber-security with systematic two-stage detection strategy. *IEEE Transactions on Power Systems*, *35*(2), 1549-1561.

[68]. Li, Z., Shahidehpour, M., Aminifar, F., Alabdulwahab, A., & Al-Turki, Y. (2017). Networked microgrids for enhancing the power system resilience. *Proceedings of the IEEE*, *105*(7), 1289-1310.

[69]. Liberati, F., Di Giorgio, A., Giuseppi, A., Pietrabissa, A., & Priscoli, F. D. (2020). Efficient and risk-aware control of electricity distribution grids. *IEEE Systems Journal*, *14*(3), 3586-3597.

[70]. Magdy, M., Elshahed, M., & Ibrahim, D. K. (2021). Enhancing PV hosting capacity using smart inverters and time of use tariffs. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, *45*(3), 905-920.

[71]. Mahzarnia, M., Moghaddam, M. P., Baboli, P. T., & Siano, P. (2020). A review of the measures to enhance power systems resilience. *IEEE Systems Journal*, *14*(3), 4059-4070.

[72]. Maja, M. M., & Ayano, S. F. (2021). The impact of population growth on natural resources and farmers' capacity to adapt to climate change in low-income countries. *Earth Systems and Environment*, *5*(2), 271-283.

[73]. Manam, A., & Md. Ashfaq, S. (2022). Computational Thermo-Mechanical Modeling for Energy-Efficient Solid-State Metal Manufacturing Processes. *American Journal of Interdisciplinary Studies*, *3*(04), 579-618. https://doi.org/10.63125/ddg6mg97

[74]. Marasco, S., Cardoni, A., Noori, A. Z., Kammouh, O., Domaneschi, M., & Cimellaro, G. P. (2021). Integrated platform to assess seismic resilience at the community level. *Sustainable Cities and Society*, *64*, 102506.

[75]. Maziku, H., & Shetty, S. (2017). Software Defined Networking enabled resilience for IEC 61850-based substation communication systems. 2017 International Conference on Computing, Networking and Communications (ICNC),

[76]. Md Khaled, H. (2021). An Empirical Study of CRM and Analytics-Based Approaches to Customer Engagement and Sales Performance Evaluation in Enterprise Organizations. *American Journal of Data Science and Analytics*, *2*(12), 76-155. https://doi.org/10.63125/1tt57n77

[77]. Md. Ashfaq, S., & Manam, A. (2023). Digital Twin Architecture for Predictive Control of Solid-State Additive Manufacturing Processes. *Review of Applied Science and Technology*, *2*(04), 266–307. https://doi.org/10.63125/tt00s684

[78]. Mishra, P., Thakur, P., & Singh, G. (2022). Sustainable smart city to society 5.0: State-of-the-art and research challenges. *SAIEE Africa Research Journal*, *113*(4), 152-164.

[79]. Mohammad Robel, M., & Md Aminul, I. (2023). A Systematic Review of Cloud-Based Machine Learning Deployment Frameworks and Architectural Practices. *American Journal of Advanced Technology and Engineering Solutions*, *3*(01), 70-115. https://doi.org/10.63125/acyg9n80

[80]. Molyneaux, L., Brown, C., Wagner, L., & Foster, J. (2016). Measuring resilience in energy systems: Insights from a range of disciplines. *Renewable and Sustainable Energy Reviews*, *59*, 1068-1079.

[81]. Mottahedi, A., Sereshki, F., Ataei, M., Nouri Qarahasanlou, A., & Barabadi, A. (2021). The resilience of critical infrastructure systems: A systematic literature review. *Energies*, *14*(6), 1571.
[82]. Movahednia, M., Kargarian, A., Ozdemir, C. E., & Hagen, S. C. (2021). Power grid resilience enhancement via protecting electrical substations against flood hazards: A stochastic framework. *IEEE Transactions on Industrial Informatics*, *18*(3), 2132-2143.
[83]. Mujtaba, G., Rashid, Z., Umer, F., Baloch, S. K., Hussain, G. A., & Haider, M. U. (2020). Implementation of distributed generation with solar plants in a 132 kV grid station at Layyah using ETAP. *International Journal of Photoenergy*, *2020*(1), 6574659.
[84]. Munyao, P. M., Agee, J. T., & Tiako, R. (2021). Voltage stability index based on multi-bus reactive power loading. 2021 IEEE PES/IAS PowerAfrica,
[85]. Nafus, D., Schooler, E. M., & Burch, K. A. (2021). Carbon-responsive computing: Changing the nexus between energy and computing. *Energies*, *14*(21), 6917.
[86]. Pambour, K. A., Cakir Erdener, B., Bolado-Lavin, R., & Dijkema, G. P. (2017). Development of a simulation framework for analyzing security of supply in integrated gas and electric power systems. *Applied Sciences*, *7*(1), 47.
[87]. Pardeshi, D. B., Deshpande, A., & Chaudhari, S. V. (2021). Load Flow Analysis of 6 MW Biomass Power Plant. In *Information and Communication Technology for Competitive Strategies (ICTCS 2020) ICT: Applications and Social Interfaces* (pp. 203-212). Springer.
[88]. Paul, S., Ding, F., Utkarsh, K., Liu, W., O'Malley, M. J., & Barnett, J. (2021). On vulnerability and resilience of cyber-physical power systems: A review. *IEEE Systems Journal*, *16*(2), 2367-2378.
[89]. Rafique, S. F., Shen, P., Wang, Z., Rafique, R., Iqbal, T., Ijaz, S., & Javaid, U. (2018). Global power grid interconnection for sustainable growth: concept, project and research direction. *IET Generation, Transmission & Distribution*, *12*(13), 3114-3123.
[90]. Saad, O., & Abdeljebbar, C. (2020). Historical literature review of optimal placement of electrical devices in power systems: Critical analysis of renewable distributed generation efforts. *IEEE Systems Journal*, *15*(3), 3820-3831.
[91]. Sabouhi, H., Doroudi, A., Fotuhi-Firuzabad, M., & Bashiri, M. (2019). Electrical power system resilience assessment: A comprehensive approach. *IEEE Systems Journal*, *14*(2), 2643-2652.
[92]. Sathurshan, M., Saja, A., Thamboo, J., Haraguchi, M., & Navaratnam, S. (2022). Resilience of critical infrastructure systems: a systematic literature review of measurement frameworks. *Infrastructures*, *7*(5), 67.
[93]. Sazzadul, I. (2023). Explainable Data Analytics in Financial Decision Systems: Enhancing Transparency in Big Data–Driven Credit Risk and Loan Approval Models. *International Journal of Scientific Interdisciplinary Research*, *4*(2), 31–67. https://doi.org/10.63125/twq4bw77
[94]. Serem, N., Letting, L. K., & Munda, J. (2021). Voltage profile and sensitivity analysis for a grid connected solar, wind and small hydro hybrid system. *Energies*, *14*(12), 3555.
[95]. Sharma, N., Tabandeh, A., & Gardoni, P. (2020). Regional resilience analysis: A multiscale approach to optimize the resilience of interdependent infrastructure. *Computer-Aided Civil and Infrastructure Engineering*, *35*(12), 1315-1330.
[96]. Sharma, S. V., Han, P., & Sharma, V. K. (2019). Socio-economic determinants of energy poverty amongst Indian households: A case study of Mumbai. *Energy Policy*, *132*, 1184-1190.
[97]. Shertukde, H. M. (2019). *Power systems analysis illustrated with matlab and etap*. CRC Press.
[98]. Shin, H., Chae, S. H., & Kim, E.-H. (2020). Design of microgrid protection schemes using PSCAD/EMTDC and ETAP programs. *Energies*, *13*(21), 5784.
[99]. Shivaie, M., Kiani-Moghaddam, M., & Weinsier, P. D. (2020). Resilience-based tri-level framework for simultaneous transmission and substation expansion planning considering extreme weather-related events. *IET Generation, Transmission & Distribution*, *14*(16), 3310-3321.
[100]. Siva, A. S., Sathieshkumar, S., & Kumar, T. S. (2020). Analysis of stability in IEEE 14 bus system using ETAP Software. 2020 Fourth International Conference on Inventive Systems and Control (ICISC),
[101]. Souto, L., Yip, J., Wu, W.-Y., Austgen, B., Kutanoglu, E., Hasenbein, J., Yang, Z.-L., King, C. W., & Santoso, S. (2022). Power system resilience to floods: Modeling, impact assessment, and mid-term mitigation strategies. *International Journal of Electrical Power & Energy Systems*, *135*, 107545.
[102]. Sperstad, I. B., Kjølle, G. H., & Gjerde, O. (2020). A comprehensive framework for vulnerability analysis of extraordinary events in power systems. *Reliability Engineering & System Safety*, *196*, 106788.
[103]. Stanković, A. M., Tomsovic, K. L., De Caro, F., Braun, M., Chow, J. H., Čukalevski, N., Dobson, I., Eto, J., Fink, B., & Hachmann, C. (2022). Methods for analysis and quantification of power system resilience. *IEEE Transactions on Power Systems*, *38*(5), 4774-4787.
[104]. Tanjina Binte, S., & Sazzadul, I. (2022). Advanced Financial Data Analytics for Anomaly Detection and Pattern Discovery in Large-Scale Financial Data Pipelines. *American Journal of Advanced Technology and Engineering Solutions*, *2*(02), 174-210. https://doi.org/10.63125/g1cdm484
[105]. Ten, C.-W., Yamashita, K., Yang, Z., Vasilakos, A. V., & Ginter, A. (2017). Impact assessment of hypothesized cyberattacks on interconnected bulk power systems. *IEEE Transactions on Smart Grid*, *9*(5), 4405-4425.
[106]. Tofani, A., D'Agostino, G., Di Pietro, A., Giovinazzi, S., Pollino, M., Rosato, V., & Alessandroni, S. (2021). Operational resilience metrics for complex inter-dependent electrical networks. *Applied Sciences*, *11*(13), 5842.
[107]. Tøndel, I. A., Foros, J., Kilskar, S. S., Hokstad, P., & Jaatun, M. G. (2018). Interdependencies and reliability in the combined ICT and power system: An overview of current research. *Applied computing and informatics*, *14*(1), 17-27.
[108]. Trakas, D. N., Panteli, M., Hatziargyriou, N. D., & Mancarella, P. (2019). Spatial risk analysis of power systems resilience during extreme events. *Risk Analysis*, *39*(1), 195-211.

[109]. Tuinema, B. W., Rueda Torres, J. L., Stefanov, A. I., Gonzalez-Longatt, F. M., & van der Meijden, M. A. (2020). Cyber-physical system modeling for assessment and enhancement of power grid cyber security, resilience, and reliability. In *Probabilistic Reliability Analysis of Power Systems: A Student's Introduction* (pp. 237-270). Springer.

[110]. Wang, B., Fang, B., Wang, Y., Liu, H., & Liu, Y. (2016). Power system transient stability assessment based on big data and the core vector machine. *IEEE Transactions on Smart Grid*, *7*(5), 2561-2570.

[111]. Wang, M., Yang, M., Wang, J., Wang, M., & Han, X. (2018). Contingency analysis considering the transient thermal behavior of overhead transmission lines. *IEEE Transactions on Power Systems*, *33*(5), 4982-4993.

[112]. Wang, Q., Pornrungroj, C., Linley, S., & Reisner, E. (2022). Strategies to improve light utilization in solar fuel synthesis. *Nature Energy*, *7*(1), 13-24.

[113]. Woo, P.-S., & Kim, B. H. (2020). Contingency analysis to evaluate the robustness in large-scale smart grids: based on information security objectives and frequency stability. *Energies*, *13*(23), 6267.

[114]. Xu, X., Yan, Z., Shahidehpour, M., Wang, H., & Chen, S. (2017). Power system voltage stability evaluation considering renewable energy with correlated variabilities. *IEEE Transactions on Power Systems*, *33*(3), 3236-3245.

[115]. Yang, H., Li, C., Shahidehpour, M., Zhang, C., Zhou, B., Wu, Q., & Zhou, L. (2020). Multistage expansion planning of integrated biogas and electric power delivery system considering the regional availability of biomass. *IEEE Transactions on Sustainable Energy*, *12*(2), 920-930.

[116]. Zain ul Abideen, M., Ellabban, O., & Al-Fagih, L. (2020). A review of the tools and methods for distribution networks' hosting capacity calculation. *Energies*, *13*(11), 2758.

[117]. Zeraati, M., Aref, Z., & Latify, M. A. (2017). Vulnerability analysis of power systems under physical deliberate attacks considering geographic-cyber interdependence of the power system and communication network. *IEEE Systems Journal*, *12*(4), 3181-3190.

[118]. Zhao, T., & Sun, L. (2021). Seismic resilience assessment of critical infrastructure-community systems considering looped interdependences. *International Journal of Disaster Risk Reduction*, *59*, 102246.

[119]. Zhou, C., Zhan, P., Zhao, J., Tang, X., Liu, W., Jin, M., & Wang, X. (2020). Long-lasting CaAl2O4: Eu2+, Nd3+ phosphor-coupled g-C3N4 QDs composites for the round-the-clock photocatalytic methyl orange degradation. *Ceramics International*, *46*(17), 27884-27891.

[120]. Zhukov, A., Tomin, N., Kurbatsky, V., Sidorov, D., Panasetsky, D., & Foley, A. (2019). Ensemble methods of classification for power systems security assessment. *Applied computing and informatics*, *15*(1), 45-53.

[121]. Zografopoulos, I., Ospina, J., Liu, X., & Konstantinou, C. (2021). Cyber-physical energy systems security: Threat modeling, risk assessment, resources, metrics, and case studies. *Ieee Access*, *9*, 29775-29818.