ESIG
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Task Force

Reliability Impacts of Large Loads

A Report by the
Energy Systems Integration Group's
Large Loads Task Force

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Preface to ESIG Large Loads Task Force Reports

This report is one of 11 reports by the ESIG Large Loads Task Force, which was formed to assist the power industry in addressing new challenges introduced by the rapid proliferation of large electronic loads such as data centers, as well as other large loads including manufacturing, electric vehicle fleets, and hydrogen production. The titles of the reports are as follows:

- Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility
- Forecasting for Large Loads: Current Practices and Recommendations
- Interconnection Processes for Large Loads: Current Practices and Recommendations
- Large Load Performance Requirements: Current Practices and Recommendations
- Large Loads: Behaviors, Capabilities, and Limitations
- Reliability Impacts of Large Loads
- Large Load Disturbance Events
- Large Load Modeling for Dynamic Studies: Current Practices and Recommendations
- Transmission Planning with Large Loads: Current Practices and Recommendations
- Resource Adequacy with Large Loads: Planning for Flexibility to Accelerate Integration
- Wholesale Market Design and Operations for Systems with Large Loads: Current Practices and Recommendations

Disclaimer

This report was produced by a project team made up of diverse members with diverse viewpoints and levels of participation. Specific statements may not necessarily represent a consensus among all participants or the views of participants' employers.

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Contents

Abbreviations

ACE	Area control error
AI	Artificial intelligence
AGC	Automatic generation control
BESS	Battery energy storage system
E-STATCOM	Enhanced static synchronous compensator
EMT	Electromagnetic transient
GFM	Grid-forming
GPU	Graphics processing unit
IBR	Inverter-based resource
IT	Information technology
MPF	Minimum power floor
NERC	North American Electric Reliability Corporation
RAS	Remedial action scheme
SCR	Short-circuit ratio
S-N	Stress vs. number of cycles
SSCI	Sub-synchronous control interaction
SSR	Sub-synchronous resonance
SSTI	Sub-synchronous torsional interaction
UFLS	Under-frequency load shedding
UVLS	Under-voltage load shedding
UPS	Uninterruptible power supply

Introduction

The composition of electricity demand on the bulk power system is undergoing a paradigm shift. Historically, load growth has been gradual and relatively predictable, dominated by conventional residential, commercial, and industrial consumers. Today, the grid is experiencing the rapid interconnection of a new class of large loads, including hyperscale data centers, artificial intelligence (AI) computing clusters, cryptocurrency mining operations, and green hydrogen electrolyzers. Many of these facilities are power electronics–interfaced and can individually demand hundreds of megawatts of power, comparable to the load of a small city. Collectively, they are expected to represent a significant portion of future load growth actors in North America and other regions.

As detailed in the ESIG Large Loads Task Force report *Large Loads: Behaviors, Capabilities, and Limitations*, a defining characteristic of many new large loads is their extensive use of power electronics and digital control systems.[1] Combined with their large size, geographical concentration, rapidly changing operational profiles, and, in some cases, limited disturbance ride-through capability, these facilities introduce a set of complex reliability challenges that differ from those traditionally associated with load (NERC, 2025a).

The reliability implications extend beyond traditional concerns such as resource adequacy and load forecasting.[2] New large loads can influence system frequency response, voltage stability, oscillatory behavior, protection system performance, emergency control actions, power quality, and operational balancing. In some cases, the sudden loss or rapid variation of a single facility can produce system impacts comparable in magnitude to the loss of a large generating unit. Recent disturbance events involving large load facilities, covered in the ESIG Large Loads Task Force report *Large Load Disturbance Events*, have demonstrated that these impacts are no longer theoretical and require increased attention from planners, operators, utilities, regulators, and load developers.[3]

The ESIG Large Loads Task Force examined large load integration from several complementary perspectives, including forecasting, interconnection processes, performance requirements, dynamic modeling, disturbance events, resource adequacy, transmission planning, and markets and operations. This report focuses specifically on the reliability implications of large loads and the mechanisms through which those impacts can manifest on the power system. While other task force reports describe how large loads behave, how they should be modeled, and what technical requirements and interconnection studies may be appropriate, this report focuses on why those requirements and studies are important in terms of these loads' reliability impacts.

This report is also complementary to two recent North American Electric Reliability Corporation (NERC) Large Load Task Force (and, later, Large Load Working Group) publications addressing new large loads. The July 2025 NERC Large Load Task Force white paper, "Characteristics and Risks of Emerging Large

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[1] https://www.esig.energy/reports-briefs/large-loads-behaviors-capabilities

[2] See the ESIG Large Loads Task Force reports *Resource Adequacy with Large Loads: Planning for Flexibility to Accelerate Integration* (https://www.esig.energy/reports-briefs/large-loads-resource-adequacy) and *Forecasting for Large Loads: Current Practices and Recommendations* (https://www.esig.energy/reports-briefs/forecasting-for-large-loads)

[3] https://www.esig.energy/reports-briefs/large-load-disturbance-events

Loads," provided an important industry-wide overview of the emerging large load landscape, identifying key reliability concerns associated with the rapid growth of these facilities (NERC, 2025a). The May 2026 NERC Reliability Guideline, "Risk Mitigation for Emerging Large Loads," provided recommendations and guidance intended to help industry stakeholders address those concerns (NERC, 2026).

This report has a different objective. Rather than providing a broad characterization of new large loads or focusing primarily on mitigation guidance, it examines the underlying reliability mechanisms and system dynamics associated with large load integration. It focuses on short-term operational and stability-related impacts, including frequency stability, voltage stability, oscillatory phenomena, protection system performance, balancing and dispatch challenges, power quality impacts, and interactions with emergency control systems. Particular attention is given to explaining how these impacts arise, the conditions under which they become significant, and their implications for planning and operations. As such, the intended audiences are practicing power system engineers, planners, operators, and technical specialists responsible for assessing and managing reliability risks associated with large load integration.

> This report examines the underlying reliability mechanisms and system dynamics associated with large load integration, focusing on short-term operational and stability-related impacts. Particular attention is given to explaining how these impacts arise, the conditions under which they become significant, and their implications for planning and operations.

The report also discusses mitigation approaches and performance requirements; however, these are presented primarily in the context of the reliability concerns they are intended to address. The objective is not to prescribe a specific set of requirements, but rather to provide the technical foundation needed to understand the rationale behind emerging industry practices and future performance expectations for large loads.

This report is a part of the Energy Systems Integration Group's Large Loads Task Force's set of four interrelated reports on large load interconnection performance requirements.[4]

- The main report, *Large Load Performance Requirements: Current Practices and Recommendations*, provides guidance for system operators and utilities as they develop interconnection performance requirements for large loads tailored to their own jurisdictions.
- The report *Large Load Disturbance Events* highlights a set of recent disturbances in which large loads played a noticeable role, either as contributors to the initiating conditions or as factors exacerbating an initial disturbance and complicating a recovery.
- The report *Large Loads: Behaviors, Capabilities, and Limitations* helps power system operators and transmission owners understand how new large loads behave and how they can affect the power system's operational security, and thus understand the risks that large loads impose on power system planning and operation.

This report also informs the ESIG Large Loads Task Force report *Large Load Modeling for Dynamic Studies: Current Practices and Recommendations*.[5]

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[4] See also *Large Load Performance Requirements: Current Practices and Recommendations*, *Reliability Impacts of Large Loads*, and *Large Load Disturbance Events*. All four reports can be found at https://www.esig.energy/working-groups/large-loads.

[5] https://www.esig.energy/reports-briefs/large-load-modeling

The report is organized as follows. It first examines the reliability implications of large load tripping during system disturbances. Although large load tripping is not itself a distinct stability category, recent disturbance events have shown that it is one of the most consequential initiating events associated with new large loads. The sudden loss of hundreds or even thousands of megawatts of load can simultaneously affect frequency, voltage, rotor-angle stability, power flows, protection system performance, and emergency control actions. Because this is a common mechanism through which many reliability impacts can manifest, the topic is addressed first before examining individual stability and operational impacts in greater detail. The report then assesses impacts on dynamic system stability, including frequency stability, voltage stability, oscillatory phenomena, and converter-driven interactions; followed by impacts on protection systems, balancing and dispatch operations, power quality, and cybersecurity. Lastly, the report discusses mitigation approaches and technical requirements that may help address these reliability concerns and concludes with a summary of key findings and recommendations.

Impacts of Load-Tripping Following System Disturbance

Unexpected load tripping following system disturbances has emerged as one of the most significant reliability concerns associated with today's large loads. Recent disturbance events, covered in the ESIG Large Loads Task Force report *Large Load Disturbance Events*,[6] have demonstrated that the simultaneous loss of large amounts of load can occur within a fraction of a second following transmission faults. New large loads are often concentrated at a single point of interconnection or a small geographical area and can represent hundreds of megawatts of demand. As a result, the loss of a single large load facility or multiple facilities responding similarly to a common disturbance can create system impacts comparable in magnitude to the sudden loss of a large generating unit or even multiple generators.

Although load tripping is not itself a stability category, it is a critical initiating event that can influence multiple aspects of power system reliability. The sudden loss of large amounts of demand creates an immediate imbalance between generation and load, causing rapid changes in power flows, voltage profiles, and system frequency. Depending on system conditions and the magnitude of the load loss, these changes can contribute to frequency excursions, voltage instability, rotor-angle instability, protection system misoperation, and emergency control system actions. For this reason, this topic is addressed here first before we examine specific stability mechanisms below.

The loss of a single large load facility or multiple facilities responding similarly to a common disturbance can create system impacts comparable in magnitude to the sudden loss of a large generating unit or even multiple generators.

Historically, power system planning and operating practices have implicitly assumed that most load remains connected following grid disturbances, except for the amount disconnected as a direct consequence of fault clearing or normal voltage-sensitive load behavior. While a certain amount of end-use process load loss has always been expected following major disturbances, the resulting impacts have generally been limited because conventional residential, commercial, and industrial loads are geographically dispersed and electrically diverse. The emergence of large, concentrated load facilities fundamentally changes this assumption. The simultaneous loss of several hundred megawatts or even multiple gigawatts of demand following a disturbance is now a credible operating scenario that must be explicitly considered.

A primary contributor to this vulnerability is insufficient ride-through capability (NERC, 2025b). Large load facilities lacking adequate ride-through capability may disconnect when voltage or frequency temporarily falls outside their operating range, even when the broader power system remains stable and capable of supporting continued operation. In addition, the restoration of load following a disturbance may not occur in a predictable or coordinated manner, introducing additional operational challenges during recovery.

To understand a large load's ride-through capability, it is important to understand the facility's load composition. In this report we use a large data center as the example. A typical data center consists of information technology (IT) equipment, power conversion systems, cooling infrastructure, back-up

[6] https://www.esig.energy/reports-briefs/large-load-disturbance-events

generation, lighting, and other supporting systems (Sun et al., 2022). During voltage disturbances, portions of the facility may temporarily transfer to uninterruptible power supply (UPS) systems designed to maintain continuity of service. In principle, these systems can help prevent immediate loss of load and allow equipment to ride through short-duration disturbances. However, the presence of a UPS system alone does not guarantee successful ride-through from a power system perspective. Substantial reductions in power consumption from the grid can still result from failures in auxiliary systems such as cooling equipment, delayed restoration of facility load following fault clearing, coordination issues among power supply components, or protective actions internal to the facility. In some cases, these responses may occur several seconds after the initiating disturbance, complicating power system recovery and restoration efforts (Adhikari et al., 2019).

While the temporary reduction of load during a severe voltage depression may be beneficial from a system perspective, the key reliability concern is whether the facility restores its pre-disturbance power consumption in a predictable and coordinated manner after system conditions recover. A facility that remains disconnected, restores load too slowly, or reconnects in a rapid uncontrolled manner can introduce additional reliability risks beyond those associated with the original disturbance.

For these reasons, robust disturbance ride-through capability requirements are increasingly being considered for large loads. Such requirements are intended to ensure that facilities remain connected during routine grid disturbance events such as voltage dips or frequency excursions, while providing predictable behavior during and after disturbances. At a minimum a robust load ride-through capability should be designed and implemented to achieve the following objectives:

- Maintain connection to the grid during disturbances when it is safe for both the power system and the load facility's equipment to do so
- Limit adverse impacts on the power system during disturbances by quickly adjusting active—and, where technically feasible, reactive—power of the large load facility, recognizing that not all loads can provide dynamic reactive support capability. (Further studies may be needed to determine whether certain high-impact loads should be required to provide dynamic reactive power support in the future.)
- Coordinate a staged, manageable, and predictable load restoration after the fault is cleared

Ride-through capability requirements are discussed in greater detail in the ESIG Large Loads Task Force report *Large Load Performance Requirements: Current Practices and Recommendations*.[7] The focus of this report is the underlying reliability implications associated with inadequate ride-through performance and the mechanisms through which large load tripping can affect bulk power system reliability. The report strives to provide a comprehensive foundation for why performance requirements for new large loads are necessary to maintain power system reliability.

[7] https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements

Impacts from Large Loads on Dynamic System Stability

The behavior of large loads can adversely affect several different aspects of power system stability, broadly defined as the ability of the system to maintain a state of equilibrium under normal operating conditions and following a disturbance (whether small or large). While the previous section focused on load tripping as a common initiating event, this section examines the specific stability phenomena that may be impacted by large loads during both disturbances and normal system operation. Consistent with industry-established power system stability definitions, the discussion here is organized around frequency stability, voltage stability, rotor-angle stability, and converter-driven stability phenomena. Unlike traditional loads, today's new large loads can influence these stability mechanisms through their size, geographical concentration, control systems, disturbance response characteristics, and rapidly changing power consumption patterns. This section aligns well with the NERC Large Loads Task Force 0categorization of these impacts (NERC, 2025a).

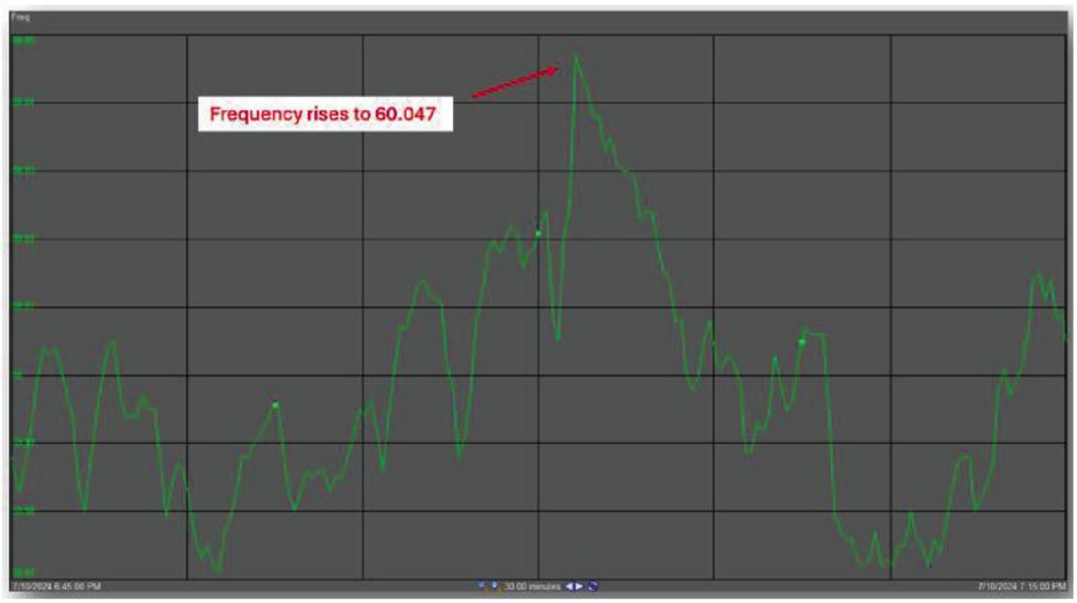
Frequency Stability

Frequency stability is the ability of the power system to maintain frequency within acceptable limits following a significant imbalance between generation and load. Large loads can affect frequency stability through both sudden changes in demand and insufficient disturbance ride-through capability. Because many new large loads are individually comparable in size to large generating units, unexpected changes in their power consumption can create frequency excursions that are increasingly relevant to bulk power system operations. However, the most significant concern is the sudden loss of large amounts of load following a system disturbance. When a large load trips (e.g., during grid fault event), generation momentarily exceeds demand, creating an instantaneous positive imbalance between production and consumption and causing system frequency to rise. While a modest frequency increase may be manageable, sufficiently large or widespread load loss can result in a frequency deviation that can challenge generator frequency controls or trigger over-frequency protections on generators, leading to negative generation and load imbalance and, potentially, cascading frequency instability. Consequently, the frequency impacts of large load tripping must be evaluated not only in terms of the immediate frequency deviation but also with respect to the broader system response.

Unlike traditional load-loss events, new large loads may exhibit highly correlated responses to common disturbances. Multiple facilities employing similar equipment, control philosophies, or protection settings may respond similarly to a voltage depression or frequency excursion. This creates the potential for the simultaneous loss of large amounts of demand across a wide geographical area, resulting in frequency excursions that are larger than those anticipated by traditional planning assumptions.

For example, on July 10, 2024, a fault in the Eastern Interconnection led to the simultaneous, unanticipated loss of approximately 1500 MW of voltage-sensitive load, much of it associated with large data centers (NERC, 2025b).[8] The resulting reduction in demand caused the system frequency to rise to 60.047 Hz before frequency control actions restored it, as shown in Figure 1. While this frequency deviation was manageable due to the large size of Eastern Interconnection and ample availability of frequency-responsive reserves, it demonstrated the potential for large load behavior to influence interconnection-wide frequency performance.

FIGURE 1
Eastern Interconnection Event Frequency Plot



Frequency plot for the Eastern Interconnection event on July 10, 2024, showing the impact of a 1500 MW large load loss/transfer event.

Source: North American Electric Reliability Corporation, "Incident Review: Considering Simultaneous Voltage-Sensitive Load Reductions" 2025b, https://www.nerc.com/globalassets/our-work/reports/event-reports/incident_review_large_load_loss.pdf.

Conversely, the rapid restoration of large loads following a disturbance, simultaneous energization of multiple large load facilities, or large unanticipated increases in demand can cause a severe under-frequency event that challenges generator frequency controls and risks the activation of under-frequency load-shedding (UFLS) schemes or the activation of generator under-frequency protection, further contributing to generation and load imbalance and frequency instability. While such scenarios are generally less common than disturbance-driven load loss, they nevertheless highlight the importance of understanding and managing the dynamic behavior of large loads.

The increasing scale and concentration of new large loads suggest that demand-side contingencies need to be considered more explicitly in future reliability assessments.

[8] This and other recent disturbance events involving large loads are covered in the ESIG Large Loads Task Force report *Large Load Disturbance Events* (https://www.esig.energy/reports-briefs/large-load-disturbance-events).

Voltage Stability

Voltage stability is the ability of the power system to maintain acceptable voltages at all buses during normal operation and following a disturbance (whether small or large). The rapid and large changes in active and reactive power consumption by large loads can influence transient and steady-state voltage stability.

Historically, voltage stability assessments focused primarily on large power transfers, generation dispatch patterns, and the behavior of conventional loads. The increasing connection of large power electronics–interfaced loads introduces new considerations. An individual facility may consume hundreds of megawatts at a single point of interconnection, creating significant localized demand for both active and reactive power. As a result, facilities' behavior during and after disturbances can materially affect system voltage performance.

A primary concern is the interaction between large load tripping and post-contingency voltage conditions. Following a disturbance, the unexpected loss of large loads may substantially alter power flow patterns across the network. While the immediate reduction in demand may initially improve local voltage conditions, the resulting redistribution of power flows can increase loading on critical transmission corridors and alter reactive power requirements elsewhere in the system. In some cases, these changes may reduce voltage stability margins or increase stress on voltage-limited transmission interfaces.

Large loads can also contribute directly to transient voltage stability challenges. During severe disturbances, rapidly changing active and reactive power consumption may interact with generator excitation systems, dynamic reactive support devices, and inverter-based resources (IBRs). If reactive power demand exceeds the capability of available voltage-support resources, post-fault voltage recovery may be delayed or, in extreme cases, the system may experience transient voltage instability. These concerns are particularly relevant in electrically weak areas of the grid where voltage support resources are limited.

Beyond the immediate post-disturbance period, large loads may influence steady-state voltage stability. Sustained operation at high power levels can increase loads' dependence on reactive power support from generators, static and dynamic reactive compensation devices, and transmission facilities. Following major contingencies, increased transfers across the system combined with continued operation of large loads may reduce voltage stability margins. As slower-acting controls such as transformer tap changers and switched reactive devices respond, the system may move toward a new operating point with reduced voltage stability reserves.

The concentration of large loads can further amplify these concerns. While the aggregate demand of a region may be similar to historical load levels, the electrical behavior of a single 500 MW facility connected at one location differs significantly from the behavior of the same demand distributed across thousands of customers. Consequently, voltage stability assessments may need to place greater emphasis on local transmission strength, dynamic reactive power performance, and post-contingency voltage recovery in areas experiencing substantial large load growth.

The potential impacts are not limited to disturbance conditions. Large and rapid changes in active and reactive power demand during normal operation of large loads (e.g. during AI training process) can create localized voltage excursions and increase demands on voltage-control equipment. Although such behavior does not necessarily constitute a voltage stability problem, it may reduce operating margins and increase the burden on system voltage regulation resources. As the scale and concentration of new large loads continue to increase, understanding these interactions will become increasingly important for both planning and operations.

Recent industry experience suggests that voltage stability concerns associated with large loads are often closely linked to ride-through capability, reactive power performance, and system strength. As a result, these areas are receiving growing attention in interconnection studies and the development of large load performance requirements.[9]

Rotor Angle Stability and Unstable Power Swings

Rotor angle stability is the ability of synchronous generators to remain in synchronism with one another after a grid disturbance. It depends on maintaining a balance between the mechanical power supplied by prime movers and the electrical power delivered to the network. Disturbances that significantly alter system power flows (such as the sudden trip of a large load or generator) can upset this balance, causing generators to accelerate or decelerate relative to one another. If synchronism cannot be maintained, generators may disconnect from the system, potentially leading to widespread outages.

Large loads can influence rotor angle stability both directly and indirectly. The most significant concern arises when a large amount of load disconnects during or immediately following a disturbance. In terms of the severity of dynamic impact, the sudden, unplanned trip of a multi-hundred-megawatt large load is analogous to a large generator trip. In the case of a large load loss, electrical demand decreases while mechanical power input to generators remains unchanged, creating an instantaneous and significant imbalance that accelerates generators and alters power transfers throughout the network.

A particularly important concern is the loss of post-fault line loading that normally helps damp generator acceleration. Following fault clearing, connected loads provide a stabilizing influence by absorbing power and helping restore the balance between generation and demand. If a large load trips during the disturbance and does not promptly restore consumption, this stabilizing effect is reduced. The resulting increase in generator acceleration can worsen post-fault power swings and reduce transient stability margins, particularly for generators electrically close to the affected load.

The redistribution of power flows following large load loss can also create significant changes in transmission line loading. Depending on system topology and operating conditions, these changes may increase stress on stability-limited transmission interfaces and reduce available transfer margins. In extreme cases, the altered power flow pattern may contribute to angular instability that would not have occurred had the load remained connected.

Large disturbances involving load loss may also produce substantial power swings on transmission lines. During these conditions, transmission line protections must correctly distinguish between a stable power swing and a fault. If protection settings are not properly coordinated, power swing impedance trajectories may encroach on relay operating characteristics, thus increasing the risk of unnecessary

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[9] See *Interconnection Processes for Large Loads: Current Practices and Recommendations* (https://www.esig.energy/reports-briefs/large-load-interconnection-process) and *Large Load Performance Requirements: Current Practices and Recommendations* (https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements).

transmission line trips. Such protection operations can further reduce system stability margins and contribute to cascading outages.

While the most significant rotor angle stability concerns are associated with disturbance-driven load tripping, large and rapid changes in load consumption can also affect system damping and power transfer patterns under non-fault conditions. As the scale and concentration of large loads continue to increase, understanding their influence on transient stability and power swing behavior will become increasingly important for planning studies and real-time operations.

Recent disturbance events have highlighted the close relationship between ride-through capability and rotor angle stability performance. Facilities that remain connected during disturbances generally help preserve system stability margins, while widespread load disconnection can significantly alter post-fault system dynamics. Consequently, rotor angle stability has become an important consideration in the development of large load ride-through requirements and disturbance performance expectations.

Resonance and Converter-Driven Stability

Unlike conventional loads, many new large loads are connected to the power system through power electronic converters with sophisticated control systems. As a result, their behavior is influenced both by the electrical characteristics of the network and the load facility and by the dynamic interactions among multiple control systems operating across a wide range of timescales. These interactions introduce a class of stability concerns that differ fundamentally from the traditional frequency, voltage, and rotor angle stability mechanisms discussed above.

Historically, load has largely been treated as a passive element in stability studies; however, large power electronics–interfaced loads challenge this assumption. Similar to IBRs, these load facilities may contain fast-acting controls, phase-locked loops, converter current regulators, voltage controls, and power management systems that continuously interact with the surrounding network. Under certain conditions, these interactions can reduce system damping or create unstable oscillatory modes.

The risk is particularly relevant in electrically weak systems where sensitivity of the grid voltage to the fast control actions is higher. In such conditions, interactions may occur between large loads and nearby IBRs, high-voltage DC systems, flexible AC transmission system (FACTS) devices, synchronous generators, or other large power electronics–interfaced loads. The resulting instability may manifest as sustained oscillations, growing oscillations, control instability, or abnormal equipment behavior. Several forms of converter-driven instability have been observed or studied in modern power systems, including:[10]

- **Sub-synchronous control interaction (SSCI):** Interactions between converter controls that produce oscillations below the fundamental frequency. SSCI has previously been observed in systems with high levels of inverter-based resources (Cheng et al., 2023) and may also become relevant for large power electronics–interfaced loads connected in electrically weak areas.

[10] See the ESIG publication *Diagnosis and Mitigation of Observed Oscillations in IBR-Dominant Power Systems: A Practical Guide* for more information on various forms of converter-driven instability, diagnostics, root-cause identification and mitigation (https://www.esig.energy/reports-briefs/oscillations-guide/).

- **Sub-synchronous torsional interaction (SSTI):** Control interactions that excite mechanical torsional modes of synchronous generator shafts, potentially resulting in excessive mechanical stress, accelerated fatigue, or equipment damage.
- **Sub-synchronous resonance (SSR):** Resonant interactions between series compensated transmission lines and Type 3 wind turbines or synchronous generators. Although historically associated with series-compensated transmission lines, changing network characteristics and the proliferation of converter-based equipment may create new pathways for excitation of sub-synchronous modes.
- **Ferroresonance:** Nonlinear interactions involving transformers, system capacitances, and network topology that can produce abnormal voltages and currents. The increasing tendency for large loads to interconnect at transmission voltages through large transformer installations may increase exposure to such phenomena under certain operating conditions.

Table 1 summarizes potential interactions between different grid components that can lead to sub-synchronous oscillatory instabilities (Isaacs, 2025).

TABLE 1

Matrix of Potential Sub-Synchronous Interactions

	Series Cap	**Power Electronics**	**Gas Turbine**	**Transformer**
Series cap	--	SSCI	SSR	SSFR
Power electronics	SSCI	Control interaction	SSTI	--
Gas turbine	SSR	SSTI	--	--
Transformer	SSFR	--	--	--

Notes: SSCI = sub -synchronous control interaction; SSR = sub-synchronous resonance, SSTI = sub -synchronous torsional interaction, FR = sub -synchronous frequency resonance

Source: A. L. Isaacs, “Study Concepts for Large Data Center Loads,” presentation at the ESIG Large Loads Task Force Webinar, April 28, 2025, Electranix, https://www.esig.energy/event/lltf-webinar-study-concepts-large-data-center-loads/.

The complexity of these interactions often requires specialized analytical techniques. Frequency-domain methods, impedance-based assessments, electromagnetic transient (EMT) simulations, and small-signal stability analyses are increasingly used to evaluate converter-driven stability risks. Such studies can help identify poorly damped modes, adverse control interactions, and resonance conditions before facilities are interconnected.

While the probability of these phenomena is highly dependent on system topology, control design, and network strength, their consequences can be severe. Potential outcomes include sustained oscillations, protection system operations, equipment damage, reduced transfer capability, and widespread system instability. As large power electronics–interfaced loads continue to grow in both size and number, converter-driven stability assessments are expected to become an increasingly important component of interconnection studies and reliability evaluations.

Forced Oscillations and System Response

Unlike natural oscillations discussed in the previous section, forced oscillations are not caused by inherent instability of the power system. Instead, they arise when an external source continuously injects a periodic disturbance into the network. If the disturbance persists, the resulting oscillation can propagate throughout the power system and, under certain conditions, excite natural system modes.

Historically, forced oscillations originated from sources such as malfunctioning generator controls, cyclic industrial processes, poorly tuned control systems, or repetitive switching actions. New large loads introduce a new potential source of forced oscillations due to the scale, speed, and periodicity of their power consumption patterns.

Particular attention has recently focused on large AI data centers. During AI model training, groups of graphics processing units (GPUs) transition between a computation-heavy phase with high power consumption and a communication-heavy phase with lower-power consumption, creating large, repetitive power swings. These swings can range from tens of megawatts to more than 100 MW, depending on the size of the cluster and workload intensity (NERC, 2025a). Depending on workload characteristics, these fluctuations may occur at frequencies spanning from fractions of a Hz to tens of Hz.

The primary reliability concern is not simply the existence of power fluctuations but their interaction with the broader power system. If the frequency of these forced oscillations aligns with a natural system mode, resonance can occur, dramatically amplifying the oscillation's magnitude. Consequently, relatively modest power fluctuations can sometimes produce disproportionately large system impacts.

These AI workload oscillation frequencies often fall into the sub-synchronous range, creating risks for different system components depending on the oscillation frequency band:

- **Below approximately 1 Hz:** Forced oscillations can excite resonant modes in long distance transmission networks with groups of generators located on both sides, leading to inter-area oscillations.
- **Approximately 1 Hz to 2.5 Hz:** Forced oscillations can excite local electromechanical modes in closely coupled generators, such as units within the same power plant.
- **5 Hz and above:** Forced oscillations can excite torsional modes in turbine-generator shafts, risking mechanical fatigue or failure as discussed in the next section, "Operational Risks to Synchronous Generators."

The severity of impact of these oscillations is highly dependent on grid strength, load ramp rates (defining amplitude of oscillations), and frequency of oscillations, as demonstrated by the following representative simulations. Figures 2, 3, and 4 demonstrate the impacts of grid strength, load ramp rate, and fluctuation frequency on system stability, respectively.

- **Grid strength (Figure 2):** Weak electrical systems (i.e., a grid with low short-circuit ratio (SCR) as defined below[11]) exhibit greater sensitivity to load-induced oscillations than stronger systems because the disturbance is absorbed by a smaller number of electrically coupled generators.

$$SCR = \frac{short - circuit\ MVA\ at\ POI}{facility - rated\ MVA}$$

- **Ramp rate (Figure 3):** Fast load ramp rates tend to excite stronger system responses and may induce instability, whereas slower ramps allow for a smooth, manageable response.
- **Frequency (Figure 4):** A load fluctuating at a low frequency (e.g., 1 Hz) can excite a generator's natural swing mode, causing resonance that dangerously amplifies power swings.

These concerns are validated by recent real-world oscillation events covered in more detail in the ESIG Large Loads Task Force report *Large Load Disturbance Events*, including:[12]

- **ERCOT 23 Hz event:** A large load facility was identified as the source of high-frequency oscillations. The power swings of approximately 37 MW experienced by the system were significantly reduced only after the facility's load was curtailed, confirming the load as the root cause.
- **Dominion Energy 14.7 Hz event:** A sustained voltage oscillation grew over time in an area with a high concentration of data centers, particularly after local hydro generation was reduced (creating weaker grid conditions).

Although the underlying mechanisms differed, both events demonstrated that large load facilities can contribute to oscillatory behavior observable across the bulk power system.

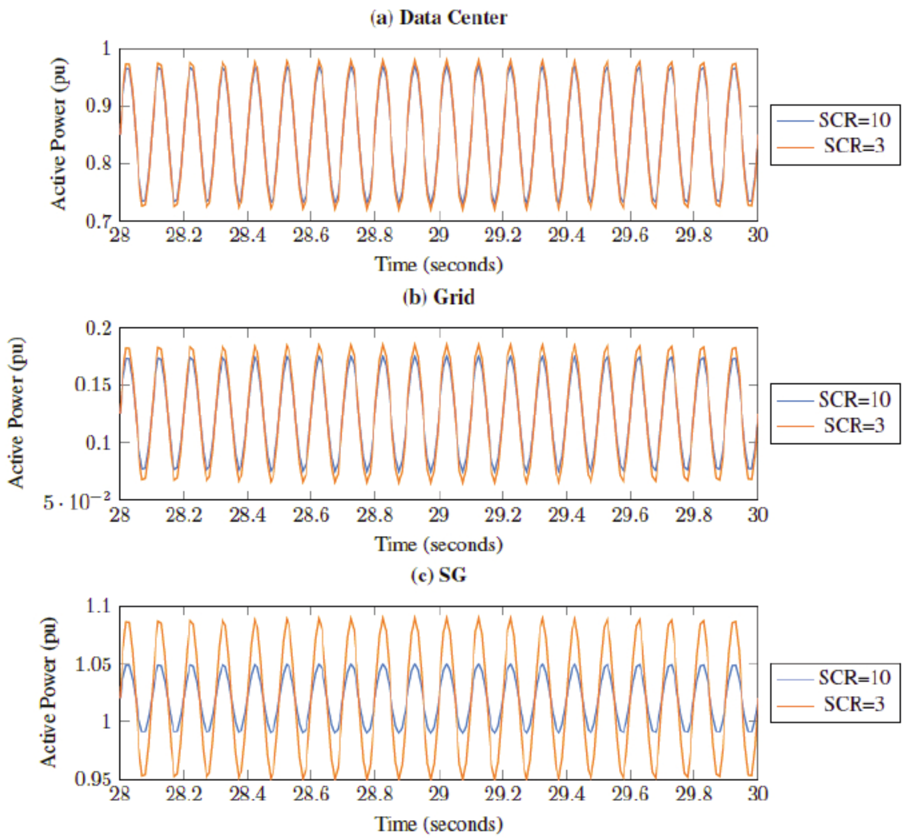
These disturbance events, together with ongoing research and simulation studies, suggest that forced oscillations may become an increasingly important reliability consideration as large power electronics–interfaced loads continue to grow in size and geographical concentration. Unlike many traditional reliability risks, forced oscillations can emerge during otherwise normal operating conditions and may not require a fault or other major disturbance to initiate. Consequently, the industry is giving increasing attention to the monitoring, detection, modeling, and mitigation of load-induced oscillations.

[11] While SCR is widely used for inverter-based generation, as a metric for system strength, there is currently no universally accepted definition of SCR for loads or for loads with co-located generation. Developing a formal metric for system strength for these cases would improve consistency in planning and stability assessments.

[12] https://www.esig.energy/reports-briefs/large-load-disturbance-events

FIGURE 2

Impact of Grid Strength (SCR)

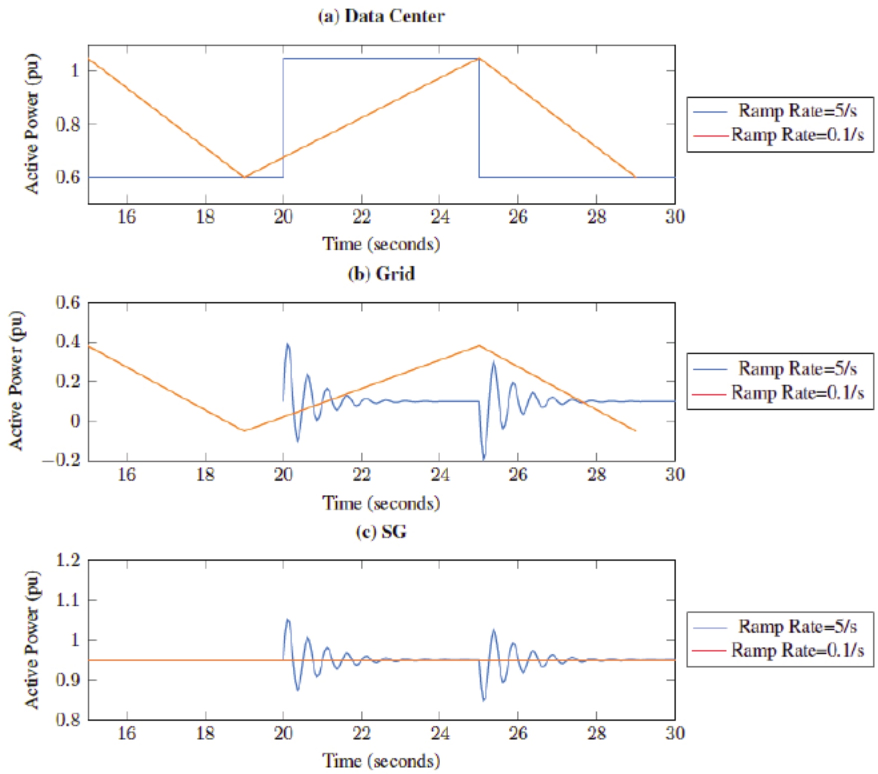


Active power variations showing a synchronous generator (SG) on a weak grid (SCR=3) absorbs more of the load fluctuation than one on a strong grid (SCR=10).

Source: Zero-Emission Grid LLC.

FIGURE 3

Impact of Ramp Rate

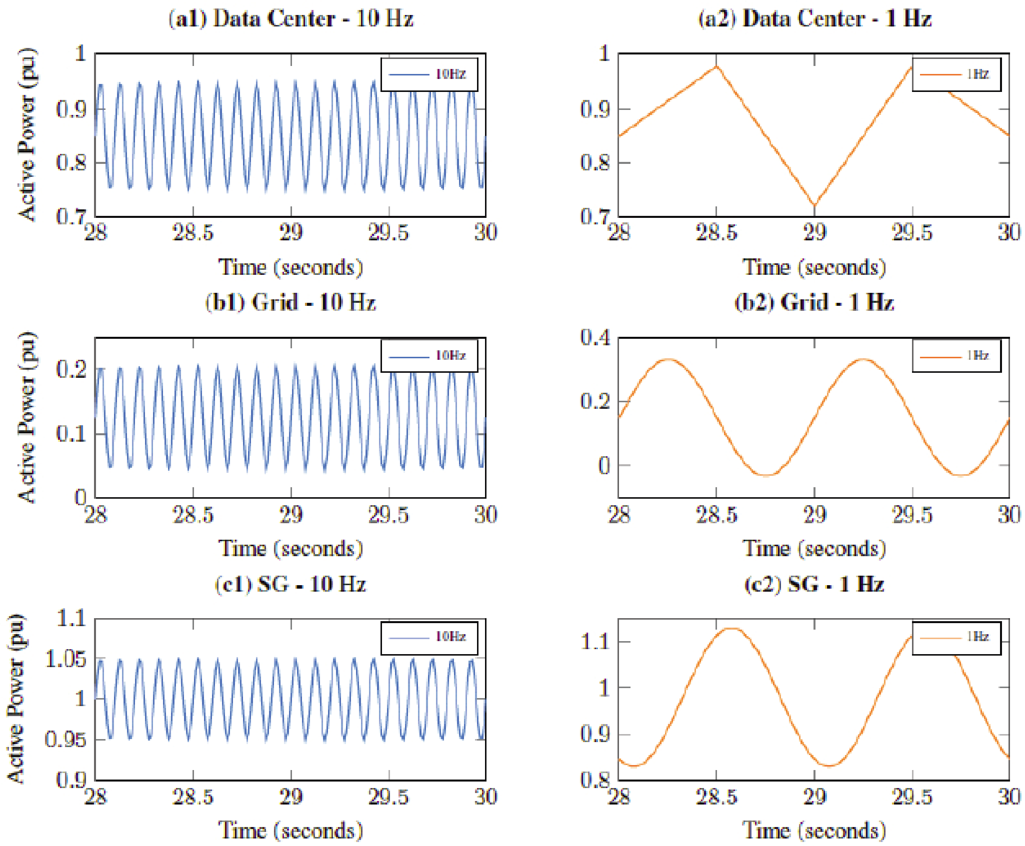


A fast load ramp rate (5pu/s) induces significant oscillations, while a slow ramp rate (0.1pu/s) results in a smooth response.

Source: Zero-Emission Grid LLC.

FIGURE 4

Impact of Frequency Fluctuations



A low-frequency (1 Hz) load fluctuation excites a resonant response in the generator while a high-frequency (10 Hz) fluctuation is attenuated.

Source: Zero-Emission Grid LLC.

Operational Risks to Synchronous Generators

The previous sections discussed the impacts of large loads on the stability and reliability of the power system overall; however, oscillatory behavior associated with large loads can also create direct, physical risks to synchronous generating units. Unlike power electronics–based equipment, synchronous generators contain large rotating mechanical systems with natural torsional and electromechanical modes. Under certain conditions, oscillations introduced or amplified by large loads can excite these modes, creating mechanical and thermal stresses that accumulate over time or, in extreme cases, result in equipment damage. Consequently, concerns associated with large load oscillations extend beyond system stability and may directly affect generator reliability, maintenance requirements, and asset life.

These risks are not limited to generators directly supplying a large load facility. Oscillations originating from large loads can propagate through the transmission network and impact synchronous generators that are electrically close to the source of forced oscillations. As large load facilities continue to increase in size and geographical concentration, understanding their potential impact on nearby generating assets becomes increasingly important:

- **Torsional oscillations and sub-synchronous interactions:** As discussed in the previous sections, large load oscillations can interact with natural modes of the power system and generating equipment. Of particular concern are sub-synchronous oscillations that occur below the fundamental system frequency. If a load fluctuation excites one of a turbine-generator shaft system's natural torsional modes, the resulting oscillation may produce excessive shaft torques. Depending on the frequency, duration, and amplitude of the oscillation, the resulting mechanical stresses can significantly exceed those experienced during normal operation. This phenomenon may arise through SSR, SSTI, or other converter-driven interactions.

  While oscillations may appear modest when viewed through system-wide measurements, the mechanical response of a generator shaft system can be greatly amplified when oscillation frequencies align with torsional modes. Under severe conditions, torsional stresses can exceed design limits, leading to accelerated fatigue, damage to couplings or turbine shafts, and, in extreme cases, catastrophic shaft failure.

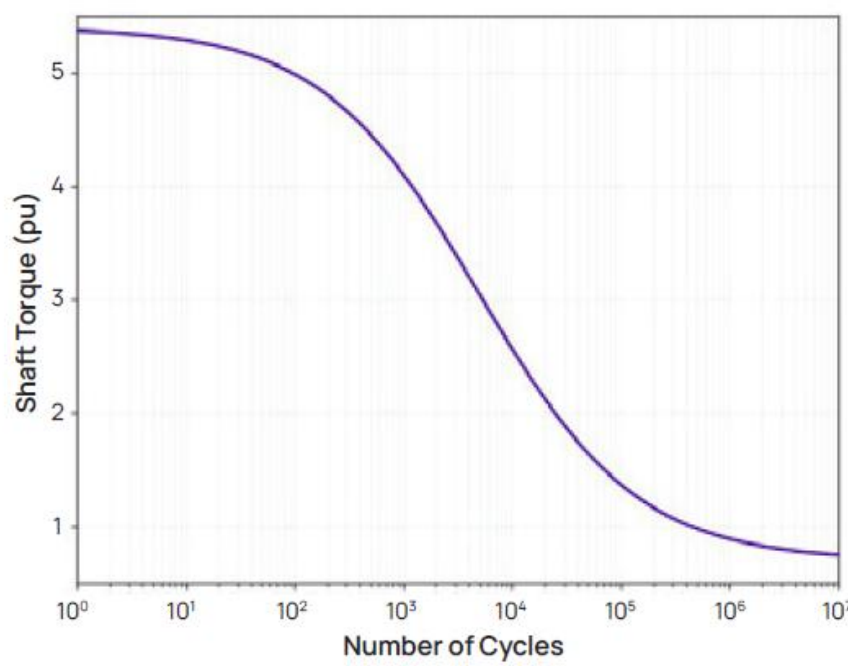
- **Local-mode oscillations and control interactions:** Similarly, large load power fluctuations can also interact with the local electromechanical modes of nearby synchronous generators, particularly if load oscillations coincide with the generator's local electromechanical modes (typically 0.8 Hz to 2.0 Hz). When repetitive load variations align with these local modes, the resulting resonance can reduce system damping and amplify the oscillations. Sustained oscillations can increase stress on generator controls, excitation systems, and power system stabilizers. In severe cases, protection systems may operate to disconnect the affected unit, further reducing system stability margins and potentially contributing to broader system disturbances.

- **High-cycle mechanical and thermal fatigue:** Even when oscillations are not severe enough to produce immediate equipment damage, repetitive loading can create cumulative fatigue effects. A load fluctuation occurring every few seconds can subject generator components to thousands of stress cycles per day. Over time, these repeated mechanical and thermal stresses can accelerate the wear of electromechanical parts of a generator, increase maintenance requirements, and significantly reduce the generator's operational lifespan. Sustained fluctuations at the generator terminals exceeding 1% to 2% of its nominal power create a credible risk of premature component failure (NERC, 2017; EPRI, 2006), and should be studied in detail with the equipment manufacturer. This concern is particularly relevant for oscillations that persist for extended periods and remain undetected by system operators.

The cumulative nature of these risks can be illustrated using the concept of a fatigue life, commonly represented by an S-N curve (stress vs. number of cycles). An S-N curve is a plot of the magnitude of an alternating stress versus the number of cycles to failure for a given material. For a given piece of equipment, the S-N curve corresponds to the fatigue life of a mechanical part. When the stress and number of cycles surpass the S-N curve, the material will fail. For synchronous generator, the repetitive power fluctuations by oscillation cause stress to the turbine and could potentially cause the fatigue and damage of the generator. An example of the S-N curve is given in Figure 5.

FIGURE 5

S-N Curve



An S-N curve is a plot of the magnitude of an alternating stress versus the number of cycles to failure for a given material. For a given piece of equipment, the S-N curve corresponds to the fatigue life of a mechanical part. When the stress and number of cycles surpass the S-N curve, the material will fail.

Source: Energy Systems Integration Group.

An important challenge for system planners and operators is that generator vulnerability is often difficult to precisely quantify. While turbine-generator manufacturers maintain torsional design data and fatigue assessments for their equipment, detailed torsional models and damage curves are frequently proprietary and not broadly available for planning studies. Furthermore, cumulative fatigue exposure can be difficult to estimate because generator operating conditions, system topology, and the characteristics of nearby large loads evolve over time. As a result, evaluating long-term equipment impacts often requires close collaboration among utilities, generator owners, equipment manufacturers, and large load developers.

Cyber-Physical Security Threats to System Stability

The preceding sections focused on reliability impacts arising from the normal operation, disturbance response, and control behavior of large loads. However, many of the same reliability consequences may also result from intentional actions by malicious actors. The convergence of IT and operational technology systems within large load facilities creates new attack surfaces that malicious actors can exploit. From a reliability standpoint, the primary concern is a cyber or physical attack that results in the sudden, simultaneous tripping of multiple large load facilities or the manipulation of their power consumption to destabilize the grid. Such an event could represent the loss or manipulation of thousands of megawatts in an instant, creating a demand-side contingency far larger than the traditional generation-loss criterion that power systems are designed for. These cyber-physical threats should be viewed as another potential initiating mechanism for reliability events involving large loads.

Key Vulnerabilities and Attack Vectors

Large load facilities, particularly data centers, contain extensive IT and operational technology infrastructure on a single site, presenting unique cybersecurity challenges. Potential vulnerabilities include:

- **Internet-exposed infrastructure management:** Data center infrastructure management applications and other operational technology systems are often insecurely connected to the internet for remote monitoring and control, providing a direct entry point for attackers if not properly secured.
- **Exploitable operational technology and Internet of Things (IoT) devices:** Critical support systems such as heating, ventilating, and cooling systems; fire detection; UPS; and physical security systems (such as closed-circuit television cameras and keypad access) are increasingly networked. These devices often use simplified operating systems with minimal encryption or authentication, creating vulnerable entry points that can be compromised to gain access to more critical systems or to directly cause a physical disruption.
- **Vulnerable communication protocols:** The use of legacy industrial communication protocols within the facility's power systems, which may lack modern security features, increases the risk of an attacker intercepting or manipulating critical operational data.

Reliability-Relevant Attack Scenarios and Grid Impacts

By exploiting these vulnerabilities, an adversary could orchestrate attacks with severe consequences for the bulk power system reliability discussed in the previous sections of this report. The scenarios extend beyond simple data theft to the direct manipulation of physical processes including:

- **Coordinated load tripping:** The most significant risk is an attacker gaining simultaneous control over multiple large load facilities and tripping them offline. This would initiate the same cascading impacts described earlier in this report: a severe over-frequency event, widespread over-voltages, and the potential for angular or dynamic instability leading to system separation.

- **Manipulation of power demand:** Attackers could manipulate data center workloads to induce rapid and large power swings. As discussed in the section “Forced Oscillations and System Response,” such manipulations could create forced oscillations that threaten the stability of nearby generators and the wider grid. A bad actor could intentionally time these swings to coincide with periods of grid stress to maximize the disruptive impact.
- **Disruption of critical support systems:** An attack targeting a facility’s cooling systems (space cooling or chillers), UPS systems, or other critical large load facility infrastructure may indirectly trigger large load reductions or complete facility shutdown to prevent equipment damage. Although the initiating event would be cyber in nature, the resulting grid impacts would be indistinguishable from other large load tripping events.
- **Loss of visibility and control:** A cyberattack could target the communication links between the large load and the utility. The loss of critical telemetry and control would blind the grid operator to the load’s behavior, negatively impacting operational balancing, delaying corrective actions, and reducing the operator’s ability to respond effectively during system disturbances potentially threatening wider system reliability.

The increasing concentration of large loads creates the possibility that a successful attack could produce a demand-side contingency comparable in magnitude to major generation outages. Unlike traditional reliability events, such actions may be intentional, coordinated, and timed to coincide with periods of system stress.

For this reason, the reliability implications of cyber-physical threats extend beyond the facilities themselves. A coordinated attack affecting multiple large loads could simultaneously trigger frequency excursions, voltage instability, forced oscillations, protection system operations, and emergency control actions. In many respects, the resulting system response would resemble the physical reliability events discussed throughout this report. Accordingly, cybersecurity considerations are becoming an increasingly important component of large load interconnection, planning, and operational discussions. While cybersecurity requirements themselves are outside the scope of this report, understanding the potential reliability consequences of cyber-induced load behavior is essential for assessing overall system risk.

Impacts on Balancing and Dispatch

The unique characteristics of large loads, discussed in previous sections, apart from system stability, also challenge conventional balancing and dispatch activities in the bulk power system, creating both operational and economic risks. A high-level overview of these impacts is presented here.

Impacts on System Balancing

Maintaining the real-time balance between electricity supply and demand is one of the grid operator's core responsibilities. This balance is measured by the area control error (ACE), which reflects the mismatch between actual and scheduled net power interchange with neighboring balancing authorities, along with frequency deviations (adjusted with frequency bias β). A balancing authority's automatic generation control (AGC) system continuously monitors ACE and dispatches regulating generators to bring it toward zero.

Historically, load has been treated as relatively predictable at the system level because the behavior of individual customers is aggregated across large populations of residential, commercial, and industrial consumers. This diversity tends to smooth short-term variations and makes aggregate demand more predictable than the behavior of any individual customer.

The emergence of very large load facilities challenges some of these traditional assumptions. Individual facilities may consume hundreds of megawatts of power and, in some cases, exhibit operating characteristics that differ significantly from conventional loads. As a result, decisions made by a relatively small number of facilities can materially influence system demand, operating reserves, and dispatch requirements. The behavior of large loads can disrupt this balance in several ways:

- **Rapid load ramps:** Unexpected, rapid ramps in load cause a significant ACE deviation by creating an immediate change in the net interchange. This forces operators to take urgent, and often less efficient, corrective actions through AGC, such as deploying fast-start peaking units or initiating large inter-area transfers. These actions are less efficient because they increase operating costs, stress system reserves, and may temporarily compromise optimal dispatch.
- **Load tripping due to lack of ride-through capability:** When a large load trips because of a voltage disturbance, both the frequency deviation and net interchange terms in the ACE equation spike, creating a sudden large positive error. In these situations, a conventional AGC mechanism may not provide an adequate response.
- **Load fluctuations:** Aside from major events, the continuous fluctuations inherent in some AI workloads place persistent strain on balancing resources. This leads to increased wear and tear on regulating generators and a faster depletion of available regulation capacity.

Large Load Impacts on Generation Unit Commitment Dispatch

Unit commitment (UC) and security-constrained economic dispatch (SCED) processes are undermined by the load forecast uncertainty and ramping needs associated with these new load classes.

Forecasting Uncertainty

Efficient grid operations and system dispatch depend on accurate load forecasting both in long (years) and shorter (months, days, and hours) time frames to ensure that the right amount of generation with the right capabilities is built, committed, and dispatched at the lowest cost.

However, the unpredictable and often exploratory nature of data center development reduces long-term load forecast accuracy. This leads to a suboptimal generation mix that potentially does not have sufficient ramping capabilities to "follow" large load variations in real-time operations. For more information on long term large load forecasting see the ESIG Large Loads Task Force report *Forecasting for Large Loads: Current Practices and Recommendations*.[13]

Additionally, information about large load demand profiles necessary to understand flexibility needs for the future generation fleet is usually not available for planning and operations processes. This lack of data and transparency adds another layer of uncertainty for planners and operators. For more information on data needs from large load data facilities, see the ESIG Large Loads Task Force report *Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility*.[14]

In shorter time frames (days and hours) load forecasting uncertainty is often tied to large load facility operational workloads. For example, AI model training can start or stop unpredictably several times per day, creating sudden deviations and generation-load imbalances that conventional short-term load forecasting models cannot capture. This short-term load forecasting uncertainty may lead to suboptimal unit commitment, less efficient real-time dispatch, depletion of regulating reserves, and higher overall production costs.

Generation Ramping Challenges and Reserve Requirements

In real time the combined ramping capability of online generators may not be sufficient to follow the steep ramp rates of large loads. This forces system operators to procure additional fast-ramping reserves and prioritize generation with better ramping capabilities over economic efficiency for unit commitment and dispatch. Moreover, this constant need for flexibility places significant mechanical and thermal stress on conventional generators and potential wear and tear on battery energy storage, leading to equipment degradation, higher failure rates, higher maintenance costs, and shorter equipment lifespans. Flexibility needs stemming from large load integration are further discussed in the ESIG Large Loads Task Force report *Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility*.[15]

Some of these challenges can be mitigated through closer coordination with large load facilities—for example, by setting ramp rate limits, incentivizing load management and provision of short-term operational schedules, and incentivizing participation in operating reserve markets or other flexibility products.

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[13] https://www.esig.energy/reports-briefs/forecasting-for-large-loads

[14] https://www.esig.energy/reports-briefs/large-load-task-force-introduction

[15] https://www.esig.energy/reports-briefs/large-load-task-force-introduction

Impacts on Power Quality

Power quality refers to the characteristics of voltage and current supplied to electrical equipment, including waveform distortion, voltage fluctuations, imbalance, frequency deviations, and other departures of voltage and current from the ideal 60 Hz sinusoidal waveform. Historically, power quality concerns associated with individual loads have largely been localized and addressed through equipment design, facility engineering practices, and, in some regions, interconnection requirements. However, the increasing size and concentration of new large loads, together with their extensive use of power electronic equipment, has increased industry attention on their potential power quality impacts.

Many large load facilities rely on significant amounts of power conversion equipment, including UPS systems, rectifiers, inverters, VFDs, and other electronically controlled devices. While these technologies enable efficient and highly reliable large load facility operation, they can also introduce power quality phenomena that may affect both the facility itself and the surrounding electrical system. The primary power quality impacts are through harmonic distortion and voltage flicker. These impacts are regulated by standards such as the IEEE 519 Standard for Harmonic Control in Electric Power Systems and IEEE 1453 Standard for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems, respectively, and discussed below.

Harmonic Distortion

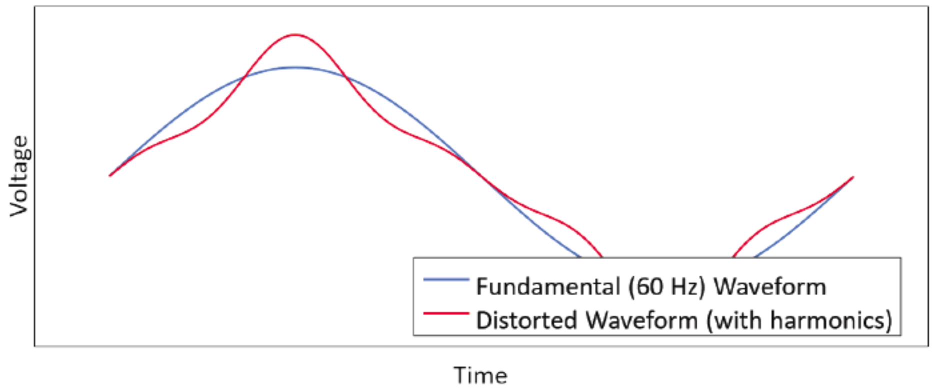
One of the most common power quality concerns associated with large power electronics–interfaced loads is harmonic distortion. Harmonics are voltage and current components occurring at integer multiples of the fundamental system frequency, while interharmonics occur at non-integer frequencies. These frequency components can be produced by converters, switching devices, and other non-linear electrical equipment.

Elevated harmonic levels may result in increased losses, transformer heating, capacitor bank stress, reduced equipment life, inaccurate metering, and undesirable interactions with protection and control systems. If an injected harmonic frequency aligns with a natural resonant frequency of the grid impedance, harmonics may also interact with system resonances, described above, leading to amplification of voltage distortion.

Large-scale data centers rely on power electronic converters, which function as non-linear loads. As a result, these systems draw non-sinusoidal currents, injecting harmonics that may distort the voltage waveform in violation of IEEE Standard 519 limits (Figure 6). Mitigation often involves harmonic filters or active front-end rectifiers, but requires careful analysis to ensure compliance with IEEE Standard 519 and to prevent adverse interactions.

FIGURE 6

Comparison of Ideal and Distorted Voltage Waveforms



Conceptual diagram showing a pure sinusoidal voltage waveform compared to one distorted by harmonic currents from non-linear loads.

Source: Energy Systems Integration Group.

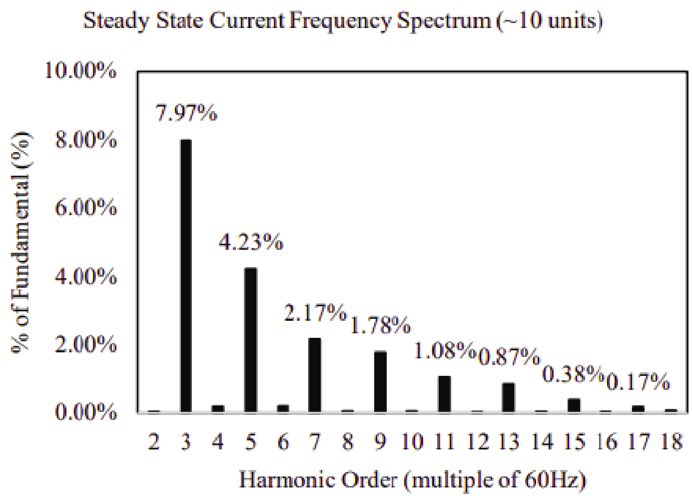
Harmonic Profile of Cryptocurrency Mines

Cryptocurrency mining facilities present a unique power quality challenge due to their architecture, which consists of thousands of single-phase ASIC miners. Each miner's power supply acts as a non-linear load, and their collective operation produces a distinct harmonic signature dominated by triplen harmonics (3rd, 9th, 15th, etc.), as shown in Figure 7 (Wheeler et al., 2018). These harmonics can lead to overheating in transformers and neutral conductors and can cause significant voltage distortion.

A common and effective mitigation strategy is the use of a delta-wye grounded transformer at the facility's substation. The delta-connected primary winding traps the zero-sequence triplen harmonic currents, forcing them to circulate within the delta winding rather than propagating upstream into the transmission system. While this significantly reduces the harmonic impact on the grid, it may not be sufficient on its own. Depending on the grid's strength and existing distortion levels, additional harmonic filtering may still be required to ensure compliance with IEEE Standard 519 at the point of interconnection.

FIGURE 7

Typical Harmonic Current Spectrum for ASIC Miners



Example harmonic spectrum from a collection of AntMiner S9 units showing high levels of triplen harmonics (3rd, 9th, 15th).

Source: K. A. Wheeler, A. W. Bowers, C. H. Wong, J. Y. Palmer, and X. Wang, "A Power Quality and Load Analysis of a Cryptocurrency Mine," 2018 IEEE Electrical Power and Energy Conference, Toronto, ON, Canada, 2018, pp. 1-6, https://doi.org/10.1109/EPEC.2018.8598358.

Voltage Flicker

Rapid variations in active and reactive power demand can produce voltage fluctuations at the point of interconnection and on nearby portions of the network. Depending on their magnitude and frequency, these fluctuations may manifest as voltage flicker—the phenomenon of noticeable (to the human eye) nuisance illumination changes from lighting equipment due to voltage fluctuations.

While many traditional industrial facilities have long been associated with voltage flicker, large data centers and other new large loads may create similar concerns. For example, the cyclical load profiles of AI data centers can cause this issue, with behavior conceptually similar to that of electric arc furnaces due to their rapid, repetitive, high-magnitude changes in power demand. The severity depends on the magnitude and frequency of the load fluctuation and grid strength. The human eye is most sensitive to fluctuations in the 8 to 10 Hz range, and since AI workloads can fluctuate up to 10 to 15 Hz, they fall directly within the spectrum of concern. Standards such as IEEE 1453 provide limits on short-term and long-term flicker severity to prevent irritation.

It is critical to understand that, while adherence to flicker and harmonic standards is necessary, it is not sufficient. A load can be fully compliant with IEEE 519 and IEEE 1453 and still exhibit large, rapid power swings, described in earlier sections of this report, that threaten grid stability. Therefore, power quality standards alone cannot mitigate the risks of load variability.

Phase Imbalance and Negative Sequence Effects

Large loads can introduce phase imbalance on the transmission system, particularly when operating multiple converters or crypto mining rigs with uneven phase loading. This imbalance generates negative sequence currents that propagate through the network. Negative sequence currents can induce opposing torque on synchronous generator shafts, accelerating mechanical fatigue and increasing the risk of shaft failure. Furthermore, imbalance can increase losses and heating in motors and transformers as well as compromise protection selectivity by causing the misoperation of phase-sensitive relays and differential protection schemes.

The extent of these impacts depends on facility design, grid strength, transformer configuration, and the characteristics of connected equipment. Consequently, evaluation of these phenomena often forms part of the interconnection assessment process.

The effects of phase imbalance underscore the need for strict phase-balancing requirements and continuous monitoring of negative sequence components at the point of interconnection. For more information, see the ESIG Large Loads Task Force report *Large Load Performance Requirements: Current Practices and Recommendations*.[16]

[16] https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements

Impacts on Grid Protection and Emergency Control Systems

Protection systems and emergency control schemes play a critical role in maintaining power system reliability during abnormal operating conditions. These systems are designed to detect faults, protect equipment, maintain system stability, and prevent cascading outages. Modern power grids are protected by a layered defense philosophy, with each layer designed to contain disturbances of increasing severity.

Historically, protection system design and performance have been based on assumptions regarding the behavior of generation, transmission facilities, and aggregate load. The increasing deployment of large, power electronics–interfaced loads, however, introduces challenges that can compromise each of the modern protection layers, from frontline protection relays to wide-area emergency control schemes and final-resort manual interventions.

Unlike traditional load, new large loads are often concentrated at a small number of locations, may contain extensive protection and control systems, and can exhibit highly correlated responses to disturbances. As a result, their behavior can influence both the operation and effectiveness of protection systems and emergency control actions.

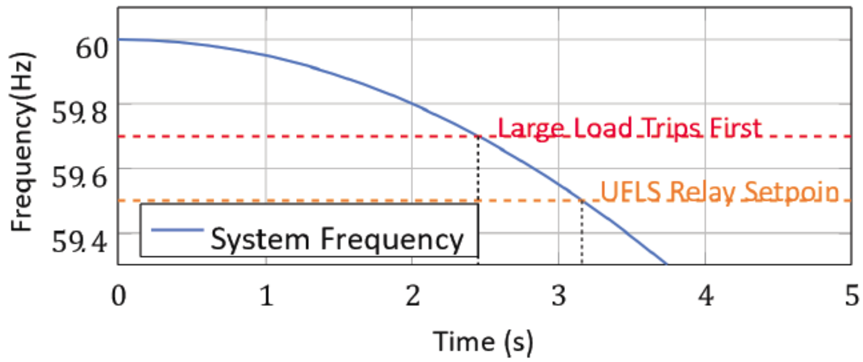
Interactions with Under-Frequency and Under-Voltage Load Shedding

The grid relies on automated, pre-programmed defense schemes such as UFLS and under-voltage load shedding (UVLS) as a last resort to arrest severe frequency or voltage disturbances and prevent cascading outages. These schemes are designed to shed specific blocks of load when frequency or voltage drop below predefined thresholds and are generally designed under the assumption that connected load remains available to be shed when required.

As discussed above, large loads often have internal protection that trips or switches them over to internal power supplies at thresholds higher (less severe) than the utility's relay settings. This means the load may already be disconnected before the UFLS or UVLS scheme acts, rendering planning simulations inaccurate and the scheme less effective during a real event, illustrated in Figure 8. In other words, planners and operators may be relying on a block of load for shedding in emergency that simply will not be available.

FIGURE 8

UFLS Scheme Compromise Timeline



Conceptual timeline demonstrating how a large load's internal protection (e.g., at 59.7 Hz) can trip before a standard under-frequency load-shedding relay acts (e.g., at 59.5 Hz), compromising the scheme's effectiveness.

Source: Energy Systems Integration Group.

Similarly, remedial action schemes (RASs), or special protection schemes, which are designed to respond to specific major contingencies, are compromised when large loads trip unexpectedly or outside predefined load blocks. A RAS may be programmed to shed a certain amount of load to maintain stability in case of a specific contingency, but if a large facility also trips unexpectedly[17] during that contingency due to its own internal protection, the RAS may be tripping more load than required, potentially destabilizing the grid.

Manual Control and Restoration

The impacts of large loads on emergency operations extend beyond the initial disturbance response. Following major events, operators must restore generation, transmission facilities, and customer demand in a coordinated manner. The restoration behavior of large loads can significantly influence these efforts.

Large load facilities that reconnect rapidly after a disconnection or restore demand in large blocks may create additional operational challenges during recovery. Shedding the entire facility can cause a severe over-frequency or over-voltage event. Conversely, facilities capable of coordinating restoration with system operators may help reduce recovery risks and improve overall system resilience.

Understanding how large loads behave during both disturbance response and system restoration is therefore becoming an increasingly important aspect of emergency operations planning and may need to be specified in the interconnection requirements.

[17] Here, "unexpectedly" means that (1) this large load trip is not a part of RAS, and (2) the trip was not observed in studies that informed the RAS design.

Protection System Operations

Large loads may also influence the operation of transmission and facility protection systems. One reason is the sheer size of these loads and the amount of current they draw from the grid. Disturbance-induced load tripping can also significantly alter power flow patterns, fault current distributions, and voltage profiles throughout the network. These changes may affect relay measurements and system conditions used by protection systems to make operating decisions.

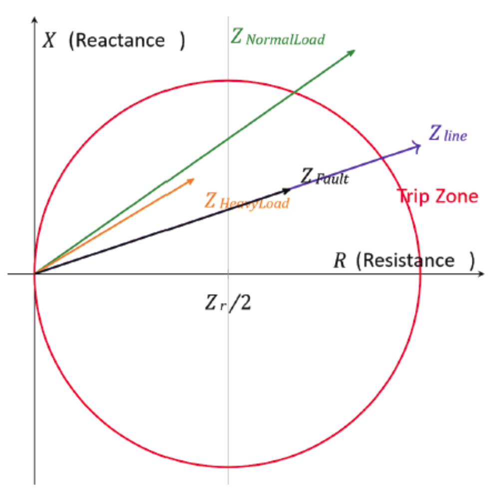
In addition, large load facilities often contain extensive internal protection systems associated with power conversion equipment, UPS systems, cooling infrastructure, and other critical components. While these systems are intended to protect facility equipment, their operation may result in significant changes in grid-supplied demand. Consequently, facility protection settings and coordination practices can have system-level implications that extend beyond the facility boundary.

Relay Loadability and Load Encroachment

Distance relays, which protect transmission lines by measuring impedance, are particularly vulnerable to load encroachment. A very large load can draw extremely high currents, causing the apparent impedance measured by the relay to decrease significantly. This phenomenon, known as load encroachment, can cause the relay to misinterpret a heavy load condition as a fault, leading to an unnecessary trip of a healthy transmission line (Figure 9).

FIGURE 9

Load Encroachment on a Mho Distance Relay



Conceptual R-X diagram illustrating how a heavy load condition can cause the measured impedance ($Z_{HeavyLoad}$) to encroach into a distance relay's trip zone, risking a false trip.

Source: Energy Systems Integration Group.

To mitigate this risk, protection settings must be reviewed and adjusted at the time of the load's interconnection to account for the magnitude of the new load. This includes expanding load encroachment logic or applying directional elements to prevent misoperation during high-current, non-fault conditions. It is essential to coordinate with system protection engineers during interconnection studies to ensure relay security under extreme loading scenarios.

Harmonic Distortion and Relay Performance

Protective relays are designed for fundamental frequency operation. As discussed in the previous section, the harmonic currents injected by large loads can corrupt the voltage and current waveforms on which relays rely. This can lead to misoperation of overcurrent relays, inaccurate directional determination, and issues with transformer differential protection.

Challenges to Protection Coordination

Effective protection coordination ensures that the protection device closest to a fault operates first, isolating the smallest possible part of the system by carefully coordinating relay operating times. However, the autonomous and rapid tripping behavior of large loads disrupts this planned coordination. A large load might trip on its own internal under-voltage or over-frequency settings before a coordinated upstream utility feeder relay has time to operate for a legitimate fault. This lack of coordination can lead to a loss of selectivity and complicate fault analysis, potentially leading to wider system disturbances.

Framework for Mitigation and Technical Requirements

Large loads can affect power system reliability via several mechanisms including load tripping, dynamic stability, oscillatory behavior, balancing operations, power quality, and protection system performance. These impacts do not imply that large loads always present an unacceptable reliability risk. Rather, they highlight the importance of understanding load behavior and ensuring that facilities are designed, interconnected, and operated in a manner consistent with reliable grid operation.

A variety of mitigation measures and technical requirements are available to address the risks discussed throughout this report. These range from performance requirements specified during the interconnection process to facility-level controls, operational procedures, monitoring systems, and hardware solutions. The objective of this section is not to prescribe a specific set of requirements, as a detailed discussion of current industry practices and recommended performance requirements is provided in the ESIG Large Loads Task Force report *Large Load Performance Requirements: Current Practices and Recommendations*.[18] Rather, this section focuses on the relationship between the reliability concerns identified in this report and the types of mitigation measures commonly used to address them.

Core Performance Requirements for Interconnection

Many of the reliability concerns discussed throughout this report originate from uncertainty regarding how large loads will behave during normal operation and system disturbances. Consequently, a foundational mitigation strategy is the establishment of clear performance expectations during the interconnection process. Interconnection requirements are intended to ensure that large loads exhibit predictable and reliable behavior under a range of operating conditions. Examples include disturbance ride-through capability, active power recovery requirements, power quality limits, ramp-rate limitations, oscillation performance expectations, and coordination with protection and emergency control schemes.

The specific requirements adopted by a utility, transmission operator, balancing authority, or regulatory jurisdiction will depend on local system needs and operating practices. However, the underlying objective remains the same: ensuring that large loads contribute to, rather than undermine, reliable system operation.

Studies and Modeling in the Interconnection Process

Many of the phenomena described in this report cannot be adequately evaluated without appropriate models and study methodologies. Dynamic performance assessments should therefore be an integral component of the interconnection process.

Depending on facility characteristics and local system conditions, studies may include positive-sequence phasor-domain simulations, small-signal analysis, frequency-domain assessments, harmonic studies, and

[18] https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements

EMT simulations. Particular attention may be warranted for facilities containing large amounts of power electronic equipment or exhibiting rapid power fluctuations.

The objective of these studies is not simply to demonstrate compliance with requirements, but to identify potential interactions between the facility and the power system before operation begins. Standardized study scopes, assumptions, models, and performance metrics can improve consistency, reduce uncertainty, as well as provide greater transparency for both large load developers and system operators. For more information on study types and scopes see the ESIG Large Loads Task Force report *Interconnection Processes for Large Loads: Current Practices and Recommendations*.[19]

In addition, to conduct these studies with needed accuracy, detailed high fidelity models of large load facilities are required accurately capturing grid impacts. For more information on modeling requirements see the ESIG Large Loads Task Force report *Large Load Modeling for Dynamic Studies: Current Practices and Recommendations*.[20]

Coordination of Protection and Load Shedding Schemes

As discussed above, large loads may influence the performance of protection systems, UFLS, UVLS, RAS, and other emergency control systems.

Appropriate coordination between facility protection systems and grid protection schemes is therefore essential. Facilities should be designed and operated such that their protection systems support overall system reliability objectives and do not inadvertently worsen disturbance conditions through unnecessary or poorly coordinated disconnections.

Consideration should also be given to post-disturbance restoration behavior and the interaction between facility controls and system recovery procedures.

Facility-Level Mitigation

While many mitigation measures are implemented through interconnection requirements and system studies, the most effective place to mitigate adverse load behavior is at the facility itself.

Modern large loads often possess sophisticated monitoring, control, and energy management capabilities. These systems can be used to reduce operational load profile variability, improve disturbance response, coordinate restoration actions, and limit adverse interactions with the power system.

It is important to note that these mitigation strategies can only be implemented if they are permitted within the interconnection process. Enabling such measures often involves coordination among multiple stakeholders and may require explicit requirements or incentives from the system operators.

Facility-level mitigation measures generally fall into three broad categories: software-based controls, hardware-level controls, and energy storage systems. Key strategies are discussed below.

[19] https://www.esig.energy/reports-briefs/large-load-interconnection-process

[20] https://www.esig.energy/reports-briefs/large-load-modeling

Software-Based Load Profile Smoothing

Software-based approaches seek to reduce the rate, magnitude, or frequency content of power fluctuations before they are reflected at the point of interconnection. Examples include workload scheduling, task distribution, power-aware computing algorithms and supervisory control systems that intentionally smooth facility demand. Another potential mitigation option is the introduction of a secondary, artificial workload to counteract fluctuations of the primary workload. These approaches are particularly relevant for data centers and other facilities whose power consumption is influenced by digital workloads.

While these approaches are flexible and require no hardware changes, they can introduce performance overhead on the primary workload due to resource contention for memory and compute. Furthermore, if the secondary workload is artificial, it results in wasted energy. Reliability can also be a concern, as software faults in the secondary process could potentially impact the primary training job and manifest themselves as rapid load reduction or forced oscillations on the grid.

Hardware-Level Controls (CPU/GPU and Rack-Level)

To address the challenges of software-only solutions, additional mitigation can be achieved through hardware-level controls that directly manage power consumption within the facility. These strategies allow large load facilities to stabilize power profiles and minimize grid impacts (Patel et al., 2024; NVIDIA, 2026; Geng, 2021; Choukse et al., 2025). The most common approaches include0:

- **Ramp rate controls:** These enforce a maximum rate of change for power-up and power-down sequences to reduce sudden power swings.
- **Minimum power floor (MPF):** This sets a minimum power level that the hardware will maintain during operation, effectively clipping the bottom of power swings. It is achieved by engaging internal power-consuming circuits when the workload's demand falls below the floor. This approach is highly reliable and introduces minimal performance overhead. But its primary drawback is wasted energy, as any power consumed to maintain the MPF above the workload's natural level is unproductive. Additionally, there may be limits to how high the floor can be set (e.g., 90% of thermal design power), which may not be sufficient to meet the tightest dynamic range specifications from some utilities.

Rack-level energy buffering: Battery back-up units at the rack level can be deployed to engage short-term energy storage during rapid load changes. Battery back-up units help maintain stability during transients, support latency-sensitive workloads, and reduce reliance on grid-side reserves.

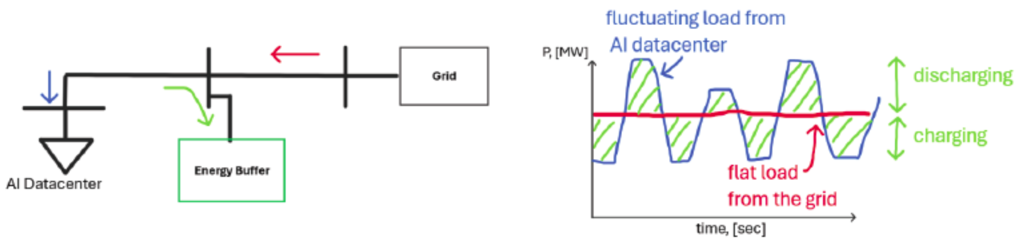
These measures may be particularly useful when software-based controls alone are insufficient to achieve desired performance objectives.

Onsite Energy Storage

Onsite energy storage systems provide another powerful mitigation option. Technologies like a battery energy storage system (BESS) (Tesla, 2025) and E-STATCOM (enhanced static synchronous compensator) (Kynev, 2025b; Siemens Energy, 2025) (a STATCOM with supercapacitors to provide very short-term storage, on the order of a few seconds) can absorb energy during the low-power communication phases of an AI workload and release it during the high-power computation phases. A conceptual illustration of this smoothing effect is shown in Figure 10, with a more detailed simulation in Figure 11. This both smooths the power profile seen by the grid and can reduce the facility's peak power demand. While this approach eliminates energy waste, it has the highest initial capital cost and requires physical space.

FIGURE 10

Effects of Energy Buffer



Conceptual system configuration with an onsite energy buffer.

Source: S. Kynev, "Application of E-STATCOM for AI Datacenters," presentation to Energy Systems Integration Group (Siemens Energy, 2025), https://www.esig.energy/wp-content/uploads/2025/03/Application-of-E-STATCOM-for-AI-datacenters-.pdf.

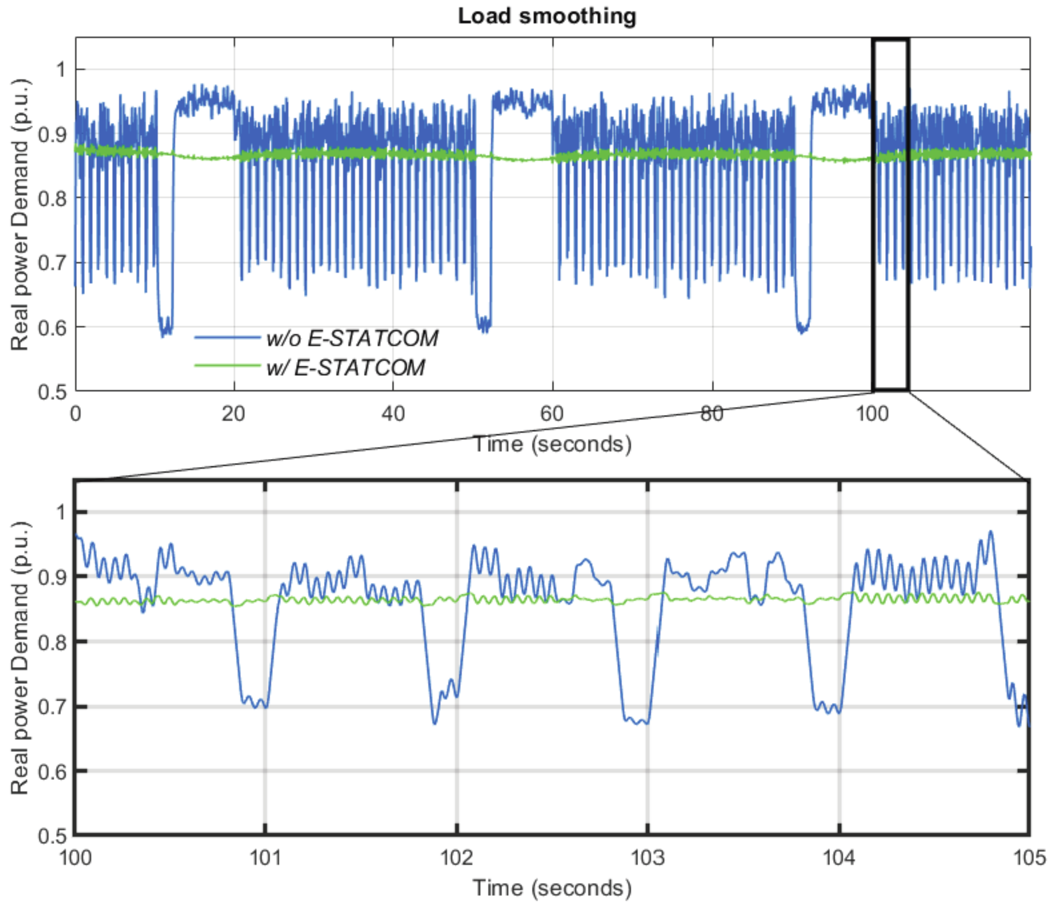
Two main control approaches are available for onsite BESS or E-STATCOM on the market:

Grid-forming control (GFM): The GFM control does not directly measure the load but instead reacts to phase-angle deviations caused by load fluctuations. This type of control responds extremely quickly but is only able to compensate for 40% to 60% of the load fluctuations. While this can reduce the issue, it does not fully resolve it (Dilley, 2025). The percentage of compensation depends strongly on the impedance split between the GFM inverter and the rest of the grid or nearby generators.

Load-following: In this approach, direct measurement of the load is used to provide precise compensation, achieving nearly 100% compensation. However, this control method relies on very rapid measurement and response times. The delay between a load change and inverter response must be within a few milliseconds in order to compensate for sub-synchronous levels of oscillation. This time delay includes load measurement, command setpoint for power, inverter internal processing delays, and, finally, current injection.

FIGURE 11

An Energy Buffer and Its Smoothing Effect



A PSCAD simulation showing the effect of an onsite energy buffer (e.g., E-STATCOM) on smoothing the real power demand seen by the grid. Plot (a) shows the full time series, and plot (b) provides a detailed view of the 100 to 105 second interval.

Source: S. Kynev, "Impact of AI Workload and E-Statcom as a Mitigation Measure," presentation to Energy Systems Integration Group (Siemens Energy, 2021), https://www.esig.energy/attachment/serve/session-7b-impact-of-ai-workload-and-e-statcom-as-a-mitigation-measure-sergey-keynev.

In addition to supporting facility operations, energy storage may help mitigate frequency impacts, oscillatory behavior, voltage fluctuations, and balancing challenges. Depending on system design and operating philosophy, storage systems may operate independently or in coordination with other facility controls.

A Combination Approach and Real-Time Protection

No single mitigation measure is likely to address every reliability concern discussed in this report. Given the trade-offs of each method, a solution involves a combination, co-designed approach. GPU-level power smoothing (via either hardware or software) can handle the slow-moving ramps associated with the start and end of a training job where the energy waste is temporary. Onsite energy storage is then used to handle the high-frequency, cyclical power swings during the job's steady-state operation, which it can do with high energy efficiency. Rack-level energy buffering using BBUs complements this approach by providing short-term energy storage directly at the rack, reducing stress on upstream systems and improving response to rapid transients. This combination minimizes energy waste while meeting both ramp rate and dynamic fluctuation requirements from the utility.

As a final layer of defense, a fast telemetry-based backstop system is recommended. This system would continuously monitor power waveforms in real time, using spectral analysis to detect the emergence of oscillations at dangerous frequencies. If a threatening oscillation is detected, the system can trigger a preplanned response such as throttling the workload or, in a critical scenario, initiating a controlled shedding of load to protect the grid (NERC, 2021).

Ultimately, the successful integration of large loads will require collaboration among facility developers, utilities, transmission operators, balancing authorities, regulators, equipment manufacturers, and other stakeholders. By combining appropriate technical requirements with robust facility design and operational practices, many of the risks identified throughout this report can be effectively managed while supporting continued growth of these important new categories of electrical demand.

Summary and Recommendations

Summary of Findings

Large loads introduce a range of reliability considerations that differ from those historically associated with conventional residential, commercial, and industrial demand. While the specific impacts vary depending on facility design, operating characteristics, and system conditions, many of the concerns discussed throughout this report can be traced to a small number of underlying behaviors, including insufficient disturbance ride-through capability, rapid changes in power consumption, repetitive power fluctuations, harmonic current injection, and interactions between facility controls and the power system.

A key finding of this report is that these behaviors can affect multiple aspects of power system operation simultaneously. For example, insufficient ride-through capability can contribute to frequency excursions as well as voltage stability concerns, altered power flows, protection system operations, and challenges during system restoration. Similarly, repetitive power fluctuations can create balancing challenges, forced oscillations, and increased mechanical stress on nearby generating equipment. As a result, effective mitigation strategies often address multiple reliability concerns at the same time.

Table 2 summarizes the principal large load behaviors and other considerations, their associated impacts on power system reliability and operation, and representative mitigation approaches. The purpose of the table is not to prescribe specific requirements, but rather to illustrate the relationship between facility behavior, system impacts, and commonly proposed mitigation measures.

TABLE 2

Summary of Large Load Behaviors and Other Considerations, Associated Impacts, and Representative Mitigation Measures

Large Load Behavior and Other Considerations	Impact	Mitigation
Insufficient ride-through capability	Sudden loss of large loads during a grid disturbance causes a severe generation-load imbalance, potentially leading to frequency excursions, voltage exceedances, thermal overloads and/or transient instability, potentially causing cascading outages.	Specify precise voltage-time and frequency-time ride-through curves the facility must withstand without tripping To prevent the load from worsening the initial fault, allow current-limiting or blocking to reduce power draw as voltage drops Establish active power recovery thresholds to quickly restore load following current-limiting or blocking Exclude or disable multiple disturbance counter–based disconnection logic

Large Load Behavior and Other Considerations	Impact	Mitigation
		Specify voltage-phase-jump withstand capability in line with IEEE and NERC requirements for inverter-based resources, as similar principles from grid needs perspective apply to large loads
High variability during normal operation	Unmanaged, rapid load changes during normal operations can overwhelm the grid's real-time balancing resources (e.g., regulation service), causing large frequency deviations (area control error (ACE)) that could lead to standard violations and the triggering of frequency-based protections. These changes also impact flows on the system, which can lead to voltage excursions that could result in voltage-level violations.	Identify the grid's primary tools for real-time balance—economic dispatch and the automatic generation control (AGC) frequency regulation service—and continuously evaluate the amounts needed for balancing Calculate a maximum load ramp rate that aligns with the grid's historical ramping capability (from generation) Set the limit that ensures the facility's maximum rate of change is aligned with the scale and timing of the grid's primary balancing resources, making its behavior predictable and manageable; the limit may need to be revised over time
Rapid, repetitive power fluctuations (oscillations)	High-speed digital controls can interact with the grid's natural frequencies, amplifying oscillations (negative damping). This can lead to sub-synchronous interactions with nearby controllers, catastrophic damage to generator shafts (sub-synchronous torsional interaction) or inter-area oscillations that can result in widespread system instability.	Restrict the injection of forced oscillations on the system Conduct studies to demonstrate that implementing limits on the amplitude and frequency of load level fluctuations results in acceptable grid performance
Injection of harmonic currents	Harmonic currents can cause voltage waveform distortion, equipment overheating, misoperation of protection, interference with control systems (phase-locked loops), and risk of harmonic resonance.	Enforce strict harmonic emission limits per IEEE Standard 519
Repetitive fluctuation in active and reactive power demand	Fluctuations in active and reactive power demand can cause voltage fluctuations at the point of common coupling can cause perceptible light flicker and must be mitigated.	Enforce strict voltage short-term and long-term flicker emission limits per IEEE Standard 1453
Reactive power capability	Large loads with significant reactive power demand can increase stress on local transmission systems; reduce voltage stability margins; delay post-disturbance voltage recovery; and	Establish reactive power capability requirements Require dynamic voltage support performance Based on system needs, specify voltage control and reactive power control modes

Large Load Behavior and Other Considerations	Impact	Mitigation
	increase reliance on generators, dynamic reactive devices, and other system resources for voltage support.	Verify performance through studies and testing
Disturbance-driven restoration and recovery behavior	Rapid or poorly coordinated load restoration following disturbances may create balancing challenges, frequency excursions, voltage impacts, and operational difficulties during system recovery.	Specify post-fault active power recovery expectations, restoration ramp rates, and coordination procedures with system operators
Modeling	Insufficient representation of large load behavior may result in inaccurate predictions of large load disturbance response, oscillations, voltage performance, power quality impacts, and system interactions, reducing confidence in planning and operational studies..	Require large load facilities to provide appropriate high-fidelity static, positive-sequence phasor-domain (PSPD), harmonic, and electromagnetic transient (EMT) models; along with accompanying high-resolution load profiles Develop and apply model validation, quality testing ,and verification requirements
Studies	The failure to adequately evaluate large load behavior may result in unidentified stability, oscillatory, protection, balancing, and power quality risks, increasing the likelihood of unexpected reliability issues following large load interconnection.	Require the interconnection process to include a standardized set of steady-state, short-circuit, and dynamic studies as well as advanced studies including system strength assessments, sub-synchronous oscillation assessments, harmonic analysis, and switching studies
Monitoring	Insufficient visibility into facility behavior may prevent early identification of oscillations, abnormal disturbance response, rapid load changes, and power quality issues, increasing the likelihood that reliability concerns remain undetected until they affect system operations.	Require monitoring equipment that can stream and record high-fidelity data to support real-time assessments and offline analyses Require specific retention and sampling rate capable of capturing high-frequency oscillations At a minimum, implement monitoring requirements consistent with NERC PRC-028 requirements for inverter-based resources

Source: Energy Systems Integration Group.

As shown in the table, many reliability concerns associated with large loads arise from a relatively small number of behaviors. Consequently, mitigation strategies that improve disturbance performance, limit rapid power fluctuations, enhance visibility into facility operation, and provide predictable system response can simultaneously address multiple categories of reliability risk.

Recommendations

To ensure a secure and reliable grid, the following consolidated recommendations from the ESIG Large Loads Task Force integrate performance-based requirements, operational protocols, and physical infrastructure standards. The recommendations are organized by decision-maker group.

For Grid Operators and Planners

- Develop a clear understanding of the dynamic behavior of large loads and incorporate that behavior into planning and operational studies
- Evaluate disturbance-driven load loss as an explicit contingency category in addition to traditional generation-loss scenarios
- Expand study practices, where appropriate, to include dynamic performance, oscillatory behavior, harmonic impacts, and converter-driven interactions
- Consider ride-through capability, restoration behavior, oscillation performance, and power quality impacts during the interconnection process
- Develop comprehensive performance and modeling requirements as well as conformity assessment and testing requirements to prevent adverse grid impacts from large loads
- Review assumptions used in protection coordination, under-frequency load shedding, under-voltage load shedding, and remedial action schemes to ensure they remain appropriate as large load penetration increases
- Expand monitoring capabilities, including disturbance monitoring and oscillation detection, in areas experiencing significant large load growth
- Improve coordination among transmission operators, balancing authorities, distribution providers, and large load developers throughout the facility life cycle

For Large Load Developers and Facility Owners

- Engage with utilities and system operators early in the development process to ensure alignment of technical performance requirements and operational expectations
- Design facilities with robust disturbance ride-through capability and predictable restoration behavior
- Evaluate and mitigate rapid power fluctuations, oscillatory behavior, harmonic emissions, and other power quality impacts during facility design
- Consider facility-level controls, workload management strategies, and energy storage systems (e.g., BESS, E-STATCOM) that can reduce adverse interactions with the power system
- Develop and provide sufficiently detailed facility models (both in PSPD and EMT) and performance information to support accurate system studies; model certification and validation against as-built performance, as per system operator requirements, should be a prerequisite for continued operation

- Develop a change management process to ensure that any material facility modifications are reflected in the latest models provided to system operators
- Incorporate cybersecurity and operational resilience considerations into facility design and operational practices
- Maintain ongoing coordination with system operators as facilities expand, equipment is upgraded, or operating characteristics change

For Industry Organizations, Standards Bodies, and Researchers

- Continue development of guidance related to modeling, performance assessment, and monitoring of large loads
- Improve understanding of oscillatory behavior, converter-driven interactions, and impacts on synchronous generators
- Improve understanding of capabilities of synchronous generators to withstand exposure to small but prolonged forced oscillations
- Develop standardized approaches for evaluating load-induced oscillations, restoration behavior, and disturbance performance
- Share lessons learned from operating experience and disturbance investigations to improve industry understanding of emerging risks
- Continue evaluating whether existing reliability standards, planning practices, and interconnection processes adequately address future large load deployment scenarios

Appendix: Simulation Methodology and Parameters

The simulation results presented in this report (Figures 2, 3, and 4) were generated using an EMT software package to demonstrate the fundamental interactions between fluctuating loads and the power system. This appendix outlines the general methodology. Site-specific studies would require detailed, validated models.

Network Model

The studies were based on a simplified single-machine infinite-bus (SMIB) system, a standard benchmark for dynamic stability analysis.

- **Generator model:** A standard synchronous machine model with governor and exciter controls was used. Key parameters were chosen to be representative of a conventional steam turbine unit (e.g., inertia constant H ≈ 3 s to 5 s, transient reactance $X_d^{'}$ ≈ 0.2 pu to 0.4pu).
- **Transmission system:** The grid was represented by a transmission line with variable impedance to simulate different SCR conditions. SCR was calculated at the point of interconnection of the large load.
- **Large load model:** The data center load was modeled as a controlled current source capable of producing specified power fluctuations (step changes, ramps, and sinusoidal variations).

Metric Definitions

- **Ramp rate (*dP/dt*):** This metric is calculated as the change in active power over a specified time interval (e.g., 100ms).
- **Flicker severity (P_{st}):** This metric is calculated according to the methodology defined in IEC 61000-4-15 and referenced in IEEE Standard 1453.

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Reliability Impacts of Large Loads

A Report by the Energy Systems Integration Group's Large Loads Task Force

This report is available at https://www.esig.energy/resources/reports-and-briefs/.

To learn more about the ESIG Large Loads Task Force and the recommendations in this report, please visit https://www.esig.energy/working-groups/large-loads/ or send an email to info@esig.energy.

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. More information is available at https://www.esig.energy.